A FAUNAL ANALYSIS OF SOUDLEYAN/LONGVILLIAN ROCKS IN SNOWDONIA, NORTH WALES

DAVID KENNETH WRIGHT B.Sc. (Hons.)

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"Time dissolves all things,
and makes them old."

Aristotle. *Physica* Bk.iv, Ch.12, sec.12

"We are as much gainers by finding
a new property in the old earth
as by acquiring a new planet."

Ralph Waldo Emerson

Representative Men : Uses of Great Men

Dedicated to my
mother and father

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D.K.WRIGHT

Since the pioneering work in the middle nineteenth century by Sedgwick, Sharpe, Ramsay and Salter, amongst others, on the geology of North Wales, the faunas of Snowdonia have received but scant treatment, falling in the shadow of the progress achieved in the structural and volcanological fields. Sampling of numerous fossil localities from selected areas within Snowdonia has revealed the faunas to be relatively diverse, consisting of numerous brachiopods, trilobites and crinoids, in addition to bivalves, gastropods, ostracodes, bryozoans, algae, corals, cephalopods, cystoids, graptolites, cricoconarids, cyclocystoids and machaeridian plates. Tectonic deformation coupled with poor preservation frequently negates accurate identifications. Fossil distortion resulting from tectonic deformation is capable of producing serious difficulties regarding identification and this problem is treated in some detail.

The Snowdonian faunas are closely comparable with Caradoc (Upper Ordovician) faunas from Shropshire, the Berwyn Hills and the Bala area, whilst the proposed Snowdonian benthic marine communities appear remarkably similar to those erected in the latter two areas. Associated sedimentary structures and faunal occurrence types aid in both elucidating palaeoenvironments and a general palaeogeography for the region. Within most sampled assemblages, the aforesaid occurrence types and valve orientations, with additional opposing brachiopod valve and articulation ratios, suggest little significant net lateral transport with minimal faunal mixing.

All the Snowdonian faunas are Caradoc in age, the brachiopods and trilobites in particular implying assignment to the Soudleyan and Longvillian Stages. On the basis of fossil evidence, correlations are proposed between all the sampled sequences in Snowdonia and for the Dolwyddelan area. Faunal data provide the following conclusions (amongst others) :-

a) The Snowdon Volcanic Group is confined to the Longvillian Stage.

b) The Crafnant Volcanic Group appears restricted to the Upper Longvillian Stage.

c) The Upper Glanrafon Beds range from the Harnagian - Lower Longvillian Stage.

d) An unconformity seems present below the Crafnant Volcanic Group.

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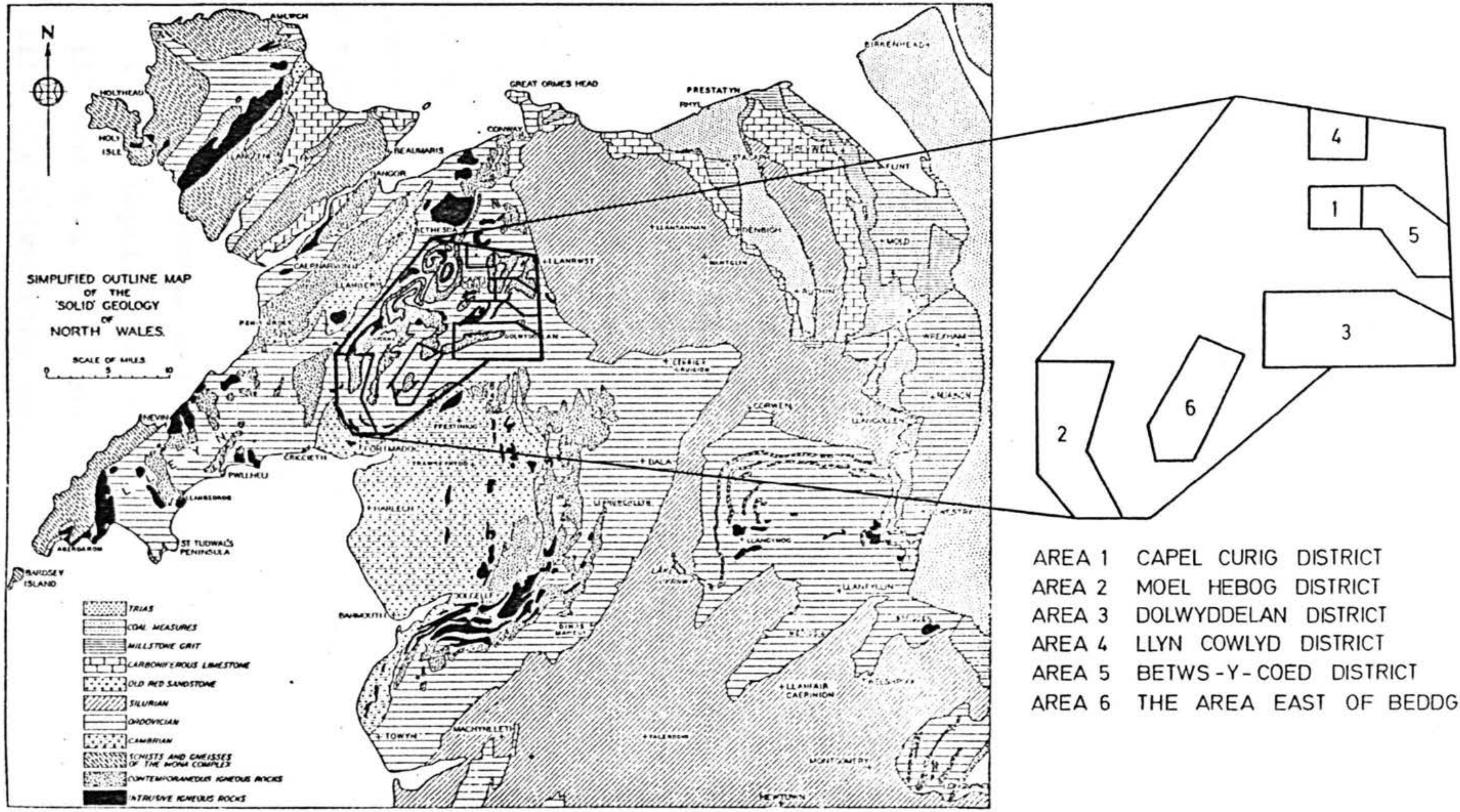
FIG. 1.1 A SIMPLIFIED OUTLINE MAP OF THE GEOLOGY OF NORTH WALES SHOWING THE RELATIVE POSITION OF THE RESEARCH AREA AND THE SUBAREAS SAMPLED WITHIN THIS AREA.
NOTE : THE OUTCROP OF THE CONTEMPORANEOUS IGNEOUS ROCKS WITHIN THE RESEARCH AREA AS SHOWN ON THE MAP IS ONLY APPROXIMATE



AREA 1 CAPEL CURIG DISTRICT
AREA 2 MOEL HEBOG DISTRICT
AREA 3 DOLWYDDELAN DISTRICT
AREA 4 LLYN COWLYD DISTRICT
AREA 5 BETWS-Y-COED DISTRICT
AREA 6 THE AREA EAST OF BEDDGELERT

Chapter 1 Introduction

a) General remarks

The research area comprises over 400 sq.kms. of Upper Ordovician rocks (Caradoc Series) in Snowdonia, North Wales, and encompasses a variety of sedimentary and volcanic facies.

Two major sequences are present:-

i) a sedimentary sequence, including conglomerates, breccias, sandstones, siltstones, shales and thin, intercalated rhyolitic tuffs, collectively termed the Glanrafon Beds (= Glanrafon Group).

ii) a volcanic sequence, including ignimbrites, sillar tuffs, bedded waterlain tuffs, lapilli tuffs, vitric, crystal and lithic tuffs, agglomerates, basaltic flows and rhyolites, with intercalated conglomerates, breccias and sediments, collectively termed the Snowdon Volcanic Group. In eastern Snowdonia, a contemporaneous volcanic sequence is termed the Crafnant Volcanic Group.

Both volcanic sequences are conformably overlain by a sequence of black, occasionally graptolitic slates, variously termed the Nod Glas Black Shales and the Black Slates at Dolwyddelan, and the Llanrhychwyn Slates (Davies 1936) at Betws-y-Coed.

The research area is divided into subareas (fig.1.1):-

i) the Capel Curig area
ii) the Moel Hebog area
iii) the Dolwyddelan area

iv) the Llyn Cowlyd area

v) the area around Betws-y-Coed

vi) the area east of Beddgelert

Most of Snowdonia is well over 300m.(1000 ft.) O.D., being dominated by Yr Wyddfa (Snowdon) at 1085m.(3560 ft.) O.D. . The area was subjected to extensive glacial action during the Pleistocene, several valleys undergoing modification by glaciers (Nant Ffrancon valley, Llanberis Pass, the Glaslyn valley,etc.). Cwms were consequently scoured out, which are now filled by lakes, e.g., Llyn Idwal, Llyn Llydaw, Glaslyn,etc. . Since the time of Darwin, Snowdonia has been regarded as a classic study area for many glacial phenomena.

Exposure is adequate on the higher ground,but becomes sporadic on the lower slopes,mainly due to thick coverings of peat. Recent dense afforestation of certain locales (e.g.,Dolwyddelan and Betws-y-Coed) has made some areas virtually inaccessible.

b) Aims

A faunal analysis of the Caradoc sediments is attempted as the Snowdonian faunas are generally only poorly known, all earlier works concentrating mostly on the general geology and structural/volcanological aspects. The associated sediments are also examined, although detailed petrological and petrographical work is not undertaken.

The research aims are to attempt :-

i) a detailed faunal analysis

ii) to recognise, if possible, discrete benthic marine communities and assign the faunas to such communities.

iii) to demonstrate possible faunal control by lithofacies.

iv) to examine and interpret the sediments, and any sedimentary structures, associated with the fauna.

v) to examine the orientation and mode of occurrence of the component fossils.

vi) From i), ii), iii), iv) and v), to postulate a possible palaeogeography and palaeoenvironments.

vii) to date, from faunal evidence, the Glanrafon Beds, Snowdon Volcanic Group and Crafnant Volcanic Group, with respect to Caradocian stages.

viii) following from vii), to postulate certain spatial correlations.

This project follows on from the work of Diggens & Romano (1968), Romano & Diggens (1969) and the Institute of Geological Sciences, e.g., Francis & Howells (1973) and Howells et al. (1973).

Comparable studies have been undertaken in the Bala area by Bassett et al. (1966), Whittington (1962, 1965, 1966, 1968), Williams (1963) and in the south Berwyn Hills by Pickerill (1974).

Chapter 2 History of Research

Active research on the geology of the Ordovician (Caradocian) rocks of Snowdonia was initiated in the nineteenth century, the earliest recorded work being by Adam Sedgwick, who, by 1831, had traced out the Snowdon syncline and had performed a traverse from the Nant Ffrancon Pass - Penmachno. In a written communication to Murchison in 1832, Sedgwick stated he was sure that "....the porphyritic system of Snowdonia" was overlain by "....the black shelly limestone of the Berwyns and Bala". The term "Caradoc" was first used by Sedgwick (1838,p.679) and Murchison (1839) in describing strata near Caer Caradoc, Shropshire, which had previously been described as Horderley and May Hill Sandstone (Murchison 1834,p.14). Indication as to the future tripartite division of the Lower Palaeozoic came when Sedgwick (1838,p.679;1843,p.221, 223) noted Upper Cambrian beds (including the fossiliferous Bala Beds) yielded fossils "....identical in species with those of the lower division of the Silurian System"(1838, p.679), a fact confirmed by Bowman in 1840 (Ramsay 1866). Snowdonian faunas were also briefly described by Sedgwick (1838,p.679;1841;1843,p.219,220).

Faunal evidence and stratigraphical relationships prompted Sharpe (1843,p.13) to conclude the Bala Beds were Lower Silurian. He later disputed (Sharpe 1846) the interpretation of Sedgwick for the Snowdon area, stating "....There is consequently a synclinal axis on the west of

Cynicht (sic.) and an anticlinal axis in the centre of Snowdon" (op.cit.,p.292;section 3,p.292) and noted "....but few" (Caradoc) "fossils" from the aforesaid synclinal core, in addition to fossils to the east and west of this axis. The Snowdonian rocks were assigned to the Lower Silurian (see sections,p.292) although Sharpe believed the central area consisted of the oldest rocks (op. cit.,p.298).

The area around Tremadoc was documented by Davis(1846) who referred the few organic remains found to the Silurian System (op.cit.,p.74). Sharpe (1847,p.91,92,fig.18) later demonstrated that cleavage dips increased westwards from Ffestiniog to near verticality just west of Snowdon. That same year, Sedgwick(1847) classified the "Fossiliferous Slates" (op.cit.,p.133) of North Wales and other areas into three. The "Orthidian" or "Snowdonian Group" (op.cit., p.157) "....is seen in the crests of the Caernarvon chain, in the chains of Arrenig(sic.), Arran Mowddwy and Cader Idris"(op.cit.). The "....fossiliferous bands of Snowdon, Moel Hebog and Llyn Ogwen"(op.cit.) were included within this Group, which was placed below the "....Upper Cambrian slate Group, or the Trilobite Group, or (geographically) the Bala Group"(op.cit.,p.158) and above the "....Festiniog(sic.) or the Tremadoc Group" (op.cit.,p.157). Furthermore, Sedgwick listed fossils from the areas around Llyn Ogwen, Snowdon and Moel Hebog (op.cit.,p.138) as well as fossils from sediments beneath the volcanic rocks on Moel Hebog and Moel Ddu (op.cit.,p.141).

In 1848, mapping within Snowdonia was initiated under the direction of Andrew Ramsay. The survey results (Ramsay 1853) demonstrated that "....No truly interstratified or contemporaneous traps occur between Moel-wyn(sic.) and the Snowdon feldspathic trap, which is 6000 feet by measurement above those of Moel-wyn"(op. cit.,p.165). The "Moel-wyn traps" were stated to "....have entirely thinned away underground" (op.cit.,p.167), thus producing the earlier, erroneous correlations between the "Snowdon" and "Moel-wyn traps". A three-fold division was implemented for the "Snowdon trap" : a lower feldspathic trap; 1000 feet of "....calcareous, sandy and feldspathic ashes"(op.cit., p.165); an upper columnar feldspathic trap. Fossils from the ashes were similar to those from the Bala Limestone and their equivalence was postulated. The "Snowdon trap" had been traced west of Llyn Ogwen, and to the north, around Llyn Cowlyd and Llyn Crafnant(op.cit.,p.166), where fossils conclusively proved correlation with the "Snowdon trap" (op.cit.). However, what is now the Capel Curig Volcanic Formation (Howells et al.1978) was included within the "Snowdon trap" (Ramsay 1853,p.166), although the "traps" of Glyn Lledr (= Capel Curig Volcanic Formation) were shown to underlie the traps of Dolwyddelan and Betws-y-Coed (see section,p.166). In addition, the calcareous ashes of the Dolwyddelan valley were considered "....precise equivalents of the Snowdon rock of the same kind" (op.cit.,p.167) and of the Bala Limestone.

1866 saw the publication of the Survey Memoir on the geology of North Wales, with the text written by Ramsay, along with a palaeontological appendix by Salter, followed by a second edition in 1881. This memoir is still regarded as one of the definitive works on Snowdonian geology. Further intimation as to the future Lower Palaeozoic tripartite division was made by Ramsay (1866,p.6) where he stated,

"....In 1853 Mr.Salter examined the fossils of the district" (Bala) "on the ground, and determined that they were generally identical with those of the Caradoc Sandstone. Caradoc Sandstone and Bala Beds are, therefore, equivalent terms, the former ever since the publication of "The Silurian System" in 1839, having been used to express the higher part of the Lower Silurian Series, while in 1838, the name of the Bala Beds for equivalent strata was used by Professor Sedgwick to express the higher parts of the Cambrian Series at that time, and for several years after, generally believed to be older than any formation of Silurian age".

Lapworth (1879a) proposed a threefold division of the Lower Palaeozoic rocks in North Wales, with Sedgwick's Upper Cambrian Division and Murchison's Lower Silurian Division being termed "Ordovician", which comprised "....strata included between the base of the Lower Llandovery Formation and that of the Lower Arenig" (op.cit., p.14). Lapworth(1879b) later subdivided the Ordovician into three, the Upper Division (Caradoc) comprising the Hirnant and the Bala Series of North Wales.

Harker (1889) in an essay on the Bala Volcanic Series, commented on the petrography of the Snowdonian lavas, amongst others, and differentiated the "lavas" found at different levels in Caernarvonshire, e.g.,

(e) Upper Snowdon lavas
(d) Lower Snowdon lavas
(c) Y Glyder Fach, Capel Curig and Conway Mountain lavas
(b) Pen-yr-Oleu Wen and Carnedd Llewellyn lavas
(a) Dwygyfylchi and Y Drosgl lavas

The Moelwyn Volcanic Series at Blaenau Ffestiniog were described by Jennings & Williams (1891) as a series of pyroclastics and thick acidic lava flows, whilst both Muggë (1893) and Geikie (1897) described the rhyolites, andesites and interbedded felsites of Snowdonia.

Dakyns (1900) was the first worker to record the fragmentary nature of the Lower Rhyolitic Series and with Greenly (1905) demonstrated that the "Felsitic Slates" were composed of fine volcanic dust, probably being deposited in a manner analogous to the Mont Peleé dust cloud eruption in 1902. This was the first indication that the Snowdonian "rhyolites" were pyroclastic in origin.

Didymograptids from the northern side of Snowdon proved to Fearnsides (1903,p.665) that Llanvirn beds underlay the Snowdon Volcanic Series, placing doubt on their accepted Bala (Upper Ordovician) age.

Regarding the age of the Snowdonian rocks, Fearnsides (1910a) noted that :-

a) Near Tremadoc,"....typical Glenkiln beds with *Coenograptus*" (=*Nemagraptus*) (op.cit.,p.797) "....are overlain by the earliest ashes of the Snowdonian series (op.cit.) (= Y Glog Volcanic Group - Shackleton 1959).

b) Sediments between Tremadoc and Moel Hebog and to the north of Ffestiniog yield "....a scanty trilobitic fauna not unlike that of the Lower Caradocian. They overlie the upper Glenkiln shales with *Climacograptus peltifer* and are overlain by the main Snowdonian rhyolites" (op.cit.,p.798).

c) At Criccieth and Dolwyddelan,"....sooty, black shales quite like the Hartfell Shales of Scotland" (op.cit., p.799), overlie the volcanic rocks. The shales "....are crowded with *Diplograpti* which mark a very low horizon in the Hartfell succession, and which when more definitely described will enable the exact horizon of the Snowdonian Series to be determined"(op.cit.).

That same year, Fearnsides (1910b) published a comprehensive account of the geology around Tremadoc and included (op.cit.,section 8,p.166-176) lithological and palaeontological descriptions of those units now termed Tyddyn - dicwm Beds, Portreuddyn Slates and Pren - teg Grits (Shackleton 1959). The "Andesitic Volcanic Rocks" (Fearnsides 1910b,p.173-175,plates XV,XVII) are now termed the Y Glog Volcanic Group (Shackleton 1959) although "....a fourth range of andesitic ashes and agglomerates" (op.cit.,p.175) corresponds to the Pren - teg Grits.

Between 1922 - 1931, four crucial papers on Snowdonian geology appeared. Williams (1922) described the "igneous" rocks of the Capel Curig anticline, and subsequently published (Williams 1927) a masterful paper entitled "The geology of Snowdon", in which he described the sedimentary and volcanic sequences (plus associated faunas), the intrusive rocks and the tectonics. Williams (op.cit.) stated that the faunas resembled lower Caradoc faunas from Bala and that furthermore, the volcanic series ranged from the upper part of the *N.gracilis* zone (middle Llandeilo) to the *D.clingani* zone (middle Caradoc). Williams (op.cit.,p.364) also reasoned that the Pitt's Head lavas were subaqueously emplaced. David Williams' (1930) account of the geology of the country between Nant Peris and Nant Ffrancon included descriptions of the Caradocian Gwastadnant Grits and Snowdon Volcanic Series and their associated faunas. He suggested (op.cit.,p.208) that fauna from the Bedded Pyroclastic Series afforded comparisons with lower Caradoc faunas from Bala, and later stated that "....the exposed Snowdon volcanic suite is probably between Upper Llandeilo (Zone of *Climacograptus peltifer*) and Middle Caradoc in age" (op.cit.,p.229). Within the Dolwyddelan syncline, Williams & Bulman (1931) described a middle Caradoc shelly fauna (op.cit.,p.431) from the Glanrafon Beds and a middle Caradoc graptolitic fauna (*Dicranograptus clingani* zone) from black slates which conformably overlie the Snowdon Volcanic Series in the synclinal core. Faunal evidence suggested (op.cit.) that the Snowdon Volcanic Series represented the lower part of the D.clingani Zone, whilst mapping revealed the characteristic basal member of the Lower Rhyolitic Series, namely the Pitt's Head Rhyolite, was absent.

On the basis of the Shropshire Caradocian faunas, Bancroft (1929a) subdivided the Caradoc Series into three Stages,i.e., the Soudleyan, Longvillian and Marshbrookian, but later implemented a seven-fold division, namely the Girvanian, Harnagian, Soudleyan, Longvillian, Marshbrookian, Actonian and Onnian (Bancroft 1929b). Bancroft (1933) later replaced the Stage name "Girvanian" with "Costonian" and made a brief correlation, from faunal evidence, between the Bala and Capel Curig successions,e.g., the lower part of the Gallt-yr-Ogof lava = Frondderw Ash of Bala, the overlying slates = the Allt Ddu Mudstone, and the Upper Lava = the Pont-y-Ceunant Ash (op.cit.,p.3).

Davies (1936) described the Ordovician rocks from the Trefriw district and noted an abundant shelly fauna from the Glanrafon Grits (op.cit.,p.69) but considered "....long range forms" did not allow exact age determinations (op.cit.). The graptolitic Llanrhychwyn Beds were concluded (op.cit.,p.77-80) to be lower Caradoc in age (Climacograptus wilsoni Zone), thus confirming earlier work by Sherlock(1918) who discovered graptolites indicating the Amplexograptus arctus Zone (lower Caradoc - Skevington 1969) from Trefriw. The Glanrafon Beds were correlated with the Glanrafon Beds at Dolwyddelan and with the Glanrafon Slates and Gwastadnant Grits of Snowdon whereas the Crafnant Volcanic Series were thought, probable lateral equivalents of the Snowdon Volcanic Series (op.cit., p.85-86). Davies (op.cit.,p.86) believed the Crafnant Volcanic Series to be Llandeilian, thus conflicting with the proposed middle Caradoc age for the Glanrafon Beds at Dolwyddelan.

Bancroft (1945) discussed, in part, the stratigraphy and faunal delimitation of the Costonian - Onnian Stages of the Caradoc and the following year, Lamont (1946) published details of Bancroft's work in the Capel Curig area, who had subdivided the area into zones, corresponding to the Caradocian Stages. Zone six (= Lower Longvillian), a brown calcareous ash, "....is clearly the Gelli Grîn correlate, as it contains Platylichas above Twll Ddu" (op.cit.,p.236).

The stratigraphy of the Moel Hebog district was documented by Shackleton (1959). The graptolitic Lower Glanrafon Beds were assigned to the N.gracilis zone (op. cit.,p.230-232), whereas shelly faunas from the Upper Glanrafon Beds suggested a Harnagian - Soudleyan age range. Shelly faunas from the upper horizons of the Lower Rhyolitic Tuffs and from the Lower Basic Tuffs implied an Upper Longvillian age (op.cit.,p.240).

Beavon (1960,1963), in a geological synthesis of the area east of Beddgelert, briefly described possible Soudleyan faunas from the Glanrafon Beds (1960,p.29;1963, p.486) and the Croesor Slates (1960,p.24;1963,p.487). A nodular limestone from the Middle Basic Series yielded trilobites suggesting an Upper Longvillian age (op.cit., 1960,p.106;1963,p.497) and lateral equivalents of the Snowdon Volcanic Series were proven to overlie Soudleyan sediments. Beavon (1963,p.494) stated that within the Lower Rhyolitic Series, the welded tuffs were subaerially emplaced, whereas the bedded tuffs were subaqueously deposited.

Rast et al.(1958) and Beavon et al.(1961) recognised some of the Snowdonian "rhyolites" as ignimbrites (welded tuffs) which they defined as the products of nuée ardentes, thus indicating subaerial deposition. Both the Pitt's Head Tuffs (I.G.S. Special Sheet, Central Snowdonia,1:25000,1972) and the lower horizons of the Lower Rhyolitic Tuff were demonstrated to be ignimbrites which Rast (1962) postulated were derived from magmatic blisters. The previous year, Rast (1961), from detailed mapping just north of Beddgelert, provided evidence for intra-Caradocian tectonic activity, which he related to the formation of the aforesaid blisters.

From this time until the present day, numerous works wholly or partly concerning various aspects of Snowdonian geology, namely the fauna, the intrusive rocks, the sediments and their probable provenance, the volcanic rocks and the structure and tectonics, have been published by several authors,e.g., Bassett et al.(1966), Brenchley (1969), Bromley (1965,1968,1969), Cave (1965), Dean (1965), Diggens & Romano (1968), Fitch (1967,1971), Floyd et al. (1976), Francis & Howells (1973), Howells et al.

(1971,1973,1978), Rast (1969), Roberts (1969), Romano & Diggens (1969), Stevenson (1971) and Wright & Coward (1977).

Chapter 3 Tectonic deformation in Snowdonia and its relationship to faunal analysis : problems and possible solutions

a) Introduction

Two factors preclude accurate identification of the components of the shelly faunas :-

1) Imperfect preservation
2) Tectonic deformation

Tectonic deformation is perhaps more important, as it often prevents speciation (especially within the sowerbyellid and dalmanellid brachiopods) and also frequently prohibits comparisons with Caradocian faunas elsewhere.

The problems encountered in studying tectonically deformed fossils are examined, as are the factors governing the degree of fossil deformation. To serve as a framework for fossil deformation in Snowdonia, the overall structural pattern in the area is briefly summarised.

Standard methods, utilizing distorted fossils, exist for calculating the values and orientations of the principal elongations, in addition to methods which compute the original ratios of mutually perpendicular dimensions of bilaterally symmetrical fossils, e.g., the ratio of the hinge and median line lengths in brachiopods, etc., (Breiddin 1956; Lake 1943; Ramsay 1967, p.240 - 243;

Sdzuy 1966; Wellman 1962). The Analogue Video Reshaper (AVR) can remove the affects of shear from distorted fossils (Appleby & Jones 1976,p.574). However, the example figured (the Tremadocian trilobite <u>Angelina</u>) comes from a locality where cleavage is parallel to bedding and how well the AVR would function using distorted material from localities where cleavage is oblique to bedding remains to be seen.

Two methods are proposed to calculate the original dimensions of bilaterally symmetrical fossils. The first concerns computation of the original lengths of mutually perpendicular parameters, which is restricted to fossils within planar faunal occurrence types (chap. 5,section b, iii). Deformation is assumed to be predominantly due to simple (rotational) shear with no significant volume change.

The second method can be applied to planar and random occurrence types (chap. 5,section b,ii and iii) within argillaceous sediments (i.e., average grain size < 0.0625 mm., Pettijohn 1975; Pettijohn et al. 1972). Deformation is assumed to result from pure (irrotational) shear. Other factors considered include pretectonic compaction, decalcification, the development of slaty cleavage, etc..

b) The problems encountered with tectonically deformed faunas

The chief problem is one of identification. The major components of the Snowdonian shelly faunas are sowerbyellid and dalmanellid brachiopods, whose speciation is now based on statistical methods (Williams 1963,1974). When dealing with tectonically deformed brachiopods, such methods become invalid, particularly with heterogeneous strain, as the brachiopod parameters are variably orientated with respect to the X, Y and Z axes of the strain ellipsoid. These parameters subsequently become variably distorted, thus negating accurate speciation of the brachiopods. Parameters including the relative width and depth of the brachial valve, the relative length of the dorsal adductor scars, the relative depth of the pedicle valve, etc., are employed to speciate Howellites (op.cit.). Similar statistical parameters differentiate species of Sowerbyella (op.cit.). Romano & Diggens (1969, p.603) state "....As the speciation of these brachiopods is now based largely on statistical methods (Williams 1963), the authors found it very difficult to obtain a satisfactory statistical comparison of the Dolwyddelan forms with those redescribed by Williams, owing to the deformed nature of the specimens", a statement supported by the author.

Tectonic deformation greatly modifies gross morphologies, e.g., valve dimensions are changed, valve convexity and concavity may be altered, etc.. External ribbing may become coarser or finer, dependent on the valve orientation with respect to the direction of maximum finite elongation. Ribbing parallel to this direction becomes apparently finer, whereas ribbing normal to this direction becomes apparently coarser (fig.3.1; plates 3.1, 3.2). Tectonic "rugae" may result from compression of non-rugose valves, whilst pre-existing rugae may become accentuated or diminished. Individual valves occasionally display unequal distortion (plate 3.3), probably due to a greater posterior thickness of shelly material which would be relatively resistant to tectonic deformation. Furthermore, this feature may imply that deformation occurred before before the original shelly material had been lost. Tectonic deformation consequently makes differentiation between closely related brachiopod genera extremely difficult (see chap.4).

Deformation within the trilobites produces similar problems. Certain easily recognisable, characteristic features often alleviate identification problems, even when a specimen is severely deformed, e.g., four pit rows within the cephalic fringe of Broeggerolithus, the glabellar lobes of calymenids and general cephalic morphology, e.g., Kloucekia, Chasmops, Estoniops, Brongniartella and Platylichas. However, certain features utilized for speciation become invalid when studying deformed specimens, a fact exemplified by examining the speciation of Broeggerolithus Lamont 1935, after Dean

(1960a).

Dean (op.cit.,p.103) subdivides this genus into three groups. Group One possesses a cephalon which is much shorter than broad, as does Group Two, along with well-developed interradial ridges, the E_1 pit row becoming elevated. Group Three is characterised by a proportionately longer cephalon, with a long, high glabella.

The glabella of *B.harnagensis* (Bancroft) is clavate, swollen anteriorly and not greatly elevated above the cheek lobes (op.cit.,p.105). *B.*cf. *broeggeri* (Bancroft) differs from *B.broeggeri* in possessing a relatively longer cephalon, a feature similarly distinguishing *B.constrictus* (Bancroft) from *B.broeggeri*. *B.globiceps* (Bancroft) is discriminated from *B.broeggeri* by a longer, rounded cephalon and conspicuous tumid glabella (op.cit.,p.119), whilst *B.longiceps* (Bancroft) possesses a long, high glabella (op.cit.,p.121). It is differentiated by its larger form and more rounded cephalon from *B.simplex* Dean (= *B.nicholsoni* (Reed) - Dean 1962; Hughes et al. 1975). A shorter, anteriorly swollen glabella (Dean 1960a,p.126) distinguishes *B.transiens* (Bancroft) from *B.longiceps*. Once tectonically deformed, these distinguishing features become invalid.

For such cryptolithines, a statistical approach as advocated by Hughes (1970) may ultimately provide the best means for speciation. Half-fringe data is employed (op. cit.), although deformation and the degree of preservation may generate "operator error" when selecting the mid-line of the cephalic fringe (op.cit.,p.4,8).

Dean (1963a), in discussing Flexicalymene cf.acantha Bancroft states "....Such differences as exist, for example, degree of inclination of the anterior border, straightening of the normally convex margins of the glabella, and variation in the shape of the frontal glabellar lobe, could well be the result of mechanical deformation and it is not proposed to regard them as distinct from F.acantha " (op.cit.,p.217), whereas Whittington (1965,p.58-62) emphasises deformation and preservation control the morphology of calymenids.

Tectonic deformation and imperfect preservation of other, less numerous groups (e.g.,ostracodes, bivalves, gastropods, etc.) present similar identification problems.

c) Factors determining the degree of fossil distortion

The degree of fossil distortion depends upon several interrelated factors :-

i) The enclosing sediment
ii) The nature and magnitude of tectonic deformation
iii) The faunal occurrence type and the pre-deformation orientation of the constituent fossils
iv) The bedding - cleavage relationship
v) The position of the faunal horizon with respect to the containing secondary structure(s) (e.g.,fold limb or hinge).

i) The enclosing sediment

The greatest degree of deformation occurs in argillaceous rocks (Ross 1978,p.943) (average grain diameter < 0.0625 mm., Pettijohn 1975; Pettijohn et al. 1972). Being incompetent and argillaceous, cleavage and deformation are relatively easily developed and poorly resisted, respectively, and are facilitated by the original large pore volume of these rocks (40-50% - Athy 1930,p.8,10,15; Ross 1978,p.943). Competent arenaceous rocks (sandstones - average grain diameter 2.0 - 0.0625 mm., Pettijohn 1975; Pettijohn et al.1972) are better able to resist cleavage development and deformation, thus faunas within such lithologies are usually distorted to a much lesser degree, but are less readily collectable, due to the differential weathering of shales and sandstones (Ross 1978,p.943).

The sampled fossiliferous strata fall into three general lithological categories :-

1) Siltstone

Fossils are always variably distorted.
Preservation : adequate - good.

2) Sandstone

Fossil distortion ranges from slight - severe, seemingly due to a simple shear mechanism.
Preservation : poor - adequate.

3) Volcanic rocks

The degree of distortion seems dependent on the degree of sediment admixture. Muddy tuffs apparently suffer similar distortion to siltstones. Purer rhyolitic tuffs seemingly take up the strain inhomogeneously, due to the increased siliceous content, resulting in variable distortion within the same rock-unit. In one instance, the fauna developed a "corrugated" appearance, probably resulting from small-scale buckling associated with inhomogeneous strain within a competent unit.

Muddy and crystal tuffs are generally well-cleaved. Purer acidic tuffs usually display a spaced or incipient cleavage. Preservation : poor - good.

ii) The magnitude of tectonic deformation

This depends on the associated structures. If the fossiliferous stratum has been folded into a large, open fold, mild - moderate distortion would be expected whereas severe faunal deformation would result from tight or isoclinal folding.

iii) The faunal occurrence type and the orientation of the constituent fossils

Fossils are confined to essentially two faunal occurrence types e.g., random and planar. Random occurrence types show no preferential valve orientations whereas planar occurrence types display preferential valve orientations (see chap.5, sections b ii, iii).

Random occurrence types display variable distortion within the same rock unit, due to the random orientations of the valves with respect to the principal axes of the strain ellipsoid. A strong three-dimensional component is introduced, as evinced by substantial flexure of the valves, which either intensifies or diminishes their original convexity/concavity and consequently makes random occurrence types unsuitable for strain analysis.

Valves within planar occurrence types all possess constant two-dimensional orientations to the form strain ellipsoid, consequently resulting in broadly the same degree of distortion, but this depends on bedding-cleavage relationships. Any variation in this relationship naturally results in changes in the degree of distortion, which become significant only over relatively large lateral distances. Generally, planar occurrence types prove suitable for strain analysis.

iv) and v) The bedding-cleavage relationship/The position of the faunal horizon with respect to the containing secondary structure(s)

These two factors can be treated simultaneously.

Voll (1960) states tectonic deformation may produce uniaxial, biaxial or triaxial deformation.

In uniaxial strain, a sphere is transformed into a spheroid by linear deformation. This may involve only volume loss or radial extension normal to c (c = normal to the slaty cleavage) - Ramsay (1967,p.333,470), Voll (1960,p.537). Pretectonic compaction is often unaxial (fig.3.2).

Biaxial (plane) strain produces an ellipsoid whose intermediate axis is unchanged from that of the original sphere - fig.3.3 (op.cit.).

Triaxial strain yields an ellipsoid in which all three axes differ from those of the parent sphere, and which may occur with or without volume loss - fig.3.4 (op.cit.).

If cleavage parallels bedding, the resultant flattening does not destroy the rotational symmetry of the bedding plane, but if cleavage forms obliquely to a fossiliferous bedding plane, any contained fauna becomes distorted (op.cit.). Distorted brachiopods are termed "broad", "oblique" or "narrow", depending on their orientation to the direction of maximum finite elongation (fig.3.1;plates 3.1,3.2,3.4-3.6). Voll (op.cit.) maintains fossil distortion depends on the degree of deformation and the bedding-cleavage angle ($= \varphi$, after Breiddin 1956). The greater the value of φ, the greater is the fossil distortion, the greatest distortion being found when $\varphi = 90^\circ$ (fig.3.3).

Within distorted brachiopods, the hinge line - median line angle becomes modified, but remains at 90°

if these parameters are parallel and normal to the bedding-cleavage intersection. The angular change depends on the degree of deformation and the original fossil orientation, the greatest change occurring when the pre-deformation angle between the above parameters and the cleavage-bedding intersection was 45°.

The bedding-cleavage relationship is ultimately determined by the position of any stratum within a structural unit. Consider a syncline possessing an axial planar cleavage. As a fossiliferous stratum is traced across the syncline, the bedding-cleavage relationship varies, which consequently engenders differing degrees of distortion as φ changes across this structure.

Distortion variation within a fossiliferous stratum across structural units possessing differing cleavage patterns is examined (figs.3.5-3.13). In these figures, the block diagram illustrates cleavage relationships to the structural unit, whilst the fold profile depicts distortion variations across the unit, such variations represented by stylised distorted "brachiopods" around the profile. The finite distortion of any strain markers within a competent layer depends on the orientation of the layer (Ramsay 1967,p.118), as any layer may undergo both extension and compression around a fold (op.cit., p.119-120). If the strain markers deform passively, the layer possesses a coaxial strain history and the strain is homogeneous, the markers will be representative of the total finite strain. Several assumptions and statements are made regarding these figures :-

1) The diagrams are purely representative - structural accuracy is neither implied nor intended.

2) Competence differences are ignored.

3) Slaty cleavage is implied.

4) Cleavage traces are parallel to the long axes of the structural units.

5) Deformation is biaxial (Voll 1960).

6) The XY plane of the strain ellipsoid is parallel to the cleavage.

7) Deformation is produced by homogeneous simple shear (Hobbs et al.1976,p.26-39;Ramsay 1967, p.53-54,83-91).

8) The illustrated folds are Class 1B folds (Ramsay 1967,p.365-367,fig.7-24).

9) Cleavage is assumed to be parallel to a plane, defined by lines of no finite longitudinal strain (fig.3.29), through the finite-strain ellipsoid, following Breiddin (1956) - see also Hobbs & Talbot (1966,p.506). This

situation can only occur for plane strain ellipsoids ($k = 1$), in which the aforesaid planes define circular sections (Ramsay 1967, p.127,136-137,157,fig.4-22). Therefore, when a fossiliferous bedding plane parallel to the cleavage is examined, the fossils will appear undeformed. However, departures from this situation are common in nature.

Each figure is briefly explained, where :-

φ = Bedding - cleavage angle (Breiddin 1956)

D_f = Fossil distortion

D_f min = Minimum fossil distortion

D_f max = Maximum fossil distortion

Fig.3.5

Zone 1 - slight fossil distortion, as φ is small, (10° - 20°). φ remains constant, as the limb (and hence the fossiliferous stratum) has no appreciable curvature.

Zone 2 - φ gradually increases towards Zone 3 as the limb curvature likewise increases, fossil distortion becoming stronger.

Zone 3 - φ increases. Fossil distortion is strongest in Zone 3, intensifying towards

B ($\varphi = 90^\circ$) where maximum distortion ($D_{f\ max}$) occurs.

Zones 4, 5 and 6 are identical to Zones 3, 2 and 1 respectively.

Fig.3.6

Zone 1 - $\varphi = 55^\circ$-60°, remains constant; D_f strong.

Zone 2 - φ increases to 90° at B; D_f increases towards B, where $D_{f\ max}$.

Zone 3 φ and D_f rapidly decrease towards A; at A, $\varphi = 0^\circ$, $D_{f\ min}$.

Zone 4 - φ and D_f gradually increase towards Zone 5.

Zone 5 - $\varphi = 35^\circ$-40°, remains constant; D_f moderate; D_f Zone 5 < D_f Zone 1

Fig.3.7

Zone 1 - $\varphi = 15^\circ$-20°, remains constant; D_f weak.

Zone 2 - φ and D_f gradually decrease towards A; at A, $\varphi = 0^\circ$, $D_{f\ min}$.

Zone 3 - φ and D_f rapidly increase towards B; at B, $\varphi = 90^\circ$, $D_{f\ max}$.

Zone 4 - φ gradually decreases towards Zone 5, as does D_f, although still strong.

Zone 5 - $\varphi = 40^\circ$-45°, remains constant; D_f moderate - strong; D_f Zone 5 > D_f Zone 1

Fig.3.8

Zone 1 - $\varphi = 40^\circ-45^\circ$, remains constant; D_f moderate-strong.

Zone 2 - Towards B, φ increases and D_f becomes severe; at B, $\varphi = 90^\circ$, $D_{f\ max}$.

Zone 3 - φ and D_f decrease rapidly, and then gradually away from B.

Zone 4 - $\varphi = 15^\circ-20^\circ$, remains constant;

D_f Zone 4 < D_f Zone 1

Fig.3.9

Zone 1 - $\varphi = 10^\circ-15^\circ$, remains constant; D_f weak.

Zone 2 - φ and D_f decrease towards A; at A, $\varphi = 0^\circ$, $D_{f\ min}$.

Zone 3 - φ and D_f increase gradually, then more rapidly towards B; at B, $\varphi = 90^\circ$, $D_{f\ max}$.

Zone 4 - φ and D_f gradually decrease away from B; D_f strong.

Zone 5 - $\varphi = 30^\circ-35^\circ$, remains constant; D_f moderate;

D_f Zone 5 > D_f Zone 1

Fig.3.10

Zone 1 - $\varphi = 40^\circ-45^\circ$, remains constant; D_f moderate-strong.

Zone 2 - φ and D_f decrease towards A; at A, $\varphi = 0^\circ$, $D_{f\ min}$.

Zone 3 - φ and D_f increase rapidly, then gradually, towards B; at B, $\varphi = 90^\circ$, $D_{f\ max}$.

Zone 4 - φ and D_f decrease slightly away from B.

Zone 5 - $\varphi = 60^\circ$-65°, remains constant; D_f severe; D_f Zone 5 > D_f Zone 1

Fig.3.11

Zone 1 - $\varphi = 9^\circ$-10°, remains constant; D_f weak adjacent to Zone 2; φ and D_f decrease away from Zone 2.

Zone 2 - φ and D_f gradually decrease towards A; at A, $\varphi = 0^\circ$, $D_{f\ min}$.

Zone 3 - φ and D_f rapidly increase towards B, at B, $\varphi = 90^\circ$, $D_{f\ max}$.

Zones 4, 5 and 6 are identical to Zones 3, 2 and 1, respectively.

Fig.3.12

Zone 1 - φ and D_f gradually increase away from Zone 2; D_f moderate-strong.

Zone 2 - φ and D_f decrease away from B ($\varphi = 90^\circ$, $D_{f\ max}$) to a minimum value ($\varphi = 32^\circ$ approx.), with D_f moderate at the Zone 1/Zone 2 junction.

Zones 3 and 4 are identical to Zones 2 and 1, respectively.

Fig.3.13

Zone 1 - φ and D_f gradually decrease away from B; at B, $\varphi = 90^{\circ}$, $D_{f\ max}$.

Zone 2 - φ and D_f decrease towards A; at A, $\varphi = 0^{\circ}$, $D_{f\ min}$.

Zone 3 - φ and D_f increase to a maximum at the Zone 3/Zone 4 junction.

Zone 4 - φ and D_f gradually decrease away from this junction.

From these examples, it can therefore be seen that many intermediate situations are also possible.

d) The general structural pattern in Snowdonia

i) Introduction

The Glanrafon Beds and Snowdon Volcanic Group attained their existing orientations mainly due to Caledonian earth-movements (late Silurian - early Devonian) which produced the folding, faulting and cleavage patterns seen today (fig.3.14). The volcanic units are folded into large, smoothly curved folds, whilst the slates are complexly folded. In North Wales, folds and cleavage are deflected from a north - south trend in the south-west to an east-west trend in the north-east (Bassett 1969). To explain this, Boswell (1949) suggests the Snowdonian folds resulted from Taconic (late Ordovician) earth movements, the gentler folds of the Denbighshire moors being Caledonian, whereas George (1955) and Rast (1961) advocate basement and volcanic control, respectively.

ii) Folding

Folding within Snowdonia displays a Caledonoid trend (Bassett 1969;Williams & Ramsay 1959;Williams & Bulman 1931), although anomalous structures are noted, e.g., the eastward trending Crib Gôch syncline (Rast 1961; Williams 1927), the east-north-east - west-south-west trending Dolwyddelan syncline (Williams & Bulman 1931) and the north/north-east trending folds between Llyn Cowlyd and Llyn Goddionduon (Davies 1936).

The major structural unit is the Snowdon synclinorium (Shackleton 1954), first noted by Sedgwick (1843). Subsidiary folds (fig.3.14) include the Clogwyn D'ur Arddu syncline (Williams & Ramsay 1959), the Cwm Idwal syncline (op.cit;Shackleton 1954;Williams D.1930; Williams & Bulman 1931) - plate 3.7 and the Cwm Tryfan anticline (Williams & Ramsay 1959). The Snowdon and Dolwyddelan synclines (fig.3.15) possess inverted limbs, the maximum overturning on the northern limb of the latter being 30° (Williams & Bulman 1931).

Rast (1961) suggests the rhyolite plugs, which are commonly found in Snowdonia, originally influenced the position of the Caledonian folds.

iii) Cleavage

The Caledonian earth-movements impressed upon the Ordovician rocks a steeply inclined - vertical cleavage (Williams D.1930), which is parallel/sub-parallel to the fold axial planes (Beavon 1960;Phillips 1843;Rast 1969; Shackleton 1954;Williams D.1930;Williams & Ramsay 1959; Williams & Bulman 1931). Although cleavage strike remains constant, the north-westerly dip (fig.3.14) steepens northwards, from 25° near Ffestiniog to 65° near Llyn Gwynant, and becomes vertical on the northern slopes of Snowdon (Beavon 1960,1963;Shackleton 1954;Sharpe 1847; Williams & Bulman 1931). Further north, the cleavage dips to the south-east (fig.3.14) consequently forming a synformal cleavage fan (Williams & Ramsay 1959) which is coaxial with the Idwal syncline (Shackleton 1954;Williams D.1930). Williams & Bulman (1931,p.451) maintain North Wales is "....traversed by several large cleavage fans" (op.cit.) whilst east of Beddgelert, Beavon (1960,1963, p.506) records a synformal and antiformal cleavage fan. Shackleton (1954,p.276) believes the cleavage is due to pure shear which produced flattening, probably combined with simple shear on some fold limbs.

In Snowdonia, the argillaceous members generally possess a slaty cleavage, whilst the arenaceous members possess what might be called a fracture cleavage or spaced cleavage (Billings 1972,p.389-390).

Rast (1969,p.329) states "....metamorphism is widely of zeolite facies". Stilpnomelane (op.cit.;Bloxham & Price 1961), prehnite and pumpellyite (Rast 1969,p.330) are all recorded. Jenkins & Ball (1964,p.1094) located pumpellyite within the margins of dolerites at Bwlch y Ddeufaen in the Conway Valley (SH 724715). Prehnite and pumpellyite are diagnostic of very low-grade metamorphism (Winkler 1976, p.73,237) whilst stilpnomelane is found in very low-grade metasediments (op.cit.,p.206), although the pumpellyite within the Conway Valley dolerites possibly formed under conditions of high shearing stress (Jenkins & Ball 1964, p.1095), the dolerites themselves being considerably faulted and sheared.

iv) The Snowdon rim-syncline

The Snowdon syncline can be traced southwards to Moel Hebog, eastwards across Traeth Mawr, northwards through the Yr Arddu syncline and to the east of Llyn Gwynant, where it recurves westwards, passing north of Llyn Llydaw and rejoins the Snowdon syncline (*senso stricto*) (Shackleton, in Beavon 1960;Shackleton, in discussion of Beavon 1963) - fig.3.16. This arcuate structure (fig.3.16) is interpreted as part of a rim-syncline surrounding the magmatic dome (op.cit.), whilst its course is marked by rhyolite plugs (fig.3.16).

In places, the F_1 cleavage transects the centre of the syncline at 90° (e.g.,Crib Gôch, south-west of Moel Hebog - op.cit.;Rast 1969) without any large-scale deflection, suggesting the syncline is pre-cleavage. Elsewhere, cleavage is sub-parallel to the long axis of the syncline. The original synclinal trace was probably approximately circular, the shape transformation resulting from the same deformation responsible for the cleavage.

e) A practical method for deriving the original dimensions of tectonically deformed fossils

This method is restricted to original bilaterally symmetrical fossils within planar occurrence types, where deformation is predominantly due to simple shear with no significant volume change.

Stylised "brachiopods" (depicted as just hinge and median lines - fig.3.17a) of standard dimensions, e.g., hinge line = 30 mm., median line = 10 mm., with orientations covering 360°, are deformed through an angular shear strain of 30° using a simple shear box. The resultant distorted "brachiopods" are then measured (fig.3.17b,table 3.1). Using these brachiopods, a strain ellipse is constructed, employing Wellman's (1962) method. The maxima and minima of the ellipse must be accurately determined, as the ellipse area is incorporated within ensuing calculations. This is achieved by employing shear variations to determine the principal strains and their orientations (Ramsay 1967,p.238-243).

With reference to fig.3.17b, an arbitrary reference line (AB) is drawn (fig.3.18). The angle (α) subtended by the hinge line and AB is measured (table 3.1), the sign of α governed by the hinge line orientation (fig. 3.19). The shearing strain (ψ), corresponding to the angle between the deformed and undeformed median lines, is also determined (table 3.1). Brachiopod orientation, with respect to the X, Y and Z axes of the strain ellipsoid, governs the sign of ψ (fig.3.20). Using the values displayed in table 3.1, a graph illustrating variation in angular shear strain (ψ) with change in orientation angle (α) is plotted (fig.3.21), from which two equal values (one positive, one negative) for the maximum shearing strain (ψ_{max}) are derived. However, the brachiopods are subjected to a known shearing strain ($\psi = 30^{\circ}$), so the graph values should be identical (fig.3.21).

A value for θ_1 is deduced from the graph (fig.3.21), θ_1 representing the angle between the principal extension direction of the strain ellipse and AB. From fig.3.21, the curve cuts the abscissa in two positions (λ_1, λ_2), which correspond to the orientations of the principal quadratic elongations with reference to AB.

The Strain Ratio (R) is calculated, using the following formulae (op.cit.,p.241) :-

$$R = \cot^2\theta_1 \qquad \ldots\ldots\ldots 1$$

$$R = 1 + 2\tan^2\psi_{max} + 2\tan\psi_{max} \cdot \sec\psi_{max} \qquad \ldots\ldots\ldots 2$$

$$R = \frac{\lambda_1}{\lambda_2} \qquad \ldots\ldots\ldots 3$$

However, the values for the strain ellipse dimensions are $\sqrt{\lambda_1}$ and $\sqrt{\lambda_2}$. Therefore, R' (the ratio of the principal axes of the strain ellipse) is

$$R' = \sqrt{\cot^2\theta_1} \qquad \ldots\ldots\ldots 4$$

$$R' = \sqrt{1 + 2\tan^2\psi_{max} + 2\tan\psi_{max} \cdot \sec\psi_{max}} \qquad \ldots\ldots\ldots 5$$

From equation 4,

$$\cot^2\theta_1 = \frac{1}{\tan^2\theta_1} \qquad \ldots\ldots\ldots 6$$

where

$$\tan^2\theta_1 = \frac{\tan 2\theta_1 - 2\tan\theta_1}{\tan 2\theta_1} \qquad \ldots\ldots\ldots 7$$

Therefore equation 4 is rewritten as

$$R' = \sqrt{\frac{\tan 2\theta_1}{\tan 2\theta_1 - 2\tan\theta_1}} \qquad \ldots\ldots\ldots 8$$

The formula for $\tan^2\psi_{max}$ (eq.7) is substituted into equation 5, thus

$$R' = \sqrt{1 + 2\,\frac{\tan 2\psi_{max} - 2\tan\psi_{max}}{\tan 2\psi_{max}} \cdots} \qquad \text{.......cont.}$$

$$\cdots\cdots + 2\tan\psi_{max} \cdot \sec\psi_{max} \qquad \text{.......9}$$

Using the values of θ_1 and ψ_{max} from the graph (fig.3.21), R' is calculated, employing equations 8 and 9. $\theta_1 = 28^{\circ}$ (fig.3.21), which is substituted into equation 8, thus

$$R' = \sqrt{\frac{\tan 2.28^{\circ}}{\tan 2.28^{\circ} - 2.\tan 28^{\circ}}} = \sqrt{\frac{1.4826}{1.4826 - 1.0634}}$$

$$= \sqrt{3.537} = \underline{1.88}$$

$\psi_{max} = -30^{\circ}$ and $+32^{\circ}$ (fig.3.21). Substituting these values into equation 9, $R' =$ <u>1.73</u> and <u>1.80</u>, respectively. These three R' values are averaged, the mean being <u>1.80</u>. Therefore the ratio of the principal axes of the strain ellipse = 1.80 : 1.

From the ellipse dimensions (x 6), the ellipse area is calculated, using the formula

Ellipse area = πab 10

where a and b are the semi-major and semi-minor ellipse axes, respectively. Assuming no volume change, the ellipse area = the area of the original circle from whence the ellipse was derived. Consequently, the circle radius may be deduced (= <u>4.025</u> cms.).

The values for the orientations of λ_1 and λ_2 (fig.3.21) provide the orientations of the major and minor axes of the strain ellipse with respect to AB (see Ramsay 1967,p.241),i.e.,

$$\lambda_1 = -17.5^\circ \qquad \lambda_2 = +71.5^\circ$$

The negative sign indicates the angle between the major axis and AB lies below AB (fig.3.22). That the values for these orientations do not add to 90° is due to slight errors incurred in graph plotting.

The orientation angles (β) for the median lines, with respect to AB, are measured, their signs depending on their orientations with respect to the reference line AB (fig.3.23). The hinge and median lines are projected through the ellipse centre (fig.3.24), using the values for α and β (figs.3.25,3.26;table 3.1). Each orientation cuts the ellipse circumference at two points (figs.3.24 - 3.26). The lengths of the projected lines are then measured (see figs.3.25,3.26). This procedure is repeated for all the hinge and median lines of the "brachiopods" (figs.3.27,3.28;table 3.1). The original pre-deformation dimensions of the "brachiopods" can be determined by employing the formula

$$\frac{l_o}{l_e}x \qquad \text{........................11}$$

where

l_e = length of the projected parameter within the strain ellipse

l_o = length of the equivalent line within the original circle (i.e.,radius)

χ = length of the distorted parameter

For projections falling within the extension field of the strain ellipse (fig.3.29),

$$\frac{l_o}{l_e} < 1$$

For projections falling within the shortening field (fig.3.29),

$$\frac{l_o}{l_e} > 1$$

For projections coinciding with lines of no finite longitudinal strain (fig.3.29),

$$\frac{l_o}{l_e} = 1$$

From table 3.1, the values for the median line of specimen 5 are :-

l_o = 40.25 mm. l_e = 48.35 mm. χ = 12.0 mm.

Employing equation 11,

$$\frac{40.25}{48.35} \times 12.0 = \underline{9.99} \text{ mm.}$$ - original median line length.

This calculation is repeated for all the measurements (tables 3.2,3.3). The slight discrepancies in the finite means for the original hinge and median line lengths accumulated during drawing and measuring of the "brachiopods".

This method may prove applicable to biometric studies. It could be employed for initially differentiating individuals (juvenile, mature) of genera possessing either isometric or allometric growth patterns and for subsequent assessment of the assemblage itself (see Fagerstrom 1964,p.1200-1203), both of which had suffered tectonic deformation. However, when dealing with large numbers, the method becomes time-consuming.

f) A theoretical method for deriving the original dimensions of tectonically deformed fossils

This method is theoretical, but nevertheless considers several factors that other methods appear to ignore.

Fig.3.30 portrays a flow diagram for this method. The notes within the flow diagram refer to points which are more fully discussed within the text.

Note 1) The method is only applicable to original bilaterally symmetrical fossils.

Note 2) This method only applies to fossils contained within argillaceous sediments.

Note 3) Only planar occurrence types are considered (see also Note 12).

Note 4) Pretectonic compaction ("diagenetic deformation") must be considered, as fossils in fine sediments are subject to some compaction and deformation prior to tectonic deformation (Ross 1978,p.943).

"Diagenetic deformation" (Voll 1960,p.537) is uniaxial, irrotational and involves volume change and dilation (Sanderson 1976,T26) - fig.3.2. Compaction reduces the sediment pore volume, causing flattening (Athy 1930,p.7; Ross 1978,p.943). In argillaceous rocks, % compaction increases rapidly during initial burial (Athy 1930,p.13-16;Perrier & Quiblier 1974;Ross 1978,p.943), compaction being initiated as soon as deposition has occurred. For one argillaceous unit, the lower part is partly compacted whilst the upper part is still being deposited. Thick layers do not undergo as much compaction as do thinner layers, the greatest compaction occurring within extremely thin layers. Fossil deformation falls within this range (Perrier & Quiblier 1974), although Ross (1978,p.943) states flat, thin fossils show little deformation.

Volume loss may be calculated if the extension and shear strain can be determined. From "cylindrical" (e.g., crinoid columnals, stems, roots, belemnites,etc.) and "quasi-cylindrical" fossils (corals, orthocones, ammonoids,etc.), Sanderson (1976,T27) derives a formula to calculate volume loss.

Investigations on fossil deformation from pretectonic compaction include those by Allen (1946, p.306-310), Ferguson (1962,1963b), Sanderson (1976) and Ross (1978).

During initial deposition when the sediment is unlithified and relatively mobile, compaction may initiate rigid rotation of the enclosed fossils (Sanderson 1976,T31). Presumably only those fossils inclined to the compactional strain are rotated, fossils parallel and normal to this strain remaining immobile. The degree of rigid rotation depends on the relative sediment mobility and the onset of lithification. The transition from unlithified-lithified sediment is gradational, as will be the decrease in rigid rotation. Pretectonic compaction therefore comprises an initial phase of rigid rotation of inclined fossils within unlithified sediments, grading into a longer phase of flattening within lithified sediments.

Convex and concave valves (e.g., dalmanellid pedicle valves, Salopia, sowerbyellid valves etc.) are more subject to flattening if orientated normal to the compactional strain than are planar valves (Macrocoelia).

However, any compaction calculation will only be a minimum estimate of the total compaction. If tectonic strains are superimposed on pretectonically deformed fossils, determination of the finite strain depends on the shape and relative orientation of the fossils after compaction (op.cit.,T32).

Note 5) Compactional volume loss may be estimated (op.cit.). If it cannot, only the original length:width ratios of the bilaterally symmetrical fossils may be calculated.

Note 6) Two cases naturally occur :-

a) Fossils possessing original shelly, skeletal or replacement material.
b) Fossils possessing no original shelly, skeletal or replacement material.

The presence of such material produces a competence difference (ductility contrast) within the sediment, which implies the fossils do not deform in an identical manner to the enclosing sediment when subjected to tectonic strain (Engelder & Engelder 1977,p.458). Therefore the distorted fossils only represent the minimum limits of deformation and are not representative of the total strain (Hobbs & Talbot 1966,p.502). Conversely, a fossil mould/cast composed of similar material to the enclosing sediment deforms homogeneously with the sediment when strained (Sanderson 1976,T30) thus providing an accurate representation of the strain state.

Decalcification must also be considered. Many physico-chemical factors are involved with this process (Chave 1964) although their exact nature can only be tentatively estimated from modern day analogies.

Several decalcification - compaction - deformation sequences are postulated (fig.3.31), the rate of decalcification controlling the final degree of fossil deformation. Each sequence (fig.3.31) will produce a different end result with respect to the deformed fossils being accurate representations of the strain state, process A presumably producing the truest representation whilst process D effects the most inaccurate representation, although the differences between the end results would probably be relatively small. However, spherical objects undergoing less volume reduction than the matrix during pretectonic (diagenetic) compaction are better indicators of the nature of the tectonic deformation than objects of similar matrix composition (Ramsay & Wood 1973,p.276-277).

Trilobite exoskeletons and ecdytes are probably more resistant to chemical changes, consequently making them less reliable strain indicators.

Note 7) The implications of the regional tectonic activity have been discussed (see section d).

Note 8) Ramsay(1967,p.177) defines slaty cleavage as a penetrative planar fabric developed during tectonic deformation. Hobbs et al.(1976,p.227) employ the term "....specifically for rocks rich in layer silicates that possess the marked fissility of roofing slate". The cleavage in most argillaceous rocks in Snowdonia may be described as a "slaty cleavage" following Ramsay's definition.

Slaty cleavage has been assumed to develop perpendicular to the direction of maximum finite shortening (Z) and to be approximately parallel to the XY plane of the finite-strain ellipsoid (Borradaile & Johnson 1973,p.253;Helm & Siddons 1971,p.527;Hobbs et al. 1976,p.404;Matthews et al.1976,p.200;Ramsay 1967,p.93; Ramsay & Wood 1973,p.266). Bayly (1974) points to this assumption as a possible source of error in strain analyses and states "....Surely we all know that slaty cleavage does not parallel the XY plane of the finite-strain ellipsoid" (op.cit.,p.207), although this statement is not corroborated by field or laboratory evidence whilst Ramsay (1967,p.93-94) documents theoretical evidence for not expecting such parallelism.

Very generally, if the rocks possess a coaxial strain history, any cleavage or foliation will be approximately parallel to the XY plane (Hobbs et al.1976,p.245-246; Williams,P.F.1976,p.192) and then only if cleavage was initiated parallel to the XY plane of the incremental ellipsoid (Williams P.F.,1976). However, rocks undergoing folding generally have a non-coaxial strain history (op.cit.) (except in the fold hinges), and consequently it is unlikely that cleavage will be parallel to the XY plane (Bayly 1974;Williams P.F.1976) although parallelism may exist for certain increments. Such discrepancies either may not be measurable (Borradaile 1974) or the degree of preferred orientation may not be sufficiently well-defined to enable measurement of any angular deviation (Matthews et al.1976). A non-coaxial strain history will only produce a cleavage or foliation parallel to the XY plane if the cleavage develops by either passive flattening, produced by homogeneous strain, of originally spherical markers or rotation of elongate markers with initial uniform orientations (Williams P.F. 1976). If the slaty cleavage is axial planar, it will tend towards parallelism with the XY plane as the magnitude of strain increases (Hobbs et al.1976,p.252).

Borradaile (1977) stereographically demonstrates that if the cleavage pole plots in the expected field containing Z (assuming a coaxial strain history and homogeneous deformation - op.cit.), the cleavage is possibly a principal plane structure (or the rotational component is too small to be measured) and vice versa.

Indeed, field data show such parallelism (".... within the limits of detection"-Borradaile 1974,p.208) exists. The continued use of the initial assumption is advocated (op.cit.) and analyses will not be jeopardised by its use, especially where stated e.g., Borradaile & Johnson 1973,p.253,258.

Strain analyses based on fossils are essentially two-dimensional (Hobbs et al.1976,p.240). To become three-dimensional, certain assumptions have to be made, e.g., cleavage is parallel to a principal plane of strain (Hobbs & Talbot 1966,p.506;Hobbs et al.1976;Williams P.F. 1976), strain around a fold is homogeneous (Williams P.F. 1976) etc., such assumptions invalidating these analyses.

If only an incipient (spaced) cleavage is developed, the strain ellipsoid cannot normally be calculated (but see Borradaile 1977).

This point obviously merits further research.

Note 9) If volume loss cannot be calculated, original dimensions likewise cannot be calculated, but the original length:width ratios may still be estimated.

Sorby (1853) discusses the possibility of volume change during tectonic deformation, and from studying reduction spots in the Cambrian slate belt, states a volume change of 11% is possible (Sorby 1908), whereas Cloos (1947,p.886) considers volume loss by compaction or water loss "....to be harmless". A volume loss of 10%-20% (by water expulsion;grain rearrangements;breaking or granulation of grains - Athy 1930,p.6) may be implied during slate formation from lithified argillaceous sediments (Ramsay & Wood 1973,p.267). Greater volume losses result if diagenetic deformation is additionally considered (op.cit.).

Note 10) If cleavage parallels bedding, the X and Y axes of the strain ellipsoid are derived by utilizing distorted fossils and Wellman's (1962) method. However, deformed objects normal to cleavage are needed to calculate Z, thus permitting construction of the strain ellipsoid (cf. note 8).

When cleavage is oblique to bedding (e.g.,Snowdonia), any constructed strain ellipse (derived from deformed fossils on the bedding plane) will not contain the principal finite-strain axes of the strain ellipsoid (except in certain specialised cases). Any ellipse consequently represents an oblique section through the strain ellipsoid and the two cannot be mathematically related. Therefore only the strain ellipse for that particular surface (= bedding plane) can be derived. Other usuable surfaces are needed.

3D strain markers are required to make this method practicable, e.g., accretionary lapilli (see Helm & Siddons 1971;Oertel 1970), reduction spots (Sorby 1908, p.220-222), oolites (Cloos 1947),etc.. Tobisch et al. (1977) document five types of strain markers (lithic lapilli, tuff-breccia fragments, accretionary lapilli, reduction spots and "ash-flow ellipsoids"). Regarding ductility contrasts (op.cit.,p.29-32), the most representative markers are the latter three, although the authors consider all these markers yield accurate, consistent results for the quantitative strain.

From mutually perpendicular sections through 3D strain markers such as these, the strain ellipsoid may be calculated.

Note 11) A linear fabric ("stretching lineation") is often developed on cleavage surfaces (Hobbs et al.1976, p.227;Ramsay 1967,p.233) - plate 3.8, which corresponds to the direction of maximum finite elongation (= X axis of the strain ellipsoid - Borradaile & Johnson 1973,p.253; Ramsay & Wood 1973,p.266). If cleavage parallels bedding and a stretching lineation is present, the orientation of the X and Y finite-strain axes of the ellipsoid may be determined (cf.note 8). If cleavage is oblique to bedding, orientated sections with appropriate strain markers are required.

Note 12) Probably, some of the aforementioned requirements will not be encountered in nature, accordingly necessitating other orientated, mutually perpendicular sections for strain ellipsoid calculations.

Randomly orientated valves may be useful in this respect. Examination of orientated specimens may reveal some valves within the cleavage and some within mutually perpendicular planes. Employing these valves and methods advocated by Ramsay (1967,p.233-238), the strain ellipsoid may be calculated. 3D strain markers, used in isolation or conjunction, are additionally valuable. Within Snowdonia, randomly orientated, abundant crinoid columnals may prove excellent strain markers (see Cloos 1947,p.892-894) although Engelder & Engelder (1977,p.458) note that thin-shelled brachiopods are more likely to deform with the matrix and hence give more representative strain determinations than those derived from columnals.

If mutually perpendicular sections with suitable strain markers are unavailable, only the original parameter ratios of the distorted fossils may be ascertained. However, if volume loss can be estimated and the strain ellipsoid can be calculated, the original dimensions of the distorted bilaterally symmetrical fossils may ultimately be calculated.

g) Summary

The aim of this chapter is to emphasise the problems in attempting to analyse tectonically deformed fauna. Faunal identification is the most difficult problem to overcome, especially when dealing with closely allied genera and genera speciated either statistically or by comparative morphological differences. The bedding - cleavage relationship and the geometric relationship of the faunal horizon with respect to the secondary structure(s) are stressed as important factors influencing the finite deformation of the fauna. The Snowdonian structural pattern is briefly analysed in an attempt to provide a framework for the processes which influence fossil deformation. Two possible solutions to the problem of deformed fauna are proposed (one practical;one, at present, theoretical), which both attempt to determine original dimensions of distorted bilaterally symmetrical fossils, thus enabling their future speciation and permitting their ultimate use in biometric studies.

Chapter 4 Evaluation of the marine benthic assemblages

a) Introduction

Most of the assemblages possess abundant brachiopods and crinoids (sessile benthos) and trilobites (vagrant benthos). Other fossil groups either have widespread minor occurrences or are localised in larger numbers. Preservation is generally poor and coupled with tectonic deformation produces identificatory problems which are, however, reasonably resolved.

b) Methods and techniques of faunal sampling

The most important requirement for faunal analysis is precise and accurate sampling, as the ability to define and recognise communities is determined by the number and size of the available samples (Stanton & Evans 1972). A common problem is to determine a realistic sample size from which the optimum faunal data can be obtained, large sample sizes being the norm (Boyd & Newell 1972; Neuman 1964).

Assemblages are divided into two types :-

i) High dominance assemblages
few genera; one or two genera dominant.

ii) Low dominance assemblages
greater number of genera; several genera equally dominant.

i) is more easily recognisable than ii) when only a small sample size is used.

When only part of an assemblage can be ascertained (as in fossil assemblages), it becomes a matter of geological judgement when the sampled and "real" assemblages are almost identical. Therefore any inferences, conclusions etc., concerning the sampled assemblage can be applied to the "real" assemblage (Krumbein 1960). Essentially, the collected sample should provide enough data to establish, with a reasonable degree of accuracy and confidence, the relative proportions of the genera present.

Collecting techniques depend primarily on the fossil compositions, their nature and the enclosing matrix (Fagerstrom 1964), plus their accessibility and relative orientations. Any biased sampling should be avoided.

Patchiness (the uneven, aggregated distribution of organisms - Hairston 1959) is inherent within modern benthic communities, and probably ancient benthic communities also exhibited lateral patchiness. Sampling, where possible, should take into account such patchiness.

However, most fossil assemblages have probably accumulated over relatively long time periods, any spatial patchiness being temporally averaged out. Therefore, the data from one sample may result in a reasonably accurate assemblage reconstruction.

Unfortunately, little or no lateral sampling is possible, due to outcrop pattern and general topography.

Each fossiliferous outcrop is sampled in detail, which allows for any compositional variations present. Planar faunal occurrence types (see chap.5) are relatively easier to obtain samples from (dependent on bedding - cleavage relationships) than random faunal occurrence types.

Field sampling is conducted along the following pattern. If only one faunal horizon is present at one small outcrop, the horizon is sampled along its complete length which effectively "averages out" any lateral inhomogeneities that may be present. If the horizon has a large lateral extent, several smaller samples of uniform lateral spacing are collected. However, of the faunal horizons sampled, few can be traced, with certainty, from one outcrop to another, due to lateral discontinuity and sporadic outcrop. Outcrops commonly reveal several fossiliferous horizons, and in these cases, each horizon is comprehensively sampled. Alternatively, specimens are collected from one horizon only (depending on the ease of collection/faunal preservation etc.). This obviously introduces errors, but the author considers any compositional variations are slight over small vertical distances.

These methods appear the most suitable for the horizons and lithologies encountered, and provide reasonably accurate representative results. Johnson (1960,p.1082-1083) and Tipper (1976) propose alternative sampling methods, but these are not readily applicable to the Snowdonian assemblages.

Community patterns can be recognised from any number of samples (Stanton & Evans 1972), although low sampling densities define only very broad patterns, whereas increased sampling densities enable more definite patterns to be recognised (op.cit.). It is resolved, that for every assemblage, to collect the largest sample that is conveniently possible, as the sampled and "real" assemblages become almost identical when a large sample size is utilised. Therefore the subsequent faunal data can be treated with a relatively high degree of confidence. No standard sample size is fixed, this parameter being decided by the sampler and the type of faunal horizon to be sampled.

c) Taphonomy

i) General considerations

In faunal analysis, information losses from the shelly assemblages must be considered. Such losses are post-mortem events, the study of which is termed Taphonomy. Lawrence (1968) defines Taphonomy as a combination of the pre- and synburial organism – external environment interrelations, along with the post-entombment histories of the organic remains, whereas Boyd & Newell (1972) define Taphonomy as those events occurring between an organism's death and its final immobilisation within an enclosing layer. The author defines Taphonomy as the post-mortem history of the fossils, i.e., the events occurring after death but before final discovery.

Many organic remains obviously do not persist to be ultimately discovered. Consequently, a fossil assemblage may not accurately reflect the composition of the original assemblage or community (Durham 1967), and is essentially only a minimum representation of the original assemblage.

There are two major types of taphonomic events :-

i) Losses through non-preservation

ii) Losses through transportation from the growth site (Lawrence 1968)

Many organisms within benthic communities are soft-bodied, and therefore leave no primary trace of their existence within a fossil assemblage, due to post-mortem decomposition. Non-preservation is primarily due to scavengers, predators, decomposer-organisms, physical forces and the lack of fossilisable hard parts. Johnson (1964) determines modern benthic communities are composed of between 7% - 67% (mean 30%) of species with resistant hard parts. Craig & Jones (1966) estimate 33% of the abundant epifauna possess hard parts and are, therefore, potentially preservable whilst Lawrence (1968) concludes that between 40% - 70% of species within a benthic community leave no trace of their existence. However, non-preserved organisms may leave evidence of their existence in the form of trace fossils, which can partly counteract non-preservational losses, but cannot counteract transportational losses (op.cit.).

The hard parts themselves may suffer post-mortem degradation, due to pre- and post-burial physico-chemical (abiotic) and biological (biotic) processes. Chemical processes dissolve or alter shelly material, physical processes (wave/current action) cause abrasion and fragmentation whereas boring organisms destroy or weaken shell structure, consequently making removal by physico-chemical processes relatively easy.

Transportation may disrupt community spatial relations which consequently constitutes an information loss (op.cit.). Transportation involves the extraction and transport of the infaunal and epifaunal elements by wave and current action. Net lateral transportation probably varies between localities and reflects the original local hydrodynamic regime, although the degree of transport is difficult to accurately assess. Boyd & Newell (1972) cite shell articulation, valve damage, valve size distribution, opposing valve ratios and the fossil layer fabric as evidence for transport, e.g., opposing valve ratios approaching unity imply little or no transport, etc. Johnson (1972) maintains large-scale transportation is rare even in relatively high energy environments, which is confirmed by Boucot (1975) who states post-mortem transport to be a relatively minor factor in most fossil associations. Van Straaten (1960,p.115) notes that wave-induced valve transport is restricted to water depths of less than 10 m.

The combination of non-preservational and transportional taphonomic losses results in only a fragmentary, ill-defined picture of the original assemblage or community. Lawrence (1968), in comparing a modern day oyster community with one of Oligocene age, estimates a 75% post-mortem loss in the fossil community. However, there is little available data concerning actual losses within marine communities, and to determine the actual quantitative information losses for the Snowdonian assemblages is impossible, as modern day analogies have very little relevance to Ordovician communities.

ii) Taphonomic problems related to the Snowdonian faunal assemblages

1) Losses through non-preservation

All soft-bodied components have been lost. Redundant information (Tasch in Lawrence 1968) is found as varying degrees of bioturbation and occasional burrows. Associated bioturbation suggests a relatively large, soft-bodied (?) component within the original assemblage. Certain unpreserved infaunal organisms may, however, be partly responsible for some bioturbation, e.g., nuculoids, which are susceptible to non-preservation on account of their small size and relatively thin valves. It is impossible, however, to quantitatively assess the relative abundance of the non-preserved component.

Original shelly material has been completely removed by chemical processes, but the post-mortem formation of casts and moulds allows analysis of these shelly components.

Another non-preservational loss within the Snowdonian assemblages is through poor preservation. In assemblages preserved in coarse lithologies or located within the surficial weathering zone, accurate faunal analysis is precluded by poor preservation, which often destroys the fossils or obliterates characteristic identificatory features.

The presence of destructive biological agents (e.g., borers) is difficult to ascertain. Some isolated valves appear to have been bored, but this has not been reliably proved. Surface features noted on some brachiopod valves (e.g., impressed pits connected by linear furrows - plate 4.1) appear similar to markings produced by the linear stolons and zooids of some boring bryozoans (Bassler 1953). Other small linear features noted on valve exteriors may correspond to algal borings (Kobluk & Risk 1977).

Tectonic deformation may be said to cause taphonomic losses by "non-preservation", as some fossils are so severely distorted as to render them virtually unidentifiable.

2) Losses through transport

Transportational losses are difficult to evaluate. In conjunction with the dominant fossil fabric, the original hydrodynamic regime can be tentatively deduced from any associated sedimentary structures. To attempt some evaluation of transportational losses, articulation and opposing valve ratios for the brachiopods are calculated.

Large-scale transportation losses are not envisaged for most of the assemblages, as evinced by opposing valve and articulation ratios (see Appendix Two) in addition to the relative size ranges of the valves. However, transportation can definitely be proved within certain assemblages from the fragmentary nature of the fauna. Probably the greatest transportational losses have occurred in those assemblages within coarse sandy lithologies, i.e., indicating deposition in a high energy environment, but these losses are presumably not of any great magnitude.

In conclusion, non-preservational losses probably greatly outnumber transportational losses.

d) Quantification of the fossil groups found within the Snowdonian assemblages and associated problems

i) Introduction

For faunal analysis, it is essential that the faunal components are identified as accurately as is possible and are quantified. One must consider the most appropriate taxonomic level to choose when analysing the assemblages. Some workers present information at a dual level, i.e., at the generic and specific levels (Bretsky 1969a,1970a, 1970b; Ziegler et al.1968) whilst others (Calef & Hancock 1974; Hurst 1975; Lawson 1975) present faunal data at the species level. Pickerill (1974) and Brenchley & Pickerill (in press) consider there is little loss of potential information if the faunal data is presented at the generic level. Pickerill (op.cit.) states that rarely are two species of the same genus co-existent and different species of the same genus, within a vertical succession, apparently show the same lithofacies relations and faunal associations.

In quantifying the Snowdonian assemblages, the former dual system is employed. The author feels that although the dual system is time consuming in operation, it is more accurate, as specific identifications are of great use in correlation. Both generic and specific identifications depend, however, on the nature of preservation and the degree of tectonic deformation.

The following groups are identified within the Snowdonian assemblages :- brachiopods, trilobites, crinoids, cystoids, ostracodes, bivalves, gastropods, corals, bryozoans, algae, graptolites, cricoconarids (Tentaculites), machaeridian plates (Lepidocoleus) and cyclocystoid submarginal plates (Cyclocystoides).

ii) Brachiopods

In the Snowdonian assemblages, brachiopods dominate the epifaunal sessile benthos. In American Upper Ordovician communities, brachiopods do not display the same dominance (Bretsky 1969a,1970a,b), with gastropods and bivalves becoming increasingly important. In Lower Silurian communities (Ziegler et al. 1968), brachiopods constitute between 75% - 98% of the studied communities.

Indeed, throughout the Palaeozoic, brachiopods dominate the majority of invertebrate shelf communities, their dominance being challenged only in onshore communities by molluscs and on outer shelf sediments by the late Palaeozoic (Upper Carboniferous-Lower Permian) foraminiferid associations (Bretsky 1969b).

Within the Snowdonian assemblages, the following brachiopod superfamilies are noted :-

Lingulacea
Discinacea
Craniacea
Orthacea
Enteletacea
Triplesiacea
Plectambonitacea
Strophomenacea
Atrypacea
Dayiacea

In quantitatively assessing the brachiopods, one major problem encountered is that of recognition of closely allied genera and species, especially when dealing with juvenile shells. Ordinarily these problems do not arise, but occur due to the overall poor preservation and tectonic deformation. Such problems are reasonably resolved as follows :-

1) Dalmanella/Howellites/Onniella/Bancroftina

These genera are members of the family Dalmanellidae Schuchert 1913 and are externally very similar. Bancroft (1928a) erected a system for assessing the character of the external ribbing in orthaceans which, he believed "....must inevitably lead to a fine discrimination between genetic series" (op.cit.,p.53) and which he used to discriminate between Resserella (Howellites), Wattsella (Dalmanella) and Onniella and later, their respective species (op.cit.,Bancroft 1945), employing features such as the crural plates, the ventral muscle field morphology, the cardinal process, the fulcral plates and the external morphology as additional discriminants. The notational representation and counting method of Bancroft (1928a) partly alleviates this problem but is time-consuming and is negated by poor preservation.

The presence/absence of fulcral plates as a discriminant is discounted by Williams & Wright (1963) who state that genera discrimination is based upon arbitrarily assessed characteristics (op.cit.,p.3). Features including the brachiophores, the fulcral plates, the cardinal process, the musculature and the radial ornamentation, plus the general shell shape are reconsidered in the light of genera discrimination (op. cit.) - see table 4.1. Dalmanellid speciation is now based on statistical methods (Williams 1963,1974) which become invalid when applied to poorly preserved/tectonically deformed material, as in the Snowdonian assemblages.

A compromise is adopted by the author. If the material is sufficiently well preserved and only weakly distorted, identification to generic level is undertaken using the criteria postulated by Williams & Wright (1963) - see table 4.1. Under very exceptional circumstances, identification to species level is undertaken by visual comparisons, although this is subjective as statistical methods are originally used. Usually however, identification can be, and is, only taken to family level, i.e., these brachiopods are identified simply as "dalmanellids".

2) *Bicuspina*/*Oxoplecia*

Williams (1974,p.124) succinctly defines this problem as follows, "....the distinction between *Oxoplecia* and *Bicuspina* is finely drawn. Ignoring the variability normally inherent to the development of a fold and sulcus, and radial and concentric ornamention, the difference ultimately rests on the spiriferoid outline and pedicle tube of *Bicuspina* (Wright in Williams et al.1965,H 358)". Therefore, if either of these two features are not confidently discerned, the particular valve is noted as "triplesiacean", inferring either *Bicuspina* or *Oxoplecia*. However, as the main distinguishing feature is confined to the pedicle valve, this necessarily produces a bias towards pedicle valves only being generically identified.

3) Kjaerina/Rafinesquina/Hedstroemina

The following discrimination criteria (Bancroft 1929a, 1945) are employed :-

Kjaerina - The pedicle medial ribs are thickened; the brachial cardinal plates are slender and small; the pedicle muscle area is never flabelliform, is not traversed by radiating ridges and the anterior margin is not well-defined; the pedicle dental plates are either widely divergent or are long and narrowly divergent; Kjaerina possesses rugae near the hinge-line and is generally smaller than Rafinesquina.

Rafinesquina - The ribs are thickened but not as in Kjaerina; the brachial cardinal plates are well developed; the pedicle muscle area is large, flabelliform, traversed by radiating ridges and the anterior margin is well-defined; the pedicle dental plates are widely divergent; rugae are either feeble or absent and Rafinesquina is generally larger than Kjaerina.

Hedstroemina - The two main distinguishing criteria are the geniculate/sharply flexed brachial valve and the regular ribbing. Kjaerina speciation is based on features noted by Bancroft (op.cit.).

4) Sowerbyella speciation

This is now based entirely on statistical methods Williams 1963,1974) although when studying tectonically deformed material, such methods naturally become invalid.

Consequently, identification is limited to simply "sowerbyellid" (= Sowerbyella sp.).

5) Sericoidea/Chonetoidea

Separation of these two genera is singularly vexatious, this problem originating from two seemingly anomalous morphological features noted in one particular sowerbyellid genus. Brachial valve internals and to a lesser extent, pedicle valve internals, show features characteristic of Chonetoidea Jones 1928, whereas pedicle and brachial valve externals are reminiscent of Sericoidea Lindström 1953. Lindström (1953) in erecting the genus Sericoidea, admits its closest affinity is with Chonetoidea and notes the external ornamentation (op.cit.) as the main morphological feature distinguishing Sericoidea from Chonetoidea. The brachial valve interior is said to be extremely Chonetoidea - like (op.cit.), possessing a median septum and lateral septules.

Williams (in Whittington & Williams 1955) assigns sowerbyellids with up to three pairs of strong lateral septules and a long, sharp, median septum to Sericoidea abdita sp.nov. Major discrimination features concerning Chonetoidea are documented by Spjeldnaes (1957), who affirms that Sericoidea is closely related to Chonetoidea although lacking the well-defined brachial arches of the latter, but is uncertain whether the Middle Ordovician species he describes should be referred to Chonetoidea or Sericoidea (op.cit.). Concerning C.alpha sp.nov., Spjeldnaes (op.cit.,p.108) states that "....It differs from *Sericoidea* (?) *abdita* Williams (1955) in having more spines in the brachial lamellae (5-6, instead of 3) and in the undifferentiated sculpture."

Havlíček (1967,p.49) emphasises the close relationship between *Chonetoidea* and *Sericoidea* and remarks that *C.gamma* (Spjeldnaes 1957), with regard to ornamentation, belongs to *Sericoidea*. In diagnosing *Sericoidea* (op.cit.,p.51), the general shape and valve interior is said to conform to *Chonetoidea*, whereas the external ornamentation is stated as the only distinguishing feature when comparing these genera.

Unfortunately, no definite solution is afforded to this problem. Williams (in Williams et al.1965, H 381 - 383) places *Sericoidea* and *Chonetoidea* in the subfamily Aegiromeninae Havlíček 1961. The description (op.cit., H 383) for *Sericoidea* is "....like *Chonetoidea* but with radial ornamentation unequally parvicostellate and segregated into well-defined segments by accentuated costellae; dorsal tubercles discrete." With the inherent variability found within the Snowdonian aegiromenines, brachial internals approach both the *Sericoidea* and *Chonetoidea* types.

The author employs the following system. The most uniform morphological feature within the aegiromenines is the *Sericoidea*-type unequally parvicostellate ribbing and for this reason alone, all aegiromenines displaying such ribbing are assigned to *Sericoidea*. *Chonetoidea* and

Sericoidea speciation is made with respect to the brachial internals. The situation arises in which the brachial valve exterior is referred to Sericoidea and the brachial internal is referred to a species of Chonetoidea, e.g.,:-

Sericoidea (aff.Chonetoidea gamma Spjeldnaes 1957)

It is clear that further taxonomic work is essential with regard to these genera and the author believes that some Snowdonian aegiromenines may ultimately prove to be an intermediate genus between Sericoidea and Chonetoidea.

6) Leptaena/Kiaromena

Pedicle valves of these genera are more frequent than brachial valves, probably due to selective destruction. When distorted, the diagnostic muscle scars of the pedicle valves appear very similar, making differentiation difficult.

Leptaena is distinguished by its sharply geniculate pedicle valve, the possession of a narrow ridge separating the disc from the trail, stronger rugae and evenly costellate ornamentation (Muir-Wood & Williams, in Williams et al. 1965,H 391-394).

7) Assessment of the biotic criteria used for brachiopod quantification

The major criteria applicable to brachiopods are assessed.

A) <u>Size-frequency distributions</u> (Boucot 1953; Fagerstrom 1964;Johnson 1960)

This criterion can determine the mode of formation of a fossil assemblage and can, furthermore, be used to discriminate between a biocoenosis or thanatocoenosis. However, Craig & Hallam (1963) maintain that S-F distributions are not as useful in differentiating life and death assemblages as first thought and Fagerstrom (1964) states that until more work on age-specific mortality is performed, the usefulness of S-F distributions are severely limited. However, tectonic deformation and poor preservation precludes their usefulness.

B) <u>Shell disarticulation</u> (Boucot 1953; Fagerstrom 1964;Johnson 1960)

The ratio of articulated:disarticulated valves affords some idea of the post-mortem current activity to which the valves were subjected. Prolonged current activity causes large-scale valve disarticulation, whereas rapid burial preserves articulated shells (Boucot 1953). However, Sheehan (1978) maintains that disarticulation studies should treat shells with different types of articulation separately.

Articulation is difficult to assess for inarticulate brachiopods and is therefore not considered, their abundance derived by halving the valve number counted.

C) Ratio of opposing valves (Boucot 1953; Fagerstrom 1964: Johnson 1960)

The ratio of pedicle:brachial valves is determined for each brachiopod genus. Ratios approaching unity indicate an unsorted assemblage, i.e., an "in-situ" life assemblage (Boucot 1953). This ratio departs from unity as the assemblage is progressively sorted by current action,as for most brachiopods the hydrodynamic properties of the two valves usually differ (Fagerstrom 1964), resulting in one valve being more easily transported. Such ratios have been extensively used in Lower Palaeozoic community studies (Pickerill 1974; Ziegler et al.1968).

D) Faunal composition (Fagerstrom 1964; Johnson 1960)

Benthic communities are characterised by the joint occurrence of several species, resulting from these species possessing similar environmental tolerances and preferences (Fagerstrom 1964). Thorson (1957) states that characteristic species associations provide a basis for recognising and nominating communities. For assemblages regarded as essentially life assemblages, the associated species can be considered to have been associated in life, from which some broad ecological inferences can be made (Johnson 1960).

The use of additional biotic criteria is negated by tectonic deformation and the overall poor preservation.

Abiotic criteria, e.g., valve fragmentation and the surface condition of the fossils are only relatively assessed (Fagerstrom 1964;Johnson 1960). Fagerstrom (1964) maintains fragmentation can be designated as either pre-burial (current induced) or post-burial (tectonically induced). Pre-burial fragmentation (op.cit.) is associated with hydrodynamic sorting (the valve size and shape may be uniform) whereas tectonically fragmented assemblages possess greater ranges of valve size and shape.

Valve fragments are included within quantitative assemblage assessments when more than half a valve is present or a distinctive feature is identified. However, this naturally leads to biases being introduced into the quantitative assessments, as certain valve fragments prove more distinctive. Presumably however, such biases affect all assessments equally.

Biotic criteria are of greater use in assessing the mode of formation of fossil assemblages (Fagerstrom 1964; Johnson 1960).

See Appendix Two regarding the calculations employed to derive opposing valve ratios, articulation ratios, % abundance and the Diversity Index.

iii) Trilobites

Trilobites dominated the vagrant benthos and like modern arthropods grew by moulting, so consequently most trilobite remains probably represent exuviae (Henningsmoen 1975,p.181). Therefore, if each trilobitic fossil is regarded as a single individual, a distorted picture of trilobite abundance results. 29 moults are estimated as occurring in *Leptoplastoides salteri* (*Leptoplastus salteri* (Callaway) - see Lake 1919,p.90-93) from early protaspid-late holaspid (Raw 1927, p.15). In larger trilobites, this number may be even greater (Harrington, in Harrington et al.1959). Harrington (op.cit.,0 111) states that only 10% of trilobite remains probably correspond to dead trilobites. Consequently, the author divides the number of identifiable remains for any one genus by 10 to allow for ecdysis, which provides a more realistic assessment of quantitative abundance (after Pickerill 1974;Ziegler et al.1968).

The dominant trilobite superfamilies and families are :-

Remopleuridacea
Asaphacea
Illaenacea
Proetacea
Trinucleidae
Raphiophoridae
Calymenidae
Homalonotidae
Cheiruridae
Phacopacea

Dalmanitacea

Lichidae

Odontopleuridae

Identification problems due to tectonic deformation and poor preservation again occur. The commonest families are the Trinucleidae (Broeggerolithus) and the Calymenidae (Flexicalymene), Broeggerolithus being found mainly as fragmented headshields. Speciation of Broeggerolithus is based on cephalic morphology, the size of pit rows, the development of interradial ridges plus the distribution and number of pits within individual rows (Bancroft 1929b,1949;Dean 1960a,1962;Hughes 1970; Hughes et al.1975;Whittington 1966). Tectonic deformation and associated poor preservation negate the use of these morphological characters (see also chap.3,section b). If speciation is impossible, Broeggerolithus specimens are assigned to one of three groups (Dean 1960a,p.102-103).In most cases, however, identification is taken only to generic level.

Similar problems are encountered in assessing the Calymenidae. Morphological characters utilised for speciation (preglabellar field,glabellar lobes, etc. - Bancroft 1949;Dean 1962,1963a;Shirley 1931,1936;Whittard 1960;Whittington 1965) are often grossly modified by tectonic deformation and/or obscured by poor preservation consequently making speciation difficult (Dean 1963a,p. 117;Whittington 1965). Therefore, in most cases, calymenids are identified simply as either "Calymene sp. sensu latu (s.l.)" or "calymenids" (see also chap.3, section b).

Henningsmoen (1960) documents the problems of identifying tectonically deformed asaphids, but as Snowdonian asaphids are usually fragmented, they are identified simply as isotelinids (Whittington 1966,p.76-77).

Other trilobite genera are sufficiently distinctive even when tectonically deformed and/or poorly preserved.

iv) Crinoids

Crinoids are the second most abundant group within the epifaunal benthos, being represented by disarticulated columnals, cirrals, pinnates and plates. Complete individuals and pinnae are rare, but sections of articulated stems (pluricolumnals - Moore et al.1968) are frequent. It is very difficult to determine crinoid abundance purely from disarticulated remains. Ziegler et al.(1968) simply assess all crinoid columnals in one assemblage as one individual. However, when columnals are few and well dispersed, Pickerill (1974) assigns them to a single individual, whereas in assemblages containing closely packed columnals, each set is regarded as one complete individual (op.cit.).

As disarticulated columnals comprise a relatively significant part of most assemblages, it is resolved to erect a provisional classification scheme for them and to assess their relative abundances, although crinoid ossicles are excluded from quantitatitve assemblage assessments - see Appendix One for this classification.

However, the systematic names of this classification scheme are without standing in zoological nomenclature and are, therefore, nomina nuda.

Each columnal, cirral, pinnate and plate is individually counted, although their true abundance is only relatively assessed.

v) Ostracodes

Ostracodes, like other arthropods, pass through successive moult stages (instars - Kesling, in Benson et al. 1961), so therefore the majority of ostracode remains are probably comprised of instars, the number of instars produced by one individual varying between 6 - 9 (op.cit.). Pickerill (1974) maintains that very small, early instars are not recognised and to compensate, each ostracode counted is treated as a single individual (op.cit.), a method adopted by the author.

Indifferent preservation and tectonic deformation produce identification problems but carapace ornamentation and lobation is sufficiently distinctive for identification to family level and occasionally to generic level. The dominant families are :-

Quadrijugatoridae
Sigmoopsidae

Tetradellidae

Zygobolbidae

vi) Bivalves

Bivalves are rare and usually poorly preserved. In assessing bivalves, opposing valve ratios are not employed, abundance being derived by halving the total valve number, although articulation ratios are calculated. Errors are probably introduced by adopting these methods but they presumably affect each assemblage equally.

Poor preservation and tectonic deformation produce identification problems which are compounded by the scarcity of comprehensive modern monographs and references concerning Lower Palaeozoic bivalves. Of those available, the most useful are by Bretsky (1970a), Cox et al.(1969), McAlester (1968) and Soot-Ryen (1960).

vii) Gastropods

Each gastropod is counted as a single individual. However, they prove difficult to accurately identify due to the lack of recent studies on Lower Palaeozoic gastropods. Internal moulds and casts are of little use, whereas poor preservation and deformation often make the identification of external features tentative. Identification is usually taken to family level (Brookes Knight et al. 1960) and occasionally to generic level (op.cit.).

viii) Corals

Corals are assessed both quantitatively and relatively. Complete individuals are assessed as such, whereas coral fragments are only relatively assessed and are not included within the quantitative assemblage assessments.

ix) Bryozoans

As bryozoans are usually fragmented, they are only relatively assessed. Accurate identification is impossible, as no original skeletal material is present, so bryozoans are subsequently identified simply as "ramose bryozoans, circular bryozoans (representing basal sections of the zoaria of trepostomes, possibly batostomellids (*Esthoniopora*/*Orbipora* ? - Bassler 1953, G99-101), encrusting bryozoans" etc..

x) Other groups

Entire algae are quantitatively assessed, whereas algal fragments are only relatively assessed, as are machaeridians (disarticulated *Lepidocoleus* sp. plates), cyclocystoids (disarticulated submarginal plates of *Cyclocystoides* Salter & Billings 1858 - Kesling 1966) and cystoids (Paul 1973).

Cricoconarids (*Tentaculites* Schlotheim 1820 - Boucek 1964; Fisher, in Hass et al.1962,W 102) and orthoconic cephalopods (*Orthoceras* sp.?) are quantitatively assessed, whilst graptolites are assessed on a presence/absence basis (Bulman 1945-1947;Elles & Wood 1901-1918).

The following list contains those authors whose publications are employed in identifying the components of the Snowdonian faunal assemblages.

Bancroft 1928a,b,1929a,b,1945,1949;Bassler 1953;
Bates 1968;Beaver et al.1967;Begg 1934,1940;
Benson et al.1961;Bretsky 1970a;Brookes Knight et al.
1960;Bulman 1945-1947
Cave & Dean 1959;Cocks 1978;Cowper-Reed 1920,1921;
Cox et al. 1969
Davidson 1866,1867,1869,1871,1882,1883,1884;Dean 1958,
1960a,1961,1962,1963a,b,c,1965;Diggens & Romano 1968
Elles & Wood 1901-1918
Harper 1947;Harrington et al.1959;Hass et al.1962;
Havlíček 1967;Henningsmoen 1960;Hughes et al.1975
Johnson 1952;Johnson & Konishi 1959
Kesling 1966
Lindström 1953
MacGregor 1962,1963;McAlester 1968;Mitchell 1977;
Moore 1939;Moore & Jeffords 1968;Moore et al.1968
Owens 1973
Paul 1973;Pia 1927
Ramsbottom 1961
Salter 1864-1883;Salter,in Ramsay 1866;Shirley 1931,
1936;Soot-Ryen 1960;Spjeldnaes 1957
Whittard 1955,1958,1960,1964,1967;Whittington 1938b,c,

1962,1965,1966,1968;Whittington & Williams 1955;Williams 1949,1962,1963,1974;Williams & Wright 1963;Williams et al. 1965;Wright 1963,1964

Yeltysheva 1956

Chapter 5 Faunal occurrence types and preferred valve orientations with their interpretations

a) Introduction

Examination of the faunal assemblages reveals that the disposition of the shelly components can be assigned to several different types of faunal distribution, henceforth referred to as "faunal occurrence types" (Pickerill 1974) which provide important data concerning palaeoenvironmental conditions.

Faunal analysis and community recognition depend on the ability to recognise any degree of transport (allied with compositional modifications) an assemblage may have suffered. Faunal occurrence types and preferred valve orientations provide some relevant information. Assemblages thought to have suffered little net lateral transport can be confidently assigned to any previously erected community, and in these assemblages any transported genera can be relatively easily separated from the indigenous forms. Assemblages thought to have suffered some net lateral transport (with concomitant compositional modifications) can be treated with greater care when considering community assignment, as indigenous and transported genera can prove difficult to differentiate. However, faunal and lithological associations, along with quantification data, are additionally studied when assessing transportation.

These faunal occurrence types are grouped into four e.g., random, planar and intermittent types and undisturbed life positions (op.cit.). Valve orientation is considered in terms of preferred concave-up, convex-up and mixed orientations.

b) Faunal occurrence types

i) Introduction

Faunal occurrence types frequently vary from one fossiliferous horizon to another. These variations reflect biotic, depositional and post-depositional processes of varying kinds (Toots,1965a,p.219), therefore constituting valuable palaeoenvironmental and palaeogeographical evidence (op.cit.). Such occurrence types are obviously related to energy levels and corresponding environmental zones (op.cit.). As natural environments are defined by variously interracting physical and biological characters (Brenchley & Newall 1970,p.186), the behaviour of shells and disarticulated valves is dependant on any permutation of these characteristics (op.cit.).

ii) Random faunal occurrence types (figs.5.1a,5.2; plates 5.1,5.2,5.3,5.4)

1) Introduction

Preferred fossil orientations have received considerable attention (Brenchley & Newall 1970;Clifton 1971;Clifton &

Boggs 1970;Johnson 1957;Kelling & Williams 1967;Richter 1942;Shrock 1948,p.284-326;Toots 1965a,b), whereas references to random orientations are much sparser (Pickerill 1974;Toots 1965a,b).

It is important to distinguish between true and apparent random orientations. Toots (1965b,p.59) defines a true random orientation as one with no preferred orientation whatsoever. The author extends this definition to include two- and three-dimensional outcrops (figs. 5.1a,5.2;plates 5.1,5.2,5.3,5.4). The valve density in such occurrence types is variable (fig. 5.2;plates 5.2,5.3,5.4).

Random occurrence types are common, usually being confined to fine grade lithologies, but are also less frequently noted in sandstones.

Three types of processes may possibly account for such randomness, e.g., biological, mechanical and post-depositional processes.

2) Biological processes

Only animals living at the site of deposition can become buried in their life positions (Toots 1965b,p.60) and it was thought that random orientation was due solely to normal life and depositional processes. However, within the Snowdonian assemblages, some random occurrence types are almost entirely composed of disarticulated brachiopod valves, therefore implying that in this case, random occurrence types are not produced by normal life processes (op.cit.).

3) Mechanical processes

Disarticulated valves only assume random orientations when directional forces are absent (op.cit.,p.60). Settling-out processes produce preferred orientations (Compton 1962,p.226-227), as does wave and current action, the valves attaining hydrodynamically stable positions. The only mechanical process causing random valve orientations is the removal of the influence of water movement, a situation occurring in seafloor sediment traps (op.cit.).

Another possible method is by scouring (Menard & Boucot 1951), which depends on the relationship between the competent velocity of the valves (i.e., the current velocity required to initiate valve movement) and the sand grains on which the valves are resting. If these grains are set into motion before the valves, scouring is initiated around the valves, each valve gradually settling into a scoured depression. If transported sand grains are redeposited within this depression, each valve becomes buried in a hydrodynamically unstable position. The complete scouring process is comprehensively documented by Johnson (1957,p.532).

4) Post-depositional processes

Such processes seem the most probable causes of random valve orientations, subsequently inducing reorientation from initially planar orientations by differential rotational movements within unlithified sediments. Intraformational folding, which produces penecontemporaneous sediment deformation, rotates sediment grains and any entombed valves, but random orientations are probably only rarely produced (Toots 1965b,p.61). Toots (op.cit.,p.61) states "....most sediments containing randomly orientated fossils lack recognisable internal structure or show only irregular mottling", an association noted within the Snowdonian assemblages and which can probably be attributed to one of two processes.

A) This involves contemporaneous deformation, resulting from viscous flow within the sediment. After the sudden restoration of cohesion, any entombed valves become preserved in a random orientation (Dott 1963) but this mode of origin is not thought to be common in the geological record (Toots 1965b,p.61).

B) The primary fabric of most sediments is obliterated by the activity of burrowing organisms (Moore & Scruton 1957) and the association of random valve orientations, sediment mottling and no internal sedimentary structures is correlated with biogenic activity (op.cit.; Rhoads 1967;Richter 1942;Toots 1965b;van Straaten 1959). Polished sections of seemingly homogeneous rocks reveal intense biogenic reworking, indicating the original presence of an abundant infaunal component in well-oxygenated bottom waters (Rhoads & Morse 1971;Watkins & Berry 1977).

If an infaunal organism burrows close to an entombed valve, this valve becomes slightly rotated from its original position. If burrowing continues, the primary sedimentary fabric is eventually obliterated, the sediment becomes mottled and random valve orientations are produced. Consequently, an initial planar occurrence type may be transformed into a random occurrence type. As bioturbation is common in most submarine environments, it is probable that this is the normal cause of random orientations (Toots 1965b,p.61) and this interpretation is applied to random occurrence types in the Snowdonian assemblages.

Although the author believes that biogenic reworking is the principal cause of random valve orientations, some randomness may possibly be due partly to scouring (Menard & Boucot 1951). Johnson (1957,p.532) states that current velocities needed to initiate scouring around valves are lower than those required to move surface sand grains in the absence of any valves, whilst Brenchley & Newall (1970,p.217) note valve transportation is initiated at lower velocities on sand than on mud and that burial (by scouring) also begins at lower velocities on sand.

It appears therefore that random valve orientations in fine grade lithologies are due entirely to biogenic reworking, whereas random orientations in coarser grade lithologies are possibly due to a combination of scouring and biogenic reworking.

Random occurrence in coarse and fine grade lithologies probably indicates weak current activity within the (inner ?-) outer sublittoral zone (Toots 1965a, p.228). Frequently, random occurrence types grade laterally and vertically into unfossiliferous beds or are bounded by planar occurrence types (plates 5.1,5.4). This latter example probably results from fluctuating sedimentation and current velocities coupled with periodic shallow deformative bioturbation (Reineck & Singh 1975,p.138, after Schäfer 1972,p.404).

Valve rotation may result from compaction of unlithified sediment (chap.3,section f). The author believes this process operates only if the valves are initially randomly orientated and which, therefore, may possibly destroy random occurrence types.

Pickerill (1974) places "life clusters" within the random occurrence category. Although no conclusive evidence is found for their existence, monospecific aggregates of articulated and disarticulated randomly orientated valves of sowerbyellids, Sericoidea and dalmanellids are noted. Each accumulation may represent one spatfall and therefore may correspond to such "life clusters" (op.cit.).

iii) Planar faunal occurrence types

1) Thin planar occurrence types (fig.5.1b;plates 5.4,5.5,5.6)

Thin planar occurrence types are common and three subtypes are arbitrarily distinguished, e.g., scattered, medium and crowded (fig. 5.1b), each being based on the quantity of fossils present. Usually, these types are restricted to one or two layers of fossils (shell pavements - Bradley 1957,p.670;Pickerill 1974;Toots 1965a, p.226), disarticulated brachiopod valves being the dominant component. Valve orientation varies between convex-up, mixed and concave-up (section c).

Planar occurrence types are the end products of mechanical processes, i.e., wave and current activity (Toots 1965a,p.222). As the valves are obviously not in life positions, this indicates some reworking on the seafloor and possible valve transport, associated with localised erosion, redeposition and burial. Such occurrence types are noted within fine and coarse grained lithologies, but the component valve size often differs. Small valves (sowerbyellids, dalmanellids,etc.,) comprise planar occurrence types in fine lithologies, whereas larger valves (Dinorthis, Macrocoelia, etc.,) are found within planar types in coarser lithologies.

Planar occurrence types are well developed in the Multiplicata Sandstone at Llyn Cowlyd (Diggens & Romano 1968), at Capel Curig and in coarser lithologies within the Glanrafon Beds and Carneddau Group at Dolwyddelan and Betws-y-Coed, respectively. Some planar types within the Glanrafon Beds at Dolwyddelan are composed almost entirely of disarticulated crinoid columnals, being analogous to similar occurrence types within the "Glyptocrinus Flags" of the Onny Valley in Shropshire (Dean 1958,p.204;1964, p.277; Dean in Greig 1968,p.111).

A fairly high rate of sedimentation and clastic input is probably associated with the formation of planar occurrence types, as such shell-beds require rapid burial by a substantial thickness of sediment to prevent biogenic reworking. Planar occurrence types are characteristically found in sediments possessing some remanent bedding, e.g., planar laminations, low-angle cross-bedding etc., indicating either an absence of infaunal burrowers and/or a high sedimentation rate. These occurrence types afford evidence for relatively high energy environments with fluctuating current activity and imply location within the inner (-outer ?) sublittoral/littoral zones (Toots 1965a, p.226,table 1,p.228).

If modern-day analogies are made, shallow subtidal environments are dominated by infauna adapted for deep burrowing, e.g., up to depths of 30 cms. (McAlester & Rhoads 1967; Seilacher 1967) which further demonstrates that planar occurrence types must have been rapidly buried by a considerable thickness of sediment to prevent biogenic reworking and to maintain their integrity. Nichols et al. (1978) demonstrate that if the components of modern-day soft bottom communities (bivalve-polychaete) are suddenly buried to depths of approximately 30 cms. or more, no escape is initiated (op.cit.,p.425) and no bioturbation is produced.

2) Laterally continuous shelly horizons (fig.5.3, plates 5.7,5.8,5.9)

This occurrence type is commonly associated with planar types, being formed by coalescence of several planar horizons to produce relatively thick shelly accumulations which are broadly analogous to "coquinas" (Bridges 1975,p.87-88; Gary et al.1972,p.156) or "shell hashes" (Gary et al.1972,p.652; Kelling & Williams 1966, p.931). Statements and inferences regarding planar occurrence types are equally applicable to laterally continuous shelly horizons. Van Straaten (1952) notes that some modern-day shell concentrations result from biogenic reworking, but the essentially planar nature of these occurrence types appears to invalidate this hypothesis. Johnson (1957,p.534) states that rapid sedimentation terminates the accumulation of shelly layers, whereas lower sedimentation rates allow thick accumulations, with high valve densities, to form, this theory being applied to the Snowdonian shelly horizons.

Coalescence of planar horizons occurs when the sedimentation rate decreases. Such decreases, however, are only localised and transitory. Once sedimentation decreases, shelly accumulations begin to build up, but on increasing, any further accumulation is temporarily terminated, the existing accumulation becoming buried. Therefore these accumulations reflect local hydrodynamic and depositional fluctuations and may mirror seafloor topography. Consequently, these horizons may represent what originally were laterally extensive, low-angle shell banks on the seafloor, acting as small-scale topographic "highs" which were "starved" of sediment but allowed repeated shell accumulation. Only when sedimentation significantly increased did the shell bank become buried.

iv) Intermittent faunal occurrence types

1) Lenticular shelly concentrations (fig. 5.4a)

This occurrence type may possibly be classed as random but is distinguished in possessing a restricted lateral extension. The valves within such concentrations are randomly orientated (but are not associated with bioturbation) or are, less frequently, concave-up. This particular occurrence type is more common in fine lithologies, e.g., the Portreuddyn Slates (Shackleton 1959), being occasionally associated with thin planar occurrence types (medium/crowded). Calcareous lenses containing small brachiopod valves are found within sandstones at Capel Curig and are assumed to be similar occurrence types.

Such concentrations probably accumulated in sediment traps (Toots 1965a, p.225; 1965b, p.60), the valves being transported into small seafloor depressions by current activity and consequently becoming buried. Random valve orientations probably result from those valves first deposited in the sediment trap forming impediments to successive valves, causing them to assume various attitudes (Bridges 1975). The author believes that the gradient of the sides of the sediment trap also controlled the final valve orientations (chap.8,section b,ii,1).

This explanation may appear unlikely when applied to occurrence types in the Portreuddyn Slates, but here these types are frequently associated with thin planar occurrence types, thus attesting to some current activity. Further associations with thin, wispy silty horizons imply slight fluctuations in current velocity and clastic input.

2) <u>Univalve horizons defining the base of trough cross-bedded sets</u> (fig.5.4b)

This subtype is very rare, being positively identified at only one locality (205 - SH 73655157 - Cwm Penamnen, south of Dolwyddelan). Large-scale (Allen 1963) trough-cross beds are noted within fine sandstones, the erosional base of each set demarcated by a single layer of small, disarticulated, preferentially convex-up brachiopod valves.

Each set is interpreted as a scour trough (van Beek & Koster 1972;Harms et al.1963;McGowen & Garner 1970; Morton 1978), the shell layer representing a shell lag concentrate (Harms et al.1963;Morton 1978) which was quickly buried by a cross-stratified trough infill (van Beek & Koster 1972;McGowen & Garner 1970) deposited by migrating duneforms (van Beek & Koster 1972) or perhaps large-scale linguoid ripples (Allen 1963), possibly under lower flow regime conditions (Harms & Fahnestock 1965; Simons et al.1965). Morton (1978) suggests similar valve-bedding associations represent storm deposits.

v) <u>Undisturbed life orientations</u> (fig.5.5;plate 5.10)

Although rare, in situ linguloid (obolid) brachiopods are found in the Glanrafon Beds at Dolwyddelan (chap.9) and in the Carneddau Group at Betws-y-Coed (chap.10). Here the obolids are orientated posterior end downwards in medium-coarse siltstones, at 60°- 80° to underlying and overlying fossiliferous bedding planes. Their attitudes and orientations suggest the obolids are preserved in their original life positions. Modern-day linguloid life orientations range from vertical - horizontal (Chuang 1956;Craig 1952,1954;Ferguson 1963a;Pickerill 1973,1974; Richards 1972;Rudwick in Williams et al.1965). The orientation of the Snowdonian obolids is presumably a combination of an original high-angle, oblique life orientation and later small-scale rotation due to cleavage formation.

These obolids were probably preserved with the pedicle retracted, burial resulting from burrow mouth collapse (Ferguson 1963a) coupled with rapid sedimentation (as evinced by overlying thin planar occurrence types with preferred convex-up valve orientations and laminated sandstones). If the obolids had died in their normal feeding positions i.e., at the burrow mouth, they would have floated free (op.cit.,p.671). Likewise, if death had occurred when the pedicles were retracted but the burrows were not infilled, the shells would have risen up the burrows due to posthumous pedicle relaxation and probably have floated free (op.cit.,p.671). Ferguson .

(op.cit.,p.672) states "....In the event of the animal dying with its pedicle contracted, the entire animal may be entombed within the burrow, by collapse of the mouth of the burrow which would prevent the exit of the shell or body". This interpretation is favoured for the Snowdonian obolids.

Provable fossilised pedicles are not seen, although several vertical pipes packed with small secondary pyrite cubes are associated with these obolids. They may represent fossil pedicles, the pyrite resulting from anaerobic decay of organic matter, causing eventual precipitation of iron sulphide (after Myers 1942 in Craig 1952;Ferguson 1963a,p.675).

Life orientations usually indicate location within the outer sublittoral zone (Toots 1965a,p.228), the zone to which these obolids are assigned.

Articulate brachiopods and other fossil groups are not found in provable life positions. Ager (1967,p.166) maintains "....brachiopods are most unlikely to be found in life position". Those either with perishable pedicles or resting on the seafloor are certain to suffer some post-mortem movement (op.cit.,p.166). Of the two dominant brachiopod groups, the dalmanellids are not found with certainty in their life positions e.g., beak down, with the commissure vertical (Bretsky 1969a,1970b,fig.13,p.21; Pickerill 1974;Richards 1972). Similarly, strophomenids are not found in their characteristic life orientations e.g., convex valve resting freely on the substrate

(Lamont 1934;Pickerill 1974;Richards 1972;Rudwick 1965), which were extremely susceptible to post-mortem movement.

c) Valve orientations

i) Introduction

Consideration and possible verification of transport is essential in faunal analysis (Boucot 1975,p.40-41). Transport is capable of grossly modifying assemblage compositions, consequently presenting an unrepresentative picture of the actual assemblages. Conclusions regarding the degree of transport can be made by considering preferred valve orientations. If a fossil assemblage is proven to have resulted from the accumulation of transported components, it can be treated with greater caution, concerning faunal composition, etc., and community assignment. However, it is stressed that the maximum information concerning depositional sites, hydrodynamic regimes etc., can only be obtained from consideration of all available evidence e.g., occurrence types, preferred valve orientations, sedimentary structures, lithofacies relationships, ichnology, plus opposing valve and disarticulation ratios (Boucot et al. 1958).

Several conclusions pertaining to disarticulated valve orientations, which serve as bases for later interpretations, are summarised:-

a) Valve transportation occurs more readily in the concave-up position (Brenchley & Newall 1970; Johnson 1957;Menard & Boucot 1951), this being the most stable position during transport (Crowell et al.1966).

b) Valves initially concave-up are transported farther on sands than on muds (Brenchley & Newall 1970, p.210).

c) Valves are transported in a variety of episodic modes e.g., rolling (Kelling & Williams 1967; Menard & Boucot 1951; Nagle 1967), sliding (Menard & Boucot 1951), skidding (Nagle 1967), saltation (Brenchley & Newall 1970) and gravity slips down ripple lee faces (Kelling & Williams 1967).

d) To initiate transport, a moving carpet of sediment grains has to be developed beneath a valve (Brenchley & Newall 1970,p.210; Johnson 1957,p.533).

e) Concave-up valves are more easily inverted on muds than on sands (Brenchley & Newall 1970,p.215).

f) Rapid burial preserves the integrity of valve orientations (Johnson 1957,p.533).

g) Scouring occurs at lower current velocities when valves are present than when they are absent, scouring beginning around the valves (Brenchley & Newall 1970; Johnson 1957; Menard & Boucot 1951).

h) Once scouring is initiated around a valve, it will become ultimately buried (Johnson 1957,p.532-533).

i) Scouring begins at lower current velocities on sands than on muds (Brenchley & Newall 1970,p.219).

j) Valves are buried in concave-up and convex-up orientations (Brenchley & Newall 1970; Johnson 1957;

Menard & Boucot 1951).

k) Convex-up valves are more easily buried by scour (Brenchley & Newall 1970; Johnson 1957).

Four types of valve orientations are recognised in the Snowdonian assemblages e.g., concave-up, mixed, convex-up and random. Random orientations have previously been discussed (section b,ii).

ii) Preferred concave-up valve orientations (fig.5.6; plates 5.6,5.11,5.12)

1) Introduction

Planar occurrence types with preferred concave-up valve orientations are more frequently noted within coarser lithologies. These orientations are hydrodynamically unstable (Brenchley & Newall 1970,p.215), unless any morphological features confer stability (Richter 1942) and are thought by Toots (1965a,p.223) to be preserved only "....in the absence of a significant horizontal force".

Emery et al. (1965) and Emery (1968,p.1264,1268) note that 62% - 91% of pelecypod valves lie concave-up on continental shelf sands, whereas Kornicker & Armstrong (1959,p.183) and Toots (1965a) note concave-up orientations at the extreme upper limit of wave action (upper swash zone). Clifton (1971) records concave-up pelecypod valve orientations in quiet waters.

2) Possible processes

Several processes are postulated for the formation of concave-up orientations:-

A) An undisturbed life orientation (Compton 1962; Toots 1965a,p.223).

B) When valves are rapidly deposited from highly concentrated flows or sink to the bottom of a standing water body, they usually attain concave-up orientations (Middleton 1967,p.229,232;Toots 1965a, p.222).

C) Accumulation in sediment traps (Toots 1965a).

D) Morphological peculiarities bestow hydrodynamic stability to concave-up valves (Richter 1942).

E) An undisturbed orientation following disarticulation possibly by oscillatory water currents (Boucot et al. 1958).

F) By migrating trains of small-scale ripples (Clifton & Boggs 1970).

G) In quiet waters, concave-up orientations may be due to bioturbation and the action of scavengers and predators (Clifton 1971).

H) Valves initally concave-up may be transported across sandy substrates by low velocity currents. Transport eventually ceases, due to:-
   a) current velocity decrease
   b) seafloor impediments
   c) friction between the valves and the substrate
   d) sediment accumulation within the upturned concave faces of the valves producing a "weighting" effect

   or a combination of these suggestions.

As the valves are subjected to low velocity currents on sandy substrates with no extended movement along the bottom by traction, large-scale valve inversion does not occur. The concave-up orientation is then preserved, due to burial by scour and/or rapid sedimentation.

3) Conclusions

Of the above suggestions, the author favours C, F and H.

C) Concave-up orientations are noted from what seem to be sediment traps in the Portreuddyn Slates (section b,iv,1).

F) At Capel Curig, concave-up valves (plates 5.6,5.11, 5.12) are frequently associated with planar laminated sandstones. Jopling (1966) and Newton (1968) note horizontal laminae are produced by migrating ripple trains, whilst Clifton & Boggs (1970) maintain the migration of wave- and current-generated ripples is capable of producing valve reorientations, although Clifton (1971) notes only small valves are affected. The author believes, however, that larger ripples would be capable of reorientating larger valves.

H) This process also appears feasible.

It is notable that these methods all require relatively low velocity currents for their operation and probably occur within the sublittoral zone. In conclusion, it is stated that preferred concave-up valve orientations probably result from several processes, rather than one dominant process.

iii) Preferred convex-up valve orientations (fig. 5.6; plates 5.4,5.5,5.13)

1) Introduction

Planar occurrence types containing convex-up valves seem to exhibit no lithological preferences. Valves are hydrodynamically more stable in this orientation (Brenchley & Newall 1970,p.215) and once this orientation is attained, the possibility of transportation ceases unless the valves are subjected to instantaneous high current velocities (Johnson 1957). Sanders (1965,p.203), Shrock (1948) and Toots (1965a) maintain this orientation is produced by current activity, being the normal orientation in subaqueous environments (Toots 1965a,p.222).

2) Possible processes

Several processes are postulated for the formation of preferred convex-up valve orientations:-

A) An essentially in situ orientation resulting from disarticulation, due possibly to low energy, oscillatory current activity (Boucot et al.1958).

B) Negligible net lateral transport under upper flow regime conditions, the valves quickly attaining a convex-up orientation.

C) Negligible net lateral transport under lower flow regime conditions, valve inversion to convex-up orientations being due to either seafloor impediments or slight current velocity increases.

D) Moderate net lateral transport under lower flow regime conditions, before eventual inversion to convex-up orientations.

3) Conclusions

It is essential to consider the lithology in which the convex-up valves are found. Regarding earlier statements (section c,i), the following conclusions are proposed :-

A) Convex-up valve orientations in fine grade lithologies (siltstones) - (plate 5.4)

Such orientations probably arise by processes A, B and C, which involve negligible net lateral transport and therefore represent the remnants of essentially in situ assemblages, corresponding to the "residual fossil community" of Fagerstrom (1964,p.1199).

B) Convex-up valve orientations in coarse grade lithologies (sandstones) - (plates 5.5,5.13)

Such orientations probably arise by processes B, C and D. The latter process involves some net lateral transport, although this is difficult to quantitatively assess which, however, the author believes was only moderate (tens of metres) with only minor compositional modifications. Consequently, these valves may represent remnants of "residual fossil communities" and "transported fossil assemblages" (op.cit.).

In conclusion, it is stated that convex-up valve orientations were produced by more persistent, relatively higher energy currents than were the concave-up orientations.

iv) Mixed valve orientations (fig.5.6;plates 5.1,5.7, 5.8)

1) Introduction

Mixed orientations are those in which there is no preferred orientation i.e., there are approximately equal numbers of concave-up and convex-up valves. Such orientations are not random as they are confined to planar occurrence types. Mixed orientations are mostly found within laterally continuous shelly horizons which appear to exhibit no lithological preferences.

2) Possible processes

Several processes are postulated for the formation of mixed valve orientations :-

A) Essentially in situ orientations resulting from disarticulation, probably due to low energy, oscillatory currents (Boucot et al.1958).

B) Transient current activity producing some valve inversion but no preferred orientations (i.e., convex-up, concave-up).

C) Such orientations possibly reflect the differing hydrodynamic responses of pedicle and brachial valves of different genera/species.

3) Conclusions

Of the above suggestions, the author favours B and C. Field evidence serves to directly substantiate process C, e.g.,

Locality 189 - Glanrafon Beds (fine sandstones/coarse siltstones) - southwest of Dolwyddelan (map 3). Here, sowerbyellid valves display preferred convex-up orientations with a ratio of 85:22 (≏ 4:1). However, the brachial valves possess a convex-up:concave-up ratio of 72:12 (=6:1), whilst the pedicle valve ratio is 13:10 (=1.3:1). Therefore:-

a) The pedicle and brachial valves of sowerbyellids appear to possess differing hydrodynamic properties.

b) Valve sorting has occurred. Relatively more pedicle valves are concave-up so consequently more were potentially transportable (section c,i), thus probably accounting for the lower percentage of pedicle valves noted.

Mixed valve orientations result from transitory, low energy currents, presumably within the (outer) sublittoral zone, higher energy currents producing preferred convex-up valve orientations. Laterally continuous shelly horizons with mixed orientations additionally imply reduced sedimentation (Johnson 1957,p.534).

v) Valve orientations as transport indicators

Valve transport has been extensively examined, e.g., Behrens & Watson 1969;Boucot et al.1958;Brenchley &

Newall 1970;Clifton 1971;Clifton & Boggs 1970;Johnson 1957; Kelling & Williams 1967;Kornicker & Armstrong 1959;Lever 1958;Lever & Thijssen 1968;Martin-Kaye 1951;Menard & Boucot 1951;Nagle 1967 and Toots 1965a. Most workers analyse bivalves, specifically reviewing bedding plane orientations, e.g., current/wave distributions and long axes alignment, factors which cannot be assessed within the Snowdonian assemblages. However, certain of their conclusions are equally applicable to brachiopods.

Preferred valve orientations (plus lithological associations) serve as transport indicators as follows :-

1) <u>Preferred concave-up valve orientations</u>

   A) Fine lithologies - negligible net lateral transport.

   B) Coarse lithologies - negligible net lateral transport, but probably greater than A.

2) <u>Preferred convex-up valve orientations</u>

   A) Fine lithologies - negligible net lateral transport.

   B) Coarse lithologies - moderate net lateral transport with minor compositional modifications.

3) <u>Mixed valve orientations</u>

   A) Fine lithologies - negligible lateral transport.

   B) Coarse lithologies - little - moderate (?)

net lateral transport.

4) Random valve orientations

Transport is difficult to assess, although some conclusions may be reached from consideration of the lithology, valve articulation, opposing valve ratios, presence/absence of valve abrasion/ fragmentation etc..

Modern-day studies (Behrens & Watson 1969;Craig 1967; Lever 1958;Martin-Kaye 1951;Warme 1969) indicate maximal transport of only several hundred metres from growth site to depositional site, whilst Ekdale (1973) reports post-mortem movement is not significant in sublittoral environments. Large-scale lateral transport is probably only effected by turbidity currents.

Chapter 6 The Snowdonian benthic marine communities

a) Introduction and general community concepts

It is impossible, when considering the Snowdonian assemblages, to ignore the idea of marine benthic communities. A brief résumé of community concepts will serve as a framework for interpreting the Snowdonian faunal assemblages.

Petersen (1911,1913) pioneered work on communities and defines a community as "....a regularly recurring combination of certain types of animals, as a rule strongly represented numerically". Elles (1939,1940) visualizes a scheme of benthic assemblages for a marginal geosynclinal area (op.cit.,1939,p.182,fig.1.;1940,p.438, fig.10.), her "Inshore Region" (op.cit.) dominated by large brachiopods, whilst her inner "offshore region" is dominated by brachiopods and trilobites. Important works on recent benthic communities include those by Johnson (1970), Sanders (1958,1960) and Thorson (1957), whilst ancient benthic community studies include those by Bayer (1967); Bretsky (1969a,1970a,b); Bretsky et al.(1969); Calef & Hancock (1974); Fox (1968); Fürsich (1977); Hancock et al. (1974); Hurst (1975); Pickerill (1974); Speden (1966); Stanton & Evans (1972); Titus & Cameron (1976); Walker (1972a,b); Walker & Laporte (1970); Ziegler (1965) and Ziegler et al. (1968), amongst others.

Recently, the validity of benthic communities as "real", natural units has been debated. Johnson (1964) states benthic communities show no fixed internal structure, and that adjacent communities often intergrade, a common feature of communities situated on clastic sediments (Johnson 1970,1972). If the environment is spatially gradational, so are any adjacent contemporaneous communities (Johnson 1972). However, Johnson (1964) and Speden (1966) maintain the natural recurrence of a limited number of species is due to similar responses to the physical environment, consequently suggesting marine communities are "real" units. Johnson (1964) defines a community as ".... an assemblage of organisms inhabiting a specified place", and later, as ".... an assemblage of species at a particular place and time" (Johnson 1972).

Communities are usually defined on the basis of abundant species (Peterson 1913, Thorson 1957), and are named after a characteristic genus or genera (Johnson 1972) although Hurst (1975) suggests community denomination should be after the most abundant, ecologically restricted genus.

Benthic communities are divided into either high dominance communities, i.e., one species is numerically dominant, or low dominance communities, i.e., several species are approximately equally dominant (Johnson 1964,Thorson 1957). Johnson (1972) further divides communities into high-or low-grade communities, low-grade communities displaying low species diversity and fluctuating compositions, whereas high-grade communities display high species diversity and stable compositions.

Species comprising benthic communities are assigned to one of three groups (op.cit.) - (fig.6.1):-

1) characteristic - their numerical abundance defines a particular community; they are usually (but not always) found together and are low order successional species for one particular community.
2) intergrading - they are found with low abundance in a community (occasionally attaining relatively high abundance), but characterise another, probably adjacent, community.
3) ubiquitous - they are not restricted to any community, although they may characterise one community when abundant, but also occur with lower abundances in other communities.

Benthic communities are dominated by filter/deposit feeders (Speden 1966). Turpaeva (1957), in studying food interrelationships within communities, erected five trophic (feeding) groups of organic detritus eaters, e.g., swallowers, collectors, filterers-A, filterers-B and awaiters (op.cit.,p.137), whereas Walker (1972a), in a similar study, assigned the terms "low filterers" and "high filterers" to Turpaeva's (1957) "filterers A" and "B" respectively. Trilobites, gastropods, ostracodes, etc., are collectors, infaunal organisms are swallowers, brachiopods and bivalves are both high and low filterers, whilst awaiters are passive suspension feeders (?)(Walker 1972a). Turpaeva (1957) concludes that any benthic community is dominated by any one of these five trophic groups.

Two important community concepts to consider are community controls and the effect of environmental changes upon community composition. Shallow marine benthic communities are usually low grade (Johnson 1972) and are directly controlled by the physical environment. Such factors as water depth, substrate nature, salinity, food resources and temperature ("spatially heterogeneous parameters" - Bretsky & Lorenz (1970)) probably control benthic communities. Ager (1965,1967), Craig & Jones (1966), Johnson (1971), Pickerill (1974), Speden (1966) and Williams (1963,1973) all suggest substrate nature exerts a primary control upon community structure, whereas Cocks (1967), Hancock et al. (1974), Ziegler (1965) and Ziegler et al. (1968) suggest water depth and temperature are controlling factors. However, Speden (1966, p.417) considers depth of secondary importance and only rarely to be a direct controlling factor. Evidence from the Snowdonian assemblages suggests substrate is a controlling factor, certain genera being found within widely differing lithologies of similar grain size, e.g., Sericoidea is restricted to fine grain lithologies.

Environmental change produces complementary changes in community structure (Bretsky & Lorenz 1970; Johnson 1970; Pickerill 1974; Speden 1966). Margalef (1968) relates the establishment and consequent diversification of communities to stages of succession, early successional stages corresponding to early stages of community establishment on the seafloor, whilst later successional stages are related to well-established communities. Pioneering, immature benthic communities (early successional stage) commonly display low species diversity (op.cit.; Johnson 1972) and are directly physically controlled (Sanders 1958), such communities usually indicating "physically rigorous" environments (Bretsky & Lorenz 1970) e.g., the linguloid - molluscan association (Bretsky 1969b). Mature, well-established communities (late successional stage) display high species diversity (Margalef 1968), which usually indicates stable environments (Bretsky & Lorenz 1970). Contemporaneous benthic communities comprise a temporal mosaic, each community being at a slightly different successional stage (Margalef 1968).

Johnson (1972) maintains environmental disturbances (erosion, increased sedimentation, etc.) downgrade communities to earlier successional stages, with concomitant decreases in diversity. Therefore, in a recently disturbed environment, only low order succession, characteristic species (for any one community) and ubiquitous species are found, such species being found frequently on other substrates (which differ from their own characteristic substrate), as they are eurytopic (op.cit.) - fig.6.1.

In conclusion, shallow marine benthic communities are low grade, possess relatively low diversities and are directly controlled by the physical environment. Such communities are developed on clastic substrates, and intergrade temporally and spatially (fig.6.1).

Environmental change downgrades communities to lower succession stages. Nearshore communities possess low diversities (Bretsky & Lorenz 1970), whereas offshore communities display high diversities (op.cit.).

b) Previously defined Caradocian marine benthic communities in North Wales and their applicability to the Snowdonian marine benthic assemblages

i) Caradocian communities from the areas around Bala and the south Berwyn Hills, North Wales

Williams (1963,pt.II,p.333-344) notes that certain faunal associations in the Bala area are restricted to certain lithologies, e.g.:-

Onniella/Sericoidea/Paracraniops characterise muddy environments.

The *Nicolella* association (with *Eoplectodonta/Leptestiina/Platystrophia/Rhactorthis/Strophomena*) is usually found in a lime-rich environment.

The *Dinorthis* association (with *Bicuspina/Dalmanella/Heterorthis/Leptaena*) prevails in sandy lithologies.

The *Howellites* association (with *Sowerbyella/Rostricellula/Macrocoelia/Reuschella*) is usually found in silty, muddy lithologies.

Williams (op.cit.,p.342) regards this latter association as the "....chief indigenous group in the Bala assemblages". Williams (1973,p.242-243,fig.1) later reiterates these conclusions, adding ".... a silty substrate supported all three associations" (Nicolella/Onniella/Dinorthis)" and especially a fourth including Howellites with Sowerbyella" (op.cit.,p.243).

These associations provide the basis for the detailed community studies of Pickerill (1974) in the south Berwyn Hills, who initially recognises four communities, e.g., the Dinorthis, Howellites, Nicolella and Onniella communities. The Dinorthis community is subdivided into the Dalmanella, Dinorthis and Macrocoelia populations, whereas in later unpublished work (Brenchley & Pickerill, in press) the Dalmanella population is elevated to community status. The Onniella community is subdivided into the Onniella and the Bivalve populations. Previous lithological associations (Williams 1963,1973) are equally applicable to all these marine communities.

ii) The relationship of previously defined Caradocian benthic communities to the Snowdonian faunal assemblages

Pickerill's (1974) communities occur at the same stratigraphic horizons as the Snowdonian faunal assemblages and recurrent species associations and lithological relationships (op.cit.) are broadly similar to those in the Snowdonian assemblages. Therefore, the author applies the same broad community framework (op.cit.), with minor adjustments, to the Snowdonian assemblages, and sees no reason to doubt the overall environmental interpretations for these communities (op.cit.), consequently relating them to the Snowdonian communities.

c) The proposed Snowdonian benthic marine communities

i) Introduction

The proposed communities are broadly similar to those of Pickerill (1974) and Williams (1963,1973) in terms of composition, and where possible, Snowdonian community denomination is directly related to those communities.

Four communities are proposed:-

a) *Sericoidea* community
b) *Nicolella* community
c) *Dinorthis* community
d) Dalmanellid-sowerbyellid "mega" community

ii) The *Sericoidea* community (tables 6.1.,6.2)

This community is characterised by the aegiromenine *Sericoidea* sp., which is found in all assemblages assigned to this community with a mean abundance of 75.5%, and the dalmanellid *Onniella* (where preservation/lack of deformation enables confident identifications). *Ampyx* (cf.*linleyensis* Whittard) of Whittard 1955 appears a characteristic trilobite, *Ampyx* sp. being associated with *Chonetoidea* sp. (= *Sericoidea* ?, see chap.4) in Onnian mudstones within the Cross Fell inlier (Lamont 1948,p.416).

Intergrading genera (figs 6.2,6.3) include ubiquitous sowerbyellids (low order succession genera of the dalmanellid-sowerbyellid "mega" community), *Horderleyella* sp.

and *Rafinesquina* sp., from the aforementioned "mega" community and the *Dinorthis* community, respectively. Ubiquitous intergrading trilobites include *Broeggerolithus* sp. and *Calymene* sp. (s.l.) (*Flexicalymene* sp.). Ubiquitous crinoids and ramose bryozoa are also present. All intergrading genera usually possess low abundance.

Examples of the *Sericoidea* community are found in the Portreuddyn Slates (localities 4A,7,8 - see Appendix Two and map 2) in the Moel Hebog district. Here, assemblages are found in fine grain, well-cleaved siltstones, indicating the community originally flourished on muddy substrates in a low energy, offshore (?) environment, in slightly greater water depths than the dalmanellid-sowerbyellid "mega" community. Tillman (1960) suggests the long anterior process and genal spines of *Ampyx* sp. stabilised the animal when resting on the seafloor, a particularly useful function on the original soft muds.

A good indication as to sediment grade being a primary community control is exemplified by the *Sericoidea* community. This community originally developed on fine grain sediments, e.g., the Portreuddyn Slates, and is an abundant intergrading component within the *Nicolella* community which is developed within extremely fine grain, waterlain, airfall tuffs within the Upper Rhyolitic Tuff Formation at Dolwyddelan. Although both lithologies are diverse, they are essentially very fine grained.

At locality 242 (southwest of Betws-y-Coed - see Appendix Two and map 5), an assemblage apparently representing the Bivalve Population of Pickerill (1974, p.293) is noted (table 6.2). This assemblage is characterised by infaunal nuculoids, epifaunal ambonychiaceans, and *Tallinnella* sp. (intergrading from the dalmanellid-sowerbyellid "mega" community), plus frequent orthoconic cephalopods, gastropods, trinucleids and isotelinids, and is developed within black, well-cleaved, fine grain siltstones, presumably deposited under extremely low energy conditions.

The *Sericoidea* community is closely comparable to the *Onniella* association (Williams 1963,1973), the *Onniella* community(Pickerill 1974) and the Trilobite-*Onniella* community (Cocks & McKerrow 1978). *Sericoidea* sp. replaces *Onniella* sp. as the characteristic brachiopod in view of the abundance of *Sericoidea* sp. and the difficulty in accurately identifying tectonically deformed dalmanellids.

iii) *The Nicolella community* (tables 6.1,6.3)

Assemblages referable to this community are very easily recognisable. The characteristic genera are the orthaceans *Skenidioides*, *Rhactorthis*, *Cremnorthis*, *Nicolella*, *Dolerorthis* and *Orthambonites*, the plectambonitacean *Leptestiina*, the atrypacean *Protozyga*, the pterygometopid *Estoniops* and the cyclocystoid *Cyclocystoides*. Other abundant, characteristic forms are the ubiquitous crinoids and bryozoans, with cystoids (*Haplosphaeronis*) becoming locally abundant. Disarticulated machaeridian plates (*Lepidocoleus*) are also extremely abundant.

Important intergraders (fig.6.3) are the ubiquitous sowerbyellids and dalmanellids, *Reuschella* and *Sericoidea* (*Chonetoidea*), the latter becoming the dominant component in the *Nicolella* community from the lower Upper Rhyolitic Tuff Formation (locality 179 - see Appendix Two and map 3) at Dolwyddelan.

The Snowdonian *Nicolella* community is closely comparable with the *Nicolella* communities in the south Berwyn Hills and at Bala (Pickerill 1974; Williams 1963), and comprises genera which migrated from the Baltic faunal province. Snowdonian assemblages assigned to this community are broadly similar to assemblages from the mid-Costonian Derfel Limestone (Whittington & Williams 1955), consequently implying migration from the Baltic region occurred during the Costonian and the Longvillian.

This community has a widespread occurrence throughout Snowdonia (Betws-y-Coed, Dolwyddelan and west of Moel Hebog), appearing at approximately the same stratigraphical horizon (Upper Longvillian). The abundance of characteristic genera varies laterally. In western localities *Dolerorthis* is abundant, but markedly decreases eastwards. *Skenidioides* abundance increases to the east, as does that of *Nicolella*, *Protozyga*, *Leptestiina* and *Estoniops*, whereas *Orthambonites* possesses an overall low degree of abundance. Principal intergraders, e.g., *Reuschella*, have a widespread low abundance, whilst *Sericoidea* is restricted to easterly assemblages.

Associated biogenic reworking indicates an abundant infaunal component was originally associated with this community, and further implies reduced sedimentation (Heckel 1972). Although further sampling may reveal otherwise, the Nicolella community appears restricted to calcareous sediments of varying grades. The absence of any well-defined sedimentary structures, the high degree of biogenic reworking, and the faunal occurrence types (random - thick shelly accumulations) all suggest relatively low sedimentation rates. Environmental. assessments are difficult, but low sedimentation coupled with a stable environment, as suggested by the high diversities (Bretsky & Lorenz 1970) implies an offshore environment. Van Straaten (1959,p.210) notes calcareous sediments are frequently found in an outer zone close to the edge of continental shelves. Intergradation by low order succession genera from the dalmanellid-sowerbyellid and Sericoidea communities possibly implies the Nicolella community occupied an intermediate position between these two communities (figs.6.2,6.3).

"Type" assemblages referable to the Nicolella community are found at localities 243 (SH 78655759) and 244 (SH 78535755) - see Appendix Two and map 5.

iv) The Dinorthis community (tables 6.1,6.4)

This community is characterised by the orthacean Dinorthis, the strophomenaceans Macrocoelia and Rafinesquina, the linoporellid Salopia, the harknessellid

Reuschella and the craniacean *Petrocrania*, along with ubiquitous crinoids and bryozoans. Intergrading, low order succession genera are noted, e.g., dalmanellids and ubiquitous sowerbyellids, in addition to rarer triplesiaceans, *Broeggerolithus*, bivalves and bellerophontids (figs.6.2, 6.3). The characteristic brachiopods (*Dinorthis*/*Macrocoelia*/*Salopia*) are all locally abundant. Intergrading sowerbyellids occasionally achieve isolated dominance (locality 155 - SH 72375846 - Capel Curig East; locality 134 - SH 62044523 - Gareg Bengam, east of Beddgelert - see maps 1 and 6, respectively).

It is not proposed to subdivide the *Dinorthis* community (see Pickerill 1974), as the author believes more Snowdonian assemblages referable to this community need analysing before any subdivision may be implemented. The Snowdonian *Dinorthis* community appears broadly comparable with the *Dinorthis flabellum* community (Cocks & McKerrow 1978).

Assemblages possessing dominant *Dinorthis*/*Salopia* appear confined to coarse sandstones, whereas *Macrocoelia* dominated assemblages appear restricted to slightly finer sandstones, although this relationship does not always hold true, e.g., in coarse volcaniclastic sediments above the Garth Tuff at Capel Curig (locality 143A - SH 70955788 - map 1) a sparse fauna, composed predominantly of *Macrocoelia* (89%), is found. It therefore appears *Macrocoelia* was the "pioneer" brachiopod in what was obviously a shallow water, physically rigorous environment

(Bretsky & Lorenz 1970), being subject to environmental fluctuations. Possibly the concavo-convex, free-living Macrocoelia (Rudwick 1965) was better adapted to high energy conditions and coarse, unstable, shifting substrates (Rudwick 1970, p.160) than Dinorthis or Salopia, which were pedically attached with the commissure being vertical (Richards 1972). Monospecific Macrocoelia assemblages are thought characteristic of shallow water, nearshore, high energy environments, resulting from environmental adaption, lack of competition and hydrodynamic sorting.

Hurst (1975) and Pickerill (1974) state that two species of the same genus are rarely co-existent and the Dinorthis community supports this view. The Multiplicata Sandstone at Llyn Cowlyd (Diggens & Romano 1968), locality 155 at Capel Curig (SH 72375846), and localities 134/134A (SH 62044523; SH 62004523) within the Upper Grits (Beavon 1963) at Gareg Bengam, east of Beddgelert (see maps 4,1 and 6 respectively) display good examples of the Dinorthis community with abundant Dinorthis (Plaesiomys) multiplicata[1] Bancroft all horizons being restricted to coarse sandstones. However, to the south and east e.g., Dolwyddelan, Betws-y-Coed, the Dinorthis community possesses abundant Dinorthis cf. berwynensis (Whittington) of Williams 1963, the assemblages appearing restricted to finer grade sandstones (197/197A/197B, SH 72405057 - south of Dolwyddelan - see map 3). No assemblage possesses these two species coexisting, the slight difference in original substrate probably partially governing their occurrence.

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[1] now Plaesiomys multifida (Salter) - see Cocks 1978, p.50

Assemblages dominated by *D.* (*P.*) *multiplicata*[1], *Macrocoelia* and *Salopia* are usually restricted to laterally continuous shelly horizons or thinner planar horizons with preferred valve orientations indicating deposition by water currents, with only moderate net lateral valve transport and negligible compositional modifications. Shelly horizons intercalated with unfossiliferous horizons suggest fluctuating sedimentation,the unfossiliferous horizons representing times of rapid sedimentation, whilst the shelly horizons represent times of decreased sedimentation with little or no biogenic reworking.*Dinorthis*/*Salopia* - dominated assemblages, associated with coarse sandstones possessing planar laminations and/or low-angle cross-bedding imply a shallow water, inner sublittoral environment, subject to fluctuating current velocities and clastic input. Low-medium faunal diversities similarly indicate a physically rigorous environment (Bretsky & Lorenz 1970).

Assemblages dominated by *Macrocoelia* and *D.* cf. *berwynensis* are usually restricted to planar horizons or laterally continuous shelly horizons and are commonly associated with planar laminated sandstones, although certain horizons possess randomly orientated valves, suggesting some biogenic activity. Similar environmental conditions are envisaged for most of the *Macrocoelia*-dominated assemblages, although the finer sandstone lithology suggests a slightly more offshore location.

[1] now *Plaesiomys multifida* (Salter) - see Cocks 1978,p.50

v) The dalmanellid-sowerbyellid "mega" community (tables 6.1,6.5)

Williams (1963) and Pickerill (1974) distinguish a distinct Howellites community. Pickerill (op.cit.) further distinguishes, as a subdivision of the Dinorthis community, a Dalmanella population, which is later elevated (Brenchley & Pickerill, in press) to community status.

Two factors generally preclude discrimination of the Howellites and Dalmanella communities in Snowdonia:-

1) Tectonic deformation/poor preservation make differentiation between Dalmanella and Howellites extremely difficult.

2) Intergradation between these communities is common and highly complex. Sowerbyellids, characteristic brachiopods for the Howellites community (Pickerill 1974, p.287), intergrade within the Dalmanella community, frequently becoming dominant. Low order succession genera from the Dalmanella community commonly intergrade within the Howellites community and vice versa (op.cit.).

These problems are slightly alleviated by consideration of other characteristic, low abundance genera for these communities (op.cit.) which may possibly enable assemblages to be assigned to either the Dalmanella or Howellites community. However, in view of the aforesaid precluding factors, the author proposes to combine these communities into the dalmanellid-sowerbyellid "mega" community, although it is occasionally possible to tentatively assign assemblages to either of the aforesaid communities. Faunal diversities range from medium (5-9) to high (>9). Assemblages referable to the "mega" community are found in lithologies ranging from medium-coarse siltstones to fine sandstones.

The dalmanellid-sowerbyellid "mega" community appears to be the chief indigenous group in Snowdonia. Comparisons are noted between this "mega" community and the Sowerbyella-Onniella community (Bretsky 1969a,1970b) and especially the Dalmanella-Sowerbyella community (Bretsky 1970a;Cocks & McKerrow 1978), whilst Onniella and Sowerbyella are commonly associated in fine grade Upper Ordovician sediments of the Nicolet Valley, Quebec (Bretsky & Bretsky 1975).

1) The Dalmanella community (tables 6.1,6.6)

Characteristic genera, along with Dalmanella, are triplesiaceans (Bicuspina), the strophomenacean Leptaena, the orthacean Horderleyella, the proetid Decoroproteus (see Owens 1973), ambonychiaceans, ptereineids, ostracodes e.g., the hollinaceans Tallinnella and Tetradella and the beyrichiacean Zygobolbina, plus abundant crinoid columnals. Intergradation from the Howellites and Dinorthis communities is frequent (figs. 6.2,6.3).

Associated extensive bioturbation indicates the presence of an abundant infauna and well-oxygenated bottom waters (Heckel 1972, p.244; Rhoads &

Morse 1971,p.426;Watkins & Berry 1977,p.275), whereas vertical skolithid burrows imply deeper burrowing in slightly shallower waters (McAlester & Rhoads 1967).

The author concurs with the postulated environmental interpretation for this community (Pickerill 1974), in that the Dalmanella community was probably situated farther offshore and in deeper water (outer sublittoral zone) than the Dinorthis community. Most faunal occurrence types are noted, with random and planar occurrence types predominating. Relatively higher degrees of articulation and opposing valve ratios approaching unity suggest the assemblages have suffered little significant lateral transport, with negligible compositional modifications. Bioturbation implies slow steady sedimentation but associated sedimentary structures, e.g., low-angle cross-bedding and thin planar laminations, indicate phases of increased sedimentation and energy levels.

Examples of assemblages referable to the Dalmanella community are found at localities 183. Horizon 1 (SH 71045089), 186 (SH 70965074) and 187 (SH 70855064), southwest of Dolwyddelan, whereas at locality 175 (SH 71765161), west of Dolwyddelan, an example of the Dalmanella community with dominant intergrading sowerbyellids is noted (see Appendix Two, map 3).

2) The Howellites community (tables 6.1,6.7)

Excluding Howellites, this community is characterised by abundant sowerbyellids. Paracraniops, although characteristic elsewhere (op.cit.), appears ubiquitous within the dalmanellid-sowerbyellid "mega" community. Characteristic trilobites are Parabasilicus and Brongniartella, with Tentaculites also appearing preferentially abundant.

Of all the benthic communities, the Howellites community suffers most intergradation, mostly from the Dalmanella community (tables 6.1,6.7), as their environmental parameters are so similar, but also from the Dinorthis and Sericoidea communities (tables 6.1,6.7).

Extensive bioturbation indicates an abundant infaunal (soft-bodied ?) component was originally present. Assemblages are moderately diverse in contrast to the low diversities noted for the community in the South Berwyn Hills (op.cit.). The Howellites community appears confined to medium-coarse siltstones which often display thin planar laminations.

The relatively fine grained lithology and abundant bioturbation, coupled with dominant random occurrence types, all suggest low energy conditions, in water depths slightly deeper than for the Dalmanella community (i.e., slightly more offshore), but probably within the outer sublittoral zone. Opposing valve ratios approaching unity similarly attest to low energy conditions with only minor net lateral valve transport.

Examples of assemblages referable to this community are found south-west of Dolwyddelan at localities 180 (SH 71995167) and 196 B (SH 71185136) and north - west at localities 232 (SH 69695208) and 232A (SH 69755211) - see Appendix Two and map 3.

Fig.6.2 illustrates sediment-community interrelationships for the Dinorthis,dalmanellid-sowerbyellid and Sericoidea communities, and how these quantitatively affect community intergradation, whereas fig.6.3 shows the important intergradation between the four Snowdonian benthic marine communities and how intergradation and community composition appear, to some extent, facies controlled.

Chapter 7 The Capel Curig area

a) Introduction

The sampled rocks outcrop to the west, south-west and east of Capel Curig (fig.1.1;map 1). The area is drained from the west by the Nantgwryd which flows into the twin lakes of Llynau Mymbyr and meets at Capel Curig the southerly flowing Afon Llugwy. West of Capel Curig, the glaciated Mymbyr valley is broad, U-shaped, and trends east-west and it is here that most sampling was undertaken.

The Capel Curig Volcanic Formation (Francis & Howells 1973) outcrops on both sides of the valley, having been folded into a north-east - south-west trending anticline by Caledonian earth movements and consists of three units, the lower and middle units being ignimbrites, whilst the upper unit contains a distinctive accretionary lapilli horizon. Below and intercalated between the volcanic horizons are coarse volcaniclastic sandstones, fine sandstones and siltstones which are all occasionally fossiliferous.

The reasons for studing this area are :-

1) To analyse, in detail, the faunal assemblages associated with the Capel Curig Volcanic Formation.

2) Faunal and sedimentological data may indicate the conditions prevalent at the time of the problematical deposition of the Capel Curig Volcanic Formation, in addition to the overall palaeoenvironmental conditions.

3) Faunal analysis enables the intervolcanic fossiliferous sediments to be dated (with respect to Caradocian stages) which consequently allows possible correlations with other sequences. Faunal correlation is more accurate and reliable over long distances than is correlation based on the petrology of the volcanic rocks, which is often laterally changeable.

4) For this project to be viable, each area had to be known to be fossiliferous. To ascertain whether an area thought to be unfossiliferous, contained fossils, would involve large-scale mapping, which would be time consuming and repetitious.

b) The stratigraphy, faunal occurrence types and associated sedimentary structures

i) Stratigraphy

The adopted stratigraphy and stratigaphical terms are derived from the work of Francis & Howells (1973) and from sheet SH 75 (Capel Curig and Betws-y-Coed,1:25000) of the Geological Survey of Great Britain (England and Wales), additional information being derived from Williams (1922) and Davies (1936). The stratigraphical sequence is illustrated in fig. 7.1.

ii) Major faunal occurrence types and their interpretations

1) Capel Curig West (fig.7.2)

Sparse strophomenid valves are exclusively convex-up within coarse volcaniclastic sediments of the lowermost horizons of the Lower Racks Sandstone (fig.7.2) which represent the reworked top of the underlying Garth Tuff. Such orientations reflect the high current velocities under which the sediments and their associated organic constituents were deposited.

Although not sampled, the middle and upper parts of the Lower Racks Sandstone reveal convex valves (Dinorthis ? /Salopia ?) and large planar valves (Macrocoelia ?) within either thin planar occurrence types possessing preferred convex-up (>5:1) and concave-up valve orientations (plate 5.6) or thicker (10 - 20 cms. or more) laterally continuous shelly horizons, convex-up, mixed and concave-up valve orientations all being noted (plates 5.9,5.13). These thin planar horizons are related to rapid sedimentation, the convex-up orientations resulting from the action of high velocity currents (upper flow regime conditions - Harms & Fahnestock 1965;Simons et al.1965), the valves then becoming rapidly buried, thus preserving their integrity. Thin planar types possessing preferred concave-up valve orientations are associated with thin (<1 cm.) planar laminations and can probably be attributed to the action of migrating trains of small-scale ripples (Clifton & Boggs 1970).

The planar fabric of the thicker horizons (plate 5.9) suggests accumulation by moderate - high velocity currents associated with decreased sedimentation, which enabled these horizons to increase in thickness (Johnson 1960). They probably represent what were once masses of shelly debris accumulating in large, shallow, seafloor depressions within the inner sublittoral zone. Such accumulations often possess planar upper surfaces (plate 5.9), indicating constant modification by high energy currents and which were probably level with, or very slightly above, the low-angle lip of the depression. The lateral wedging-out of these horizons similarly suggests accumulation in shallow seafloor depressions (megaripple or inter-dune troughs ?).

The variable thicknesses of the shelly horizons indicate fluctuating sedimentation. Low valve articulation ratios imply some lateral transport, as do several opposing valve ratios which depart from unity. However, the absence of valve fragmentation/abrasion, along with no obvious faunal mixing indicates only relatively small-scale net lateral transport.

The Middle Racks Siltstone (unit d) contains thinner faunal horizons with preferred convex-up valve orientations (fig.7.2). The finer lithology implies slightly lower energy conditions (slightly more offshore ?) than for the Lower Racks Sandstone. Valve articulation ratios are much higher and 75% of the opposing valve ratios approach unity, all implying negligible net lateral transport. The faunal assemblages probably represent essentially "in situ" remnants of the original low-grade dalmanellid-sowerbyellid "mega" community (section c,ii,1B). However, current velocities must have been strong enough to cause valve inversion which occurs with greater frequency at relatively low current velocities on muds (Brenchley & Newall 1970).

The base of the Upper Racks Sandstone (unit e) is characterised by thin planar occurrence types showing preferred convex-up valve orientations which indicate increases in current velocity and sedimentation. Planar and thick laterally continuous occurrence types are common within the sandstones of the middle and upper parts of the Upper Racks Sandstone (fig.7.2;plates 5.3,5.11). The thin planar types display preferred convex- and concave-up valve orientations, whereas the thicker horizons display random fabrics.

Interpretations for the planar occurrence types and their constituent valve orientations are identical to those for similar occurrence types and orientations within the Lower Racks Sandstone.

Valve randomness within the thicker shelly horizons (plate 5.3) is not primarily due to biogenic reworking. The presence of planar occurrence types and undisturbed sedimentary structures throughout the Racks member suggests either an impoverished infauna or a complete absence of burrowers, due possibly to the sediment being too coarse (Heckel 1972,p.244). Plate 5.3 shows the valves are not closely packed together which, coupled with their randomness, is interpreted as being due either to scouring (Johnson 1957) or to penecontemporaneous soft sediment deformation (section b,iii,1B). Rapid vertical changes in occurrence type (e.g., thin planar types interspersed between thicker shelly bands) suggest rapidly fluctuating current velocities and sedimentation.

The topmost part of the Upper Racks Sandstone contains thin planar horizons with preferred concave-up valve orientations and some randomness. Certain opposing valve ratios depart markedly from unity and with very low valve articulation ratios indicate some net lateral transport. However, the combined effects of the current and the sandy substrate did not produce widespread valve inversion (see Brenchley & Newall 1970).

Two distinct occurrence types are found within the fossiliferous sandy horizons of the Cefn-y-Capel Siltstone (fig.7.2). Thin planar occurrence types with preferred convex-up valve orientations form the upper and lower bounding surfaces to a thicker unit containing randomly orientated valves. Such bounding horizons imply deposition by relatively high energy currents associated with rapid sedimentation, whereas the intercalated horizon indicates the onset of temporary lower energy conditions with reduced sedimentation, the randomness resulting from shallow deformative bioturbation (Reineck & Singh 1975, p.138;Schäfer 1972,p.404).

2) <u>Capel Curig East</u> (fig.7.2)

The uppermost horizons of the Cefn-y-Capel Siltstone apparently contain laterally impersistent,lenticular shelly concentrations (fig.7.2) which possess preferred convex-up valve orientations and are associated with laminated, rippled, fine sandstones. Such lenticular concentrations possibly represent accumulations within small seafloor depressions or within ripple troughs, convex-up orientations being obtained when the valves were tipped into the depressions by current activity.

Thin planar occurrence types (medium-crowded) are associated with thicker, laterally continuous shelly horizons throughout unit m (fig.7.2), convex-up and mixed valve orientations predominating. Such assemblages are similar to those within the Lower Racks Sandstone. The thicker shelly horizons indicate relatively high velocity current deposition, but with decreased sedimentation. Such a sequence of occurrence types indicates a shallow water (inner sublittoral ?) environment subject to fluctuating current velocities and sedimentation.

A relatively thick (10-12 cms.) shelly horizon composed predominantly of small disarticulated sowerbyellid valves with mixed orientations (fig.7.2;plate 5.7) and which appears to laterally wedge out, is noted within the coarse sandstones of unit p. Very little sediment is intercalated between the valves, this horizon comprising what might be called a "coquina" (Gary et al.1972) or "shell hash" (Gary et al.1972;Kelling & Williams 1966). Valve articulation ratios are very low, with some opposing valve ratios departing markedly from unity (locality 155 - Appendix Two), although the lack of valve abrasion/fragmentation implies negligible net lateral transport. This evidence suggests accumulation by moderate velocity currents with greatly reduced sedimentation, the mixed orientations probably reflecting the differing hydrodynamic responses of the pedicle and brachial valves of the brachiopod genera present. Bridges (1975,p.87-88) notes that the first deposited valves probably formed impediments to those following, which subsequently assumed various attitudes, although this implies some randomness. Presumably the sowerbyellids would disarticulate relatively quickly, even if only briefly transported. This assemblage probably represents the remnants of an essentially "in situ" community ("residual fossil community" - Fagerstrom 1964) which resulted from accumulation by moderate velocity currents within a shallow seafloor depression.

iii) Major sedimentary structures and their interpretations

Usually, sedimentary structures were examined only in association with fossiliferous sequences.

1) Capel Curig West

Field examinations were confined to the northern part of this area (map 1).

A) The Garth Tuff (fig.7.1)

This unit becomes coarsely bedded at its top. Thin parallel beds and planar cross-stratifications (McKee & Weir 1953) are noted within coarse, poorly sorted volcaniclastic sediments. The low-angle cross-beds are often solitary (Allen 1963,p.99,fig.2), being bounded by the thin parallel beds.

Thin parallel stratifications result from tidal current variations and wave activity in beach/shoreface situations (Clifton 1969;Howard 1971;McKee 1957;Reineck & Singh 1975;van Straaten 1959) and tidal flat situations (de Raaf & Boersma 1971;Reineck 1967;Reineck & Singh 1975; van Straaten 1959,1961). They may also be derived by the sedimentation of suspension clouds (Reineck 1967;Reineck & Singh 1972,1975;Terwindt 1971). Allen (1963) interprets this type of cross-bedding as due to the construction of solitary banks, often in offshore shallows. The association of parallel laminated coarse sands with low-angle cross-bedding often characterises beach sediments (Klein 1970;McKee 1957;van Straaten 1959),parallel-laminated sands being commonly found in upper shoreface facies, i.e., water depths of 1 - 2 m. (Reineck & Singh 1975). Therefore the bedded top of the Garth Tuff corresponds to what was the unwelded top of the ignimbrite (Martin 1959) which was reworked in a beach/tidal flat environment.

B) The Lower Racks Sandstone (fig.7.2)

The bedded top of the Garth Tuff grades into this unit. Three groups of sedimentary structures are noted :-

a) Parallel laminations in fine-medium sandstones, some being uneven and wavy, which laterally wedge out (fig.7.3;plates 5.9,5.13,7.1,7.2).

b) Discrete horizons within the laminated sandstones of black, fine grained, round - angular clasts, often with intercalated brachiopod valves (plates 7.2,7.3).

c) Discrete horizons of contorted sandstones (figs.7.3,7.4,7.5).

As previously discussed, laminated sands are noted in beach and tidal flat situations. Wavy laminations may reflect original surface undulations (ripples ?). The absence of bioturbation presumably indicates physical reworking and rapid sedimentation in a low tidal flat/ foreshore - shoreface situation (Howard 1971,1972; Reineck 1967;Terwindt 1971;van Straaten 1959).

The black clast horizons, with or without intercalated valves, are found within the lower and middle parts of this unit (plates 7.2,7.3) and are interpreted as clay pebble beds. Some clasts are curved and bent, indicating deposition whilst still relatively plastic. Clay pebble beds are diagnostic of migrating channel floor deposits on the lower parts of tidal flats (Klein 1967,1970; de Raaf & Boersma 1971;Reineck 1967,1972;Reineck & Singh 1975;Terwindt 1971;van Straaten 1952,1954,1959,1961). They probably form as lag concentrates accumulating under upper flow regime conditions (Harms & Fahnestock 1965;Simons et al.1965). Within such deposits,clay pebbles and valves are often imbricated (van Straaten 1959), a feature noted within some horizons in this unit (plates 7.2,7.3). Clay pebbles form by deposition of mud during slack water (Terwindt 1971; van Straaten 1961) which is then "ripped up" by subsequent higher velocity currents and redeposited as clay pebbles. Black muds often characterise tidal flat environments (McKee 1957), the black colour resulting from finely disseminated FeS, which may account for the black colouration of these clasts. Laminated sands above the clay pebbles (plate 7.2) are interpreted as point bar sequences (Klein 1967). Intense tidal/wave action may inhibit tidal mud flat formation, in which case tidal sand bars/flats may form, each bar separated by a tidal channel network (Blatt et al.1972,p.151).

Shell beds are also common in low tidal flat sequences (Klein 1967,1970;McKee 1957;de Raaf & Boersma 1971;Reineck 1967,1972;Terwindt 1971;van Straaten 1952, 1954,1959,1961). However, the shell beds in the middle and upper parts of this unit probably accumulated just below the lower part of the tidal flat (i.e., shoreface). The abundance of brachiopods is proof of a fully marine environment (Heckel 1972),although the absence of crinoids/ bryozoa probably indicates some turbidity (op.cit.) above an unstable,shifting sandy substrate, the undisturbed laminations probably derived from sedimentation of suspension clouds (Reineck 1967;Reineck & Singh 1975; Terwindt 1971).

Two distinct horizons of contorted bedding are developed, one in the middle and one nearer the top. The structures are somewhat unusual, being confined to beds consisting entirely of fine sandstone. Such structures fall within the Type 1 (Internal) Category of Allen (1977) and may be regarded as non-current convolute laminations (Dzulynski & Smith 1963,p.616).

Within the middle horizon are noted "dish-like" structures, possessing laminations which become upturned at the "dish" peripheries, the "dishes" themselves surrounded by structureless fine sand and appear partly truncated by an erosion plane (figs.7.3,7.4).

The appearance of the "dish" structures corresponds closely to that of "pseudonodules" (Blatt et al.1972; Brenchley & Newall 1977; Kuenen 1953; Potter & Pettijohn 1963; Rolfe 1960; Stewart 1963) which, however, usually lie within a muddy matrix. These "dish" structures are closely analogous to "sandstone rolls" (Brenchley & Newall 1977,p.829) and "sand rolls" (Lowe 1975). Brenchley & Newall (1977,p.829) describe such rolls as "....fragments of bedded material usually with rounded ends and upturned laminae lying in an unlaminated matrix" and which originate from homogenisation of laminated sand by either fluidisation or liquefaction, the residual blocks of laminated sand sinking through the mobile sand. Liquefaction is postulated as the source of bed instability (op.cit.) and Lowe (1975) asserts liquefaction is the only process which can produce these "dish" structures.

A trigger mechanism initiates liquefaction e.g., some kind of seismic activity or shock (Brenchley &

Newall 1977;Dzulynski & Smith 1963;Kuenen 1953;Lowe 1975; Potter & Pettijohn 1963), which may be only slight (Anketell et al.1969,1970). This theory conforms with the geological framework at Capel Curig, as presumably the volcanic activity which produced the ignimbrites would be accompanied by some seismic activity.

The "dish" structures appear partly truncated by an erosional surface (figs.7.3,7.4). This, however, does not always indicate current activity, as developing diapiric folds may become dissipated at the sediment/water interface, producing dilute suspensions which settle out as thin laminae upon the truncated deformed layers, thus presenting the superficial appearance of an erosional surface (op.cit.;Williams 1960). However, the truncation surface in question is interpreted as an erosional surface due to its laterally irregular nature (Anketell et al.1969).

Brenchley & Newall (1977) interpret laminated sandstones containing similar sandstone rolls as "....channel-fill sands within a high subtidal shoreface environment" (op.cit.,p.829), this interpretation being applied to similar horizons in the Lower Racks Sandstone.

Towards the top of this unit, a large, sub-vertical, pipe-like structure is developed (fig.7.3). Sedimentary laminations are sharply deflected upwards at its periphery, whilst structureless sand is noted within the pipe and at its base. Possibly the pipe represents the base of a sand volcano (Burne 1970;Gill & Kuenen 1958;Reineck & Singh 1975). However, the best analogy is with liquefied intrusions (Lowe 1975) as in such structures, the intruded sediment is structureless and the surrounding sediment is intensely deformed (cf.fig.7.3). The initiation of liquefaction is again related to seismic shocks.

At approximately the same horizon is a small diapiric structure, approximately 25 cms. high (fig.7.5). Contorted laminations are seen within the structure, whilst remnants of primary laminations are noted in immediately adjacent sediments, with undisturbed laminations above and below the "diapir". The structure bears a close resemblance to "gas-heave structures" (Coleman & Gagliano 1965,p.136, fig.3), but is perhaps better classified as a liquefied intrusion (Lowe 1975,p.178).

It appears the formation of these penecontemporaneous deformation structures is probably restricted to a shallow marine environment (i.e., high subtidal shoreface environment (inner sublittoral) - Brenchley & Newall 1977, p.829), which conforms with the environmental interpretation of the author and to the fluctuating current velocities and sedimentation (Klein 1970) suggested by the faunal occurrence types. As the top of the sequence suggests slightly deeper water conditions, this unit may represent transgression of a tidal flat.

C) The Middle Racks Siltstone

The finer lithology suggests lower energy conditions, although no sedimentary structures are seen. The abundance of bryozoa (Locality 143C - Appendix Two) suggests clearer water above stable substrates (Heckel 1972). As this unit is thin and laterally inextensive, deposition in a sheltered environment is suggested, due possibly to the local development of barrier sandbars/pointbars.

D) The Upper Racks Sandstone

This unit is similar to the upper Lower Racks Sandstone in terms of sedimentary structures and shell beds and a similar environment is postulated. A coarsening upwards lithology with low angle cross- and planar bedding is correlated with a beach/shoreface environment, but in this case representing a minor marine regression, probably resulting from local minor uplift prior to volcanic eruption. A thin, impersistent, unfossiliferous mudstone (unit f - fig.7.1) below the Racks Tuff may correspond to the upper muddy reaches (van Straaten 1959) of this tidal flat.

E) The Dyffryn Mymbyr Tuff

This unit presents a distinct tripartite sequence :-

Coarse planar/cross-bedded volcaniclastic sandstone 1.5m. - 2.0m.
Rhyolitic tuff 50cm.
Accretionary lapilli tuff 50cm. - 70cm.

The coarse upper unit displays planar bedding, low-angle planar and trough cross-bedding and megaripples (?) (plates 7.4,7.5,7.6,7.7,7.8). Angular rhyolitic clasts are common, which occasionally disturb the sedimentary laminations (plate 7.8). These structures indicate deposition in an extremely high energy, shallow marine environment (foreshore - upper shoreface).

Accretionary lapilli usually form in the ash cloud of an eruptive column (Brenchley 1972;Moore & Peck 1962). Consequently their presence implies subaerial eruptions and conditions (op.cit.,Fiske 1963), although they are found in shallow marine environments (Bateson 1965; Brenchley 1972;Fiske 1963;Schiener 1970) but disintegrate if subjected to long immersion (Moore & Peck 1962).

The following environmental interpretation is proposed. The Dyffryn Mymbyr Tuff rests upon a muddy siltstone (unit h - fig.7.1) which merges, to the east, with unit f, which is tentatively interpreted as the upper part of a tidal flat. The accretionary lapilli were possibly deposited on this flat after the initial subaerial eruptive blast, the overlying rhyolitic tuff representing the successively deposited finer air-fall material. The overlying coarse sandstone may represent establishment of a beach environment, resulting from a transgressing shoreline which was possibly related to post-eruptive subsidence, some constituent rhyolitic clasts derived from partial erosion of the underlying tuff.

F) The Cefn-y-Capel Siltstone

This sparsely fossiliferous unit displays no sedimentary structures. The original environment was apparently unfavourable for benthic colonisation, subsequently indicating probable accumulation within a barred basin/lagoonal environment, i.e., slow deposition within standing water. Abundant pyrite, along with no bioturbation, substantiates this proposal. Infrequent fossiliferous sandy horizons probably represent periodic breaches of offshore bars (by storm activity ?), causing influxes of coarser sediment into the area.

2) Capel Curig East

At the top of the Cefn-y-Capel Siltstone, a laterally impersistent sandstone is developed, possessing well developed planar bedding with occasional low-angle cut-offs which may represent shallow channel or scour infills (fig.7.6). An overlying fine rhyolitic tuff (unit l - fig.7.1) represents a waterlain airfall deposit. An extremely complex tuff/sandstone boundary is developed, which may be related to partial liquefaction caused by seismic shocks. Laterally impersistent sedimentary intercalations within the tuff (plates 7.9, 7.10) imply almost synchronous sandstone-tuff deposition in an inner-sublittoral environment.

The tuff displays an erosive rippled (?) contact with an overlying sandstone (unit m - fig.7.1), which possesses planar bedding with occasional low-angle truncations and horizons of disarticulated brachiopod valves possessing convex-up and mixed orientations. Horizons of rounded, black, fine-grained clasts are noted below some shelly horizons but are not intercalated. With respect to the Lower Racks Sandstone, this unit is interpreted as the result of tidal channel migration on the lower parts of a tidal flat.

c) The fossiliferous assemblages

i) Introduction

The fossiliferous localities are shown on map 1, their overall compositions are shown in fig.7.2 and their complete faunal analyses are contained in Appendix Two.

ii) Faunal analysis (fig.7.2;table 7.1)

1) The Racks member

A) The Lower Racks Sandstone (table 7.1,cols.A,B)

Due to outcrop, induration and preservation, fauna is only easily sampled from the lowest and topmost fossiliferous horizons. Assemblages are dominated by *Macrocoelia expansa* (J.de C.Sowerby). Common associates are *Salopia globosa* (Williams), *Dinorthis* cf.*berwynensis* (Whittington) of Williams 1963 and dalmanellids.

The lowermost faunal horizon is located within coarse volcaniclastic sediments forming the diffuse boundary between the Garth Tuff and the Lower Racks Sandstone. *Macrocoelia* dominates the sparse fauna, obviously being the "pioneer" brachiopod, and being flat with a large surface area, was well adapted to a free-living mode of life in an area subjected to strong bottom currents. At Capel Curig, Macrocoelia is usually abundant within coarse lithologies. Within most sampled assemblages, Macrocoelia pedicle valves predominate, which probably resulted from differing hydrodynamic properties and mechanical strengths of the valves, the brachial valves being either selectively transported or fragmented.

The upper faunal horizons are again dominated by M.expansa, with lesser S.globosa, D.cf.berwynensis and dalmanellids, although their diversities are greater than the "pioneer" assemblages (fig.7.7) which is correlated with an upward fining in lithology, presumably reflecting a decrease in environmental stress (Bretsky & Lorenz 1970) as the environment gradually stabilised. The appearance of dalmanellids and rarer sowerbyellids may "anticipate" (Worsley 1971) the later incoming of silts.

B) The Middle Racks Siltstone (table 7.1,col.C)

Here, a faunal composition change is directly related to a fining in lithology. Abundant dalmanellids are associated with sowerbyellids and fragmented ramose bryozoa. Dinorthis is the only common remnant of the earlier Macrocoelia - dominated assemblages, indicating that Dinorthis probably had a broader substrate tolerance. Such a compositional change indicates some degree of facies control for the shelly assemblages.

C) The Upper Racks Sandstone (table 7.1,cols.D,E)

The lowermost horizons are dominated by dalmanellids and sowerbyellids, presumably representing remnants of the earlier assemblages although *S.globosa* and *Dinorthis* are common, possibly reflecting their broader sediment tolerances. *Macrocoelia*-dominated assemblages become re-established in the middle and upper horizons, with disarticulated crinoid columnals becoming relatively abundant (table 7.1,col.E), indicating sporadic colonisation of a sandy seafloor. *Macrocoelia* dominance appears to be correlated with a slight increase in grain size.

2) The Cefn-y-Capel Siltstone (table 7.1,cols.F,G)

Faunal horizons are located within thin, coarse siltstone horizons, the lower horizons containing high dominance assemblages with abundant dalmanellids and infrequent sowerbyellids. The upper horizons show a reversal, with sowerbyellids becoming dominant with fewer dalmanellids and rare *Dinorthis*/*Macrocoelia*.

3) Unit m (table 7.1,col.H)

Due to outcrop and induration, this horizon cannot be adequately sampled. Visual examination reveals *Dinorthis* (*Plaesiomys*)cf.*multiplicata* Bancroft[1] of Bancroft 1945 is extremely abundant within a coarse sandstone (plates 7.11, 7.12), with rare *Macrocoelia*. Faunal and lithological

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[1] now *Plaesiomys multifida* (Salter) - see Cocks 1978,p.50

comparisons suggest this horizon is laterally equivalent to the Multiplicata Sandstone (Diggens & Romano 1968).

4) Unit p (table 7.1,col I)

Faunal assemblages, confined to coarse sandstones, are dominated by sowerbyellids, with Dinorthis as a common associate, and are similar in faunal composition and lithology to assemblages in the Upper Grits (Beavon 1963) at Gareg Bengam (SH 62044523), south-east of Beddgelert.

Finally, the graph in fig.7.7 illustrates two important points :-

a) Sudden changes in the physical characteristics of any environment (sedimentation/sediment type, etc.) usually produce a decrease in faunal diversity. Immature assemblages consist only of "pioneer" genera, for any one lithology.

b) As an environment stabilises, assemblages diversify as more genera become established, e.g., in the Upper Racks Sandstone. In the Snowdonian assemblages, large-scale compositional and diversity changes are directly related to lithological changes, being reflected by faunal replacement and/or depletion.

d) Interpretation of the fossiliferous assemblages in terms of the proposed Snowdonian benthic communities

i) The Racks member

1) The Lower Racks Sandstone (fig.7.2;table 7.1)

The Macrocoelia-dominated assemblages from the lower horizons are consequently assigned to the Dinorthis community. In this case, Macrocoelia is the "pioneer" genus (i.e.,low in the succession order) in what was a very shallow, nearshore, "physically rigorous" environment (Bretsky & Lorenz 1970), the low diversity index attesting to unstable conditions. Macrocoelia was better adapted to the prevailing bottom conditions than the pedically attached, biconvex Salopia and Dinorthis, although similar large,globose brachiopods are common in shallow,"rough water",sandy bottom environments (Anderson 1971,p.794).

Assemblages from the upper horizons are characteristic of the Dinorthis community. Their diversity indices are slightly higher, indicating some environmental stabilisation in what was still a "physically rigorous" environment (Bretsky & Lorenz 1970). This increase, coupled with a slight upward fining in lithology, indicates a slightly more offshore location.

2) The Middle Racks Siltstone (fig.7.2;table 7.1)

A lithological change occasions a concomitant change in faunal composition (see section c,ii,1B and Appendix Two). This assemblage is assigned to the dalmanellid-sowerbyellid "mega" community, but further distinction is not possible. Low succession order intergrading genera from the Dinorthis community (Dinorthis/Salopia)possess low abundance.

These faunal changes indicate substrate nature to be of prime importance in controlling community composition. This low-grade community implies that the environment was still unfavourable for further diversification, the finer lithology suggesting a slightly more offshore location.

3) The Upper Racks Sandstone (fig.7.2 table 7.1)

Assemblages from the lower horizons contain abundant dalmanellids with secondary sowerbyellids, indicative of the dalmanellid-sowerbyellid "mega" community, and probably represent remnants of the earlier "mega" community which briefly persisted on the coarser sandy substrates. Lower valve articulation ratios suggest higher energy conditions.

The middle and upper horizons yield assemblages readily referable to the Dinorthis community. Apparently this community eventually became re-established on the coarser sandy substrates. With progressive environmental stabilisation, the Dinorthis community gradually diversified (fig.7.7), probably being located within the inner sublittoral zone.

ii) The Cefn-y-Capel Siltstone (fig.7.2;table 7.1)

Abundant dalmanellids with minor sowerbyellids characterise assemblages which are consequently referred to the dalmanellid-sowerbyellid "mega" community. Low diversities suggest low-grade communities, which are composed of low order succession genera, an unstable environment probably preventing further diversification.

A sparse fauna from the top of this unit is assigned to the aforementioned "mega" community, with intergrading low order succession genera from the Dinorthis community (Dinorthis/Macrocoelia) which possibly "anticipated" (Worsley 1971) the later development of coarse sands.

iii) Unit m (fig.7.2;table 7.1)

Bedding-plane exposures reveal abundant Dinorthis (D.(Plaesiomys)cf.multiplicata)[1] with infrequent Macrocoelia and dalmanellids, which indicate the Dinorthis community.

iv) Unit p (fig.7.2;table 7.1)

Although dominated by ubiquitous sowerbyellids, assemblages are assigned to the Dinorthis community. Sowerbyellids commonly intergrade into, and become dominant within, the Dinorthis community, whereas other intergrading low order succession genera from the dalmanellid-sowerbyellid "mega" community rarely achieve such dominance. These low diversity assemblages represent what were low-grade Dinorthis communities colonising an environment unfavourable for further diversification.

e) Age determination of the Capel Curig sequence from faunal evidence

i) Capel Curig West

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[1] now Plaesiomys multifida (Salter) - see Cocks 1978,p.50

1) The Racks member

The following characteristic genera and species are identified (table 7.1) :-

Dinorthis cf.*berwynensis* (Whittington)of Williams 1963
*D.*aff.*flabellum* (J.de C.Sowerby)of Williams 1963
Horderleyella sp.
Macrocoelia expansa (J.de C.Sowerby)
Petrocrania cf.*dubia* Williams of Williams 1974
Reuschella sp.
*R.*cf.*horderleyensis* Bancroft of Williams 1963
Salopia globosa (Williams)

Their distributions, along with those of genera from overlying formations, are plotted in relation to Caradocian stages (table 7.2). Data was derived from the works of Bancroft (1928b,1933,1945), Bassett et al. (1966), Dean (1958,1960b), Dean in Stevenson (1971), Diggens & Romano (1968), Harper & Rast (1964), Lamont (1946), Spjeldnaes (1957), Whittington (1938a,b), Whittington & Williams (1955), Williams (1949,1963,1974) and Williams et al. (1972).

Salopia globosa is considered to be lower Soudleyan (Diggens & Romano 1968) and *Dinorthis* cf.*berwynensis* is mainly restricted to the Soudleyan Stage (Williams 1963). Consequently, the faunal evidence presented in table 7.2 suggests the Racks member is probably lower-middle Soudleyan.

2) The Cefn-y-Capel Siltstone

Although the assemblages are not distinctive as regards age, it seems reasonably certain that from their stratigraphical position, they can be assigned to the upper Soudleyan.

ii) Capel Curig East

The topmost assemblages from the Cefn-y-Capel Siltstone are not diagnostic as regards age.

The overlying faunal assemblages, from units m and p respectively, contain *Dinorthis* (*Plaesiomys*)cf.*multiplicata*[1] which is regarded as an upper Soudleyan form (Bancroft 1933,1945;Diggens & Romano 1968). Bancroft (1933,1945) considers *D*.(*P*.)*multiplicata*[1] indicates the upper part of the upper Soudleyan, being very common at this horizon at Glyn Ceiriog in the Berwyn Hills. The occurrences of *Howellites*, *Reuschella* (table 7.2) and *Leptaena* (?), although not distinctive, are consistent with an upper Soudleyan age.

In conclusion, the Capel Curig West sequence, from the Lower Racks Sandstone - lower fossiliferous horizons within the Cefn-y-Capel Siltstone, is probably lower-middle Soudleyan in age, whereas the Capel Curig East sequence, from the upper Cefn-y-Capel Siltstone - middle part of unit p,is upper Soudleyan in age.

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[1] now *Plaesiomys multifida* (Salter) - see Cocks 1978,p.50

f) Conclusions

Faunal assemblages within this area are dominated by components from the *Dinorthis* community, the dalmanellid-sowerbyellid "mega" community assuming secondary importance. The *Dinorthis* community is variably dominated by *Macrocoelia* (common), *Salopia* (rare), *Dinorthis* (rare) and intergrading sowerbyellids (rare) and is best developed in medium/coarse sandstones. Lithological changes are usually accompanied by distinct faunal and community changes. Trilobites are infrequent, with only *Broeggerolithus* being common. Crinoids are sparse, being restricted to the upper part of the Upper Racks Sandstone, whilst bryozoa are common only within the Middle Racks Siltstone.

Faunal occurrence types and sedimentary structures indicate shallow water deposition, with fluctuating sedimentation and current velocities. The Lower Racks Sandstone represents a transgressive sequence, a basal beach/tidal flat sequence being superseded by a subtidal (shoreface) sequence. The Middle Racks Siltstone represents a short depositional phase within a more offshore sheltered area, the Upper Racks Sandstone marking a return to a high subtidal/low tidal flat environment. The Dyffryn Mymbyr Tuff was probably deposited on the upper parts of a tidal flat, with a beach environment being successively developed, related to transgression following possible subsidence, whereas the Cefn-y-Capel Siltstone may represent a shallow barred basin/lagoonal - type deposit.

The lower Capel Curig East sequence represents a transgression, passing upwards from low tidal flat/ marginally subtidal (upper shoreface) deposits to lower shoreface - upper offshore deposits.

Faunal evidence suggests a lower - upper Soudleyan age range for the combined sampled sequences.

It remains to place the Garth and Racks Tuff within the environmental framework for this area.

Both units display "eutaxitic" (Beavon et al.1961, p.604;Fitch 1967,p.203;Ross & Smith 1961,p.4) and "parataxitic" (Beavon et al.1961,p.604;Fitch 1967,p.203) welding fabrics, frequently right up to the sediment - volcanic contact, the basal unwelded zone usually found in ignimbrites (Martin 1959) being absent. Welding usually implies subaerial conditions (Beavon 1963;Beavon et al.1961; Brenchley 1964;Fitch 1971;Hollingworth 1954;Oliver 1954; Rankin 1960;Rast 1961,1962,1969;Rast et al.1958). However, Francis & Howells (1973), Howells et al.(1971,1973, 1978) and Wright & Coward (1977) suggest welding may develop in subaqueous environments. Rankin (1960,p.21) believes subaqueous ash flows cannot exist, as they would become easily dispersed, but considers ash flows may flow unchanged into water, producing "....both subaerial and subaqueous deposits identical in character" (op.cit.,p.22). Sedimentary associations are stressed in deducing the original mode of emplacement (op.cit.). Fiske (1963), Fiske & Matsuda (1964) and Mutti (1965) describe wholly submarine ash flows, but welding is either absent or weak.

The Garth and Racks Tuff show uneven basal contacts in the form of large "load-casts", which must have been produced by the ignimbrites downloading into waterlogged sediments. Therefore the original density of the ignimbrites must have exceeded that of the sediments. The ignimbrites are separated, to the north, by the Racks member (section b,ii,1,iii,1,A-D). Therefore the Racks Tuff was probably emplaced within a shoreface - upper offshore (inner sublittoral) environment (i.e., < 10m. water depth). The author believes that emplacement of relatively large ash flows into shallow water would not preclude the development of welding fabrics (see Wright & Coward 1977,p.139). This mode of emplacement presumably produced erosional hollows in the slightly irregular, unconsolidated sediments, such hollows being accentuated by downloading of the ignimbrite. Associated seismic shocks initiated sediment liquefaction which accelerated ignimbrite collapse into the sediment (Francis & Howells 1973,p.633). If the Garth Tuff was emplaced in a similar environment, as seems likely, the basal convolutions (op. cit.,p.625,fig.3)may possibly represent infills of tidal channels, as ash flows commonly fill topographic lows, which then became further accentuated by penecontemporaneous downloading. Beavon (1974,p.479) imagines emplacement of ash flows in tidal flat environments followed by penecontemporaneous erosion, which partly disagrees with the theory of Francis & Howells (1973), as the top of the Garth Tuff is subaqueously reworked.

In conclusion, the Garth and Racks Tuff are considered to be directly emplaced into a shoreface - upper offshore (inner sublittoral) environment. These units are part of the Capel Curig Volcanic Formation (op.cit.) which probably originated from subaerial eruptions farther north (from the Irish Sea Landmass ?), although Fitch (1967, p.209) suggests an origin from a vent near Glyder Fach.

Chapter 8 The Moel Hebog area

a) Introduction

The Moel Hebog area lies to the west and south-west of Beddgelert (SH 592482) and to the north of Tremadoc (SH 562402) (fig.1.1;map 2). The outcrop pattern of the sedimentary and volcanic rocks is controlled by the north - south trending Moel Hebog syncline to the west, which is a continuation of the Snowdon syncline (figs.1.1, 3.14,3.16;map 2) and the similarly trending Moel Ddu syncline to the east (figs.1.1,3.14,3.16;map 2), along with several minor synclinal/anticlinal structures.

The Glanrafon Beds comprise a lower sequence of graptolitic slates and an upper sequence of alternating sandstones and slates/fine siltstones. The Snowdon Volcanic Group is represented by sillar and welded tuffs (ignimbrites), in addition to some waterlain tuffs, agglomerates, basaltic flows and basic tuffs.

Faunal sampling is restricted to the southern and western parts of this area.

The reasons for studying this area are :-

1) To analyse the faunal assemblages within the Upper Glanrafon Beds (Shackleton 1959,p.232).
2) To analyse the sporadic faunal assemblages within the Snowdon Volcanic Group.
3) To establish possible correlations, utilising faunal evidence, with other areas in Snowdonia.

4) By studying the faunas, associated sediments and volcanic rocks, one may possibly determine the overall palaeoenvironment.
5) The southern and western subareas were known to be fossiliferous (Fearnsides 1910a;Ramsay 1866,1881;Sedgwick 1847;Shackleton 1959).

b) The stratigraphy, faunal occurrence types and associated sedimentary structures

i) Stratigraphy

The earliest recorded work is by Sedgwick (1841; 1847,p.138,141) who noted fauna from sediments below the Snowdon Volcanic Group, and Davis (1846). The area was systematically mapped by the Geological Survey (1848-1853), whilst the Survey Memoir (Ramsay 1866,1881) contains some geological descriptions of this area (Ramsay 1866,p. 109,119,120,122,136,137,figs.39,46). The area to the south of Moel Hebog was later remapped by Fearnsides (1910b), whereas the area was completely remapped by Shackleton (1959), who erected a modified stratigraphy which, along with his map, are still the accepted models for the Moel Hebog area.

The author adopts the aforesaid stratigraphy (op. cit.,p.218) for the area (fig.8.1).

ii) Faunal occurrence types and their interpretations

1) Introduction

Three major occurrence types are distinguished, the commonest being the random type. The remainder, i.e., planar and intermittent occurrence types, are confined to the Portreuddyn Slate (fig.8.1). Their distributions and relationships to benthic communities and assemblage compositions are shown in fig.8.2.

2) Intermittent faunal occurrence types

These occurrence types are defined as lenticular shelly concentrations (chap.5,section b,iv,1). Within the Portreuddyn Slate, two variants are noted, the first revealing random valve orientations, whilst the second displays preferred concave-up orientations.

A) Lenticular shelly concentrations - variant one

Here, the dominant component is the diminutive aegiromenine Sericoidea. As the valves of Sericoidea probably disarticulated very easily (Bergstrom 1968), relatively low velocity currents could presumably induce large-scale disarticulation, with consequent unequal valve dispersion resulting from their relative thinness and differing hydrodynamic properties. For Sericoidea, the relatively high articulation ratios, opposing valve ratios approaching unity and unfragmented valves all suggest very little current activity. In association with fine lithologies, the overall evidence indicates a low energy, offshore environment.

This occurrence type is interpreted (chap.5,section b,iv,1) as the result of accumulation within seafloor sediment traps (Toots 1965a,b). Slight increases in current velocity would be sufficient to relocate the extremely light, free-living aegiromenines (Sericoidea) within pre-existing seafloor depressions, although net lateral transport must be negligible as opposing valve ratios do not significantly depart from unity despite 69% of the shells being disarticulated. Such current velocity increases were probably accompanied by simultaneous increases in sedimentation, due either to renewed clastic input or seafloor reworking, thus effectively preserving the random valve orientations which resulted from gradual accumulation, by low velocity currents, within relatively steep-sided seafloor depressions.

Assemblages within this occurrence type correspond to "residual fossil communities" (Fagerstrom 1964, p.1199).

B) Lenticular shelly concentrations - variant two

In this variant, the dominant component is again Sericoidea. Here, the valves possess preferred concave-up orientations and extremely low articulation ratios, suggestive of increased current velocities which presumably induced widespread disarticulation. The valves were consequently transported, concave-up (Brenchley & Newall 1970), across the muddy seafloor and accumulated in shallow seafloor depressions. Increased opposing valve ratios attest to greater net lateral transport and stronger current activity which was, however, not strong enough to induce large-scale valve inversion to the convex-up position.

The preservation of concave-up orientations may result from decreased current influences within the depressions and the stabilising effect of syn- and post-valve transport sediment accumulation within the concave faces of the valves. Another factor may be the relative depth of the depression itself. If the sides were relatively shallow, then presumably the valves could enter it in their transportation position, i.e., concave-up, their motion being arrested by a combination of the aforesaid factors. If, however, the depressions were steep-sided, the valves, on reaching the edge, would be "tipped" over, and would assume random orientations, the initially deposited valves forming impediments to successive valves.

Assemblages comprising this occurrence type correspond to "residual fossil communities" (Fagerstrom 1964,p.1199) or possibly "transported fossil assemblages" (op.cit.).

3) Planar faunal occurrence types

These are noted at only one locality (SH 56914139 -

map 2), probably being a lateral extension of the aforementioned variant one (fig.8.2). Some planar occurrence types probably result from relatively prolonged current activity, but the extremely high articulation ratio of the dominant Sericoidea brachiopods and their mixed valve orientations are not the expected results of such activity.

A short phase of slightly increased current activity preceeding an increase in sedimentation seems a likely cause for these phenomena. Some disarticulated valves would become inverted, possibly after a short transportational phase, whereas articulated, free-living Sericoidea brachiopods would remain anchored in the soft "sticky" mud, this assemblage then becoming buried by renewed sedimentation. Therefore some articulated brachiopods are probably in their original life positions.

The assemblage comprising this occurrence type corresponds to a "residual fossil community" (op.cit.), the "in situ" brachiopods corresponding to a "fossil community" (op.cit.). However, as this assemblage resulted from mass mortality, it should be more correctly termed a "residual fossil census community" (op.cit.).

4) Random faunal occurrence types

These types are associated with the dalmanellid-sowerbyellid and Nicolella communities.

Randomness noted in the assemblage assigned to Nicolella community (fig.8.2) is directly related to biogenic reworking coupled with reduced sedimentation. Polished sections reveal intense deformative bioturbation, which has modified or obliterated any primary sedimentary structures (Moore & Scruton 1957). Frequent clusters of randomly orientated articulated sowerbyellids are interpreted as probable "life clusters" (Pickerill 1974). Random occurrence is also noted in the Portreuddyn Slate, the Gorllwyn Slate and the Gorllwyn Grit (fig.8.2) and is similarly interpreted. Intervening, apparently unfossiliferous horizons represent times of continual, relatively rapid sedimentation which were unfavourable for the development of epifaunal and infaunal communities.

Random occurrence types are correlated with open marine conditions (see section d) which generate well-oxygenated bottom waters, thus permitting diverse epifaunal and infaunal communities to flourish.

iii) Major sedimentary structures and their interpretations

1) Introduction

To briefly reiterate, only sedimentary structures directly associated with faunal horizons or encountered during investigations for fossiliferous horizons are discussed.

2) Y Glog Volcanic Group (figs.8.1,8.3;map 2)

A) Basal rhyolitic tuff (fig.8.3)

The basal tuff frequently possesses very fine, undisturbed, parallel and low-angle cross-cutting laminations (plates 8.1,8.2), some appearing rippled (plates 8.1,8.3) or "wrinkled". Inweathering, laterally discontinuous sedimentary intercalations are also noted.

Several features of this tuff, e.g., fine grain size, flinty texture, sedimentary structures, sediment intercalations and its stratigraphical position (overlying a marine sequence) imply it is a waterlain airfall tuff. The fine ash initially fell onto an extensive water body and was subsequently deposited in a low energy environment by settling out from suspension, which produced the aforesaid laminations. Slight current velocity increases (lowest part of the lower flow regime - Harms & Fahnestock 1965,plate 1; Simons et al.1965, p.52,fig.21) possibly generated small ripples and in association with minor coeval increases in clastic sedimentation, caused the sedimentary intercalations. Convolute laminations (Ten Haaf 1956; Kuenen 1953,p.1054, fig 5; Potter & Pettijohn 1963,p.152-155) are noted (plate 8.4), possibly being produced by load deformation (Potter & Pettijohn 1963), the "wrinkled" layers conceivably representing the initial stages of lamination convolutions, which Ten Haaf (1956) considers are generated by "....slight differential stresses, usually due to current rippling, in a growing hydroplastic bed" (op.cit.,p.194).

At SH 55634141 (map 2), a broad, pipe-like structure (plate 8.5) is developed within the basal part of the tuff (cf. fig.7.3). Comparisons may be made with "sand volcanoes" (Burne 1970;Gill & Kuenen 1958) but the best comparison is with "liquefied intrusions" (Lowe 1975), although this example appears incompletely developed. Liquefaction is initiated by seismic shocks (Brenchley & Newall 1977;Dzulynski & Smith 1963;Lowe 1975;Potter & Pettijohn 1963) which may be related to this phase of volcanicity.

B) Agglomerate (fig.8.3)

Slates, developed between the basal tuff and this unit possess tuffaceous bands which thicken upwards, until the slate immediately below the agglomerate is wholly tuffaceous, being obviously related to an increase in pyroclastic activity.

The agglomerate displays several important features (fig.8.3):-

1) The abundance of angular - subrounded slate clasts decreases vertically.
2) These clasts display gradational boundaries.
3) The overall clast size decreases vertically.
4) The matrix mud content decreases vertically.
5) The agglomerate possesses an irregular base (plate 8.6).

The agglomerate grades into a coarse crystal lithic tuff overlain by a finer grey tuff displaying planar and trough cross-bedding (plates 8.7,8.8).

These features suggest the agglomerate was emplaced as a subaqueous "debris-flow"(Blatt et al.1972) (subaqueous pyroclastic flow - Fiske 1963;Fiske & Matsuda 1964) derived from volcanic debris plus some lithics, which accumulated on the flanks of a subaerial/submarine volcano and became sloughed away when rendered unstable by seismic activity.

The upward decrease and gradational boundaries of the slate clasts suggest derivation from the underlying muddy sediments, the cohesive clasts being incorporated whilst still relatively plastic, which were presumably "ripped-up" during erosive emplacement of the "agglomerate", as shown by the irregular basal contact (cf.Allen 1970, p.205;Dott 1963,fig.13,p.118;Kuenen 1953,p.1049,fig.1H; Stanley 1963,p.787). Overall slate clast concentration in the lower horizons (fig.8.3) suggests they underwent little lateral transport, whereas clasts higher in the sequence were subjected to much greater transport.

The upward fining (including the overlying tuffs) indicates an overall energy decrease and results from gradual settling out of material from suspension. In the overlying fine tuffs, waning current activity appears likely as alternating planar laminations and small-scale trough cross-bedding are overlain by current (and wave-induced ?) ripples (plates 8.7 - 8.12). These tuffs also have a gradational upper boundary with slates, in which thin tuffaceous bands persist, thus suggesting a gradual cessation of pyroclastic activity.

Similar thicker sequences within the Moelwyn

Volcanic Group (Bromley 1965;Fearnsides & Davies 1944; Jennings & Williams 1891;Ramsay 1866) are exposed on the southern slopes of Moelwyn Bach (SH 660438) where vertically fining agglomeratic units are noted with rippled bedding planes being exposed at their tops. Bromley (1968,p.9-11) considers this Group consists of submarine accumulations of volcanic material within sediments "....showing no evidence of shallow water deposition" (op.cit.,p.10).

3) Portreuddyn Slate (fig.8.1)

Parallel laminations of variable thickness (<1 cm.) are the commonest structures and comprise slightly coarser laminae within fine siltstones, reflecting short phases of increased current velocities and clastic input, the coarser material presumably being deposited from suspension in slowly moving waters (Harms & Fahnestock 1965,p.97). Faunal and lithological evidence suggests deposition in a barred or restricted basin.

Approaching the contact with the Pren-teg Grit (fig. 8.1), sandy beds with thin planar laminations are developed, which indicate current velocity fluctuations plus renewed clastic input, the sandy beds representing brief episodes of higher energy conditions. Their bases frequently exhibit small load and flame structures, indicative of minor density gradients. Small-scale (1 - 2 cms.) liquefied intrusions (Lowe 1975) filled with sandy mud occasionally penetrate fine sandstones, indicating minor density re-adjustments triggered by seismic shocks.

4) Gorllwyn Slate (fig.8.1)

Primary sedimentary structures are absent, but small (5-10 cms.) fining-up sequences are frequent i.e., fine silts - laminated coarser silts —fine silts etc., representing slight periodic fluctuations in current energy and clastic input. The laminated silts were deposited by slightly higher velocity currents, although these sequences were probably deposited under lower flow regime conditions (Harms & Fahnestock 1965;Simons et al.1965). Within the laminated siltstones, infrequent small (2 cms.) cut and fill structures are noted, which probably originated from small runnels produced by weakly erosive bottom currents.

5) Gorllwyn Grit (fig.8.1)

This unit displays many sedimentary structures, all indicating fluctuating current activity (plate 8.13). Pebble beds, some displaying imbrication, are common, with occasional associated horizons of convoluted laminae. The pebbles are mainly rhyolitic or shaley, the rhyolitic pebbles being subrounded-rounded, indicating prolonged transportation, whereas the angular-subangular shale clasts suggest local derivation. Some pebble beds consist entirely of shale clasts, presumably derived from a cohesive, unlithified, muddy bed which was "ripped up" by a sudden increase in current velocity. One such bed infills a channel cut structure indicating the presence of high energy erosive currents.

Sedimentary structures in this unit are too numerous to fully document. However, a full description and interpretation for one small sequence (plate 8.13) adequately exemplifies the original variable current regime.

Basal planar laminated sands which probably formed in the upper flow regime under plane bed conditions (op. cit.) occasionally reveal very low-angle cross-cutting relationships, similar structures characterising beach sediments (Dickinson et al.1972;McKee 1957;van Straaten 1959). A cross-stratified coset (McKee & Weir 1953) sits with erosive contact upon the laminated sands, the cross-stratification being closely comparable with pi cross-stratification (Allen 1963,fig.4G) which was probably derived from migrating large-scale, asymmetrical ripple trains under lower flow regime conditions. Overlying laminated sands reflect a return to plane bed deposition under upper flow regimes (Harms & Fahnestock 1965;Simons et al.1965). To the right (plate 8.13), these sands infill a channel cut. Above is a thin set of cross-stratified sandstones with a rippled top which contain rhyolitic pebbles displaying isolate imbrication (Laming 1966), these sandstones probably deposited by lower velocity currents.

No sediment disturbance directly attributable to infaunal activity (Moore & Scruton 1957) is seen, thus indicating rapid sedimentation in an environment unsuitable for colonisation by faunal communities.

The Gorllwyn Grit comprises shallow water sediments which were "....carried by currents which have moved normal or parallel to the coast, and intimately associated with volcanic islands" (Bassett 1963,p.47). The volcanic/ quartzose material comprising most of the sediment was probably derived from the Anglesey-Rosslare ridge. (Brenchley 1969,p.196-197).

6) Intra-Pitt's Head conglomerate (fig.8.1)

Exposed on the western limb of the Hebog syncline is a conglomerate composed of poorly sorted, subangular-rounded pebbles of rhyolitic and bedded purple-green siltstone lithologies within a tuffaceous matrix (plates 8.14.,8.15), the rhyolitic pebbles being compared to lithologies from the Precambrian Arvonian Series (Greenly, in Shackleton 1959). On the eastern synclinal limb, the author notes a thinner unreported extension of this conglomerate, which comprises smaller rounded rhyolitic pebbles in a tuffaceous matrix (plate 8.16).

This conglomerate suggests:-

a) A substantial period existed between emplacement of the lower and upper Pitt's Head flows. Both units are ignimbrites and by comparison with modern day examples must have been rapidly emplaced and in the geological sense are "instantaneous". Consequently, a similar time gap must be present elsewhere within the Pitt's Head Rhyolite Group (Shackleton 1959).

b) Prolonged transport by water action must be proposed to account for the provenance and roundness of the pebbles.

c) The overall decrease in pebble size approximately north-west - south-east across the syncline suggests a northerly derivation. This may be correlated with the lateral wedging-out (?) of the Gorllwyn Slate in the same direction (fig.8.1), suggesting lower energy (deeper water ?) conditions to the south-east.

d) Local exposure of Precambrian rocks in Caradocian times.

Possibly some form of localised fluvial run-off, from a northerly landmass, deposited this conglomerate, the tuffaceous matrix conceivably derived from reworking of the unconsolidated ignimbrite top (Martin 1959,p.397,399) and interim pyroclastic activity.

7) Lower Rhyolitic Tuff (fig.8.1)

Bedded, crudely graded, thin crystal tuffs indicate deposition by subaqueous gravity settling, some primary sorting having occurred in the eruptive column. Certain of these aforesaid tuffs are extensively bioturbated

(Moore & Scruton 1957), consequently implying the presence of a diverse infauna in an offshore environment subject to reduced sedimentation.

c) The fossiliferous assemblages

i) Introduction

The stratigraphic relationships and components of the faunal assemblages are shown in fig.8.2 and table 8.1. For full faunal analyses, see Appendix Two.

Shackleton (1959,p.240-241) records fauna from an impure limestone within the Lower Basic Tuff "....formerly exposed 1490 yds.S.48°W. of Moel Hebog summit" (op.cit.). The author was granted permission to examine this and other faunas within the Shackleton Collection housed at Liverpool University. Faunas from two localities within the Lower Basic Tuff were studied (locality 864 - SH 55404610;locality 1151 - ungridded) and were assessed on a presence/absence basis. Consequently, all statements and conclusions appertaining to the faunas of the Lower Basic Tuff are made solely from these specimens.

ii) Faunal analysis

1) Tyddyn - dicwm Beds (figs.8.1,8.2)

At the base, fine silty bands are crowded with poorly preserved graptolites, e.g., :-

Climacograptus peltifer Lapworth

Climacograptus scharenbergii Lapworth
climacograptids referable to groups 1 and 3
of Elles & Wood (1901-1918,p.183-184)
which are assessed on a presence/absence
basis. One metre below the graptolite horizon was collected a large fragmentary *Ogygiocaris* pygidium.

2) *Portreuddyn Slate* (figs.8.1,8.2;table 8.1, cols. A,B,C)

The lower cleaved siltstones contain medium diversity assemblages dominated by *Sericoidea*, with high articulation ratios attesting to negligible lateral transport, along with lower abundance dalmanellids, *Onniella* sp. and *Horderleyella* sp.

Trilobites are relatively abundant, with *Broeggerolithus* sp. (cf.*broeggeri* (Bancroft), cf. *harnagensis* (Bancroft), both of Dean 1960a) and *Calymene* sp.(s.l.) (*Flexicalymene* cf. *acantha* Bancroft of Dean 1963a) being equally common. *Ampyx* sp. (cf. *linleyensis* Whittard of Whittard 1955) and *Remopleurides* sp. (cf. *colbyi* Portlock of Whittington 1966) achieve minor importance.

Several complete crinoid arms referable to *Balacrinus basalis* (M'Coy) (Ramsbottom 1961,p.25) indicate "in situ" assemblages in a relatively low energy, offshore environment.

Within medium diversity assemblages in the upper third of this unit, sowerbyellids replace Sericoidea sp. as the dominant brachiopod whilst Broeggerolithus sp. becomes the dominant trilobite. Ampyx sp. and Remopleurides sp. are absent and Parabasilicus sp. is noted for the first time.

The topmost assemblages are again dominated by Sericoidea sp.. Specimens are referable to S.abdita Williams and S.restricta (Hadding) as well as to Chonetoidea gamma Spjeldnaes and C.iduna Öpik. Lower abundance associates are sowerbyellids, rarer dalmanellids and Horderleyella sp. The lower articulation ratio for Sericoidea (0.02/1) suggests some net lateral transportation.

3) Gorllwyn Slate (figs.8.1,8.2;table 8.1,cols.D-J)

This unit is the most fossiliferous within the Moel Hebog sequence.

The medium - high diversity lower assemblages (table 8.1,col.D) are variably dominated by sowerbyellids and Paracraniops sp.. Dalmanellids (Dalmanella sp./Onniella sp.), Sericoidea sp., obolids and Kjaerina sp. are common minor associates. The most abundant trilobite is Broeggerolithus sp.(cf.broeggeri, cf.harnagensis, cf. soudleyensis (Bancroft), B.sp. - Group 2, all of Dean 1960a). Parabasilicus (powisi (Murchison), cf.marstoni (Salter)? of Dean 1963a), Calymene sp. (s.l.) (F.cf. acantha) and Brongniartella minor (Salter) are also frequently noted. Assemblages in the middle of the lower subunit (table 8.1,col.E) contain two complete specimens of *B.basalis*, along with several arms and pluricolumnals. Their association with abundant unbroken ramose bryozoa attests to a sessile epifauna in an offshore, low energy environment subject to slow, steady sedimentation. Gastropods (*Lophospira*/bellerophontids) achieve moderate abundance within overlying assemblages (table 8.1,col.F).

Medium diversity assemblages within the middle subunit (table 8.1,col.G) are essentially similar to underlying assemblages, with *Paracraniops* sp. being the dominant brachiopod.

The medium/coarse grained siltstones of the upper subunit contain medium - high diversity assemblages (table 8.1,cols.H,I,J) which are all totally dominated by sowerbyellids. *Kjaerina* sp. (cf.*horderleyensis* Bancroft, cf.*latericostata* Bancroft of Bancroft 1929a) is noted with variable abundance, along with some inarticulates (*Paracraniops* sp./*Palaeoglossa* sp./*Schizocrania* sp./ *Schmidtites* sp.). Gastropods and cricoconarids (*Tentaculites* sp.) achieve minor abundance within the upper assemblages (table 8.1,col.J).

4) *Gorllwyn Grit* (figs.8.1,8.2;table 8.1,col.K)

A sparse, medium diversity assemblage within medium/ coarse grained siltstones is dominated by sowerbyellids. *Kjaerina* sp. and dalmanellids possess secondary abundance, with *Broeggerolithus* being the predominant trilobite. Notable minor occurrences are *Kjaerina* aff. *jonesi* Bancroft of Bancroft 1929a, *Heterorthis* sp. and *Flexicalymene* (*Reacalymene*) *pusulosa* (Shirley).

5) *Lower Rhyolitic Tuff* (figs.8.1,8.2;table 8.1,col.L)

High diversity assemblages within calcareous muddy tuffs display noticeable faunal changes, being co-dominated by sowerbyellids, dalmanellids (*D*.cf.*lepta* (Bancroft)[1] of Bancroft 1945;*D*.cf.*modica* Williams of Williams 1963) and *Dolerorthis* (*duftonensis prolixa* Williams). *Reuschella* sp., *Nicolella* cf.*actoniae obesa* Williams of Williams 1963, *Strophomena* cf.*grandis* (J. de C.Sowerby) of Williams 1963, *Rhactorthis* cf.*crassa* Williams of Williams 1963 and *Cremnorthis* sp. attain minor importance. Rare *Brongniartella bisulcata* (M'Coy), *Broeggerolithus* sp., *Chasmops* sp., *Estoniops alifrons* (M'Coy) and *Platylichas* sp. are recorded, whilst *Tentaculites* sp., ostracodes and gastropods (bellerophontids) display variable abundances.

6) *Lower Basic Tuff* (figs.8.1,8.2;table 8.1,col.M)

These assemblages are similar to underlying assemblages, with notable occurrences of *Reuschella* cf.*horderleyensis* Bancroft of Williams 1963 and *Orthambonites* sp. (cf. *cessata*[2] Williams of Williams 1963;cf.*exopunctata*[3] Williams of Williams 1974).

The fauna from locality 1151 of Shackleton contains an

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[1] now *Dalmanella* cf.*indica* Whittington - see Cocks 1978,p.61

[2] now *Orthambonites* cf.*cessatus* Williams - op.cit.,p.39

[3] now *Orthambonites* cf.*exopunctatus* Williams - op.cit.,p.39

Orthambonites pedicle valve (cf.exopunctata Williams 1974,[1] p.53-57,pl.8,figs.10-17) which is unique in possessing a posterolateral ala on one side, the other side being damaged. The author is unaware of any Orthambonites species showing such alae. Therefore this valve possibly constitutes a new genus or species, but collection of similar specimens is needed to verify this.

d) Interpretation of the fossiliferous assemblages in terms of the proposed Snowdonian benthic communities

i) Portreuddyn Slate (figs.8.1,8.2;table 8.1,cols.A,B,C)

The lowermost assemblages are dominated by Sericoidea and provide the best examples of the Sericoidea community in Snowdonia. Other associated characteristic species are Onniella sp., Ampyx sp. and Remopleurides sp., with intergrading Horderleyella sp./Parabasilicus sp. (dalmanellid-sowerbyellid "mega" community) and Rafinesquina sp. (Dinorthis community). The rare association of Sericoidea with Remopleurides is interesting, as a similar association of Sericoidea (restricta) with Remopleurides (cf.lata Olin) is noted from the Sularp Shale (Bergstrom 1968).

Opposing valve and articulation ratios for Sericoidea sp. suggest the assemblages represent biocoenoses as these valves were probably only loosely articulated (op.cit.). Bedding plane assemblages (SH 56914139 - map 2) show many

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[1] now Orthambonites cf.exopunctatus Williams - see Cocks 1978,p.39

planar orientated, articulated Sericoidea specimens, possibly in their original life orientations, Sericoidea being free-living, convex valve down (Rudwick 1970). In addition, complete crinoid arms and relatively abundant trilobites suggest a low energy, offshore muddy environment.

However, the mode of life of Sericoidea is far from certain. Some morphological features, e.g., the small, thin valves and the reduction of the brachial ridge to several papillae (thus reducing shell weight) are considered adaptations to epiplanktonic life (Bergstrom 1968,p.236-237), although thin valves are also thought of as adaptations for life on fine grained, soft sediments (Fürsich & Hurst 1974; Sheehan 1977; Thayer 1975). Brachiopods like Sericoidea and Chonetoidea may have been attached to planktonic algae e.g., floating Sargassum - like seaweed (Bergstrom 1968; Spjeldnaes 1967,p.55; Watkins & Berry 1977). From the Utica Shales, Ruedemann (1925,p.78;1926,p.64) records drifted seaweed strands covered by very small brachiopods, whereas Sheehan (1977) suggests sessile benthic seaweed fronds could be brachiopod attachment surfaces. Bergstrom (1968) notes bedding plane assemblages of articulated Sericoidea valves are often confined to "dark areas" (of algal origin ?) and are associated with graptolites (op. cit.). However, such associations are not seen within the Snowdonian assemblages, in which the author believes Sericoidea possessed a free-living benthic mode of life.

Sericoidea was the dominant component of a relatively impoverished sessile benthos, the low-medium diversities suggesting that although the environment was not "physically rigorous" (Bretsky & Lorenz 1970), it may have been slightly toxic or partially restricted, with reduced nutrient supplies (Sheehan 1977).

Assemblages in the middle part of this unit are assigned to the dalmanellid-sowerbyellid "mega"community (Howellites ? community), with intergrading Sericoidea sp., Dinorthis sp. and Horderleyella sp.. Sowerbyellid dominance is correlated with slight sediment coarsening and combined with increased diversities, imply these assemblages developed during a period of increased marine influence.

Abundant Sericoidea from overlying assemblages denote the re-establishment of the Sericoidea community. Very low articulation ratios suggest some net lateral transport, although unbroken valves signify only localised movement. The rarity of crinoids and bryozoa, which require reasonably firm substrates for attachment (Heckel 1972,p.280-281), indicates an original soft muddy seafloor, the low diversity and fine lithology signifying a low energy, restricted (?) marine environment.

ii) Gorllwyn Slate (figs.8.1,8.2)

1) Lower unit (fig.8.2;table 8.1,cols.D,E,F)

All the assemblages are confined to medium/coarse siltstones.

The lowest assemblages are dominated by sowerbyellids, with secondary dalmanellids and craniopsids and are assigned to the dalmanellid-sowerbyellid "mega" community, faunal associations tentatively suggesting the Howellites community. Increases in bryozoa, the variety of crinoid columnals and diversity suggest fully marine conditions (outer sublittoral zone?).

Low dominance assemblages in the middle part are similarly assigned to the aforementioned "mega" community, with slight intergradation from the Sericoidea community. Diverse crinoid columnals and bryozoans indicate the development of firm, supportive substrates whilst abundant trilobites, the higher diversity index and unfragmented crinoids and crinoid arms suggest stable, low energy conditions (outer sublittoral zone).

The upper assemblages are similarly referred to this "mega" community, intergrading Onniella sp. (Sericoidea community) and Skenidioides sp. (Nicolella community) achieving minor importance. In certain cases, dominance can be correlated with diversity, e.g., low dominance correlates with high faunal diversity and vice versa, which may reflect the inherent patchiness present in modern benthic communities or may relate to localised micro-environments. High dominance indicates that one or two species (usually low order succession species) adapted to a particular niche and proliferated, due to reduced competition for food, attachment sites etc.. High dominance assemblages and communities are usually low grade, consisting mainly of low order succession species. Environmental stabilisation encourages faunal diversification as higher order succession species become established. Consequently, competition increases and no species becomes highly dominant.

2) Middle unit (fig.8.2;table 8,1,col.G)

A similar low dominance, high diversity assemblage is assigned to the dalmanellid-sowerbyellid "mega". community, with intergradation from *Sericoidea* and *Onniella*, probably developing within a low energy, outer sublittoral environment.

3) Upper unit (fig.8.2;table 8.1,cols.H,I,J)

Lower assemblages seem best referred to the well-established "mega" community, as do overlying high diversity assemblages. *Horderleyella* sp., *Onniella* sp. and *Skenidioides* sp. intergrade, along with abundant ubiquitous sowerbyellids, dalmanellids, *Broeggerolithus* sp. and calymenids. Low dominance can again be correlated with high faunal diversity. Moreover, a low energy offshore environment is envisaged for these assemblages.

The "mega" community persisted (table 8.1,col.J), the slight diversity decrease possibly reflecting environmental fluctuations (Bretsky & Lorenz 1970) prior to the development of the Gorllwyn Grit facies.

iii) Gorllwyn Grit (figs.8.1,8.2;table 8.1,col.K)

The sparse fauna is best referred to the dalmanellid-sowerbyellid "mega" community and indicates a brief period of decreased sedimentation and lower energy conditions, although a lowered diversity index signifies fluctuating physical environmental conditions.

iv) Lower Rhyolitic Tuff (figs 8.1,8.2;table 8.1,col.L)

Lithological change in the upper part is reflected by significant faunal changes, calcareous muddy tuffs containing low dominance- high diversity assemblages with abundant Dolerorthis sp., Nicolella sp., Platylichas sp., Chasmops sp., and Estoniops sp., consequently signifying the Nicolella community, in which intergradation is well developed, e.g., from sowerbyellids, dalmanellids, Kjaerina sp. and Reuschella sp..

Environmental conditions relating to this community are difficult to assess but an offshore, open marine environment is postulated (outer sublittoral or deeper). Although within a volcanic sequence, high diversity indices suggest a stable environment with little environmental stress (op.cit.).

An adjacent high diversity, low dominance assemblage (loc.121- SH 55414696 - map 2) within an identical lithology possesses dominant sowerbyellids and dalmanellids, thereby suggesting assignment to the dalmanellid-sowerbyellid "mega" community (Howellites community ?), with intergrading genera from the Nicolella community being Dolerorthis sp.,Cremnorthis sp., Skenidioides sp.,Estoniops sp. and Chasmops sp.. Possibly the spatial separation of these "in situ" communities corresponds to their original spatial seafloor separation.

v) Lower Basic Tuff (figs.8.1,8.2;table 8.1,col.M)

Faunal associations strongly suggest the Nicolella community, with marked intergradation from the dalmanellid -sowerbyellid and Dinorthis communities.

e) Age determination of the Moel Hebog sequence from faunal evidence

i) Evidence from the graptolite fauna

Shackleton (1959,p.228) states the Tyddyn-dicwm Beds (fig.8.1) belong to the Nemagraptus gracilis Zone (middle Llandeilo - lower Caradoc (upper Costonian) - Skevington 1969,p.167,fig.32;Williams et al.1972,figs. 2,3). Graptolites from these beds (see section c,ii,1) exclude the characteristic N.gracilis (Hall), but along with a large fragmentary pygidium referable to Ogygia (=Ogygiocaris sp.of Whittard 1964,p.231-245)cf.scutatrix Salter of Salter (in Ramsay 1866), attest to a low Caradocian (Costonian) age.

Regarding the overlying Tan-yr-Allt Slates and Y Glog Volcanic Group, Bassett (in Williams et al.

1972,p.20) states that "....The suggestion that the fauna found in the tuffs near the base of the Y Glog Volcanic Group is from near the top of the gracilis Zone or even a little higher is confirmed by the discovery of a shelly fauna closely comparable to that of the Derfel Limestone in the upper tuff horizon of the laterally equivalent Moelwyn Volcanic Group (Bates in Bromley 1965, p.254)" i.e., upper Costonian - lower Harnagian.

ii) Evidence from the shelly fauna

1) Portreuddyn Slate (fig.8.1)

A) Horizon A (fig.8.2;table 8.1,col.A,8.2)

The association of Broeggerolithus cf.harnagensis, B.cf.broeggeri, Flexicalymene cf. acantha and F. (Reacalymene) cf. pusulosa (Shirley) of Dean 1963a (table 8.2) suggests a low Caradocian age (Bancroft 1929b,1933,1945;Bassett et al.1966;Dean 1958,1960a, 1963a,b;Harper 1956;Shirley 1936;Whittard 1958; Whittington 1938a,1966;Whittington & Williams 1955), their respective time ranges (table 8.2) indicating a Costonian - lower Harnagian age. Ampyx cf.linleyensis and Remopleurides cf.colbyi are not distinctive age-wise, although Ampyx sp. is described from probable Harnagian strata (Whittington 1968,p.93).

B) Horizon B (fig.8.2;table 8.1,col.B)

The combination of Broeggerolithus cf.broeggeri and *B*.cf.*soudleyensis* suggests a Soudleyan age but the stratigraphic horizon implies a Harnagian (upper ?) age is more probable.

C) *Horizon C* (fig.8.2;table 8.1,col.C)

This fauna is not diagnostic, although *Horderleyella* cf.*plicata* Bancroft of Bancroft 1945 indicates a low Caradoc horizon (Bancroft 1928b,1933,1945;Bassett et al. 1966;Dean 1958;Whittington & Williams 1955;Williams 1974). Problems in accurately discriminating between *Sericoidea* and *Chonetoidea* (chap.4) preclude *C*.*gamma* and *C*.*iduna* as age determinants. Stratigraphic relationships again suggest a Harnagian age.

2) *Gorllwyn Slate* (fig.8.1)

A) *Horizon D* (fig.8.2;table 8.1,col.D)

B.cf.*broeggeri* and *B*.cf.*soudleyensis* suggest a Soudleyan age, the former indicating a lower Soudleyan horizon (Bancroft 1929b,1933;Dean 1960a,c) although possessing a greater range (upper Harnagian - upper Soudleyan - Whittard 1958), whereas *B*.*soudleyensis* is found only in upper Soudleyan strata at Bala (Bassett et al.1966,p.265;Whittington 1966,p.86,1968,p.111,113).

The occurrence of *Kjaerina* sp. and *Brongniartella* cf.*bisulcata* (M'Coy) of Dean 1961 is puzzling as both usually indicate Longvillian horizons (Bancroft 1929a, 1933,1945;Dean 1958,1959,1960b,c,1961,1962,1963b;

Dean in Stevenson 1971;Harper 1947,1956;Lamont 1948; Whittington 1938a,c), although Dean (1960c,p.167) notes K. aff. jonesi from Soudleyan strata, but stratigraphical relationships and the cryptolithine combination suggest a Soudleyan age.

B) Horizon E (fig.8.2;table 8.1,col.E,8.3)

The association of B.cf.harnagensis, B.cf.broeggeri, B.cf.soudleyensis, Flexicalymene cf. acantha (not included in table 8.3), Brongniartella minor (Salter), Parabasilicus powisi, Onniella cf.soudleyensis (Bancroft) of Williams 1963 and Sericoidea abdita, on balance , strongly suggests a Soudleyan (middle ?) age (Dean 1960c, p.167).

C) Horizon F (fig.8.2;table 8.1,col.F)

The repeated combination of B.cf.broeggeri, B.cf. soudleyensis, Brongniartella sp. (minor ?) and P.powisi again indicates a Soudleyan (middle ?) horizon.

D) Horizon G (fig.8.2;table 8.1,col.G)

Similar faunal combinations imply assignment to the Soudleyan stage.

E) Horizon H (fig.8.2;table 8.1,col.H)

The combination of B.broeggeri and Parabasilicus sp. and the stratigraphic relationships suggest a Soudleyan (middle ?) age.

F) *Horizon I* (fig.8.2;table 8.1,col.I,8.4)

B.cf.*broeggeri*, *B*.cf.*soudleyensis*, *P*.*powisi*, *F*.(*Reacalymene*) cf.*limba* (Shirley) of Whittington 1965 and cf.*F*.*planimarginata* (Reed) of Whittington 1965 plus *Kjaerina* (cf.*horderleyensis*,cf.*latericostata*) and *Howellites* sp. (table 8.4) suggest, with stratigraphic relationships, a Soudleyan (middle - upper ?) age.

G) *Horizon J* (fig.8.2;table 8.1,col.J)

The recurrent combination of *B*.cf.*broeggeri* and *P*.*powisi* infers a Soudleyan (middle - upper ?) age.

3) *Gorllwyn Grit* (fig. 8.1)

A) *Horizon K* (fig.8.2;table 8.1,col.K)

Kjaerina aff.*jonesi* and *Heterorthis* sp. are both noted from this horizon. To which species of *Heterorthis* this specimen is referable is doubtful. *H*.*retrorsistria* (M'Coy) is noted from lower - middle Soudleyan strata (Bancroft 1933,1945;Bassett et al.1966;Dean 1958; Lamont 1946;Whittington 1938a,p.449,450,1938c,p.251), whereas *H*.*alternata* (J. de C.Sowerby) ranges from the Upper Longvillian - Actonian (Dean 1958), although Harper (1978) reports this species from the Onnian (*O*.*superba* zone) of south Shropshire. *K*.*jonesi* usually indicates a low horizon in the Lower Longvillian (Bancroft 1929a, 1945;Dean 1958,1959,1960c;Harper 1947,1956;Whittington 1938a,p.451,1938b,p.52), although the stratigraphic position of this horizon suggests a Soudleyan (upper ?) age. *K*.aff.*jonesi* possibly indicates a horizon approaching the Soudleyan/Lower Longvillian stage boundary, as *K*.aff.*jonesi* is noted from Soudleyan strata by Dean (1960c,p.167).

4) *Lower Rhyolitic Tuff* (fig.8.1)

A) *Horizon L* (fig.8.2;table 8.1,col.L,8.5)

Trilobite - brachiopod associations indicate assignment to the Upper Longvillian (Bancroft 1929a,b, 1933,1945;Bassett et al.1966;Cave 1965;Dean 1958,1959, 1960b,c,1961,1962,1963a,b,1965;Dean in Stevenson 1971; Harper 1956;Lamont 1946,1948;Williams 1963;Whittington 1938a,1966;Wood & Harper 1962). *Nicolella* cf.*actoniae obesa* and *Estoniops alifrons* (M'Coy) merit assignment to the upper Upper Longvillian, a proposition supported by most of the fauna (table 8.5). Indeed, *E*.*alifrons* (= *Pterygometopus jukesi* (Salter) of Harper 1956,p.389) is "....a characteristic trilobite in the upper half of the Upper Longvillian", "....in North Wales and the Cross Fell Inlier" (Dean 1960b,p.84). *E*. *alifrons*, noted from the Moel Hebog and Dolwyddelan sequences (chap.9),is previously unreported from Snowdonia.

5) *Lower Basic Tuff* (fig.8.1)

A) *Horizon M* (fig.8.2;table 8.1,col.M)

E. *alifrons* similarly supports assignment to the upper Upper Longvillian.

f) Conclusions

1) Random faunal occurrence types predominate throughout the sequence, with intermittent lenticular concentrations and planar occurrence types being confined to the Portreuddyn Slate.

2) A two fold emplacement for the Y Glog Volcanic Group is suggested :-

a) an early pyroclastic phase producing airfall, waterlain, rhyolitic tuffs and tuffaceous slates.

b) later deposition of a graded unit (subaqueous pyroclastic flow) derived from material which accumulated on the flanks of a volcano (subaerial/submarine) and became sloughed away due to seismic-induced instability.

3) The Portreuddyn Slate was deposited in a quiet, low energy environment which was possibly partially barred or restricted. Upper horizons show a transition to open marine conditions.

4) The Gorllwyn Slate was deposited in a quiet, stable, low energy, fully marine environment which favoured the development of an epifaunal benthos and diverse (?) infauna.

5) The Gorllwyn Grit exhibits sedimentary structures indicating relatively rapid deposition under upper and

lower flow regimes, with increased clastic sedimentation. Pebble/clast compositions indicate exotic (Anglesey - Rosslare ridge ?) and local derivation.

6) A conglomerate (a remanié deposit ?) within the Pitt's Head Rhyolite Group is indicative of a relatively long time period between emplacement of the two flows. Beavon (1963,p.489) notes a local rhyolitic conglomerate overlying the Lower Lapilli-tuff which may be laterally equivalent to this conglomerate. The roundness of the constituent pebbles suggests prolonged water transport, possibly from a northerly source (Anglesey - Rosslare ridge ?), the conglomerate being tentatively interpreted as the result of fluvial run-off (fanglomerate ?) from northerly Precambrian upland masses.

7) Shelly faunas and bioturbation in the upper part of the Lower Rhyolitic Tuff indicate localised marine conditions which persisted during deposition of the lower parts of the Lower Basic Tuff.

8) Assemblages from the Portreuddyn Slate indicate sequential development of the Sericoidea community and the dalmanellid-sowerbyellid "mega" community, with the Sericoidea community subsequently becoming re-established whereas the Gorllwyn Slate and the lower Gorllwyn Grit are dominated by the aforementioned "mega" community. Coeval, mutually intergrading Nicolella and Howellites (?) communities occur in the Lower Rhyolitic Tuff, the former

community persisting into the Lower Basic Tuff.

9) Graptolitic evidence suggests assignment of the Tyddyn - dicwm Beds, Tan-yr-Allt Slates and the Y Glog Volcanic Group to the uppermost part of the N.gracilis Zone.

Faunal evidence suggests a Harnagian (middle - upper ?) age for the Portreuddyn Slate, whereas Gorllwyn Slate faunas indicate the Soudleyan Stage, the upper assemblages inferring the middle - upper Soudleyan, whilst the Gorllwyn Grit fauna suggests an upper (?) Soudleyan age. The Lower Rhyolitic Tuff and Lower Basic Tuff faunas definitely suggest assignment to the Upper Longvillian.

Consequently, the age of the Pitt's Head Rhyolite Group arises. Three points need consideration, e.g.,

a) The time period during which the Gorllwyn Grit was deposited.

b) The Pitt's Head flows are ignimbrites and are, geologically speaking, "instantaneous" deposits.

c) The time period represented by the intra-Pitt's Head conglomerate.

Only the basal Gorllwyn Grit is fossiliferous, whilst sedimentary structures within the unit indicate relatively rapid deposition, consequently suggesting confinement to the Soudleyan (upper ?) Stage. Shackleton (1959, p.237) states the lower Pitt's Head flow conformably overlies the Gorllwyn Grit, suggesting a topmost Soudleyan - basal Lower Longvillian age for this flow.

Dalmanella lepta (Bancroft)[1] from the basal Lower Rhyolitic Tuff implies a mid-Lower Longvillian age (Harper, in Shackleton 1959,p.249). However, if Harper correctly identified "....a large plane Kjaerina" (op.cit.) as either "....K.bipartita (Salter) or K.hedstroemi Bancroft " (op.cit.), this suggests either the Upper Longvillian or the upper Lower Longvillian, both seeming more acceptable within the proposed age schemes (fig. 8.4).

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[1] now Dalmanella indica Whittington - see Cocks 1978,p.61

Chapter 9 The Dolwyddelan area

a) Introduction

The location and geology of the area is illustrated in fig. 1.1 and map 3.

The Glanrafon Beds and Snowdon Volcanic Group are exposed along the Lledr valley in a west-south-west - east-north-east trending syncline, the northern limb being partly overturned (fig.3.15). The volcanic rocks are conformably overlain by poorly exposed graptolitic black slates. Southwards are frequent exposures of Glanrafon Beds with intercalated rhyolitic tuffs and nodular rhyolites whereas to the south-east, these beds overlie the Lledr Valley Tuffs (= Capel Curig Volcanic Formation, Francis & Howells 1973). Northwards are sporadic exposures of Glanrafon Beds and dolerites. Within a north-east - south-west trending syncline on the southern slopes of Moel Siabod are exposed Glanrafon Beds, rhyolitic tuffs and tuffs equivalent to the Lower Rhyolitic Tuff Formation of the Snowdon Volcanic Group.

Most sampling is confined to sediments on the southern synclinal limb, although previously undescribed localities are sampled from the volcanic rocks and sedimentary rocks on the northern limb.

The reasons for studying the area are :-

a) The southern sediments were known to be fossiliferous.

b) A complete, relatively accessible sequence is exposed.

c) To analyse the faunal assemblages within the sediments and volcanic rocks.

d) Here, the basal unit of the Snowdon Volcanic Group is the Lower Rhyolitic Tuff Formation, the Pitt's Head Tuffs (I.G.S. Special Sheet, Central Snowdonia, 1:25000, 1972) being absent. Faunas from underlying sediments and the volcanic rocks themselves will hopefully provide a relatively accurate age for the Group (after Romano & Diggens 1969).

b) The stratigraphy, faunal occurrence types and associated sedimentary structures

i) Stratigraphy

The early work performed at Dolwyddelan is credited mainly to Sedgwick (1843,p.219),Ramsay (1853,p.166-167; 1866,p.97-100,110,112,119,260-261,263-265,267-270,272, figs.23,24,29,30;1881) and, albeit brief, Fearnsides (1910a,p.799).

However, the major work is by Williams & Bulman (1931) who remapped the area, erected a stratigraphy and described the differing lithologies and tectonics. Longvillian faunas are described by Romano & Diggens (1969) from Glanrafon sediments immediately underlying the volcanic rocks, these units being later analysed by Howells et al. (1973). Recently the I.G.S. remapped the eastern part of the syncline (Sheet SH 75,1:25000,Capel Curig and Betws-y-Coed,1976 and handbook (Howells et al.1978)).

The stratigraphy (fig.9.1) is adapted from Sheet SH 75 (op.cit.) and Williams & Bulman (1931).

ii) Faunal occurrence types and their interpretations

1) Introduction

The abbreviations following each heading indicate in which sequence a particular type is present :-

SE - South-eastern sequence
CP - Cwm Penamnen sequence
SC - South-central sequence
SW - South-western sequence
N - Northern sequence
MSS - Moel Siabod (South) sequence

Occurrence type distributions and relationships to benthic communities and assemblage compositions are shown in figs. 9.2-9.7.

2) Random faunal occurrence type (figs.9.2-9.7; plates 5.1,5.2,5.4)

(SW,SC,CP,SE,N,MSS)

This type is common, often forming diffuse bands of variable thickness which are frequently capped by planar occurrence types. Randomly orientated, often disarticulated valves are interpreted as the result of intense biogenic activity (Moore & Scruton 1957;Rhoads 1967; Toots 1965a,b;van Straaten 1959). Random occurrence types are often associated with burrows (localities 201A/226B), fresh surfaces and polished sections of associated lithologies revealing intense deformative bioturbation which usually indicates well-oxygenated bottom waters (Watkins & Berry 1977,p.275) thus allowing a diverse, infauna to develop. Oxygen deficient bottom waters result in either azoic conditions (0.1 ml./1.O_2) or severely reduced infaunas (0.3 - 1.0 ml./1.O_2) (Rhoads & Morse 1971,p.426). Random fossil occurrence represents periods of reduced sedimentation, allowing the shallowly burrowing infauna to rework the sediments.

Rarely, random occurrence types merge laterally into planar occurrence types which probably resulted from localised infaunal activity related to fluctuating marine conditions.

3) Planar faunal occurrence types (figs.9.2-9.7)

A) Preferred convex-up valve orientations
(figs.9.2-9.6;plate 5.4)
(SW,SC,CP,SE,N)

Convex-up orientations are commonly found in bands of variable thickness, frequently "capping" horizons of randomly orientated valves. Such orientations probably resulted from relatively high velocity current activity (Toots 1965a). Commonly associated sandy lithologies attest to such currents. Within these horizons, articulation ratios are quite low, although opposing valve ratios do not significantly depart from unity, accordingly indicating moderate net lateral transport with only minor compositional modifications.

The strophomenid *Macrocoelia* usually displays significantly different brachial (rare) and pedicle (common) valve counts. From studies of the morphologically similar strophomenid *Rafinesquina* (Lamont 1934,p.163; Richards 1972,p.395;Rudwick 1965,H202), it is assumed the concavo-convex *Macrocoelia* lived convex valve down on the sediment, in which position a thin brachial valve would facilitate valve opening (Rudwick 1970). The author therefore believes the scarcity of *Macrocoelia* brachial valves is due to selective destruction after disarticulation. Richards (1972,p.396) further suggests that on account of the large area of shell-sediment contact and the ability to keep the commissure above the sediment, *Rafinesquina* (=*Macrocoelia*)could colonise muddy seafloors. The author similarly views these features as adaptions for colonising unstable sandy seafloors, a lithology commonly associated with *Macrocoelia*.

"Capping" horizons of convex-up valves resulted from current velocity increases accompanied by increases in sedimentation and clastic input. Rapid sediment deposition consequently ensued as shown by laminated, undisturbed fine sands above these shelly horizons which effectively preserved the valve orientations. This was either because deposition was so rapid that any infauna could not rework the sediment (Heckel 1972,p.244;Moore & Scruton 1957; Reineck & Singh 1975,p.145) i.e., sedimentary structures formed quicker than the burrowers could modify them (Imbrie

& Buchanan 1965,p.167;Moore & Scruton 1957,p.2744) or in areas of rapidly shifting sand, the substrate was too mobile or too coarse for many burrowers (Heckel 1972,p.244). Convex-up valve horizons overlain by laminated sands may be related to storm activity (Morton 1978).

B) <u>Mixed valve orientations</u> (figs.9.2-9.6;plate 5.8) (SW,SC,CP,SE,N)

This type is usually confined to relatively thick bands (2-20 cms.), the valves often being closely packed together (= coquinas - Gary et al.1972). Frequently the bands laterally bifurcate, the upper and lower boundaries often being gradational with interband horizons (5-10 cms.) either being unfossiliferous or containing randomly orientated valves.

This type is more frequent within siltstones, the transition from mixed to random orientations accompanied by no discernable lithological difference, indicating large current velocity changes were not involved. For mode of formation, see chap.5, sections b,iii,3 and iv.

Generally, valve sizes are comparatively small, implying they have been "winnowed out" by low velocity currents. Although articulation ratios are relatively low, opposing valve ratios approaching unity and unbroken, unabraded valves signify negligible net lateral transport.

Such shelly accumulations probably formed low-angle shell banks on the seafloor, the diffuse lower and upper boundaries attributable to decreases and increases in sedimentation, respectively. Lateral bifurcation either resulted from localised sedimentation related to seafloor topography or shifting sediments which partly buried the shell bank. Undisturbed valve orientations indicate no biogenic activity. Once sedimentation increased, the shelly accumulations became buried. Overlying horizons possessing randomly orientated valves indicate the re-establishment of a burrowing infauna (Howard 1972). Nevertheless, the shelly bands are relatively undisturbed, indicating they either formed barriers to further downward burrowing or the burrowers were confined to the upper oxygenated horizons within the sediment (op.cit.,p.216; Rhoads 1967), as in fine grained, organic rich Recent environments, sediments become oxygen deficient at a few centimetres in depth (op.cit.).

C) Preferred concave-up valve orientations
(figs.9.2,9.5,9.7)
(SW,SE,MSS)

This rare type "caps" units displaying random valve orientations, the transition not accompanied by any lithological change.

A possible interpretation is as follows :-

A brief current velocity increase induced transport of those disarticulated valves already concave-up on the seafloor (Brenchley & Newall 1970;Crowell et al.1966; Johnson 1957;Menard & Boucot 1951). Opposing valve ratios around unity indicate little lateral transport. Once transport ceased, due to a combination of :-

a) current velocity decrease

b) sediment accumulation within the concave faces of the valves

c) friction

scouring began (op.cit.), and coupled with rapid sedimentation, the valves ultimately became buried.

4) Intermittent faunal occurrence types (fig.9.4)

A) Univalve horizons defining the base of trough cross-bedded sets (fig.9.4)
(CP)

See chap. 5, section b,iv,2 for interpretation.

5) Undisturbed life orientations (figs.9.2,9.3,9.6; plate 5.10)
(SW,SC,N)

Obolid brachiopods in probable life orientations are associated with sparse, randomly orientated valves and horizons containing planar convex-up and mixed valve orientations, usually within slightly coarser lithologies. See chap. 5, section b,v for further discussion.

Documented in-situ linguloids (obolids/lingulids) (Craig 1952,1954;Ferguson 1963a;Richards 1972;Ziegler et al.1968) possess orientations ranging from vertical - near horizontal (Craig 1952,1954;Ferguson 1963a;Pickerill 1973, 1974;Richards 1972;Rudwick 1965,1970).

Some authors maintain recent linguloids are intertidal (Ferguson 1963a;Heckel 1972,p.270) whilst others contend they are best suited to slightly deeper waters (Paine 1970;Richards 1972), although an oft-quoted depth range is from the intertidal zone - approximately 40m. (Hatai in Craig 1952;Ferguson 1963a;Heckel 1972;Pickerill 1973). Modern-day species usually inhabit sands (Paine 1970), a lithology thought preferential (Heckel 1972), although some species prefer muds (Craig 1952) and muddy sands (Chuang 1956,p.167,188). Modern _Lingula/Glottidia_ occupy finer sediments with increasing depth (Paine 1970). Fossil linguloids show no substrate preferences, although greater abundances are recorded from muddy sediments (Craig 1952; Ferguson 1963a;Pickerill 1973;Richards 1972). It therefore appears that the Dolwyddelan specimens were not intertidal. Their association with extensively bioturbated sediments attests to the existence of other contemporaneous infauna.

Faunal and sedimentological evidence suggests the obolids were situated in a quiet, low energy marine environment (outer sublittoral zone) and correspond to the "fossil community" of Fagerstrom (1964,p.1199).

For the other occurrence types, opposing valve ratios, unbroken, unabraded valves and only sparse epizoan colonisation (Richards 1972) suggest assignment to the "residual fossil community" (op.cit.).

iii) _Major sedimentary structures and their interpretations_

1) Glanrafon Beds

A) Planar laminations (SW,SC,CP,SE,N)

These are the commonest sedimentary structures, being noted in medium-coarse grain sandstones - medium grain siltstones. Thin varve-like laminations (plate 9.1) and coarser laminations are noted. Laminated sandstones cap bioturbated horizons, whilst similar units are capped by cross-bedded horizons, the laminations occasionally possessing low-angle cross-cuts.

Undisturbed planar laminations in sandstones suggest rapid deposition in the lower part of the upper flow regime (Harms & Fahnestock 1965,plate 1;Harms et al.1963, p.577;Simons et al.1965,p.52,fig.21) by plane bed or standing wave transport on a sea-bed with no prominent topographical features (Harms & Fahnestock 1965;Pickerill 1974). Relatively high velocity currents are envisaged with high concentrations of suspended sediment (Morton 1978;Reineck 1967) which may be related to periodic storm activity (Morton 1978) in a sublittoral environment.

Sandstones with low-angle, cross-cutting laminations passing vertically into coarse siltstones with dark shaley pellets and little biogenic reworking suggest shallow, marginally subtidal (shoreface) conditions (Klein 1967; Reineck 1967;van Straaten 1959,1961). Sequences comprising basal laminated sandstones passing into bioturbated sediments which are truncated by laminated sandstones etc. (plate 9.2) correspond to shoreface sequences (Howard 1971,1972) which represent "....a record of storm and post-storm activities" (Howard 1971,p.161).

Varve-like laminations in fine siltstones imply slow settling from suspension (Pickerill 1974). Current velocities were probably too low to transport coarser material and weak water turbulence permitted deposition of finer material, possibly being related to calmer conditions following storm activity (Morton 1978).

B) Cross-bedded units (SW,SC,CP,N)

Large and small-scale trough cross-bedded cosets possessing erosional and non-erosional basal contacts bound planar laminated beds within fine sandstones/coarse siltstones. These bedforms originate under lower flow regime conditions, probably by migrating ripples and dunes (Harms & Fahnestock 1965;Simons et al.1965).

Small-scale (1-5 cm.) cross-bedded units are related to rippled bedforms, attributed to either scour infills in the lee of lunate ripples (Harms et al.1963) or migration of linguoid ripples (Allen 1963;Hamblin 1961). As they often overlie parallel laminated sediments, an upper - lower flow regime transition is envisaged, such a succession possibly being related to a point-bar sequence (Harms & Fahnestock 1965;Harms et al.1963) within a non-barred, high energy environment (Clifton et al.1971).

Larger trough cross-beds (plate 9.3) seem best compared to "pi cross-stratification" (Allen 1963,p.110) which originated from migration of large-scale asymmetrical ripples (op.cit.). Plate 9.3 reveals these beds to be apparently truncated by planar bedded sandstones, a lower-upper flow regime transition (but see section C). Erosion surfaces signify fluctuating current velocities.

C) Scour and fill structures (SW,CP,SE)

Such structures are ascribed to localised, high energy, bottom scour (Pickerill 1974). Several different infills are noted :-

a) symmetrical infill by laminated sands (fig.9.8a; plate 9.4)

b) as for a), passing upwards into horizontally laminated sands (fig.9.8b;plate 9.5)

c) planar bedded sands passing up into low-angle, cross-bedded sands (fig.9.8c;plate 9.2)

d) shelly sediment infill, passing up into planar laminated and small-scale cross-bedded fine sandstones (fig.9.8d;plate 9.6)

Scour and fill structures have been noted in channel floor deposits (van Straaten 1961,p.206) and backshore beach deposits (McKee 1957, p.1712).

Indeed, the large-scale trough cross-bedding illustrated in plate 9.3 more probably represents a cross-bedded asymmetrical infill of either a scour depression/ trough (Terwindt 1971,p.518) or a shallowly incised channel, both of which presumably formed under high energy current action, probably in tidal channel and shoal areas (op.cit., p.516).

D) Dark shale clasts (SW,SC,SE,N)

Dark, fine grained, subangular-subrounded shale clasts of variable size (longest axis = <1 cm. - 5 cms.) are associated with coquinite horizons and planar laminated beds. The clasts possess slightly gradational boundaries indicating they were partly unlithified when incorporated.

Such clasts appear diagnostic of migrating channel floor deposits on the lower parts of tidal flats (de Raaf & Boersma 1971;Klein 1967;1970;Reineck 1967,1972;van Straaten 1952,1954,1959,1961;Terwindt 1971). Aforementioned associations suggest relatively high energy conditions such as would probably be found in shoreface - upper offshore areas adjacent to the lower parts of tidal flats, although it is more likely that these clasts were transported into deeper water(outer-sublittoral zone).

Infrequent clasts associated with diffuse shelly bands displaying random valve orientations may indicate either similar transport or a clast - coquinite association subsequently modified by biogenic activity.

E) Load structures (SW,CP,SE,N)

Small-scale load structures are frequently developed at sandstone-siltstone boundaries, the denser sandstone downloading into the underlying siltstone due to density gradients within the unlithified sediments.

F) Ichnofauna (plates 9.7,9.8)
(SW,SC,SE)

Excluding deformative bioturbation, isolated vertical-oblique tubes are seen to disrupt laminated sediments, some originating from erosional surfaces. Occasionally, overlying sediment is piped down into these tubes (obolid burrows ?).

The vertical burrows("shafts" - Frey 1973,p.10,table 3) seem best referred to the ichnogenus Skolithos Haldeman. Asterosoma von Otto Form Cylindrichnus (Frey & Howard 1970,p.160,figs.2a,7b) and Ophiomorpha Lundgren (op.cit., p.160,fig.7d) cannot be discounted although the Dolwyddelan forms are unbranched and lack knobbly exterior surfaces (op.cit.,p.163;Heinberg,ibid.,p.233).

If classified as Skolithos sp., these burrows consequently indicate the Skolithos facies (Seilacher 1967, p.418,figs.2,3) which is restricted to littoral sands (op. cit.,Crimes 1970,p.102) and denotes high energy conditions (Banks,ibid.,p.30;Frey & Howard,ibid.;Rhoads 1967), the associated sediments inhabited mostly by suspension feeders which construct strong burrows to combat the shifting sediment (Frey & Howard 1970,p.151). These particular burrows (plate 9.8) are located within a probable shoreface sequence (Howard 1971,1972) (plate 9.2), penetrating laminated upper shoreface sandstones. Crimes (1970,p.103), however, notes Skolithos within the Cruziana community (Cruziana facies of Seilacher 1964,1967)whilst Pickerill (1977,p.12,fig.3) records Skolithos from all four marine benthic communities of the South Berwyn Hills, where it is commonest within the Howellites community (op.cit.,p.13, fig.4) which is considered an outer sublittoral community (op.cit.,p.12,fig.3).

Geniculate burrows (fig.9.9) may represent oblique sections through Arenicolites (as no spreite (Frey 1973, p.10,table 3;Seilacher 1967,p.419) are noted - Häntzschel 1962,W 183-184), but could equally be referred to Asterosoma Form Cylindrichnus (Frey & Howard 1970,p.160,figs.2a,7b), both forms suggesting nearshore deposition but in a slightly lower energy (deeper water ?) environment than Skolithos (op.cit.,p.151,fig.6;Seilacher 1967). Associated fine grade laminated sandstones attest to this interpretation.

2) Snowdon Volcanic Group

Bedding is developed within the Dolwyddelan and Moel Siabod sequences. Plate 9.9 shows a graded agglomerate, forming the base of the Upper Unit of the Lower Rhyolitic Tuff Formation on Moel Siabod (Howells et al.1973,p.28), overlain by cross-bedded crystal tuffs, which suggests deposition in a shallow water, high energy environment as does planar bedding within the upper sub-unit of the Upper Unit of the aforementioned Formation (op.cit.) - plate 9.10.

The Upper Rhyolitic Tuff Formation at Dolwyddelan frequently displays bedding (plate 9.11). Features attributable solely to shallow water conditions are not seen. Some rhyolitic tuffs occasionally possess thin planar laminations resulting from the gradual deposition of material from suspension and alternate with units of greater terrigenous admixtures, indicative of fluctuating sedimentation and clastic input.

Tuff-sediment boundaries are often complexly convoluted (fig.9.10), resulting partly from downloading and partly from liquefaction reactions which were presumably triggered by seismic activity (Anketell et al. 1969,1970; Brenchley & Newall 1977; Dzulynski & Smith 1963; Lowe 1975; Potter & Pettijohn 1963).

Graded crystal tuffs (5-10 cms.thick) are noted, the grading resulting from :-

a) primary airfall grading (Kuenen 1953)

b) secondary grading by settling through water (op.cit.)

Feldspar crystals are concentrated at the base of each graded unit which often show small-scale load structures, these graded units being best compared with those illustrated by Kuenen (1953,p.1049,figs.1A,1C). An overall upward fining is recorded in most beds of this Formation which presumably resulted from the gradual settling out of material from suspension although such grading may also result from the emplacement of some units as turbid flows or slurries (Howells et al. 1973).

c) The fossiliferous assemblages

i) Introduction

Faunal analyses are conducted in six subareas (figs. 9.2-9.7,map 3). In the text, numbers in parentheses refer to fossiliferous localities (map 3). See also Appendix Two and table 9.1

ii) Faunal analyses

1) South-eastern sequence (fig.9.5;table 9.1;col.SE)

The lowest horizons (225) are dominated by *Salopia*, subordinate sowerbyellids and triplesiaceans (*Bicuspina*). Algae are also abundant, three types being differentiated.

The most abundant type is provisionally referred to the genus *Dasyporella* (*norvegica* Hoeg) which was originally placed in the family Dasycladaceae (Johnson 1952,p.38; Pia 1927,p.61-62) but has since been placed in the "Algae Incertae Sedis" by Johnson & Konishi (1959,p.26,table iv, p.71,151-157) who believe it should be classed within the Rhodophyceae (op.cit.).

The next most abundant type is sheet-like and possesses a characteristic branching thallus, bearing a striking resemblance to corallinaceans (Chapman 1962, p.238-241; Pia 1927,p.100-103) which, however, did not appear until the Cretaceous (Pia 1927,p.135). Consequently, this form is referred to the extinct family Solenoporaceae (Johnson 1952,p.29-34; Pia 1927,p.97-99) and provisionally to the genus *Solenopora* (op.cit.,Johnson & Konishi 1959, p.29-34,138-146). *Solenopora* thalli are usually rounded/ nodular, although sheet-like forms are known (Johnson &

Konishi 1959,p.30).

The third rarer type is referred to the dasycladacean genus Mastopora (Johnson 1952,p.44;Johnson & Konishi 1959,p.51-52;Pia 1927,p.66).

Consecutive horizons (226A/B,227) reveal variable dalmanellid/sowerbyellid dominance, Reuschella, Macrocoelia, Dinorthis, Paracraniops and triplesiaceans being commonly associated, with Broeggerolithus the dominant trilobite. Higher horizons (220,221) reveal similar faunal compositions.

In the southern sequences, two laterally persistent rhyolitic tuffs are considered useful marker horizons (map 3). Between these tuffs, horizons (218,219) are dominated by dalmanellids, sowerbyellids being subordinate. Ramose bryozoan fragments and crinoid columnals are variably abundant.

Horizons above the upper tuff (210,214,216) are alternately dominated by sowerbyellids and dalmanellids, Broeggerolithus maintaining its dominance amongst the trilobites (Kloucekia apiculata (M'Coy), Brongniartella minor (Salter), Decoroproteus sp. and Flexicalymene sp.). Ostracodes achieve only minor abundance.

This pattern is paralleled in overlying horizons (211,212A/B,215,217) although dalmanellids are totally dominant. Parabasilicus sp. occasionally becomes the dominant trilobite.

The topmost horizon (213) reveals sowerbyellids are once again dominant,dalmanellids attaining secondary dominance. Kjaerina (jonesi Bancroft) is an important minor associate along with rare submarginal ring plates of the cyclocystoid Cyclocystoides sp..

2) Cwm Penamnen sequence (fig.9.4;table 9.1,col.CP)

The lowest horizons (208) are dominated by dalmanellids (Howellites > Dalmanella). Macrocoelia is commonly associated and is confined to sandy lithologies. Broeggerolithus sp. is the dominant trilobite whilst crinoid columnals are extremely abundant.

Overlying horizons (205) reveal sowerbyellids to be secondarily abundant to dalmanellids. Dinorthis sp. is frequent within sandy lithologies, Macrocoelia being considerably rarer. Trilobites are scarce and crinoid columnals possess decreased diversities.

Similar faunal compositions are recorded from the uppermost horizons (204). Dinorthis however, attains secondary dominance. Rare Lepidocoleus plates also occur.

3) South-central sequence (fig.9.3;table 9.1,col.SC)

The basal horizons (197/A/B) are dominated by Dinorthis (berwynensis (Whittington)), Reuschella being commonly associated. Crinoid columnals are relatively diverse and abundant.

Dalmanellids dominate consecutive horizons (203) with Broeggerolithus the commonest trilobite. Higher horizons (201A/B/C) reveal similar dominance. Reuschella, Macrocoelia and Dinorthis (all restricted to thin sandy horizons) are common associates. Tentaculites sp. attains minor importance whilst bellerophontaceans, pleurotomariaceans, bivalves and obolids are locally abundant.

Sparse faunas from the upper horizons (198,199) reveal low dominance assemblages, Reuschella and dalmanellids being variably abundant.

4) South-western sequence (fig.9.2;table 9.1,col.SW)

A) Glanrafon Beds (table 9.1,col.SW-GB)

The lowermost sparsely fossiliferous horizons (185) are dominated by dalmanellids with rarer Horderleyella (cf.plicata Bancroft of Bancroft 1928b,1945) and Paracraniops sp., ramose bryozoan fragments being relatively abundant.

Dalmanellids (Dalmanella sp.) attain increased dominance in consecutive horizons (186,187) whilst ambonychiaceans achieve localised abundance. Certain thin horizons are composed entirely of disarticulated crinoid columnals and an analogy is drawn between these and similar horizons from the Horderley Sandstone in Shropshire (= "Glyptocrinus Flags" - Dean 1958,p.203-204;1960c,p.165;1964,p.277;Dean in Greig et al.1968,p.111).

Sparser assemblages (188) again reveal dalmanellid dominance with ostracodes (Tallinnella sp./hollinaceans) attaining some importance.

Consecutive low dominance assemblages (183-Horizon 1) show reduced dalmanellid dominance with *Reuschella*, *Horderleyella*, *Dinorthis* and triplesiaceans all restricted to sandy lithologies. The trilobite contingent consists of *Brongniartella* cf.*minor* of Dean 1961, *Calymene* sp. (*Flexicalymene caractaci* (Salter), *F.* (*Reacalymene*)*limba* (Shirley)) and *Broeggerolithus* sp. (Group 2 - Dean 1960a), the latter being dominant.

Higher horizons (183-Horizon 2;189,195) are faunally similar but possess higher diversities. Sowerbyellids laterally replace dalmanellids as the dominant brachiopod. Ptereineids are locally abundant.

Below the lower rhyolitic tuff (fig.9.2), horizons (196/196A) are variably dominated by sowerbyellids and dalmanellids with *Kjaerina* (aff.*jonesi* of Bancroft 1929a) a significant addition to an impoverished brachiopod contingent. *Kloucekia* (*apiculata*) replaces *Broeggerolithus* (cf.*nicholsoni* (Reed) of Dean 1962; Group 3 - Dean 1960a) as the chief trilobite.

Above this tuff (173,173A,174,181 - Horizons 1/1A/2),sowerbyellids are dominant. *Kjaerina* (cf.*hedstroemi* Bancroft and cf.*jonesi*, both of Bancroft 1929a) is again recorded, with trilobite dominance varying between *Broeggerolithus*, *Kloucekia* and *Parabasilicus*. Important minor associates are *Tentaculites* sp. and ostracodes (*Tallinnella* sp./hollinaceans).

Overlying high dominance assemblages (180) reveal dalmanellid predominance whilst consecutive assemblages

(175) are dominated by sowerbyellids.

B) Snowdon Volcanic Group (table 9.1,col.SW-SVS)

Sparse faunas (176-Horizons 1/2) from the lower Lower Rhyolitic Tuff Formation are variably dominated by sowerbyellids and dalmanellids, ostracodes (hollinaceans) becoming locally common. *Broeggerolithus* once again dominates the sparse trilobite component.

Intercalated tuffaceous sediments between this Formation and the Bedded Pyroclastic Formation yield assemblages (178) displaying radical faunal changes. *Dolerorthis* (*duftonensis prolixa* Williams) is the main brachiopod with *Skenidioides* (*costatus* Cooper), *Nicolella* (*actoniae obesa* Williams), dalmanellids, *Sericoidea* sp. and sowerbyellids commonly associated. Trilobites are rare whereas crinoid columnals, although of limited diversity, are abundant as are ramose bryozoa. Rare cystoid fragments, along with *Lepidocoleus* and *Cyclocystoides* plates, are recorded.

An extremely diverse assemblage (179) from the lower Upper Rhyolitic Tuff Formation is dominated by *Sericoidea* sp. with secondary dalmanellids, *Nicolella*, *Rhactorthis* (*crassa* Williams), etc.. Of the diverse trilobites, *Estoniops* (*alifrons* (M'Coy)) is predominant. Gastropods are common e.g., the bellerophontacean *Cyrtolites* sp., the murchisoniacean *Murchisonia* sp. and the platyceratacean *Cyclonema* sp.

C) Black Slates (table 9.1,col.SW-BS)

These (228) contain poorly preserved graptolites referable to Climacograptus bicornis (Hall), Diplograptus multidens (Elles) and Orthograptus truncatus (Lapworth).

5) Northern sequence (fig.9.6;table 9.1,col.N)

The lowest horizons (235A/B/C) are dominated by dalmanellids (Howellites > Dalmanella) with associated Dinorthis and sowerbyellids. Monospecific gastropod horizons (lophospirids/bellerophontids) are recorded, being similar to localised patches of bivalves and gastropods noted within strophomenid - trilobite communities (Bretsky 1969a). Broeggerolithus sp. (Group 3 - Dean 1960a) is the most abundant trilobite. Succeeding assemblages (236,231,237) are compositionally similar except sowerbyellids attain dominance.

Probable faunal control by lithology is exemplified in consecutive horizons (232A). Siltstones are dominated by dalmanellid-gastropod-nuculacean assemblages whereas overlying sandstones contain less diverse assemblages dominated by sowerbyellids. The topmost horizon (232) is faunally similar, sowerbyellids attaining slight dominance over dalmanellids.

6) Moel Siabod (South) sequence (fig.9.7;table 9.1, col.MSS)

The only sampled assemblage (233/233A) is dominated by sowerbyellids with Skenidioides and Sericoidea (aff. Chonetoidea alpha Spjeldnaes of Spjeldnaes 1957) achieving secondary importance. Brongniartella (bisulcata (M'Coy)) is the dominant trilobite. Abundant crinoid columnals, Lepidocoleus plates and rare Cyclocystoides plates are recorded.

d) Interpretation of the fossiliferous assemblages in terms of the proposed Snowdonian benthic communities

i) Moel Siabod (South) sequence (fig.9.7;table 9.1, col. MSS)

Although sowerbyellids are dominant, the abundance of Skenidioides plus Leptestiina, Nicolella, Orthambonites, Dolerorthis and common Lepidocoleus plates suggest assignment to the Nicolella community which probably developed within a low energy offshore (outer sublittoral) environment removed from "environmental stress" (Bretsky & Lorenz 1970).

Intergradation from the dalmenellid-sowerbyellid and Sericoidea communities implies the Nicolella community had not become fully established and suggests this community occupied an intermediate spatial location between the intergrading communities.

ii) Northern sequence (fig.9.6;table 9.1,col.N)

The assemblages are assigned to the dalmanellid-sowerbyellid "mega" community.

Intergradation by low order succession species of the Dinorthis community (Dinorthis/Macrocoelia) occurs in the lowest assemblages (235A/B/C). Scarce crinoids and bryozoa imply the substrate was either too unstable or too soft to provide support (Heckel 1972), faunal and sedimentological evidence indicating the outer sublittoral zone. Monospecific gastropod horizons presumably represent current accumulations from adjacent onshore environments. McKee (1957,p.1736) notes similar accumulations within estuarine sediments bordering a lagoon.

Increased diversity indices within consecutive assemblages (236) indicate environmental stabilisation thus permitting community diversification.

Similar overlying assemblages (231,237) show greatly reduced diversities, intergradation from the Dinorthis community being restricted to low order succession species. A change in one or more physical parameters possibly caused this phenomenen (Bretsky & Lorenz 1970) although the most distinct parameter, lithology, appears unchanged. Consequently, non-preservable parameters (nutrient supply, temperature, salinity, etc.) must be implied. The incoming of relatively abundant ostracodes is related to a statement by Heckel (1972) that "....many genera" (of ostracodes) "are confined to specific ranges of salinity tolerance" (op.cit.,p.282) and salinity variations may have lowered faunal diversities.

Successive assemblages (232A) are assigned to the dalmanellid-sowerbyellid "mega" community (see section c, ii,5). Lithological change downgraded individual communities to low order succession species which was related to environmental changes (e.g., current energy, clastic input).

The uppermost dalmanellid-sowerbyellid "mega"community (232) displays an increased faunal diversity attesting to a stabilising environment.

iii) Southern sequences (figs.9.2-9.5,9.11;table 9.1, cols. SW,SC,CP,SE)

In assessing lateral community distributions, two assumptions are made :-

a) the two rhyolitic tuffs (see section c,ii) are not diachronous.

b) the "nodular rhyolites" (Williams & Bulman 1931) are laterally equivalent to the Lledr Valley Tuffs (Francis & Howells 1973).

1) Glanrafon Beds

Assemblages below (197/A/B)and above (225) the Lledr Valley Tuffs are assigned to the *Dinorthis* community, with major intergradation from the dalmanellid-sowerbyellid "mega" community. The localised abundance of algae (225) implies, following modern day examples, shallow (inner - outer sublittoral), tropical - subtropical (?) marine waters (Chapman 1962,p.92;Heckel 1972,p.277). Moderate - high diversity indices indicate a stable environment. A high grade Dinorthis community immediately overlying the Lledr Valley Tuffs implies their emplacement did not radically modify any physical parameters apart from some localised shallowing.

Most assemblages below the lower rhyolitic tuff (figs.9.2-9.5) are referable to the dalmanellid-sowerbyellid "mega" community,with significant intergradation from the Dinorthis community. Stratigraphical and field relationships permit some lateral correlation (fig.9.11).

Assemblages between and above these tuffs (figs.9.2-9.5) are similarly referred to the "mega" community, but with little intergradation from the Dinorthis community probably resulting from the overall lithological fining. Fluctuating diversities indicate progressive community diversification related to environmental stabilisation, community downgrading resulting from changing environmental parameters (Bretsky & Lorenz 1970).

In-situ obolids within an orthid-strophomenid-trilobite-crinoid community seem anomalous (cf.Pickerill 1973). Common linguloid (onshore) communities were the lingulid-rhynchonellid-nuculoid-bellerophontid-modiomorphid-ambonychiid (Bretsky 1969b,table 1,pp.50-51) and linguloid-nuculoid communities (Anderson 1971). The obolids are found within bioturbated sediments which reveal the former presence of burrowing infauna. Craig (1952,p.118) notes lingulids are often associated with burrowing bivalves.

Regarding the Snowdonian shelly community - obolid association (albeit rare) "...a combination of a favourable substrate, an abundant food supply and an absence of predators were probably important" (Pickerill 1973,p.150), and "...given the optimum conditions and opportunities, linguloid populations can be expected in situations thought previously to be unfavourable" (op.cit.).

The orthid-strophomenid-trilobite-crinoid community is similar to those described by Bretsky (1969a,b;1970a,b) who postulates a shallow shelf (inner infralittoral) environment for them. Evidence suggests that this community, where associated with in-situ obolids, is a "residual fossil community" (Fagerstrom 1964,p.1199).

In conclusion, assemblages within the Glanrafon Beds indicate a shallow shelf (outer sublittoral) environment.

2) Snowdon Volcanic Group

A) Lower Rhyolitic Tuff Formation (figs.9.2,9.11)

Sparse faunas are assigned to the dalmanellid-sowerbyellid "mega" community with minor intergradation from the Nicolella and Sericoidea communities.

B) Intercalated sediment between the Lower Rhyolitic Tuff and Bedded Pyroclastic Formations (figs. 9.2,9.11)

Calcareous sediments yield assemblages referable to the *Nicolella* community, the high diversity, low dominance community attesting to a stable offshore environment (see Heckel 1972,p.240-242). Intergradation from the dalmanellid-sowerbyellid and *Sericoidea* communities strengthens the theory that the *Nicolella* community occupied an intermediate spatial location. This community appears similar to the *Zygospira* - *Hebertella* community (Bretsky 1969a,1970b) found in fine grained calcareous sediments which accumulated in a "....shallow epicontinental sea" "....in areas away from sources of terrigenous clastics" (Anderson 1971,p.291), interpretations which are applied to the *Nicolella* community.

C) Upper Rhyolitic Tuff Formation (figs.9.2,9.11)

An apophysis of this Formation contains the most diverse, stratigraphically highest shelly fauna yet found in Snowdonia, which consists of remnants of the *Nicolella* community with dominant intergrading *Sericoidea*, probably signifying initial community replacement, i.e., the *Nicolella* community by the *Sericoidea* community. The extremely high diversity implies a stable, low energy environment presumably removed from terrigenous clastic supplies (op.cit.). As faunal analyses indicate a "residual fossil community" (Fagerstrom 1964,p.1199), a favourable substrate, abundant food supplies and an absence of predators may possibly account for this diversity.

e) Age determination of the sequences from faunal evidence

i) South-eastern sequence (figs.9.5,9.11;table 9.1, col.SE)

Salopia globosa (Williams) suggests a low Soudleyan age (Dean 1960b,p.83;Diggens & Romano 1968,p.42,46) for the lowest horizon (225). If comparisons with Capel Curig are accepted, the association of *S.globosa*, *Dinorthis berwynensis* (Whittington) and *Horderleyella* sp. suggests a lower - middle Soudleyan age (table 7.2), whilst *Bicuspina* cf.*spiriferoides* (M'Coy) of Williams 1963 may correlate with similar occurrences within the Lower Allt Ddu Group (middle Soudleyan) at Bala (Williams 1963,p.335, 338).

The combination of *D*.cf.*berwynensis* of Williams 1963, *Reuschella horderleyensis* Bancroft, *Macrocoelia expansa* (J.de C.Sowerby), *Macrocoelia* cf.*prolata* Williams of Williams 1963 and *Parabasilicus powisi* (Murchison) coupled with stratigraphical position implies an upper Soudleyan age for consecutive horizons (226A/B,227) (tables 7.2,8.3;Bassett et al.1966,p.264;Romano & Diggens 1969,p.605;Williams 1963,p.458).

The overlying horizon (221) displays Soudleyan and Longvillian affinities, but B.cf.spiriferoides, Kjaerina sp.and cf.Flexicalymene planimarginata (Reed) of Whittington 1965 probably indicate a Lower Longvillian horizon (Bancroft 1929a,1933,1945;Romano & Diggens 1969; Whittington 1965;Williams 1963), consequently suggesting the Soudleyan - Longvillian boundary has been crossed.

Consequent horizons (220,218,219) possess some dalmanellids seemingly referable to Dalmanella cf.lepta[1] (Bancroft) of Bancroft 1945 and Howellites cf.antiquior (M'Coy) of Williams 1963, thereby indicating a Lower Longvillian age (Bancroft 1945,p.194;Bassett et al.1966, p.263;Cave & Dean 1959,p.296;Dean 1958,p.221;1964,p.277-278;Whittington 1938a,p.450;Williams 1963,p.336,340,390).

However, such comparative identifications must be treated with caution regarding the accurate identification of poorly preserved, tectonically deformed dalmanellids. The author contends that they should not be singly utilised for deducing Caradocian stages but should be jointly employed with more easily identifiable genera and species.

Respective stratigraphic location and the occurrence of Paracraniops sp. and Brongniartella minor (Salter) attest to a Lower Longvillian age (Bassett et al.1966, p.265;Dean 1959,p.192,206;1961,p.351-352;1962,p.106; 1963b,p.15;Harper 1947,p.165-167;Williams 1963,p.336, 340,349).

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[1] now D.cf.indica Whittington - see Cocks 1978,p.61.

Overlying horizons (in ascending order- 210;214/216; 211/212A,B/215/217;213) are confidently assigned Lower Longvillian ages, attributable to D.cf.lepta[1],H.cf. antiquior,Kjaerina sp., K.jonesi Bancroft, Leptaena cf. ventricosa Williams of Williams 1963, B.minor, Flexicalymene cf.caractaci (Salter) of Whittington 1965, F.planimarginata and Kloucekia apiculata (M'Coy) (Bancroft 1929a,p.34,47;1933;1945,p.246-247;1949,p.306,311;Bassett et al.1966,p.265;Cave & Dean 1959,p.296;Dean 1958,p.206, 221-224;1959,p.206,212,214,220;1960c,p.168;1961,p.326; 1962,p.97,114;1963a,p.217-218;1963b,p.11,15,16;1963c,p.62; Harper 1947,p.167-172;1956,p.387-388;Romano & Diggens 1969,p.603;Shirley 1931,p.27;Whittington 1938a;1962,p.9-12; 1965,p.62;1968,p.111,113;Williams 1963,p.336,340,390,463) - table 9.2. K. apiculata is "....a reliable indicator of the Longvillian stage" (Dean 1963c,p.62) which is ".... characterised throughout by the genus Kjaerina" (Bancroft 1929a,p.34).

ii) Cwm Penamnen sequence (figs.9.4,9.11;table 9.1, col. CP)

The lower horizons (208) possess Soudleyan and Longvillian elements but on balance, an upper Soudleyan age seems probable. Kjaerina sp. suggests a Lower Longvillian horizon (Bancroft 1929a,p.34;1945,p.246-247; Dean 1958,p.221;1959,p.206) but Bancroft (1945) first notes Kjaerina sp. from "....a high horizon in the zone of Reuschella horderleyensis in the Soudleyan" (op.cit.

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[1] now D.cf.indica Whittington - see Cocks 1978,p.61.

p.246), whilst *K*.aff.*jonesi* is recorded from Soudleyan strata in Shropshire (Dean 1960c,p.167).

The combination of *M*.*expansa* and *D*.cf.*berwynensis* within consecutive horizons (205), coupled with stratigraphic location, implies an upper Soudleyan age. Although successive horizons (204) display Soudleyan and Longvillian affinities, the aforementioned combination probably indicates a similar age.

iii) *South-central sequence* (figs.9.3,9.11;table 9.1, col. SC)

If the "nodular rhyolites" (Williams & Bulman 1931, p.429-432) are laterally equivalent to the Lledr Valley Tuffs (Francis & Howells 1973) then the horizons at 197/A/B are stratigraphically the lowest at Dolwyddelan. The faunal combination of *D*.*berwynensis*, *R*.*horderleyensis*, *M*.cf.*expansa* of Williams 1963 and *B*.*minor* suggests an upper Soudleyan age (Dean 1958,p.199,220;Whittington 1966, p.65;1968,p.111;Williams 1963) whilst the stratigraphical position suggests at least a middle Soudleyan horizon.

A consecutive horizon (203) presents an anomalous faunal assemblage regarding stratigraphic location e.g., *M*.*expansa*, *Kjaerina* sp., *K*.cf.*horderleyensis* Bancroft of of Bancroft 1929a and *P*.cf.*powisi* of Dean 1963a and from sheet SH 75, Capel Curig and Betws-y-Coed, 1:25000, 1976, corresponds with horizons in Cwm Penamnen (205/208).

Kjaerina sp./K.cf.horderleyensis suggest a Lower Longvillian horizon (Bancroft 1929a,p.34,36-39,50-51; 1945,p.246-247) which conflicts with the location of the Soudleyan/Longvillian boundary south of Dolwyddelan and would necessitate assigning the Cwm Penamnen horizons (204/205/208) to the Lower Longvillian.

Therefore from stratigraphic position this horizon is assigned to the upper Soudleyan. The occurrence of Kjaerina may be resolved as follows :-

a) Kjaerina is noted from Soudleyan strata in Shropshire (Bancroft 1945,p.246-247;Dean 1960c, p.167).

b) The specimens were mis-identified, due to poor preservation/tectonic deformation (=Rafinesquina?).

c) The specimens may be referable to a new upper Soudleyan species of Kjaerina.

Overlying horizons (201A/B/C) containing Soudleyan and Longvillian elements are considered "boundary horizons", i.e., being so near the Soudleyan/Longvillian boundary, the faunas are not diagnostic of either stage.

Consecutive horizons (198/199) present a similar picture. B.spiriferoides and Kloucekia sp.(?) imply the Lower Longvillian (Bancroft 1949,p.311;Bassett et al.1966, p.263,265;Dean 1959,p.212,214,220;1961,p.326;1962,p.97; 1963b,p.11,15,16;1963c,p.62;Whittington 1962,p.9-12;1968, p.111,113;Williams 1963,p.335,337,425) although R.cf. horderleyensis of Bancroft 1928b and Williams 1963,D.cf.

berwynensis and cf.*Heterorthis retrorsistria* (M'Coy) of Williams 1963 suggest an upper Soudleyan age (Bancroft 1945,p.240;Bassett et al.1966,p.263;Dean 1958,p.220; Whittington 1938b,p.251;Williams 1963,p.420). However, on balance, a Lower Longvillian age appears likely. From a locality approximately on strike with 198/199, a fauna containing "...*Broeggerolithus*? *nicholsoni*, *Flexicalymene planimarginata* and *Dinorthis* cf.*berwynensis* (Whittington)" is considered Longvillian (Romano & Diggens 1969,p.603).

iv) *South-western sequence* (figs.9.2,9.11;table 9.1, col.SW)

1) *Glanrafon Beds* (table 9.1,col.SW - GB)

Faunas from 185,186/187,188 include *R.horderleyensis* and *Parabasilicus* sp. which indicate an upper Soudleyan horizon.

Successive horizons (183-1;183-2/189/195) possess Soudleyan and Longvillian elements, e.g., *R.*cf.*horderleyensis*, *D.*cf.*berwynensis*, triplesiaceans (*B.spiriferoides*), *Broeggerolithus* cf.*broeggeri* (Bancroft), cf.*soudleyensis* (Bancroft), both of Dean 1960a, *B.minor*, *F.caractaci*, *F.planimarginata*, *F.*(*Reacalymene*) *limba* (Shirley) and *Kloucekia* sp. and are considered "boundary horizons".

Subsequent horizons (196A) reveal Lower Longvillian faunas e.g., *D.*cf.*lepta*[1],*Bancroftina* sp.,*Kjaerina* sp.,*K.*aff.*jonesi* of Bancroft 1929a, *Broeggerolithus* cf.

[1] now *Dalmanella* cf.*indica* Whittington - see Cocks 1978,p.61

nicholsoni (Reed) of Dean 1962, *K. apiculata*, *F. planimarginata* and *B.minor* (tables 9.2,9.3). *B.nicholsoni* ranges from the Lower Longvillian - lower Upper Longvillian (Bassett et al.1966,p.259,265;Dean 1959,p.206, 212,214,220;1960a,p.120;1962,p.80;1963b,p.11,15;1963c,p.61; 1965,p.311;Diggens & Romano 1968,p.46;Lamont 1948,p.416; Romano & Diggens 1969,p.603;Whittington 1966,p.87;1968, p.111,113) and "....probably occurs at several localities in North Wales, associated with faunas of Longvillian age" (Dean 1962,p.81).

Similar associations are found in overlying horizons (196B,173/173A,174,181-1,1A,2) consequently indicating a Lower Longvillian age (table 9.3). A slightly higher horizon (180) is, by virtue of its stratigraphic position, also Lower Longvillian.

The highest horizon (175) yields a diagnostic Lower Longvillian fauna (table 9.3) and regarding its position above the Soudleyan/Longvillian boundary probably lies within the upper Lower Longvillian.

2) *Snowdon Volcanic Group* (table 9.1,col.SW-SVS)

Faunas from the lower part of the Lower Rhyolitic Tuff Formations (176-1,-2) are not diagnostic but their stratigraphic position suggests an Upper Longvillian age (see section f,ii;figs.9.11,9.12). Intercalated sediments (178) between the Lower Rhyolitic Tuff and Bedded Pyroclastic Formations reveal *Dolerorthis duftonensis prolixa* Williams, *Skenidioides costatus* Cooper, *Nicolella* actoniae obesa Williams, Protozyga cf.diversa (Reed) of Williams 1962, Cremnorthis parva Williams, Rhactorthis sp., B.cf.spiriferoides and Kjaerina sp., a distinctive Upper Longvillian combination (tables 8.5,9.3).

Of those species not figured in tables 8.5 and 9.3, C.parva is found only above the Cymerig Limestone at Bala (Williams 1963,p.340) whilst P.cf.diversa is found in the basal Ardwell Mudstones (Williams 1962,p.243) which are Longvillian (Williams et al.1972,fig.9).

The Upper Rhyolitic Tuff Formation yields a diagnostic Upper Longvillian fauna (179) e.g., S.costatus, N.actoniae obesa, Bellimurina incommoda Williams, Rhactorthis sp., C. parva, Eoplectodonta rhombica (M'Coy), Estoniops alifrons (M'Coy) and Platylichas nodulosus (M'Coy). Table 8.5 illustrates their stratigraphical distributions where :-

Skenidioides sp. = S.costatus
Platylichas sp. = P.nodulosus
Eoplectodonta sp. = E.rhombica

Regarding table 8.5, the following points are noted :-

a) Rhactorthis crassa Williams, although described from Upper Longvillian strata at Bala (Bassett et al.1966, p.264;Williams 1963,p.336,340,373), probably ranges down into the upper Lower Longvillian (op.cit.,p.340).

b) At Bala, N.actoniae obesa, although commonest in the upper Upper Longvillian, occasionally ranges down into the Lower Longvillian (op.cit.,p.340).

c) *B.incommoda* is found within the Longvillian at Bala (op.cit.).

d) *P.nodulosus* is noted from the middle - upper Lower Longvillian and possibly the lower Upper Longvillian (Whittington 1968,p.113).

However, the most definitive Upper Longvillian species is *E.alifrons* (Bassett et al.1966,p.259,265;Cave 1965,p.283,289;Dean 1959,p.194,207,220;1960b,p.84;1962,p.102-103;Elles 1922;Harper 1956,p.389;Harper in Shackleton 1959,p.250;Harper in Tremlett 1962,p.175,176;Pickerill 1974;Whittington 1938a,p.451;1962,p.17;1968,p.111,113;Williams et al.1972,p.21,25).

From the Oslo region, Stormer (1953,p.65,104) records *Pterygometopus* (= *Estoniops*) from 4bγ beds (Upper *Chasmops* Shale/*Cyclocrinus* Zone) which may indicate *Estoniops* ranges into the Marshbrookian (Dean 1960b,p.87).

3) *Black Slates* (table 9.1,col.SW-BS)

Graptolites referable to *Climacograptus bicornis* (Hall), *Diplograptus multidens* (Elles) and *Orthograptus truncatus* (Lapworth) imply the *Dicranograptus clingani* Zone (Williams & Bulman 1931,p.444) which encompasses the Lower Longvillian - upper Onnian (Dean 1958,p.228-229; Williams et al.1972,fig.2).

v) Northern sequence (figs.9.6,9.11;table 9.1,col.N)

From the lowest horizons (235A/B/C), D.cf.berwynensis, Paracraniops sp., M.expansa, P.powisi, B.minor and K. apiculata (tables 7.2,9.2,9.3) possibly infer a Lower Longvillian age. Consecutive horizons (236) reveal different combinations, e.g., D.cf.berwynensis, M.expansa, Kjaerina sp., K.cf.jonesi, K.cf.typa Bancroft of Bancroft 1929a, B.cf.nicholsoni and F.planimarginata which, however, attest to a similar age (tables 7.2,9.2,9.3).

Overlying assemblages (231,237) are not diagnostic but stratigraphic location suggests a Lower Longvillian age, whilst the topmost horizons reveal faunal combinations similar to those for (236) and with additional B. spiriferoides and K.apiculata denote the Lower Longvillian.

In terms of stratigraphic distribution, the presence of D.cf.berwynensis appears anomalous (table 7.2), which may be explained as follows :-

a) D.cf.berwynensis ranges into the Lower Longvillian at Dolwyddelan.

b) This species may be better related to D. berwynensis angusta Williams, which at Bala ranges from the uppermost Soudleyan - Lower Longvillian (Bassett et al.1966,p.263;Williams 1963,p.335,340). Identification to subspecies level can only be tentative, poor preservation and tectonic deformation preventing utilization of the statistical parameters needed to distinguish this subspecies (Williams 1963,p.364-369).

c) This form represents a new subspecies of D. berwynensis which either ranges into or originates within the Lower Longvillian.

vi) Moel Siabod (South) sequence (figs.9.7,9.11; table 9.1,col.MSS)

Horizons (233/233A) reveal S. costatus, Leptestiina oepiki (Whittington), Nicolella sp. and Brongniartella bisulcata (M'Coy), inferring an Upper Longvillian age (tables 8.5,9.3).

At Bala, L.oepiki is confined to the Longvillian (op. cit.,p.340) and is noted from Longvillian (Upper ?) strata in Snowdonia (Dean 1965,p.309-310,312), whereas Whittington (1938a,p.451;1938b,p.256) notes Sampo öpiki (= L.oepiki) from Upper Longvillian beds. Within the Cross Fell inlier, S. (L.) oepiki is found in Lower Longvillian and Marshbrookian strata (Dean 1959,p.197,207,213,214). The N.actoniae - S.cf.öpiki association "....recalls the Nicolella actoniae beds at Llansantffraid (Whittington 1938a,p.451) i.e. Upper Longvillian" (Harper 1956,p.389).

f) Discussion

To avoid unnecessary reiteration, conclusions regarding sedimentary structures, faunal occurrence types etc., are not summarised. However, certain points are discussed which could not be conveniently considered elsewhere.

i) Correlation of the Lledr Valley Tuffs

These tuffs are almost certainly laterally equivalent to the tuffs at Capel Curig (see sheet SH 75, Capel Curig and Betws-y-Coed, 1:25000, 1976). Correlation with individual tuffs at Capel Curig is less certain. However, the overall lithology and lithological sequence within the Lledr Valley Tuffs (Francis & Howells 1973, p.629) appear similar to the Garth Tuff (op.cit.,p.625-626). This correlation broadly conforms with the faunal evidence as horizons (225) above the Lledr Valley Tuffs yield S.globosa which compares with fauna from the Racks member (chap.7). S.globosa usually indicates a Soudleyan age (Dean 1960b,p.83;Diggens & Romano 1968,p.42,46; table 7.2) and in conjunction with stratigraphical location, a middle - upper Soudleyan horizon appears likely for the Lledr Valley Tuffs (= Garth Tuff?).

ii) Correlation of the Moel Siabod (South) sequence with the Dolwyddelan sequences

A seemingly straightforward correlation ultimately propounds a possible uncomformity below the Lower Rhyolitic Tuff Formation at Dolwyddelan, as :-

1) Faunas from this Formation on Moel Siabod suggest

an Upper Longvillian age.

2) Presupposing the correlation between the Lower Crafnant Volcanic Formation and the Lower Rhyolitic Tuff Formation is correct (Howells et al.1973,p.31,fig.7), an interesting fact emerges. On tracing the intercalated Upper Longvillian sediments southwards from Moel Siabod it becomes apparent that the sediments immediately underlying the Lower Rhyolitic Tuff Formation on the southern synclinal limb at Dolwyddelan must be Upper Longvillian. However, fauna from adjacent sediments (175) suggests an upper Lower Longvillian age which consequently implies a small-scale unconformity (non-depositional unconformity (?) - Tomkeieff 1962,p.412,fig.13,Type III) beneath this Formation.

Williams & Bulman (1931) make no mention of any uncomformity. Howells et al. (1973,p.26) note "...a sharp contact" between the Lower Rhyolitic Tuff Formation and underlying sediments whilst the lower unit of the aforesaid Formation "...conformably overlies siltstones and fine sandstones" (op.cit.,p.27) on Moel Siabod and "...the relationship between the sediments and acid tuffs seems generally to be conformable" (op.cit.,p.30). However, "...Even where unconformity seems possible, as at the base of the volcanic sequence at Dolwyddelan", "...the tuffs were deposited on unlithified muds" (op.cit.).

Howells et al. (1973,p.31,fig.7) and Williams & Bulman (1931,p.437) note the tuffs thin across the Dolwyddelan syncline e.g., the basal tuff of the Lower

Rhyolitic Tuff Formation wedges out southwards.

A model (fig.9.12) is therefore proposed, the position of the time line being arbitrary. Consequently, a thin wedge of Upper Longvillian sediments should be present on the southern limb but this is unproven. Alternatively, a small-scale non-depositional unconformity (Tomkeieff 1962) may occur beneath the Lower Rhyolitic Tuff Formation on the southern synclinal limb at Dolwyddelan. The diagnostic Upper Longvillian species at Moel Siabod (_S.costatus_; _L.oepiki_; _Nicolella_ sp.; _B. bisulcata_) are possibly diachronous but this appears unlikely when similar assemblages are considered (chap.10).

Finally, faunas from (176-1,-2) must be Upper Longvillian on account of their stratigraphical position (fig.9.12).

iii) Faunal correlation within the Dolwyddelan area

A possible correlation of the sequences is presented in fig. 9.11 (see section e).

iv) The Black Slates (fig. 9.1)

1) Stratigraphical range

The slates conformably overlie the Upper Rhyolitic Tuff Formation with no break in sedimentation, as shown by subangular - subrounded black slate clasts (plate 9.12) within the upper horizons of this Formation (Williams & Bulman 1931,p.444). Clast boundaries are usually sharp

- slightly gradational.

Cave (1965,p.280,fig.1) suggests that many of the black slates throughout North Wales (e.g.,Pwllheli, Dolwyddelan, Llanystwmdwy, Meifod etc.) should be assigned to the Nod Glas from which, around Welshpool, graptolites suggest the upper D.clingani zone whilst a shelly fauna suggests the O.gracilis zone (middle Onnian - Dean 1958, p.190,fig.3).

However, at Llanystwmdwy (Harper 1956,p.389) black slates are underlain by strata containing E.alifrons, as at Dolwyddelan "...indicative of a horizon above the Cymerig Limestone" (Whittington 1968,p.114). Therefore it seems impractical to assign the Black Slates to the Nod Glas. The thirty metres of exposed slates seem unlikely to represent the Longvillian - Onnian. However, Churkin et al. (1977) suggest an accumulation rate of 4m. ± 1m./m.y. for black graptolitic slates from the Cordilleran foldbelt in North America. By determining the approximate thickness of individual graptolitic zones, they estimate the D.clingani zone had a duration of 6.2m.y. (op.cit.). Applying these results, the time period in which the Black Slates accumulated (taking thirty metres as a minimum thickness) was possibly 6-10 m.y. and presumably could totally include the D.clingani zone. But for the Black Slates it is unknown how much of the D.clingani zone they comprise and whether they originally accumulated at the same rate as did the American examples.

Cave (1965,p.288) maintains a non-sequence (=Actonian-Onnion) beneath the Nod Glas "....is a strong possibility" (op.cit.) but this is patently not so at Dolwyddelan. Accordingly, the Black Slates probably comprise the topmost Upper Longvillian and part (if not all) of the Marshbrookian with the tentative possible inclusion of higher Caradocian stages.

2) Depositional environment

The Black Slates - Upper Rhyolitic Tuff Formation contact is transitional, the aforementioned clasts (plate 9.12) indicating transitory "black shale deposition". Increased current activity associated with renewed volcanism effectively "ripped-up" the semi-plastic black mud which was re-deposited as clasts within the volcanic sediments. Volcanism subsequently waned with "black shale conditions" becoming re-established.

Opinion has differed as to the depositional environment of black shales. Twenhofel (1939) concludes "....each black shale formation should receive interpretation on the basis of the characteristics of that black shale formation" (op.cit.,p.197). Black muds accumulate under quiet conditions (Cave 1965;King 1923; Marr 1925;Ruedemann 1925,1926;Rich 1951;Twenhofel 1939) with greatly reduced water circulation within the depositional environment (op.cit.;Heckel 1972;James 1971) which ultimately produces anoxic conditions. These resulted from poor water ventilation and the onset of anaerobic conditions, anaerobic bacteria effectively "poisoning" the lower water levels (Bonde 1974;Cave 1965; Heckel 1972;Marr 1925;Pettijohn 1975;Ruedemann 1925,1926; Rich 1951). Anoxic water at depth may also result from rich surface production (which consumes great volumes of oxygen) combined with slow circulation at depth (Bonde 1974;Brongersma-Sanders 1971).

Stagnation and impoverished nutrient supplies consequently produce reduced dwarfed benthic faunas (Cave 1965;Hallam 1960,1965;Heckel 1972;King 1923;Marr 1925; Pettijohn 1975;Ruedemann 1925,1926;Sheehan 1977;Williams & Bulman 1931) e.g., Zangerl et al. (1969) note very small bivalves (5mm.-10mm.long) from a reduced benthic fauna in black shales. Oxygen concentrations of less than 0.1 ml./l. restrict benthic invertebrates (Rhoads & Morse 1971), no metazoans being found in waters with lower concentrations. Black shales frequently possess prolific graptolite faunas (Cave 1965;King 1923;Marr 1925;Pugh 1923;Ruedemann 1925,1926;Twenhofel 1939;Williams & Bulman 1931) which Twenhofel (1939,p.1185) attributes to either rapid reproduction or the introduction of large numbers into overlying waters. Graptolite occurrence may demonstrate the existence of restricted circulation and access of marine currents (Elles in discussion of King 1923 and Marr 1925;Williams & Bulman 1931,p.445).

The extremely fine-grained sediment implies either location far from any shoreline (Marr 1925;Rich 1951) or negligible terrigenous sediment supplies(Cave 1965;Heckel 1972;King 1923;Rich 1951).

Features of the Black Slates are :-

a) Black colour
b) Extremely fine-grained
c) Pyritiferous
d) Graptolitic
e) No associated benthic fauna
f) No sedimentary structures
g) No intercalated coarser horizons

Such features are those expected in a quiet, stagnant environment subject to restricted circulation. Pyrite results from a combination of limited circulation, low O_2 concentration and toxic accumulations resulting from anaerobic bacterial activity (Twenhofel 1939). Hallam (1960) considers pyrite may form as an early diagnetic product under anaerobic conditions. The black colour may be due to the presence of organic matter, black iron monosulphide and manganese oxides (Twenhofel 1939).

Ruedemann (1925,p.77-78) distinguishes two groups of black graptolitic shales :-

a) possess dwarfed benthic fauna
b) possess only graptolites - deep water origin (?)

The Black Slates seem best assigned to the latter group, although Williams & Bulman (1931,p.445) consider they were shallow water deposits. Underlying tuffs afford no evidence suggestive of such deposition, some of which suggest slow sedimentation of fine airfall material from suspension in a quiet environment. Such an environment probably permitted fine material to remain in suspension, large volumes in suspension possibly engendering a temperature drop in the photic zone. Hallam (1965,p.136) considers a temperature drop unlikely to affect marine invertebrates but that discernible effects are probable over large areas(op.cit.,p.145). Temperature drop may therefore be a minor contributory factor to the overall effects resulting from reduced circulation etc.

Delimination of the depositional area is problematical but it probably encompassed Dolwyddelan, Betws-y-Coed,west of Trefriw and Llanystwmdwy, apparently being one of reduced water circulation, low energy and severe stagnancy, graptolites suggesting the periodic ingress of water currents.

Water depth and environmental location are less certain. Submarine topography probably controlled the formation of these black sediments (Heckel 1972;Ruedemann 1925;Twenhofel 1939;Williams & Bulman 1931). An open marine environment is envisaged, bounded by the north-westerly Irish Sea landmass (Fitton & Hughes 1970,p.226;

Phillips et al.1976,p.586-587,figs.3,4) and the southeasterly Midland Platform, with the Welsh Basin, by Upper Longvillian times, no longer subsiding (Brenchley 1969,p.198). Submarine barriers formed by seafloor accumulations of volcanic detritus may have produced localised areas of reduced water circulation and coupled with a diminution in clastic sedimentation may have produced conditions (e.g.,stagnancy, etc.), especially in the bottom waters of these "restricted areas", which were inimical to an abundant benthos.

In Upper Longvillian times, Howells (1977,p.404) implies a rising ridge separated the shallow water environment of central Snowdonia from a subsiding deep water basin in eastern Snowdonia. Possibly the "rising ridge" formed a substantial barrier which initiated black shale deposition. This postulated uplift may be related to pre-Ashgillian uplift which occurred in north Montgomeryshire (Cave 1965,p.292) and to uplift which produced the basal Ashgillian unconformity at Bala (Bancroft 1928c).

Chapter 10 The areas around Llyn Cowlyd, Betws-y-Coed and east of Beddgelert

a) Introduction

These areas are not sampled in detail, but are equally important in terms of the stratigraphic horizons at which faunas are sampled.

The location and geology of each area is shown in fig. 1.1 and maps 4,5 and 6.

i) Llyn Cowlyd area

The Glanrafon Beds are exposed mainly to the south of Pen Llithrig-y-Wrâch (800 m.), whereas thick rhyolitic tuffs are encountered towards Clogwyn Du and Marian Mawr along the north-western and south-eastern sides of Llyn Cowlyd, respectively (map 4). Faunal sampling is confined to the Glanrafon Beds.

The reasons for studying the area are :-

1) the sediments are known to be fossiliferous.

2) to analyse the fossiliferous assemblages.

3) to establish an age range for the fossiliferous sediments.

4) to complement the earlier work of Diggens & Romano (1968).

ii) Betws-y-Coed area

To the west, Carneddau Group sediments (sheet SH 75, Capel Curig & Betws-y-Coed, 1:25000, 1976) are exposed south of the Afon Llugwy whilst the Crafnant Volcanic Group (overlain by the Llanrhychwyn Slates - Davies 1936) is mainly exposed to the north (map 5).

Fauna is sampled from the Carneddau Group and intercalated sediments within the Crafnant Volcanic Group.

The reasons for studying this area are similar to those for the previous area (excluding point 4). In addition, intercalated sediments within the Lower Crafnant Volcanic Formation were known to be fossiliferous.

iii) The area east of Beddgelert

Fauna was sampled from three subareas (map 6) :-

1) Gareg Bengam (SH 620453)

2) Llynau Cerrig-y-myllt (SH 631472)

3) Hafodyddbrithion (SH 640494)

At 1) and 2), shelly faunas were collected from the Glanrafon Beds (Gorllwyn Grits - Beavon 1960; Upper Grits - Beavon 1963) immediately underlying the Snowdon Volcanic Group (Lower Lapilli-tuff, op.cit.). At 3), shelly faunas were sampled from the uppermost Upper Grits and the basal stratified facies of the Llyn Dinas Breccias (op.cit., p.491-493).

The reasons for studying this area are broadly similar to those for the previous areas.

b) The stratigraphy, faunal occurrence types and associated sedimentary structures

i) Stratigraphy

1) Llyn Cowlyd area (fig.10.1)

The area is first documented by Ramsay ("Llyn Cwlyd" (sic.) - 1852,p.166; "Llyn Cawlyd" (sic.) - 1866,p.104,105, fig.26) whereas Davies (1936) later remapped it as part of a larger area. Ramsay (1852,p.166) noted fossils from around Llyn Cowlyd were the same as those from the Snowdon area, whilst much later, Lamont (1946,p.137,fig.5) figured Bancroft's fossil localities "....in Soudleyan Beds" (op. cit.) around the southern termination of Llyn Cowlyd, which are, nevertheless, inaccurate.

Diggens & Romano (1968) comprehensively mapped the area and erected a detailed stratigraphy (op.cit.,p.33,table 1) which the author adopts for the Llyn Cowlyd area (fig.10.1).

However, problems of nomenclature exist. Sediments underlying the Crafnant Volcanic Group are referred to the Carneddau Group (sheet SH 75, 1976). The overlying volcanic units exposed within the Llyn Cowlyd area are continuous with similar units north of the Llugwy valley (= The Crafnant Volcanic Group - Davies 1936, Howells et al. 1973) so consequently, those beds termed "Glanrafon

Beds" (Diggens & Romano 1968) should be referred to the Carneddau Group. However, to avoid confusion, the term "Glanrafon Beds" is retained.

The aforesaid volcanic units are referred to the Snowdon Volcanic Series (op.cit.,p.38-39), whereas Davies (1936) and Howells et al. (1973) refer them to the laterally equivalent Crafnant Volcanic Group, a proposal the author adopts.

At the top of the Bwlch Cowlyd Sandstone Formation (Diggens & Romano 1968,p.33-36), a thin unit of coarse sandstone is termed the *Multiplicata* Sandstone (op.cit., p.36) due to the presence of numerous valves of *Dinorthis* (*Plaesiomys*) *multiplicata* Bancroft. Dr. A.W.A. Rushton (pers.comm.) believes this unit should not be individually distinguished purely on account of its faunal content. However, the author contends that until any stratigraphic revision of the area is undertaken, this unit should be retained. (N.B. *Dinorthis* (*Plaesiomys*) *multiplicata* Bancroft has been previously described as :-

Orthis flabellum	J. de C.Sowerby var.*multifida* (Salter, in Ramsay 1866,p.338, plate 21,fig.17)
Orthis flabellum	J. de C.Sowerby (Davidson 1869, p.248,plate 34, figs.6,11 - n.b., fig.7 is wrongly labelled - see Cocks 1978,p.50. Davidson 1871,p.248)

Orthis sarmentosa M'Coy (Davidson 1871,p.262,plate
36,figs.35-38)

Dinorthis (Plaesiomys) multiplicata Bancroft
(Bancroft 1945,
p.244-245,plate
35,figs.4-6,plate
36,figs.1-3)

Dinorthis multiplicata Bancroft (Diggens & Romano 1968,
p.47,plate 5,fig.m)

However, this species is now referred to as *Plaesiomys multifida* (Salter) - Cocks (1978,p.50,193,196); Howells et al. (1978,p.18,68). As the majority of the research was initiated before the above redesignation took effect, the species name *Dinorthis (Plaesiomys) multiplicata* Bancroft is retained throughout the thesis, although now taxonomically without standing).

2) *Betws-y-Coed area* (fig.10.2)

This area has been neglected in recent years in favour of the classic areas in central Snowdonia. Intensive afforestation has prevented large-scale mapping although the Institute of Geological Sciences, in conjunction with the Geological Survey, have recently published (1976) a 1:25000 sheet (SH 75) embracing this area.

Ramsay (1866,p.100-109) first mapped and described the Betws-y-Coed district and in the appendix of the Survey Memoir (Salter,ibid.) numerous references are made to Caradoc fossils from the area (ibid.,p.261-272,343) which amplified an earlier list by Sedgwick (1843,p.220). The Crafnant Volcanic Group along the Llugwy Valley was mapped by Williams (1922) whilst Davies (1936) included part of the area when mapping the Trefriw district. Howells et al.(1973) recently completely remapped the Crafnant Volcanic Group.

For the area, the author adopts the stratigraphy from sheet SH 75 (1976) - (fig.10.2).

3) The area east of Beddgelert (fig.10.3)

The earliest recorded research is by Sharpe (1846) who noted "....but few fossils" (op.cit.,p.293) west of Cnicht (op.cit.,p.293-294) and Sedgwick (1847,p.142-144), who examined only parts of the area. Ramsay (1866,chaps. XV,XVII and XVIII) made several references to the area and "....On Cynicht (sic.) Homalonotus bisculatus (sic.)" (= Brongniartella)" was found and other Bala fossils in the neighbourhood" (op.cit.,p.95). Detailed remapping was undertaken by Beavon (1960), whose revised stratigraphy (Beavon 1963) is adopted for the area (fig.10.3).

ii) Faunal occurrence types and their interpretations

1) Introduction

The abbreviations following each occurrence type heading indicate in which area a particular type is present :-

LC/GB - Llyn Cowlyd area - Glanrafon Beds
BC/CG - Betws-y-Coed area - Carneddau Group
BC/LCVF - Betws-y-Coed area - Lower Crafnant Volcanic Formation
EB/UG - East of Beddgelert - Upper Grits
EB/LDB - East of Beddgelert - Llyn Dinas Breccias

Figs. 10.4, 10.5 and 10.6 illustrate occurrence type distributions and their relationship to benthic communities and assemblage composition.

2) Random faunal occurrence types (figs.5.2,10.4, 10.5,10.6)

(LC/GB: BC/CG: BC/LCVF: EB/LDB)

This type is relatively common, usually found within diffuse bands of variable thickness. As elsewhere (chaps.5,7,8,9), this type is the direct result of deformative bioturbation (Moore & Scruton 1957; Rhoads 1967; van Straaten 1959; Toots 1965a,b). Examination of hand specimens containing randomly orientated valves reveals intensely bioturbated lithologies, fresh surfaces often possessing indistinct mottled appearances.

Bioturbation indicates slow or reduced sedimentation and well-oxygenated bottom waters (Heckel 1972,p.244; Rhoads & Morse 1971,p.426; Watkins & Berry 1977,p.275), the activity of burrowing organisms being effective in low energy environments (Toots 1965a,p.225) whilst biogenic reworking is "....an indication of low energy conditions" (Wunderlich 1972,p.51). Allen (1967,p.440) records intense bioturbation within "....interbedded facies" of sands and silty muds at "....intermediate distances from shore" and "...."mud" facies" found at "....comparatively large distances from shore". The random occurrence types in question are usually found in medium-coarse siltstones which are probably equivalent to the "interbedded facies" (op.cit.), "....intermediate distances from shore" (op.cit.) presumably signifying the sublittoral zone. Heckel (1972,p.244,fig.7) shows bioturbation is most intense at or below wave base (sublittoral zone) whilst Toots (1965a,p.228,table 2) believes random orientations denote the outer sublittoral zone. Howard & Reineck (1972, p.106) note bioturbation to be strongest in the upper off-shore zone (5-10m. water depth) and that it is not "....strictly tied either to water depth or distance off-shore; rather, it is related to variations in the physical energy of the area" (op.cit.).

At localities 238/239 (BC/CG - map 5) cross-bedded units overlie horizons displaying randomly orientated valves (plate 10.1) which signify slight increases in current energy, sedimentation and suspended bedload, the cross-beds resulting from ripple trains migrating across the seafloor (Allen 1963).

At Llyn Cowlyd (166B - map 4) planar occurrence types associated with randomly orientated valves (fig.10.4) attest to fluctuating sedimentation, current velocities and infaunal activity.

3) Planar faunal occurrence types

A) Preferred convex-up valve orientations
(fig.10.5)
(BC/CG: BC/LCVF)

This orientation is noted within thin planar and laterally continuous shelly horizons.

Thin horizons of convex-up valves in sandstones at Betws-y-Coed (240/241 - fig.10.5,map 5) probably resulted from a short "burst" of increased current activity which generated widespread valve inversions, but not before some minor lateral transport had occurred (Brenchley & Newall 1970). Rapid sedimentation and possible scouring (Johnson 1957; Menard & Boucot 1951) then effected burial, subsequently preventing biogenic reworking and the formation of thick shell layers. Overlying parallel laminated sandstones signify deposition by relatively high velocity bottom currents in the lower part of the upper flow regime (Harms & Fahnestock 1965,plate 1; Harms et al. 1963; Simons et al. 1965,p.52,fig. 21), possibly through sedimentation of suspension clouds (Reineck & Singh 1975,p.106). Morton (1978) suggests such sequences may reflect storm activity.

Thicker shelly bands (>5cms.) are encountered in impersistent "limestones" within intercalated sediments of the Lower Crafnant Volcanic Formation (243/244 - fig. 10.5, map 5). Johnson (1957,p.534) notes reduced sedimentation ultimately produces thick, dense, shelly accumulations. Accordingly, many valves would remain exposed long after death, ultimately becoming overturned by currents (Richards 1972,p.395-396). Within the horizons under consideration, large brachiopod valves (e.g., Nicolella, Orthambonites) are always convex-up, unfragmented and unabraded, but have usually suffered post-mortem epizoan colonisation e.g., encrusting corals/ bryozoa and boring. Smaller valves (e.g., Skenidioides, Protozyga, Sericoidea etc.) are commonly fragmented, have low articulation ratios, show no evidence of epizoan colonisation and possess mixed orientations.

The author believes the larger valves are essentially "in situ", as once convex-up, they would be more hydrodynamically stable which, coupled with gradual burial by scour, would render them immobile whereas the smaller valves have probably been winnowed out from similar, adjacent, contemporaneous communities. Therefore, although these assemblages represent "mixed communities" (Fagerstrom 1964,p.1199), derivation from similar communities ensures only minimal compositional modifications.

B) Mixed valve orientations

(figs. 10.4,10.5,10.6;plate 10.2)
(LC/GB;BC/CG;BC/LCVF;EB/UG)

Such orientations occur in two modes :-

a) thin planar horizons

b) thicker, laterally continuous shelly horizons often laterally grading into a)

a) resulted from accumulation under medium velocity currents, coupled with rapid sedimentation. Some concave-up valves were probably transported (Brenchley & Newall 1970,p.204,210), whilst any convex-up valves remained immobile, the currents not being strong enough to create widespread valve inversion. Swift sedimentation then effectively arrested valve transport and buried the valves, consequently producing a thin planar occurrence type with mixed valve orientations.

b) resulted from similar conditions, except the period of reduced sedimentation was longer, accordingly allowing thick shell accumulations to form, their variable thicknesses possibly reflecting original seafloor topography.

C) Preferred concave-up valve orientations

(figs. 10.4,10.6)
(LC/GB; EB/UG)

This orientation is restricted to laterally continuous shelly accumulations which are almost "coquinas" (Gary et al. 1972,p.156) or "shell hashes" (op.cit.,p.652; Kelling & Williams, 1966,p.931). Their planar fabric suggests relatively high current velocities, fabric preservation attributable to valve scour and rapid burial.

The valves (*Dinorthis*, rare *Macrocoelia*) probably underwent transport, their shape and weight possibly enabling them to remain concave-up even when subjected to relatively high velocity currents. Sediment accumulations within the concave faces of the valves would confer stability. Combinations of current velocity decrease, friction, seafloor obstacles and increased sediment accumulation within the concave valve faces may effectuate the cessation of valve transport, decreased sedimentation allowing shell layers to build up.

Such shelly accumulations may also have resulted from the valves being re-orientated into concave-up orientations by migrating ripple trains (Clifton & Boggs 1970) although Clifton (1971) maintains only small valves are thus affected. However, if the ripples possessed a large amplitude (Potter & Pettijohn 1963,p.93 = ripple height, Reineck & Singh 1975,p.14), they may effect concave-up orientations of large valves. Successive ripple trains may construct thick coquinas (Bridges 1975).

These valve orientations probably originated in marginal subtidal (shoreface - upper offshore) areas within relatively shallow (10m.?) water, being subject to rapid, fluctuating sedimentation, the shelly "coquinas" possibly forming quite rapidly.

4) Undisturbed life orientations (fig.10.5) (BC/CG)

An isolated example (240 - map 5) of an "in situ" obolid is noted (see chap.5, section b,ii,v).

iii) Major sedimentary structures and their interpretations

1) Planar bedding and laminations (LC/GB; BC/CG; EB/UG; EB/LDB)

Such structures are commonly noted within sandstones and coarse siltstones, both types often displaying low-angle cross-cutting relationships. Their undisturbed nature suggests rapid deposition (Reineck 1972,p.150), probably in the plane-bed phase of the upper flow regime (Harms & Fahnestock 1965; Harms et al.1963; Reineck & Singh 1975,p.106; Simons et al.1965).

In sandstones, such structures probably resulted from rapid settling out of suspended sediment in turbulent water (Reineck 1967; Terwindt 1971). High energy currents may have periodically reworked the sediments which possibly accounts for the low-angle cross-cutting relationships. Similar conditions probably occur in littoral/marginal sublittoral (shoreface - upper offshore) zones.

Fine laminations occasionally bound planar fossiliferous horizons which may be related to sediment settling out from suspension clouds (Reineck & Singh 1975), possibly following storm activity.

Laminated sandstones are noted within an alternating sandstone - siltstone sequence (252 - map 6). The sandstones were deposited by relatively high velocity currents although the sequence suggests fluctuating sedimentation and current velocities (weak tidal influences ?). Gradational boundaries denote gradual, rather than sudden, environmental changes.

Finally, varve-like laminations within fine sandstones-coarse siltstones originated through slow settling out from suspension.

The preservation of all these structures reflects rapid sedimentation (Reineck 1972) which prevented biogenic reworking in littoral/sublittoral environments.

2) Cross-bedding
(LC/GB; BC/CG)

Within the Arkosic Quartzite (fig.10.1) at Llyn Cowlyd is faintly discerned large-scale cross-bedding (plate 10.3) best referred to "pi cross-stratification" (Allen 1963,p.109,fig.4,p.110) which originated from "....the migration of trains of large-scale asymmetrical ripple marks...." (op.cit.) whereas small-scale cross-bedding resulted from migrating trains of small-scale current ripples (op.cit.). Cross-bedding (large-/small-scale) is occasionally erosively overlain by planar beds (figs.10.5,10.7) implying a current velocity increase.

Within the Carneddau Group (fig.10.2)(238/239 - map 5) cross-bedded units (signifying rapid sedimentation) are intercalated with bioturbated horizons (fig.10.5) which imply reduced sedimentation and low energy conditions (Wunderlich 1972). Such conditions permitted re-establishment of a diverse infauna which reworked the sediment (Heckel 1972; Howard 1971; Moore & Scruton 1957). Some preserved sedimentary structures suggest infauna concentrations within the oxygen-rich surface layers (Howard 1972,p.216; Rhoads & Morse 1971). McAlester & Rhoads (1967,p.386-387) note that for bivalves, deeper subtidal environments are dominated by near surface burrowers. Possibly this sequence was located within the outer sublittoral zone.

Howard (1972,p.216) likens beds possessing sedimentary structures to gaps in the biogenic record, which are brought about either by pulses in sedimentation or occasional storms which resuspended material. One therefore expects to find sharply defined bedding planes which separate beds showing no basal reworking but with increasing upward bioturbation (cf.plate 9.2).

3) Dark fine-grained clasts
(LC/GB)

Intercalated bands of dark, fine-grained, subangular-subrounded clasts, along with isolated clasts, ranging from 1mm.-4cms. are commonly noted in most sampled horizons around Llyn Cowlyd. Some clasts were probably plastic when incorporated, as suggested by gradational boundaries (plate 10.4) shape and matrix embayments. Clast horizons are associated with both shelly and unfossiliferous horizons (plates 10.4,10.5). At locality 163 (SH 72116219 - map 4) black clasts are intercalated with disarticulated sowerbyellid valves (plate 10.4), whereas within the Multiplicata Sandstone (fig.10.1) clast horizons are developed just below shelly horizons. The clasts are occasionally imbricated (plate 10.5) with single clasts displaying isolate imbrication (Laming 1966)- fig.10.8 .

Associated sedimentary laminations (plate 10.5) are only rarely biogenically deformed by rare Skolithos-like shafts (Frey 1973) and vertical shafts (plate 10.6) with retrusive spreite (Seilacher 1967,p.420)(-escape burrows ?) which, along with the undisturbed laminations, indicate rapid sedimentation (Reineck 1972,p.150; Seilacher 1967,p.419). Such ichnofauna connote the Skolithos facies (Seilacher 1964,1967; cf.Pickerill 1977) in which figurative bioturbation (Schäfer 1972; Reineck & Singh 1975,p.138) represents responses to sedimentation in littoral - shoreface sands.

All this evidence suggests deposition by migrating tidal channels on the lower parts of tidal (sand) flats (de Raaf & Boersma 1971; Klein 1967,1970; Reineck 1967, 1972; Reineck & Singh 1975; Terwindt 1971; van Straaten

1952,1954,1959,1961), the clast horizons representing channel floor lag concentrates (op.cit.) - see chap.7, section b iii, 1B. The association of relatively coarse sediments, planar occurrence types, rare figurative bioturbation and clast horizons testifies to a shallow water, high energy, littoral/inner sublittoral (shoreface-upper offshore) depositional environment.

4) Laharic breccia
(LC/GB)

A distinctive breccia is developed within the Llethr Gwyn Sandstones at Llyn Cowlyd (Diggens & Romano, 1968) - fig.10.1; plates 10.7,10.8; map 4. At the base, individual breccia units (3m.-3.5m.) are noted which progressively thin and fine upwards and contain large angular fragments of rhyolite and smaller mudstone, siltstone, sandstone, rhyolite and quartz fragments. Trough cross-bedding is developed within underlying coarse sandstones (plates 10.7,10.8,10.9) which are probably intimately related to the breccia. The basal part of each trough set possesses alternations of finer and coarser material. Above these beds the sandstones display planar laminations with low-angle cross-cuts.

This deposit represents one or several lahars (op. cit.). The breccias fit, reasonably accurately, the definition of a lahar as "....any unsorted or poorly sorted deposit of volcanic debris that moved and was deposited as a mass and owed its mobility to water"

(Mullineaux & Crandell 1962,p.857). Fisher (1960,p.978) proposes the term "laharic breccia" for "....volcanic breccias formed by lahars, regardless of cause". Poor sorting, the absence of bedding and angular fragments within the breccias are characteristic features of lahars (Mullineaux & Crandell 1962,p.857) and presumably indicate mass flowage, the high flow velocity and viscosity precluding any sorting (Schminke 1967,p.444).

Several breccia units imply spaced phases of emplacement. The absence of exceptionally large fragments indicates that these lahars had travelled some distance from source (distal ?) and sedimentological evidence suggests emplacement in a low tidal flat environment. Overlying bedded, graded (Kuenen 1953) sandstones indicate the top of the lahar was reworked and sorted by wave and current action (Schminke 1967), the grading indicating gradual deposition of material from suspension (op.cit.). Alternatively, they may imply a sandy turbidity flow was associated with the lahars, which flowed over their tops, bedding resulting from deceleration of the moving sediment mass (Hendry 1972).

If the cross-bedded sandstones are related to the lahars, several explanations are possible :-

1) They represent deposition from watery slurries that "....advanced and greased the way for the remainder of the lahar" (Schminke 1967,p.446).

2) Sandstones overlain by breccias may be regarded as inverse grading (Sanders 1965,p.208; Schminke 1967) which probably results from inertia flow (op.cit.), in which the larger grains move towards the zone of least shear strain, i.e., the mid-parts of the flow.

Evidence for this theory is afforded by field examples. Close examination of plates 10.8,10.10 reveal the breccia possesses inverse grading (indicative of mass flow - Crowe & Fisher 1973; Fisher 1971). Alternations of fine - coarse material found at the base of individual trough cross-beds (plates 10.7,10.9), which pass up into coarser laminated material, similarly afford proof for inertia flow. It seems likely that the lahars originated as avalanches of subaerially weathered clastic and volcanic fragments (derived from the Irish Sea landmass), triggered by seismic shocks, flowing into water or by heavy rains triggering loose debris (op.cit.,p.446). This approximates to a proposal by Greenwood (1956,p.172) who, however, postulates submarine deposition preceeded mudflow initiation. The decreased gradient of the tidal flats produced a waning flow which possibly deposited the underlying cross-stratified sandstones.

3) The cross-bedded sandstones may represent several phases of a "base-surge" depositional mechanism which preceeded the breccias. Large-scale cross-bedding and dune-forms (antidunes) are commonly developed within base-surge deposits (Bond & Sparks 1976; Crowe & Fisher

1973; Fisher & Waters 1970; Schminke et al. 1973; Waters & Fisher 1971). Bond & Sparks (1976,p.5,fig.2) record mudflows directly overlying cross-bedded base-surge beds.

4) Blissenbach (1954,p.186) and Reineck & Singh (1975,p.256) note mudflows (debris-flows) overlying cross-bedded stream sediments within alluvial fan deposits, the commonest sedimentary structures being cross-bedded channel cut and fills (op.cit.; see also Bull 1972). In assessing this theory, one must consider the proposed depositional environment for the Llethr Gwyn Sandstones (littoral - inner sublittoral). Consequently, these breccias may represent encroachment into such an environment by distal mudflow lobes (see Hooke 1967,p.444,fig.4) during a short phase of increased erosion (and uplift ?) although cut and fill structures are commonest near the fan apex (Bull 1972,p.75).

5) Ichnofauna
(LC/GB; BC/CG)

Excluding deformative bioturbation, evidence for ichnofauna is furnished by occasional vertical shafts (Frey 1973) referred to Skolithos Haldemann 1840 (Häntzschel 1962) which penetrate laminated or cross-bedded units (figs.10.5,10.7,10.9;plate 10.1) and apparent vertical shafts with retrusive spreite (Seilacher 1967,p.420) - plate 10.6.

Skolithos implies the Skolithos facies (Seilacher 1964,1967; cf. Pickerill 1977) which is located in littoral sands (Crimes 1970; Seilacher 1967) and furthermore, denotes relatively high energy conditions (Banks 1970; Frey & Howard ibid.;Rhoads 1967). In connection with bivalves, deep vertical burrowing occurs in intertidal/ shallow subtidal environments to escape stresses at the sediment-water interface (McAlester & Rhoads 1967,p.386-387). Therefore, Skolithos within the Llethr Gwyn Sandstones (fig.10.1) seemingly correlates with their proposed depositional environment.

Within the Carneddau Group (238/239 - map 5), Skolithos occurs within cross-bedded fine sandstones (plate 10.1) overlying outer sublittoral sediments, which may relate to fluctuating environmental energy (see Howard & Reineck 1972,p.98) plus slight shallowing, rapid sedimentation, etc..

An example of a rippled bedding plane covered by crawling tracks and trails is recorded from the Bwlch Cowlyd Sandstone Formation (fig.10.1).

c) The fossiliferous assemblages

i) Introduction

In the text, numbers in parentheses refer to fossiliferous localities (maps 4, 5, 6). See also

Appendix Two and table 10.1.

ii) Llyn Cowlyd area (figs.10.1,10.4;table 10.1,col.LC; map 4)

1) Bwlch Cowlyd Sandstone Formation

A) Multiplicata Sandstone (158/158A/159/159A)

Coarse sandstones yield low diversity assemblages dominated by Dinorthis ((Plaesiomys) multiplicata Bancroft)[1] with Macrocoelia (cf. expansa (J.de C. Sowerby) of Williams 1963) and sowerbyellids alternately attaining secondary dominance.

2) Llyn Cowlyd Sandstone Formation

A) Arkosic Quartzite (160/160A/162)

High diversity assemblages are dominated by dalmanellids with subordinate sowerbyellids. Gastropods, ostracodes, Leptaena and Sericoidea achieve minor importance.

B) Llethr Gwyn Sandstones (163/166/166A/166B)

Sowerbyellids invariably dominate low-medium diversity assemblages, along with secondary dalmanellids, Kjaerina (cf. jonesi Bancroft of Bancroft 1929a) being an important minor associate. Calymene sp. (s.l.) (cf. Flexicalymene (Reacalymene) limba (Shirley) and F. cf. planimarginata (Reed) both of Whittington 1965) is the principal trilobite.

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[1] now Plaesiomys multifida (Salter) - see Cocks 1978,p.50

One of several "intrusive rhyolites" (Diggens & Romano 1968, p.33,37) yields medium diversity assemblages (170/172) which are dominated by sowerbyellids with *Reuschella* and dalmanellids alternately attaining secondary dominance. Trilobites are generally rare, *Broeggerolithus* (cf. *nicholsoni* (Reed) of Dean 1962) being commonest.

iii) Betws-y-Coed area (figs.10.2,10.5;table 10.1, col. BYC; map 5)

1) Carneddau Group

Within a black, cleaved, fine siltstone, the stratigraphically lowest horizon (242) yields a distinctive medium diversity assemblage dominated by *Tallinnella* with abundant molluscs and inarticulate brachiopods (*Paterula/Pseudolingula*). From this horizon was collected an almost entire specimen of *Parabasilicus powisi* (Murchison) - plate 10.11.

Consecutive horizons (239) reveal low diversity, dalmanellid dominated assemblages whereas medium - high diversity assemblages are recovered from higher horizons (238/240/241). Easterly assemblages (240/241) are dominated by *Paracraniops* with subordinate sowerbyellids and dalmanellids, the former being slightly more abundant. *Dinorthis* and gastropods (*Lesuerilla/Cyrtolites*) achieve minor importance whilst ramose bryozoan fragments and *Lepidocoleus* plates are frequent. Westerly assemblages

(238) are dominated by Tallinnella.

2) Crafnant Volcanic Group

Horizons (245/246/247) between the lower and middle units of the Lower Crafnant Volcanic Formation afford high diversity shelly assemblages variably dominated by Tallinnella, Tentaculites and Skenidioides costatus Cooper, with quadrijugatorids, Nicolella (actoniae obesa Williams) and Sericoidea achieving secondary dominance. Calymenids, e.g., Flexicalymene caractaci (Salter) cf. F. planimarginata, F. sp. nov. and cf. Gravicalymene praecox (Bancroft) of Dean 1963a, are common. Crinoid columnals are abundant and diverse, cystoids are frequent and Lepidocoleus plates and ramose bryozoan fragments are variably abundant.

Between the middle and upper units of the aforementioned Formation, high diversity assemblages (243/244) reveal similar faunal compositions although S. costatus always predominates, with Nicolella and Protozyga (cf. diversa (Reed) of Williams 1962) being variably subordinate.

iv) East of Beddgelert (figs.10.3,10.6;table 10.1, col.EB; map 6)

1) Glanrafon Beds

A) Upper Grits

The lowest sampled horizons are around Gareg Bengam (SH 620453), within bedded coarse sandstones which bear faunas dominated by sowerbyellids, with secondary D.(P.) multiplicata [1] and minor M.expansa, Bicuspina spiriferoides (M'Coy) and Cyclocystoides plates.

Consecutive medium diversity faunas (252/252A/252B/LCYM) possess predominant dalmanellids although assemblages around Llynau Cerrig-y-myllt (SH 633471) are dominated by triplesiaceans (B.spiriferoides). The former horizons also yield Macrocoelia, Kjaerina (aff.jonesi), craniopsids and Rostricellula sparsa Williams.

2) Llyn Dinas Breccias

Medium diversity assemblages (251/251A) from the stratified facies (Beavon 1960,p.59-62) are likewise dominated by dalmanellids with secondary Tentaculites, Tallinnella and nuculoids. Broeggerolithus (cf.nicholsoni) is the chief trilobite with associated Kloucekia apiculata (M'Coy).

d) Interpretation of the fossiliferous assemblages in terms of the proposed Snowdonian benthic communities

i) Llyn Cowlyd area (fig.10.4;table 10.1 - col.LC)

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[1] now Plaesiomys multifida (Salter) - see Cocks 1978,p.50

1) Multiplicata Sandstone

High dominance, low diversity assemblages (158/158A/159/159A) are assigned to the Dinorthis community. The characteristic low succession order brachiopod Dinorthis was the "pioneer" genus in what was a low tidal flat/shoreface - upper offshore environment. Low diversities and articulation ratios attest to a high energy, "physically rigorous" (Bretsky & Lorenz 1970) environment although opposing valve ratios indicate negligible lateral transport, as does the occurrence of Macrocoelia brachial valves, thought to have been fragile and hence easily destroyed.

In addition, little associated intergradation suggests the community was in an early successional stage (Margalef 1968), in an environment unfavourable for further diversification. Similar low grade communities are usually situated in shallow marine environments (Johnson 1972), the absence of crinoids/bryozoa being a response to the unstable shifting sandy substrates frequently developed in such environments (Heckel 1972, p.280,281).

2) Arkosic Quartzite

High diversity, low dominance assemblages (160/160A/162) are allocated to the dalmanellid-sowerbyellid "mega" community, with intergradation from the Dinorthis and Nicolella communities. Increased faunal diversities attest to progressive environmental stabilisation (Bretsky & Lorenz 1970). Consequently the "mega" community presumably developed in a slightly more offshore environment, but one in which relatively high velocity currents were in operation (periodically ?) as valve ratios suggest lateral transportation.

3) Llethr Gwyn Sandstones

Assemblages (163/166/166A/166B) again denote the dalmanellid-sowerbyellid "mega" community with rare intergradation from the Dinorthis community. Articulation/opposing valve ratios suggest only minor net lateral transport which, from sedimentological evidence, probably occurred within a low tidal flat/inner sublittoral environment. Here, environmental disturbances (Johnson 1972) would be commonplace and these would downgrade mature benthic communities (low dominance/high diversity) to high dominance/low diversity (low-grade) communities (Johnson 1972; Margalef 1968).

Environmental change is exemplified by the lower assemblages being more diverse than the overlying assemblages. This may accordingly be related to localised uplift (precursor of later vulcanism ?) of which the overlying laharic breccia was possibly a direct result.

A bedded rhyolitic tuff (plate 10.12) at the top of the Llethr Gwyn Sandstones yields sparse high dominance faunas which seem best allotted to the dalmanellid-sowerbyellid "mega" community. Intergradation from the

Dinorthis, Sericoidea and Nicolella (?) communities occurs. Opposing valve ratios imply some net lateral transport although a high sowerbyellid articulation ratio suggests no large-scale movement from original growth sites.

ii) Betws-y-Coed area (fig.10.5;table 10.1 - col.BYC)

1) Carneddau Group

Comparisons in faunal composition, diversity and enclosing lithology are noted between the stratigraphically lowest assemblage (242) and the Bivalve Population of the Onniella community (Pickerill 1974), which also broadly compare with the Utica black shales (Ruedemann 1925,1926). Employing this comparison for environmental interpretations, deposition probably occurred in a low energy, partially barred environment, with ingress of ocean currents providing enough water ventilation to support a depauperate benthic community.

Overlying high dominance assemblages (239) within bioturbated siltstones are assigned to the dalmanellid-sowerbyellid "mega" community, with little intergradation being developed, which presumably indicates a recently disturbed environment (Johnson 1972), the assemblage representing an early successional stage in shallow seafloor colonisation (op.cit.; Margalef 1968).

Consecutive assemblages (238) are allocated to the same "mega" community, progressive environmental stabilisation reflected by increased diversity. The increase in the numbers of *Tallinnella* was probably linked with a variety of interrelated environmental factors (Brondos & Kaesler 1976,p.215-216), of which salinity appears most important (op.cit.; Heckel 1972,p.282) although environmental effects upon Recent ostracodes may not necessarily be applicable to Palaeozoic ostracodes (Brondos & Kaesler 1976). Localised salinity fluctuations possibly engendered the proliferation in *Tallinnella* numbers. Nevertheless, such variations in open marine waters are usually not large enough to be influential (Benson et al. 1961, Q 61, but see Brondos & Kaesler 1976, p.215-216). Other effectual factors may well be nutrient supply and substrate nature (Brondos & Kaesler 1976), although of the cited factors, only the effect of substrate could possibly be assessed within fossiliferous assemblages.

Increased faunal diversities (240/241) and marked intergradation signify progressive environmental stabilisation, the assemblages representing a mature dalmanellid-sowerbyellid "mega"community. *Tallinnella* numbers are greatly reduced, suggesting that whatever factor (physico-chemical/biological) was responsible for their former proliferation either had been removed or had diminished. Opposing valve/articulation ratios generally imply minor net lateral valve transport, whereas *Dinorthis* valve ratios do not significantly depart from unity, revealing Dinorthis to be intergrading.

2) Crafnant Volcanic Group

The lowest assemblage (245 - fig.10.5; map 5) is assigned to the Nicolella community, which temporally replaced the "mega" community, as dalmanellids and sowerbyellids are commonly associated with characteristic Nicolella community genera, e.g.,Nicolella, Skenidioides, Orthambonites, Leptestiina, Platylichas etc.. The Nicolella community probably developed within a stable, low energy environment, replacement presumably being related to an increase in calcareous content within the sediment plus reduced terrigenous sediment input (Anderson 1971).

Overlying assemblages (246/247) from impersistent "limestones" reveal a mature Nicolella community, with marked intergradation from the dalmanellid-sowerbyellid and Sericoidea communities implying the Nicolella community occupied an intermediate spatial seafloor position between them. Common crinoid columnals, cystoids and ramose bryozoan fragments connote an original stable supportive substrate (Heckel 1972).

Between the middle and upper tuffs of the Lower Crafnant Volcanic Formation, assemblages (243/244) from impersistent "limestones" likewise signify a mature Nicolella community with similar intergradation patterns. Earlier (section b ii, 3A), it was suggested that these assemblages are "mixed" (Fagerstrom 1964,p.1199), probably corresponding to model II of Johnson (1960).

Diversity indices reveal that emplacement of the tuffs did not apparently downgrade the Nicolella community, such an association demonstrating that the tuffs were originally emplaced in an offshore low energy environment with little concomitant reworking. The rapid post-emplacement re-establishment of pre-emplacement conditions would consequently permit swift reinstatement and subsequent diversification of the Nicolella community, thus preventing serious downgrading. Howells et al. (1973) believe these volcanic units were emplaced as "....turbid flows" in either fairly deep water or some distance from any shoreline (op.cit.,p.30-32), interpretations which concur well with those environmental interpretations already postulated for the associated Nicolella community.

iii) East of Beddgelert (fig.10.6;table 10.1,col.EB)

1) Gareg Bengam/Llynau Cerrig-y-myllt

A) Upper Grits

At Gareg Bengam (SH 620453 - map 6), coarse sandstones contain moderate diversity, high dominance assemblages (134/134A) (plate 10.13). Although dominated by sowerbyellids, the coarse lithology and common Dinorthis and Macrocoelia suggest the Dinorthis community, the sowerbyellids being dominant intergraders along with lesser dalmanellids and rarer triplesiaceans.

Articulation/opposing valve ratios imply some transportation in what was a high energy environment subject to environmental fluctuations, which curtailed further diversification.

Overlying assemblages (LCYM) within fine sandstones possess increased diversities and reduced dominance. Faunal compositions denote the dalmanellid-sowerbyellid "mega" community, with intergradation from the Dinorthis community. Increased diversification suggests some environmental stabilisation (Bretsky & Lorenz 1970), whilst temporal community replacement (fig.10.6) implies a slightly more offshore environment.

2) Hafodyddbrithion

A) Upper Grits

Assemblages (252/252A/252B) from fine sandstones are assigned to the aforementioned "mega" community, with some intergradation from the Dinorthis community. Frequent crinoid columnals reveal the substrate was firm enough to permit colonisation (Heckel 1972).

B) Llyn Dinas Breccias

Shelly assemblages (251/251A) within fine grey siltstones from the basal stratified facies are similarly allocated to the dalmanellid-sowerbyellid "mega" community. Randomly orientated valves suggest an associated infauna (nuculoids ? - e.g., Similodonta sp., see localities 251/251A, Appendix Two).

e) Age determination of the sequences from faunal evidence

i) Llyn Cowlyd area

1) Multiplicata Sandstone (158/158A/159/159A)

The lateral equivalence of this unit to unit p at Capel Curig (East) has been discussed (chap.7), the latter unit being regarded as upper Soudleyan. Similar associations (*Dinorthis* (*Plaesiomys*) *multiplicata* Bancroft[1], *Macrocoelia expansa* (J.de C.Sowerby) and rarer *Reuschella*) at Llyn Cowlyd are likewise regarded as upper Soudleyan. The *D. multiplicata* zone represents the topmost upper Soudleyan (Bancroft 1933,1945,p.245) and the association of *D.*(*P.*) *multiplicata*[1], *Rafinesquina expansa* (J.de C.Sowerby) and *Dalmanella* aff. *horderleyensis* (Whittington) is considered upper Soudleyan (op.cit.) although *M.expansa* is noted from Lower Longvillian strata at Bala (Williams 1963,p.457).

2) Arkosic Quartzite (160/160A/162)

The faunas are not diagnostic, but *Skenidioides* cf. *costatus* Cooper of Williams 1963, *Kjaerina* sp. (?) and *Flexicalymene planimarginata* (Reed) suggest a Lower Longvillian age (Bancroft 1929a,1945; Dean 1963b,1965; Harper 1956; Whittington 1965; Williams 1963) although

[1] now *Plaesiomys multifida* (Salter) - see Cocks 1978,p.50

Dean (in Whittard 1967,p.320) notes F.planimarginata from the lower half of the Whittery Shales (Soudleyan) around Shelve, whilst Reuschella sp. (?), Kiaromena sp. and Flexicalymene (Reacalymene) limba (Shirley) imply an upper Soudleyan age (Bancroft 1928b,p.188,1945; Bassett et al. 1966; Dean 1958, 1963b; Whittington 1965; Williams 1963). These faunas do not appear diagnostic for either the upper Soudleyan or Lower Longvillian (= "boundary" faunas - chap.9, sections e iii;iv,1) but, on balance, along with stratigraphic position, possibly infer a low horizon within the Lower Longvillian.

3) Llethr Gwyn Sandstones (163/166/166A/166B)

Kjaerina sp. and Howellites cf. antiquior (M'Coy) of Williams 1963, in association with the relative stratigraphic horizon, indicate a Lower Longvillian age (Bancroft 1929a,p.43,1933,1945,p.246; Cave & Dean 1959, p.296; Dean 1958; Whittington 1938a,b) for the lower assemblages (163).

Kjaerina sp., K.cf. jonesi Bancroft of Bancroft 1929a, F.cf. planimarginata of Whittington 1965 and Brongniartella cf. minor (Salter) of Dean 1961 from overlying assemblages (166/A/B) definitely indicate a Lower Longvillian horizon (table 9.2).

From loose blocks lithologically resembling the Llethr Gwyn Sandstones, Diggens & Romano (1968,p.42) identified Broeggerolithus nicholsoni (Reed) and

Kloucekia sp., which substantiate the postulated Lower Longvillian age (Dean 1961, 1962, 1963b; Harper 1956; Whittington 1962,1966,1968). Furthermore, a combination of B.nicholsoni, F.planimarginata, B.minor and K. sp. (apiculata (M'Coy) ?) conclusively proves a Lower Longvillian age (Bassett et al. 1966,p.259) - table 9.3.

A rhyolitic tuff from the upper Llethr Gwyn Sandstones (170/172) yields B.cf.nicholsoni of Dean 1962 and cf. Flexicalymene caractaci (Salter) of Whittington 1965. In association with stratigraphic position, a Lower Longvillian horizon is proposed (Bassett et al.1966; Dean 1959,p.214;1962,p.114;1963b,p.15;1963c,p.62; Harper 1947; Shirley 1931; Whittington 1965,1966,1968).

The overlying Pen Llithrig-y-Wrâch Siltstone and Marian Mawr Mudstone Formations, by virtue of their stratigraphy, must be Lower Longvillian.

ii) Betws-y-Coed

1) Carneddau Group

Fauna from the lowest assemblage (242) is not diagnostic, but Parabasilicus powisi (Murchison) implies a Soudleyan age (Dean 1958,1963a,b; Whittington 1966,1968) although Harper (1947,1956) records this species from Lower Longvillian strata.

Consecutive assemblages (239) are likewise not characteristic, but rare Kjaerina sp.,K.cf.jonesi and H.cf. antiquior suppose a Lower Longvillian horizon (Bassett et al. 1966,p.258,263; Cave & Dean 1959,p.296; Harper 1947,1956; Whittington 1938a,b; Williams 1963,p.336,340) although *K*.aff. *jonesi* has been noted from Soudleyan strata (Dean 1960c,p.167) as has *H*.cf. *striata* Bancroft[1] of Williams 1963 (Bancroft 1945,p.205; Bassett et al. 1966, p.263). On balance, a tentative assignment to the Lower Longvillian stage is made.

It is stressed that evidence furnished by dalmanellids must be treated with caution as poor preservation and tectonic deformation make their identification to species level only conjectural.

The stratigraphic position of overlying assemblages and the occurrence of *Kjaerina* sp. (cf.Dean 1960c) within these assemblages (238) similarly suggests a Lower Longvillian horizon. Dalmanellids comparable with *D.indica* Whittington of Bancroft 1945 and *D.modica* Williams of Williams 1963 confirm this proposal (Bancroft 1945,p.195; Bassett et al. 1966,p.263; Dean 1958,p.199,205,206;1964, p.278; Whittington 1938a,c,p.247; Williams 1963,p.335,340).

2) Crafnant Volcanic Group

A) Lower Crafnant Volcanic Formation

Assemblages (245/246/247 - fig.10.5;map 5) from intercalated sediments contain diagnostic Longvillian forms, e.g., *S.costatus*, *Nicolella* cf.*actoniae obesa* Williams of Williams 1963, *Leptestiina oepiki* (Whittington), *Protozyga* cf.*diversa* (Reed) of Williams

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[1] now *Howellites* cf.*striatus* Bancroft - see Cocks 1978,p.65

1962, Cremnorthis parva Williams, Rhactorthis crassa Williams, Orthambonites cessata Williams[1], B.cf.nicholsoni, F.caractaci, cf.F.planimarginata, cf.Gravicalymene praecox (Bancroft) of Dean 1963a, K.apiculata, Platylichas nodulosus (M'Coy) and Brongniartella cf.bisulcata (M'Coy) of Dean 1961, most of which further imply an Upper Longvillian horizon (table 8.5), where :-

Skenidioides = S.costatus
Platylichas = P.nodulosus

Species not included in table 8.5 are :-

L.oepiki - L.Longvillian - U.Longvillian (Bassett et al.1966,p.264; Dean 1959,p.197,203,213, 1965, p.309-310,312; Harper 1956,p.389; Whittington 1938a,p.451, 1938c,p.256; Williams 1963,p.340).

P.cf.diversa - Longvillian (Williams 1962,p.243).

C.parva - U.Longvillian (Williams 1963,p.340).

O.cessata[1]- L.Longvillian (Bassett et al.1966,p.264; Williams 1963,p.336,340,351).

The ranges for B.cf.nicholsoni, F.caractaci, cf.F. planimarginata, K.apiculata and B.cf.bisulcata are shown in table 9.3.

G.praecox is recorded from Harnagian, Actonian and Onnian strata (Bancroft 1949; Dean 1958,p.219; 1963a, p.226; 1963b,p.15,16,17). Although not noted from the

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[1] now Orthambonites cessatus Williams - see Cocks 1978,p.39

Longvillian, "....the appearance of the genus is associated with an influx of new faunal elements" (Dean 1963a,p.226), an association similarly found within this area.

Reuschella (cf.*horderleyensis* Bancroft of Bancroft 1928b and Williams 1963) is commonly noted but is possibly better compared with *R.bilobata* (J.de C.Sowerby) which is identified from Upper Longvillian beds at Moel Hebog (Harper in Shackleton 1959,p.250).

Assemblages from impersistent "limestones" (243/244 - fig.10.5; map 5) contain almost identical faunas and are consequently assigned to the Upper Longvillian.

In conclusion, "....The association of *Nicolella actoniae*" (*obesa*) "with *Sampo* cf.*öpiki*" (*L.oepiki*) (an association frequently developed within the Betws-y-Coed area) "recalls the *Nicolella actoniae* beds at Llansantffraid (Whittington 1938a,p.451) i.e., Upper Longvillian" (Harper 1956,p.388-389).

iii) East of Beddgelert

1) Gareg Bengam / Llynau Cerrig-y-myllt

A) Upper Grits

At Gareg Bengam, faunal assemblages (134/134A) are very similar to those from the *Multiplicata* Sandstone (part i, this section) and unit p at Capel Curig (East) (chap.7, sections c,ii 4; d,iv; e,ii), e.g., all possess

D.(*P.*) *multiplicata*[1] and *M.expansa*. This association characteristically denotes the upper Soudleyan (Bancroft 1945), which concurs with the proposed age for the aforementioned assemblages. However, *Bicuspina spiriferoides* (M'Coy) usually indicates Lower Longvillian strata (Williams 1963,p.337) although is also noted from middle - upper Soudleyan horizons (op.cit.,p.335; Bassett et al.1966,p.263) whilst *F.planimarginata* is recorded from Soudleyan strata around Shelve (Dean, in Whittard 1967,p.320).

The identification of submarginal ring plates of *Cyclocystoides* is interesting, as elsewhere in Snowdonia, *Cyclocystoides* appears confined to the Longvillian. Therefore it seems *Cyclocystoides* initially advanced into the Snowdonian area during the upper Soudleyan. *Cyclocystoides* is recorded in both America and Britain. In America, the genus ranges from the Llandeilo (*C. billingsi* Wilson) to the Upper Llandovery (*C.ornatus* Savage) - Begg 1934,p.220, 1940,p.21; Kesling 1966 U203, fig.145, U209.

In England, Begg (1940,p.22) notes *C.caractaci* Etheridge "....from Cheney Longville" (op.cit.) (= Cheney Longville Flags ? - Upper Longvillian to Marshbrookian, Dean 1972, fig.7 in Williams et al.1972) and *C.marstoni* Salter "....from the Acton Scott Beds of Shropshire" (Begg 1940,p.22) (= Actonian, Dean 1972,fig.7 in Williams et al.1972). *C.wrighti* Begg and *C.decussatum* Begg are

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[1] now *Plaesiomys multifida* (Salter) - see Cocks 1978,p.50

recorded (Begg 1934,1940) from the Drummock Group at Girvan (mainly the Cautleyan-Rawtheyan Stages of the Ashgillian - Whittington 1972,fig.9, in Williams et al. 1972).

Disarticulated submarginal ring plates of *Cyclocystoides* found in the Dolwyddelan, Llyn Cowlyd and Betws-y-Coed areas (chap.9, this chap.) may possibly be correlated with the Shropshire Upper Longvillian form (*C.caractaci*), although the Llyn Cowlyd occurrences are within the probable Lower Longvillian Arkosic Quartzite (table 10.1). However, the occurrences within the Upper Grits from this area are upper Soudleyan, consequently being the earliest recorded appearance of *Cyclocystoides* in the Anglo-Welsh province. It appears *Cyclocystoides* spread gradually south-eastward across the Welsh Basin throughout Caradoc times.

Stratigraphically higher assemblages (LCYM - fig. 10.6; map 6) are dominated by triplesiaceans (*B. spiriferoides*) with *M.expansa*. *B.spiriferoides*, although found in middle - upper Soudleyan strata,is more abundant in the Lower Longvillian (Williams 1963,p.340), as is *M.expansa* (op.cit.,p.457). Consequently, a tentative low Lower Longvillian age is proposed. *Dinorthis berwynensis* (Whittington) is also recorded, but is probably better referred to the subspecies *angusta* Williams which ranges into the Lower Longvillian (Bassett et al.1966,p.263; Williams 1963,p.335,340).

2) Hafodyddbrithion

A) Upper Grits

These assemblages (252/252A/252B) possess abundant *Kjaerina* (aff.*jonesi*). *Kjaerina* is only rarely noted from the upper Soudleyan (Bancroft 1945,p.246-247; cf.Dean 1960c, p.167) but becomes abundant in and characteristic for the Longvillian, whilst *K.jonesi* is noted from the low Lower Longvillian (op.cit.). Associated *M.expansa*, *Dalmanella* cf.*lepta* (Bancroft)[1] of Bancroft 1945 and *Paracraniops* sp. attest to a low Lower Longvillian horizon (op.cit.; Williams 1963). *H*.cf. *striata*[2] is, however, a Soudleyan species, whilst *Rostricellula sparsa* Williams is noted from upper Soudleyan horizons at Bala (Bassett et al.1966,p.264; Williams 1963,p.336,340,468) although both may possibly range into the Lower Longvillian in Snowdonia.

B) Llyn Dinas Breccias

Assemblages (251/251A) from the basal stratified facies contain characteristic Lower Longvillian forms e.g., *K.apiculata*, *B*.cf.*nicholsoni*, *H*.cf.*antiquior* (tables 9.2, 9.3) and *Paracraniops* sp.. *K.apiculata* definitely indicates the Lower Longvillian (Bassett et al.1966,p.265; Dean 1958, p.221; 1959,p.212,214,220; 1961,p.326; 1962,p.97; 1963b, p.11,15-16; 1963c,p.62; Diggens & Romano 1968,p.42; Harper 1947,p.169; 1956,p.387-388; Romano & Diggens 1969,p.603; Whittington 1962,p.10; 1968,p.111,113) and is

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[1] now *Dalmanella* cf.*indica* Whittington - see Cocks 1978,p.61

[2] now *Howellites* cf.*striatus* Bancroft - see Cocks 1978,p.65

"....a reliable indicator of the Longvillian stage, at which horizon it is widespread through Wales and the Welsh Borders" (Dean 1963c,p.62).

f) Conclusions

1) At Llyn Cowlyd, one "intrusive rhyolite" (Diggens & Romano 1968,p.37) is fossiliferous and therefore must be a waterlain rhyolitic tuff. The character of the other "rhyolites" was not determined but their concordant nature suggests that they, too, may be waterlain tuffs.

2) Sedimentological evidence from the Bwlch Cowlyd and Llyn Cowlyd Sandstone Formations indicates shallow water deposition (littoral-sublittoral) subject to some tidal influences. Evidence from equivalent strata at Betws-y-Coed infers deeper water sedimentation (outer sublittoral - offshore).

A picture of deeper water to the south-east fits the proposed tectonic model for Llandeilo - lower Caradoc times (Phillips et al.1976,p.587). A north-easterly trending land ridge was situated in what is now south-east Ireland (op.cit.) corresponding to what is variously termed the Anglesey - Rosslare ridge (Brenchley 1969), the Irish Sea Land Mass (George 1963; Williams 1969a, p.141) and the Irish Sea Horst (Williams 1969b,p.259). Consequently, in traversing south-eastwards from Llyn Cowlyd, one would be moving towards the centre of the Welsh Basin (Phillips et al.1976).

Diggens & Romano (1968) note an overall fining-up within the Glanrafon Beds which possibly resulted from either decreased current activity, palaeogeographical changes displacing the provenance area or a cessation in volcanicity producing a decrease in coarse volcaniclastic supplies.

3) The stratigraphic position, lithology and appearance of the Arkosic Quartzite is broadly similar to the acidic, airfall, waterlain tuffs within the Glanrafon Beds at Capel Curig and Dolwyddelan. The coarser grain size of the Quartzite may be explained by either increased terrigenous sediment admixtures or by proximal location to the eruptive centre.

Component ash-fall particles are segregated on falling through the atmosphere, the coarsest and densest initially settling out nearest the volcanic centre (Eaton 1964,p.17; Fisher 1964,p.344,347; Scheidegger & Potter 1968,p.163,164) although this relates to terrestrial deposits. Volcanic ash settles slowly in water (Eaton 1964,p.27). Marine currents would disperse the ash such that the final distribution pattern bears little resemblance to the original distribution of the ash (op.cit.).

The author supposes the Arkosic Quartzite is laterally equivalent to one of the rhyolitic tuffs at

Capel Curig, although intervening unexposed ground makes any lateral correlations speculative.

4) From faunal compositions, the Multiplicata Sandstone is correlated with horizons at Capel Curig (East) (152; 155 - unit p) and Gareg Bengam (134/134A - Upper Grits), whilst the latter two horizons are themselves directly correlated.

5) The Llyn Cowlyd laharic breccia is interpreted as an inertia flow which was subjected to some post-emplacement reworking within a tidal flat - inner sublittoral environment.

6a) The Betws-y-Coed sequences developed in outer sublittoral waters. Temporal community replacement (dalmanellid-sowerbyellid→Nicolella) suggests :-

i) increase in water depth (basin subsidence ?)
ii) palaeogeographical changes displaced the provenance area (s)
iii) a combination of i and ii

which, coupled with the development of localised submarine (?) barriers, may have produced favourable conditions for subsequent black mud deposition (e.g., Llanrhychwyn Slates).

6b) The Nicolella community within the Lower Crafnant Volcanic Formation probably flourished on offshore calcareous sediments removed from any terrigenous clastic supplies (Anderson 1971). This interpretation compares well with the proposed deposition for the tuffs which were possibly emplaced as turbid flows in either fairly deep water (offshore) or at a distance from any shoreline (Howells et al.1973,p.30,32). Howells (1977,p.404) notes the overlying Middle Crafnant Volcanic Formation is of "....deep water character" and was emplaced in a subsiding deep water basin.

7) Faunal evidence suggests the following age ranges :-

A) Llyn Cowlyd area

Glanrafon Beds (Multiplicata Sandstone - top of the Llyn Cowlyd Sandstone Formation): upper Soudleyan - Lower Longvillian.

B) Betws-y-Coed area

Carneddau Group : Soudleyan - Lower Longvillian
Lower Crafnant Volcanic Formation : Upper Longvillian
Middle and Upper Crafnant Volcanic Formation : Upper Longvillian - Marshbrookian (?)

C) East of Beddgelert

Gareg Bengam

Upper Grits : upper Soudleyan

<u>Llynau Cerrig-y-myllt</u>

uppermost Upper Grits : Lower Longvillian

<u>Hafodyddbrithion</u>

uppermost Upper Grits : Lower Longvillian

Basal stratified facies of the Llyn Dinas Breccias : Lower Longvillian

Therefore the Soudleyan-Lower Longvillian boundary probably passes through the upper horizons of the Upper Grits.

Regarding the latter area, these statements consequently suggest :-

A) Most of the Glanrafon Beds are at least Soudleyan.

B) The Lower and Middle Lapilli-tuffs are Lower Longvillian.

C) The intravolcanic unconformity below the Lower Rhyolitic Tuff (Beavon 1963,p.490-491) must be Lower Longvillian which contradicts the proposed Soudleyan age (op.cit.).

D) The Llyn Dinas Breccias are Lower Longvillian.

E) The cumulative evidence suggests the Lower Rhyolitic Tuff must be Lower Longvillian, but if correlations with the Moel Hebog area are accepted, an Upper Longvillian age may be admissible.

8) At Llyn Cowlyd, the Crafnant Volcanic Group unconformably overlies the Glanrafon Beds, cutting out some 270m. of sediments which may have been partly Upper Longvillian. Therefore an analogous situation to that at Dolwyddelan appears to have been developed.

Around Betws-y-Coed this unconformity is not recognised, but some Carneddau Group (Upper Longvillian ?) sediments are undoubtedly missing from beneath the Crafnant Volcanic Group.

At Capel Curig, this unconformity may explain a seemingly "condensed" sequence. (chap.7). The age of two horizons are known :-

Unit p (155) - upper Soudleyan
Intercalated sediments above the lower tuff of the Lower Crafnant Volcanic Formation (assuming no diachronism) - Upper Longvillian.

Therefore, most of unit p (including units r and s) and unit t (fig.7.1) must represent the topmost Soudleyan and all the Lower Longvillian. Considering the combined thickness of Lower Longvillian beds at Llyn Cowlyd, this seems unlikely. However, if an unconformity exists, Lower Longvillian sediments which originally overlay unit t have probably been eroded.

9) The dalmanellid-sowerbyellid "mega"community was the dominant benthic community.

Llyn Cowlyd area

Here, the dalmanellid-sowerbyellid "mega"community temporally replaced the *Dinorthis* community.

Betws-y-Coed area

The Bivalve Population of the *Onniella* community (Pickerill 1974) was eventually succeeded by the dalmanellid-sowerbyellid "mega"community, with the *Nicolella* community becoming dominant in Upper Longvillian times.

East of Beddgelert

The upper Soudleyan *Dinorthis* community was replaced by the low Lower Longvillian dalmanellid-sowerbyellid "mega"community.

10) A point applicable to all Snowdonian areas is the inherent difficulty encountered in comparing Snowdonian faunas, especially brachiopods and trilobites, with those from other areas, for identification and dating purposes. The presence of certain brachiopods (and some trilobites) reflects facies control (op.cit.; Williams 1963,1973), i.e., they occur due to the development of favourable substrates, which may make some genera diachronous. Trilobites appear more reliable as Caradocian stage indicators and following Romano &

Diggens (1969,p.603), correlation has been made, where possible, with the Bala area to avoid diachronism. Brachiopods are less reliable and Bassett et al. (1966, p.258) note that from thirty species from the Gelli-grîn Calcareous Ashes, only H.antiquior can be confidently utilised.

The author bases conclusions regarding age on faunal combinations rather than on isolated occurrences. Trilobites are initially utilised, brachiopods supplying confirmatory evidence. Correlation is initially made with the Bala area, but additional evidence is derived from Shropshire, the areas around Shelve, Cross Fell, the Berwyn Hills, Dolgarrog, Ynys Galed and Llanystwmdwy in Gwynedd, the Lake District, the Arenig district, the Lleyn peninsula, localities in Ireland and within Snowdonia itself.

Chapter 11 Conclusions

a) Introduction

In this chapter, the major conclusions are summarised and any resultant points are discussed. For brevity, references appertaining to topics treated elsewhere in the thesis are omitted and minor conclusions relating to individual areas are not reiterated.

b) Faunal occurrence types and valve transport

Shelly fossil orientations (mainly of disarticulated brachiopod valves) provide valuable palaeoenvironmental information, consequently leading to assessments of valve transport. Such orientations are classified into faunal occurrence types, the commonest being :-

i) Planar faunal occurrence types - produced by current activity of variable velocities. The component valves display differing orientations :-

Preferred convex-up orientations
Mixed orientations
Preferred concave-up orientations

ii) Laterally continuous shelly horizons - produced by current activity of variable velocities in times of reduced sedimentation. Constituent valves possess similar orientations to those above.

iii) <u>Random faunal occurrence type</u> - produced by the activity of infaunal burrowers, probably being derived from either of the previous types.

iv) <u>Transport</u>

Most sampled assemblages presumably suffered only localised transportation which consequently produced little compositional modifications within the faunas. Therefore, most can be regarded as essentially "in situ", corresponding to the "residual fossil community" or more rarely the "mixed fossil assemblage" of Fagerstrom (1964, p.1199). The overall absence of valve fragmentation/abrasion and opposing valve ratios frequently approaching unity attest to little transportation. However, some subordinate winnowing of the assemblages almost certainly occurred.

Shells are seldom conveyed more than several hundred metres from growth sites to final depositional sites (Behrens & Watson 1969; Boucot 1975; Craig 1967; Lever 1958; Martin-Kaye 1951). Although transport is initiated at low current velocities (Elliott 1956, p.197,198), the only effective agents producing large-scale transportation are turbidity currents (Ekdale 1973).

c) Faunal analysis

The Snowdonian shelly faunas are relatively diverse, containing

- brachiopods
- trilobites
- crinoids
- cystoids
- ostracodes
- bivalves
- gastropods
- cephalopods
- corals
- bryozoans
- algae
- cricoconarids
- machaeridians
- cyclocystoids

in variable combinations and abundances.

Sessile benthic brachiopods dominate the shelly faunas. Dalmanellids and sowerbyellids variably predominate although *Bicuspina*, *Dinorthis*, *Dolerorthis*, *Macrocoelia*, *Paracraniops*, *Salopia*, *Sericoidea* and *Skenidioides* achieve localised abundance.

Crinoids are relatively diverse and abundant as are, to a certain extent, bryozoans, but disarticulation and fragmentation renders their true abundances impossible to assess.

Trilobites, e.g., trinucleids (*Broeggerolithus*), calymenids (*Flexicalymene*) and asaphids (*Parabasilicus*) dominate the vagrant benthos, although the dalmanitid *Kloucekia* and pterygometopid *Estoniops* attain restricted dominance. Gastropods locally replace trilobites as the dominant vagrant benthic group. Rarely, the quadrijugatorid ostracode *Tallinnella* attains restricted dominance.

The accuracy of the faunal analysis is limited however, as nearly all the faunal components have been distorted by tectonic deformation and are commonly poorly preserved which precludes meticulous identifications.

d) Snowdonian benthic marine communities

From recurrent faunal associations, four provisional benthic marine communities are proposed, substrate nature apparently being the primary controlling environmental factor.

Dinorthis community

This community is of low-medium diversity and was seemingly best developed on medium - coarse sands, within high energy inner sublittoral (shoreface - upper offshore) environments.

Dalmanellid - sowerbyellid "mega" community

This "mega" community comprises the Dalmanella and Howellites communities and possesses medium - high faunal diversity. It apparently became developed on fine sands/ medium coarse silts within the inner (?) - outer sublittoral zone, being subject to periodically fluctuating sedimentation, clastic input and energy levels.

Nicolella community

The high diversity Nicolella community seemingly flourished on fine-coarse calcareous silts. Environmental parameters are difficult to assess, but this community probably occupied an offshore position (inner ? - outer sublittoral zone) in a low energy environment subject to reduced clastic sedimentation. Possibly the Nicolella community became modified into the Upper Ordovician (Ashgill) - Upper Silurian Dicaelosia - Skenidioides community (Boucot 1975, p.234-235,249).

Sericoidea community

The optimum development of this low - medium diversity community was on fine silts in a low energy sublittoral (inner ? - outer) environment subject to reduced sedimentation.

Shallow shelf communities form a complexly intergrading continuum without sharp breaks. Consequently, community distinction becomes somewhat arbitrary.

Community composition reflects environmental stability. Enviromental changes downgrade communities to characteristic low order succession species, low diversity assemblages/communities reflecting unstable environments or ones that inhibit further community diversification. High faunal diversities imply stable environments.

The Snowdonian communities closely compare with contemporaneous communities from Bala (Williams 1963; 1973) and the Berwyn Hills (Pickerill 1974) and can be broadly referred to the strophomenid - trilobite communities described by Bretsky (1969a,b; 1970a,b) which occupied shallow shelf environments.

Within Snowdonia, the distinctive onshore-offshore pattern exhibited by other Lower Palaeozoic communities (op.cit.;Ziegler 1965; Ziegler et al.1968) is not recognised. Anderson (1971) notes such communities display two distinct lateral patterns, the Snowdonian communities being placed in Anderson's model two (op.cit.) (as are Bretsky's communities). Here, restricted onshore sedimentary environments are absent (as they appear to be in Snowdonia) due to either prograding shorelines which fill such enviroments or relatively high-slope shorelines which prevent broad onshore zones developing. Three sedimentary zones are present within this model e.g., a littoral complex (beach/bars/channels/lagoons/deltas) and an open shelf above and below wave base. For Snowdonia, a community - sedimentary zone correlation may be :-

<u>Dinorthis</u> community = littoral zone/part of the open shelf above wave base

dalmanellid - sowerbyellid "mega" community = open shelf above and partly below wave base

<u>Sericoidea</u> community = below wave base (but may also develop within inshore low energy areas subject to reduced and/or fine clastic sedimentation)

The <u>Nicolella</u> community is not part of this pattern, but probably developed within inner (?) - outer sublittoral environments removed from clastic sources.

Such a model supposedly developed in tectonically active areas (op.cit.), rising land providing a sustained supply of clastic sediments which consequently created a prograding shoreline. In Snowdonia, some clastic sediment was possibly derived from volcanic sources. Tectonic activity increased depositional slopes as basin subsidence increased to balance adjacent uplifts. A similar environment seems feasible for Snowdonia and the development of these communities.

Boucot (1975,chap.2) proposes a scheme of depth-related Benthic Assemblages into which the Snowdonian communities are provisionally integrated.

a) Dinorthis community

Benthic Assemblage 2; low intertidal
lower depth limit - 6.0m. - 9.0m. below high water

b) dalmanellid - sowerbyellid/Nicolella communities

Benthic Assemblage 3; subtidal
upper limit - 6.0m. - 9.0m. below high water
lower limit - 60m. below high water

c) Sericoidea community

Benthic Assemblage 4; subtidal
upper limit - 60m. below high water
lower limit - 120m. below high water

Although this scheme is unconfirmed, no communities can be assigned to Benthic Assemblage 1 (inshore communities).

e) Stratigraphic distribution of Caradocian benthic communities

Harnagian (upper)

The dalmanellid - sowerbyellid and Sericoidea communities became alternately established with some mutual intergradation.

Soudleyan

The dalmanellid - sowerbyellid and Dinorthis communities periodically flourished, the latter becoming increasingly common during the middle - upper Soudleyan.

Lower Longvillian

The dalmanellid - sowerbyellid "mega" community became firmly established, with common intergradation from the Dinorthis community which diminished during the late Lower Longvillian.

Upper Longvillian

This stage appears characterised by the Nicolella community, with variable intergradation from all three other communities.

Marshbrookian (?)

Although the presence of this stage is not proven, the Nicolella community possibly persisted into the Marshbrookian, eventually being replaced by the Pelagic Community (Boucot 1975, p.12,254-256).

Broad comparisons exist between the community successions in Snowdonia and the Berwyn Hills, although throughout the Lower Longvillian in the latter area the Dinorthis community predominated, with intergradation from the Howellites community. The converse situation concurrently existed in Snowdonia which probably arose from the depositional area in the Berwyn Hills being subjected to influxes of relatively coarser clastics, possibly linked with shallower water conditions (inner - sublittoral) plus increased current activity and higher energy levels.

A detailed community succession is lacking for the Bala area, but faunal evidence suggests a similar sequence.

f) Palaeogeography

i) Discussion

It has long been accepted that the Caradocian clastic sediments of Snowdonia accumulated within a depositional area termed the Welsh Basin (Brenchley 1969; Fitton & Hughes 1970; Phillips et al. 1976; Rast 1961,1969; Williams 1969a,b, 1976; Wood 1974), bounded to the south-east by the Midland Platform and to the north-west by a smaller, "linear", north-east - south-west trending landmass variously termed the Irish Sea Landmass (George 1963), the Irish Horst or the Anglesey - Rosslare ridge. The postulated basin width is approximately 160 kms. (Rast 1969, p.330) and was originally believed to be a "geosyncline" (Jones 1938), a proposal later criticised (Boswell 1961). It is now accepted that "....while the Welsh basin of sedimentation was not a major geosyncline in the strict sense, it was adjacent to one and was only separated from it by the so-called Irish Sea Massif" (Rast 1969, p.330).

Within Snowdonia, a broad pattern of sedimentation is recognised. Sedimentological and faunal evidence from northern and north-western areas suggest shallow water conditions (littoral - inner sublittoral) whereas evidence from southern and eastern areas implies deeper water sedimentation (offshore, outer sublittoral). This pattern is consistent with a landmass situated to the north-west.

Any palaeogeographical reconstruction is far from simple. Localised depositional patterns are undoubtedly generated in submarine environments adjacent to landmasses supplying clastics (e.g., the Irish Sea Landmass) and such patterns only complicate the overall picture. The lack of data from intervening areas likewise precludes detailed palaeogeographical reconstructions.

A solution to the problem of whether welding fabrics in ignimbrites can be developed if subaqueously emplaced is a pre-requisite for accurate palaeogeographical reconstructions. Welding textures are thought indicative of subaerial deposition (Beavon 1963; Beavon et al. 1961; Brenchley 1964; Fitch 1971; Hollingworth 1954; Oliver 1954; Rankin 1960; Rast 1961,1962,1969; Rast et al.1958), Rast's "blister hypothesis" (op.cit.) equating ignimbrite deposition with subaerial conditions. However, recent work indicates welding may develop in subaqueous environments (Francis & Howells 1973; Howells et al.1971, 1973,1978; Nutt, in discussion of Brenchley 1969; Wright & Coward 1977) and challenges the need to stipulate subaerial conditions for either welding or ash flow eruption and emplacement. Howells et al.(1978, p.7) believe ".... welding can occur in a submarine environment if the eruptive source is subaerial".

In resolving these contrary points, the environment in which emplacement occurred and the stratigraphic relationships should be examined. The author believes a compromise exists, i.e., certain ignimbrites were subaerial whereas others were subaqueously emplaced and further supposes that emplacement in very shallow water would produce no significant retardation in the degree of welding developed (see Wright & Coward 1977). Rast(1962) believes the basal sillar tuff of the Lower Pitt's Head Tuffs indicates that it ".... entered very shallow water or, alternatively, settled on wet ground " (op.cit., p.2). Until fully resolved, this problem obviously restricts palaeogeographical reconstructions within Snowdonia.

A temporal palaeogeographic reconstruction is proposed :-

Harnagian

Slow sedimentation prevailed with only fine sediments being deposited. The Irish Sea landmass formed a positive area of low relief, not yet having undergone tectonic uplift. Subsidence of the Welsh Basin had not yet started. Impoverished shelly faunas became established on muddy seafloors in either offshore or restricted environments.

Lower Soudleyan

Uplift of the Irish Sea landmass produced a positive area of high relief, consequently providing an abundant source of clastic sediments which formed prograding aprons into the shallow water environments (i.e., Pren-teg Grits - Shackleton 1959) of the subsiding Welsh Basin, which continued subsiding up until the Upper Longvillian. Changes in sedimentation, current velocity and current direction produced periods of finer grade clastic sedimentation.

Middle-upper Soudleyan

Clastic sedimentation continued. Further uplift of the landmass provided continual supplies of abundant clastic sediments. Shallow water facies were developed immediately adjacent to the landmass whilst outer sublittoral conditions existed further south.

The Capel Curig Volcanic Formation (Howells et al. 1978) was emplaced, probably being derived from the aforesaid landmass. The ash-flows were initially subaerial, but southwards became progressively emplaced in marginal marine and fully marine environments. The upper parts of these units were reworked, providing intrabasinal volcaniclastic sources.

The Irish Sea landmass nearshore zone possibly consisted of numerous banks and bars of unstable, coarse clastic/volcaniclastic sediments which were constantly modified and reworked by wave, current and storm activity (cf. Rast's "island archipelago" (1962,p.3)). The absence of onshore faunas was probably due to prograding shorelines (Anderson 1971).

Lower Longvillian

Associated faunal evidence suggests the eruptive activity which produced the Snowdon Volcanic Group (Howells et al. 1978) was initiated at this time. However, whilst violent volcanic activity proceeded in central Snowdonia, clastic sedimentation continued elsewhere, revealing the localised nature of the eruptive activity and implies central Snowdonia was the intrabasinal source for these volcanic units.

Evidence from the Llyn Cowlyd area indicates clastic sedimentation gradually declined throughout the Lower Longvillian. Presumably, uplift of the Irish Sea landmass had ceased. This area then became rapidly denuded (submerged ? - Rast 1969, p.330) and ceased supplying abundant clastic sediments.

West of Moel Hebog, an intercalated, laterally impersistent conglomerate divides the Pitt's Head Tuffs into two units. Below the lower unit, coarse sandstones presumably betoken shoaling prior to the emergence of the subaerial surfaces on which the ignimbrites became subsequently deposited. Wright & Coward (1977) interpret these sandstones as shallow marine shelf deposits, and from these and "....rootless vents" (op.cit.) conclude the Pitt's Head Tuffs were emplaced in a "....gently shelving shallow water environment" (op.cit.,p.139) in which low banks, bars and points would be surrounded by tracts of shallow water. Within such an environment, an ash-flow could be emplaced partly subaerially and partly in shallow water. The author believes the constituent rounded pebbles within the conglomerate and their likely provenance imply this unit embraces most of the Lower Longvillian (but see section h, note 10).

Spectacular local lahars and breccias (e.g., the Llyn Dinas Breccias) conceivably originated from landslides and mudflows associated with tectonic uplift plus seismic and volcanic activity.

Upper Longvillian

Faunal evidence indicates the remainder of the Snowdon Volcanic Group is confined to the Upper Longvillian. Clastic sedimentation and volcanic activity proceeded simultaneously in central Snowdonia as evinced by sediment intercalations between and within the volcanic units. A similar depositional environment to that of the Pitt's Head Tuffs is proposed for the Lower Rhyolitic Tuff Formation.

To the south at Dolwyddelan, the Snowdon Volcanic Group was apparently emplaced in lower offshore (outer sublittoral) waters. Near Betws-y-Coed, lateral equivalents of the Lower Rhyolitic Tuff Formation (=Lower Crafnant Volcanic Formation) were possibly emplaced as turbid flows or slurries in a similar environment (Howells et al. 1973). A probable subaerial - subaqueous transition occurs within the Lower Crafnant Volcanic Formation along a north-west (Llyn Cowlyd) - south-east (Betws-y-Coed) traverse. A probable unconformity below this Formation at Llyn Cowlyd infers uplift and subsequent erosion preceeded emplacement of the volcanic units.

Howells et al. (1973) propound the following points :-

a) At Moel Siabod, reworked volcaniclastic material within the Lower Rhyolitic Tuff Formation infers shallower water deposition than that at Dolwyddelan (conforming to the overall south-easterly deepening trend). Intercalated fossiliferous sediments indicate deposition in an outer (?) sublittoral environment.

b) The lower and middle units of this Formation were derived from central Snowdonia, whilst the upper unit (based on lithological differences) was possibly of north-easterly derivation.

Within central and western Snowdonia, the upper Lower Rhyolitic Tuff Formation attests to sporadic marine conditions with deposition in moderately shallow water.

The overlying Bedded Pyroclastic Formation was generally subaqueously deposited, whilst at Dolwyddelan, the Upper Rhyolitic Tuff Formation is demonstrably an offshore deposit.

The final act of sedimentation was the deposition of black, occasionally graptolitic shales although deposition was initiated before the volcanic episode had ceased. By now, the denuded (submerged ?) Irish Sea landmass provided little clastic sediment. Black shale deposition was possibly initiated by one of several processes :-

a) Previously deposited volcaniclastic and volcanic material conceivably formed barriers (subaerial/submarine), as would rising submarine ridges or rifted remnants of the magmatic arc, which consequently created restricted marine environments containing deoxygenated stagnant waters with infrequent ingress by oceanic currents.

b) A decrease or cessation in volcaniclastic sedimentation may have permitted possible encroachment by the "graptolitic shale belt" (see Churkin 1974) which may have been accompanied by further slight basinal subsidence.

c) A combination of a) and b).

The thickness of the Dolwyddelan Black Slates suggests black shale deposition possibly persisted into the Marshbrookian (see Churkin et al. 1977).

ii) Snowdonian palaeogeography within a tectonic setting

Recent workers (Dewey 1969; Fitton & Hughes 1970; Jeans 1973; Phillips et al. 1976) maintain the Iapetus Ocean ("proto-Atlantic") separated the north-western and south-eastern forelands of the Caledonian/Appalachian geosyncline. Iapetus expansion continued from the upper Precambrian - early Ordovician. Contraction, effected by lithospheric plate subduction, proceeded from the middle Ordovician - Devonian (Mitchell & Reading 1971). The south-eastern subduction zone possessed a north-east - south-west trend through the area just north of the present-day Lake District and County Waterford (south-east Ireland).

From Dewey's (1969) model, the Ordovician volcanism of Snowdonia was initially deduced to be part of an island-arc complex, partly from the chemical variation in magma type (tholeiitic - calc-alkali - alkali) from the Lake District to North Wales, which proved the existence of a south-eastward dipping subduction system (Fitton & Hughes 1970; Matsuda & Uyeda 1971; Mitchell & Reading 1971; Platt 1976; Williams 1976; Windley 1977; Wood 1974). However, an environment similar to that of a continental margin ("Andean-type") is now proposed (Floyd et al. 1976; Howells et al. 1978; Moseley 1977; Phillips et al. 1976), with a continental margin magmatic arc (Dickinson 1974) (= ensialic arcs, Garson & Mitchell 1976, p.81), although the volcanic chain may form islands, the back-arc area being occupied by shallow seas (Dickinson 1974). Phillips et al. (1976, p.590) consider a continental margin volcanic arc extended from the Lake District to Dingle.

The same authors conclude the Welsh Basin was an "....ensialic basin formed by small-scale, behind-arc spreading" (op.cit.) which, following rifting, migrated away from the Midland Platform (Dickinson 1974; Garson & Mitchell 1976). Similar basins are of extensional origin, resulting from ascent of a "diapiric" magma body derived from melting of the upper part of the subducted plate (Karig 1970, 1971, 1972; Matsuda & Uyeda 1971; Packham & Falvey 1971; Scholz et al. 1971), flattening and spreading of the diapir initiating back-arc spreading (Scholz et al. 1971). The Tan-y-Grisiau microgranite may be the surface expression of such a body (Jeans 1973), as Snowdonia is underlain at shallow depths by a large granitic mass (op.cit.; Rast 1969) which possibly represents a flattened "diapir".

Wood (1974, p.334,342) believes the late Precambrian Arvonian ignimbrites represent recycled upper crustal material derived by melting from the Monian rocks of Anglesey during subduction near the margin of the incipient Welsh Basin, and a similar process may account for the Caradocian ignimbrites (op.cit.). However, it is not certain whether the surface eruption of the acidic volcanics was from fissures or calderas, although a central caldera has been postulated (Rast 1969).

Within ancient and modern marginal (= back-arc) basins, distinctive sedimentation patterns are discerned (Churkin 1974; Dickinson 1974; Karig 1970; Karig & Moore 1975; Mitchell & Reading 1969, 1971). Thick prograding aprons of volcaniclastics derived from the magmatic arc are developed adjacent to the arc. These aprons may possess interbedded fossiliferous strata, airborne ash and welded ash-flows. The volcaniclastic debris usually provides the greatest volume of sediment within the basin. Beyond the distal margins of these aprons, fine calcareous sediments and brown muds accumulate (being primarily derived from the volcanic chain), reflecting a progressive decrease in volcaniclastic sedimentation with increasing distance from the volcanic chain. Brown pelagic clays become deposited (at 2-3m./m.y. - Karig & Moore 1975, p.236) if the basin subsides below the carbonate compensation depth, for which no modern-day, world-wide standard value exists (Bathurst 1971, p.268). Churkin (1974) notes the "volcaniclastic - graywacke belt" grades into a "graptolitic shale - chert belt" towards the continental mass.

The Snowdonian sediments reveal a broadly similar sequence. Soudleyan-Lower Longvillian tuffaceous sediments in central Snowdonia may be equated with the volcaniclastic aprons, generally finer sediments to the south possibly representing their distal parts. The Snowdon Volcanic

Group resulted from intrabasinal volcanic activity which probably provided additional volcaniclastic sources. Above and including the upper Lower Rhyolitic Tuff Formation, some volcanic units and intercalated sediments become calcareous, arising from a gradual decrease in volcaniclastic sedimentation. The youngest Snowdonian sediments, conformably overlying the calcareous sediments, are black graptolitic slates which may be equivalent to the brown pelagic clays (Karig & Moore 1975). A reduction in volcaniclastic sedimentation possibly followed either a cessation/decrease in volcanic activity and/or denudation or subsidence of the provenance area. Further sedimentological research may possibly reveal a correlation between the Snowdonian and marginal basin sedimentary sequences.

The concept of a contracting Iapetus Ocean explains the anomalous faunal provincialism within the Upper Ordovician. In early Ordovician times, three distinct faunal provinces, e.g., the American, Baltic and Anglo-Welsh, each possessing endemic faunas, were established. During the Caradoc, such provincialism became indistinct and can be related to the onset of subduction which initiated Iapetus contraction. Continued contraction brought each plate (the North American and North European plate, respectively - Burrett 1973, p.171, fig.2), which supported distinctive faunas, into close proximity. Faunal mixing ensued with a concomitant breakdown of provincialism. The first undoubted faunal exchange (Kukruse Wave - Spjeldnaes 1978, p.145) occurred in the upper Costonian (op.cit.) (= Derfel Limestone), followed by the Longvillian Vasalemma Wave (op.cit.), as evinced by the establishment of the Nicolella community with its reduced endemic faunas within the Upper Longvillian throughout Snowdonia. Within the Caradoc, Whittington & Hughes (1972, p.251-259) note the merging of trilobite faunal provinces, with the Welsh, English and south-east Irish faunas being assigned to a "combined" province (Remopleuridid) along with American and Baltic forms, which is interpreted as a direct result of Iapetus contraction (op.cit.). By Ashgillian times, cosmopolitan faunas were established and faunal endemism was lost (Burrett 1973; Spjeldnaes 1978; Williams 1969a,b,1973, 1976; Windley 1977). Williams (1969a,b) had previously explained such faunal phenomena by a series of currents and gyres in a narrow "Proto-Atlantic" although it is now thought the Iapetus Ocean was several thousand kilometres wide prior to contraction.

g) Climate

The following approximate palaeomagnetic/ palaeoclimatic data for the Welsh Basin are recorded :-

30°S. - Smith et al.(1973,p.34,figs.13 & 21A)
warm-temperate - Spjeldnaes (1961)
20-30°S. - Whittington (1966b,p.730,fig.16)
30°S. - Williams (1973,p.263,fig.11)
30°S. - Williams (1976,p.63,fig.18)

Data from Morel & Irving (1978) for the British Isles seemingly contradict the above evidence. At -450 Ma, the South Pole is shown in relatively close proximity to Britain (op.cit.,p.547,fig.5) and a -450 Ma palaeocontinental reconstruction (op.cit.,p.551,fig.9) places the British Isles just below 60°S., but such a reconstruction provides no adequate explanation for the late Ordovician Taconic Orogeny and cosmopolitan faunas (op.cit.,p.547). (The author takes -450Ma as a representative average reference datum for the Caradoc from Churkin et al.1977, Fitch et al.1976, Ross Jr.et al. 1976 and Whittington & Williams 1964).

Spjeldnaes (1976,p.67;1978) notes that Europe, during Iapetus contraction, moved towards warmer waters and Whittington & Hughes (1972) consider the faunas of North America and northern Europe inhabited warm waters.

h) Age relationships

It is stressed that the age determinations for each area are individually derived from faunal and stratigraphic evidence. However, in an overall synthesis (fig.11.1), some anomalies arise, which may result from faunal diachronism. Several conclusions are derived from fig. 11.1 :-

1) The Snowdon Volcanic Group is confined to the Longvillian.

2) The Crafnant Volcanic Group appears restricted to the Upper Longvillian, the uppermost horizons possibly extending into the Marshbrookian.

3) The Snowdon Volcanic Group (excluding the Pitt's Head Tuffs) and Crafnant Volcanic Group are contemporaneous but may have been partly derived from different sources (Howells et al. 1973, p.30-32).

4) The Upper Glanrafon Beds range from the Harnagian - Lower Longvillian (lowest Upper Longvillian ?).

5) The Black Slates conformably overlying the Snowdon Volcanic Group and Crafnant Volcanic Group are Upper Longvillian and probably range into the Marshbrookian.

6) The Capel Curig Volcanic Formation and Lledr Valley Tuffs are contemporaneous although individual correlations are less certain.

7) In eastern Snowdonia, the Pitt's Head Tuffs are absent. However, within the Glanrafon Beds are noted thin, laterally extensive rhyolitic tuffs which are possibly waterlain airfall tuffs. From their stratigraphic relationships and that of the Pitt's Head Tuffs, the author proposes that these tuffs represent the finer

pyroclastic "fallout" derived from the eruptive activity which generated the Pitt's Head Tuffs.Their asymmetrical outcrop may have resulted from the prevailing wind patterns during eruption (Eaton 1964; Fisher 1964).

At Dolwyddelan, these tuffs are intercalated within Lower Longvillian Glanrafon sediments (map 3) whereas at Capel Curig (map 1), consanguineous tuffs are found within Glanrafon beds of upper Soudleyan age, the uppermost tuff possibly being Lower Longvillian.

Possible solutions to this anomaly are :-

a) The tuffs are diachronous.

b) The faunas utilised for dating are diachronous with respect to comparative areas.

c) The Dolwyddelan tuffs are stratigraphically slightly higher than the Capel Curig tuffs and are therefore not laterally equivalent.

Unfortunately this problem is, at present, unresolved.

8) At Llyn Cowlyd, a relatively large unconformity is apparently present below the Crafnant Volcanic Group, but is not recognised at either Capel Curig or Betws-y-Coed. However, the author extends this unconformity to explain the "condensed" sequence at Capel Curig. Only the upper horizons of unit p plus unit t (chap.7) can reasonably be assigned to the Lower Longvillian. Therefore it is unlikely these units are wholly equivalent to the Lower Longvillian sediments (> 600m.thick) at Llyn Cowlyd,

but the presence of an unconformity would account for this. Such an unconformity at Betws-y-Coed remains to be proven.

9) The intra-Pitt's Head conglomerate implies a significant time period elapsed between emplacement of the Lower and Upper Pitt's Head Tuffs. The author earlier proposed the conglomerate represented most of the Lower Longvillian (chap.8). On comparison with the area to the east of Beddgelert, it seems the conglomerate represents only part of the Lower Longvillian, as the Llyn Dinas Breccias (which are probably Lower Longvillian) unconformably overlie the Lower and Middle Lapilli-tuffs (= Lower and Upper Pitt's Head Tuffs, respectively). Therefore, the Upper Pitt's Head Tuffs may be mid-Lower Longvillian. Consequently, an unconformity may be present below the Lower Rhyolitic Tuffs on Moel Hebog, perhaps equating with the disconformity below the Upper Lapilli-tuffs (Beavon 1963,p.489) to the east of Beddgelert.

10) Faunal evidence from Dolwyddelan and Moel Siabod suggests either an unconformity or a thin wedge of Upper Longvillian sediments exists below the Lower Rhyolitic Tuff Formation in the Dolwyddelan area. An unconformity may be inferred at Dolwyddelan from the variable thickness between the rhyolitic tuffs intercalated within the Glanrafon Beds and the base of the aforesaid Formation.

11) Faunal evidence from Dolwyddelan and Betws-y-Coed supports the correlation (Howells et al. 1973, p.31,fig.7) between the Lower Rhyolitic Tuff and Lower Crafnant Volcanic Formations.

In conclusion, the possibility of faunal diachronism, when correlating the Snowdonian faunas with faunas from other areas (e.g., Bala, Shropshire) should not be ignored (chap.10,section f,10). Facies control as demonstrated by the benthic communities, plus provincial mixing, may engender complex faunal diachronism. In Snowdonia, the situation may ultimately arise when comparing faunas with the nearest comparable area (e.g., Bala) that horizons are referred to as "pre-" and "post-Cymerig Limestone" rather than as Lower and Upper Longvillian, Stages which were originally differentiated utilising faunas from Shropshire (Bancroft 1929a,b,1933,1945).

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Foreword to the list of cited references

In the following reference list, the abbreviations of the cited serial publications are those as catalogued in the "List of serial publications held in the library of the Geological Society, London " (published by the Geological Society, 1978, 172pp.). Such abbreviations are in accordance with B.S.4148, which is an agreed international system of abbreviating periodical titles and replaces the World List of Periodicals. However, certain serial publications (marked *) are not held in the library of the Geological Society and are therefore not contained within the aforesaid "List". Consequently, these publications are abbreviated in accordance with the World List of Scientific Publications.

CITED REFERENCES

AGER, D.V. 1965. The adaptation of Mesozoic brachiopods to different environments. Palaeogeogr.Palaeoclimatol. Palaeoecol. 1, 143-172.

AGER, D.V. 1967. Brachiopod palaeoecology. Earth Sci.Rev. 3, 157-179.

ALLEN, J.R.L. 1963. The classification of cross stratified units, with notes on their origin. Sedimentology. 2, 93-114.

ALLEN, J.R.L. 1967. Depth indicators of clastic sequences. Mar.Geol. 5, 429-446.

ALLEN, J.R.L. 1970. Physical processes of sedimentation. Allen & Unwin, London, 248pp.

ALLEN, J.R.L. 1977. The possible mechanics of convolute lamination in graded sand beds. J.geol.Soc.London. 134, 19-31.

ALLEN, P. 1946. Notes on Wealden fossil soil beds. Proc.Geol.Assoc.London. 57, 303-314.

ANDERSON, E.J. 1971. Environmental models for Palaeozoic communities. Lethaia. 4, 287-302.

ANKETELL, J.M., CEGLA, J. & DZULYNSKI, S. 1969. Unconformable surfaces formed in the absence of current erosion. Geologica Romana. 8, 41-46.

ANKETELL, J.M., CEGLA, J. & DZULYNSKI, S. 1970. On the deformational structures in systems with reversed density gradients. Rocz.Pol.Tow.geol.Krakowie. 40, 3-30.

APPLEBY, R.M. & JONES, G.L. 1976. The Analogue Video Reshaper - a new tool for palaeontologists. Palaeontology.London. 19, 565-586.

ATHY, L.F. 1930. Density, porosity and compaction of sedimentary rocks. Bull.Am.Assoc.Petrol.Geol. 14, 1-24.

BANCROFT, B.B. 1928a. On the notational representation of the rib-system in Orthacea. Mem.Proc.lit.phil.Soc. Manchester. 72, 53-90.

BANCROFT, B.B. 1928b. The Harknessellinae. Mem.Proc.lit. phil.Soc.Manchester. 72, 173-196.

BANCROFT, B.B. 1928c. On the unconformity at the base of the Ashgillian in the Bala district. Geol.Mag. 65, 484-493.

BANCROFT, B.B. 1929a. Some new genera and species of Strophomenacea from the Upper Ordovician of Shropshire. Mem.Proc.lit.phil.Soc.Manchester. 73, 33-65.

BANCROFT, B.B. 1929b. Some new species of Cryptolithus, (s.l.), from the Upper Ordovician. Mem.Proc.lit.phil. Soc.Manchester. 73, 67-98.

BANCROFT, B.B. 1933. Correlation tables of the Stages Costonian to Onnian in England and Wales. Privately published at Nibley House, Blakeney, Glos., 4pp.

BANCROFT, B.B. 1945. The brachiopod zonal indices of the Stages Costonian to Onnian in Britain. J.Paleontol. 19, 181-252.

BANCROFT, B.B. 1949. Upper Ordovician trilobites of zonal value in south-east Shropshire. Proc.R.Soc.London. Sect.B 136, 291-315.

BANKS, N.L. 1970. Trace fossils from the late Precambrian and Lower Cambrian of Finnmark, Norway. In Crimes, T.P. & Harper, J.C. (eds.). Trace fossils. Geol.J.Spec. Issue. 3, 19-34.

BASSETT, D.A. 1963. The Welsh Palaeozoic Geosyncline : a review of recent work on stratigraphy and sedimentation. In Johnson, M.R.J. & Stewart, F.H. (eds.). The British Caledonides. Oliver & Boyd, Edinburgh, 35-69.

BASSETT, D.A. 1969. Some of the major structures of early Palaeozoic age in Wales and the Welsh Borderland. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 67-116.

BASSETT, D.A., WHITTINGTON, H.B. & WILLIAMS, A. 1966. The stratigraphy of the Bala district, Merionethshire. Q.J.geol.Soc.London. 122, 219-271.

BASSLER, R.S. 1953. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part G, Bryozoa. Geological Society of America and University of Kansas Press, 253pp.

BATES, D.E.B. 1968. The Lower Palaeozoic brachiopod and trilobite faunas of Anglesey. Bull.Br.Mus.nat.Hist. Ser.Geol. 16, 125-199.

BATESON, J.H. 1965. Accretionary lapilli in a geosynclinal environment. Geol.Mag. 102, 1-7.

BATHURST, R.G.C. 1971. Carbonate sediments and their diagenesis. Dev.Sedimentol. 12, 620pp.

BAYER, T.N. 1967. Repetitive benthonic community in the Maqouketa Formation (Ordovician) of Minnesota. J.Paleontol. 41, 417-422.

BAYLY, B. 1974. Cleavage not parallel to finite-strain ellipsoid's XY-plane : discussion. Tectonophysics. 23, 205-207.

BEAVER, H.H. et al. 1967. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part S, Echinodermata 1. Geological Society of America and University of Kansas Press, 650pp.

BEAVON, R.V. 1960. The geology of an area east of Beddgelert (North Wales). Unpublished Ph.D. thesis, University College of Wales, Aberystwyth.

BEAVON, R.V. 1963. The succession and structure east of the Glaslyn river, North Wales. Q.J.geol.Soc.London. 119, 479-512.

BEAVON, R.V. 1974. Discussion of Ordovician transgressive ash-flow tuffs of Snowdonia, North Wales. J.geol.Soc.London. 130, 479-480.

BEAVON, R.V., FITCH, F.J. & RAST, N. 1961. Nomenclature and diagnostic characters of ignimbrites with reference to Snowdonia. Liverpool Manchester geol.J. 2, 600-611.

BEEK, J.L. VAN & KOSTER, E.A. 1972. Fluvial and estuarine sediments exposed along the Oude Maas (the Netherlands). Sedimentology. 19, 237-256.

BEGG, J.L. 1934. On the genus Cyclocystoides. Geol.Mag. 71, 220-224.

BEGG, J.L. 1940 (for 1939). On the genus Cyclocystoides, with the description of a new species from the Ashgillian of Girvan. Trans.geol.Soc.Glasgow. 20, 21-28.

BEHRENS, E.W. & WATSON, R.L. 1969. Differential sorting of pelecypod valves in the swash zone. J.sediment.Petrol. 39, 159-165.

BENSON, R.H. et al. 1961. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part Q, Arthropoda 3. Geological Society of America and University of Kansas Press, 442pp.

BERGSTROM, J. 1968. Some Ordovician and Silurian brachiopod assemblages. Lethaia. 1, 230-237.

BILLINGS, M.P. 1972. Structural geology. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 606pp.

BLATT, H., MIDDLETON, G. & MURRAY, R. 1972. Origin of sedimentary rocks. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 634pp.

BLISSENBACH, E. 1954. Geology of alluvial fans in semiarid regions. Bull.geol.Soc.Am. 65, 175-189.

BLOXHAM, T.W. & PRICE, N.B. 1961. Stilpnomelane in North Wales. Nature.London. 190, 525-526.

BOND, A. & SPARKS, R.S.J. 1976. The Minoan eruption of Santorini, Greece. J.geol.Soc.London. 132, 1-16.

*BONDE, N. 1974. Palaeoenvironment as indicated by the "Mo-clay formation" (lowermost Eocene of Denmark). Tertiary Times. 2, 29-36.

BORRADAILE, G.J. 1974. Contribution to discussion concerning the relationship between slaty cleavage and the XY-plane of the strain ellipsoid. Tectonophysics. 23, 208.

BORRADAILE, G.J. 1977. On cleavage and strain : results of a study in West Germany using tectonically deformed sand dykes. J.geol.Soc.London. 133, 146-164.

BORRADAILE, G.J. & JOHNSON, H.D. 1973. Finite strain estimates for the Dalradian Dolomitic Formation of Islay, Argyll, Scotland. Tectonophysics. 18, 249-259.

BOSWELL, P.G.H. 1949. The Middle Silurian rocks of North Wales. Edward Arnold & Co., London.

BOSWELL, P.G.H. 1961. The case against a Lower Palaeozoic geosyncline in Wales. Liverpool Manchester geol.J. 2, 612-624.

BOUCEK, B. 1964. The Tentaculites of Bohemia. Publishing House of the Czechoslovak Academy of Sciences, Prague, 215pp.

BOUCOT, A.J. 1953. Life and death assemblages among fossils. Am.J.Sci. 251, 25-40.

BOUCOT, A.J. 1975. Evolution and extinction rate controls. Elsevier, Amsterdam, 427pp.

BOUCOT, A.J., BRACE, W. & DEMAR, R. 1958. Distribution of brachiopod and pelecypod shells by currents. J.sediment.Petrol. 28, 321-332.

BOYD, D.W. & NEWELL, N.D. 1972. Taphonomy and diagenesis of a Permian fossil assemblage from Wyoming. J.Paleontol. 46, 1-14.

BRADLEY, W.H. 1957. Physical and ecological features of the Sagahadoc Bay tidal flat, Georgetown, Maine. In Ladd, H.S. (ed.). Treatise on marine ecology and paleoecology. Vol.2. Paleoecology. Mem.geol.Soc.Am. 67(2), 641-682.

BREIDDIN, H. 1956. Die tektonische Deformation der Fossilien im Rheinischen Schiefergebirge. Z.Deutsch. geol.Ges. 106, 227-305.

BRENCHLEY, P.J. 1964. Ordovician ignimbrites in the Berwyn Hills, North Wales. Geol.J. 4, 43-54.

BRENCHLEY, P.J. 1969. The relationship between Caradocian volcanicity and sedimentation in North Wales. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 181-202.

BRENCHLEY, P.J. 1972. The Cwm Clywd Tuff, North Wales : A palaeogeographical interpretation of some Ordovician ash-shower deposits. Proc.Yorkshire geol.Soc. 39, 199-224.

BRENCHLEY, P.J. & NEWALL, A.G. 1970. Flume experiments on the orientation and transport of models and shell valves. Palaeogeogr.Palaeoclimatol.Palaeoecol. 7, 185-220.

BRENCHLEY, P.J. & NEWALL, A.G. 1977. The significance of contorted bedding in Upper Ordovician sediments of the Oslo region, Norway. J.sediment.Petrol. 47, 819-833.

BRENCHLEY, P.J. & PICKERILL, R.K. (in press) (See PICKERILL, R.K. & BRENCHLEY, P.J. 1979).

BRETSKY, P.W. 1969a. Central Appalachian late Ordovician communities. Bull.geol.Soc.Am. 80, 193-212.

BRETSKY, P.W. 1969b. Evolution of Paleozoic benthic marine invertebrate communities. Palaeogeogr.Palaeoclimatol. Palaeoecol. 6, 45-59.

BRETSKY, P.W. 1970a. Upper Ordovician ecology of the Central Appalachians. Bull.Peabody Mus.nat.Hist. 34, 1-150.

BRETSKY, P.W. 1970b. Late Ordovician benthic marine communities in north central New York. Bull.New York State Mus.Sci.Serv. 44, 1-34.

BRETSKY, P.W. & BRETSKY, S.S. 1975. Succession and repetition of late Ordovician fossil assemblages from the Nicolet River valley, Quebec. Paleobiology. 1, 225-237..

BRETSKY, P.W. & LORENZ, D.M. 1970. An essay on genetic-adaptive strategies and mass extinctions. Bull.geol. Soc.Am. 81, 2449-2456.

BRETSKY, P.W., FLESSA, K.W. & BRETSKY, S.S. 1969. Brachiopod ecology in the Ordovician of eastern Pennsylvania. J.Paleontol. 43, 312-321.

BRIDGES, P.H. 1975. The transgression of a hard substrate shelf : the Llandovery (Lower Silurian) of the Welsh Borderland. J.sediment.Petrol. 45, 79-94.

BROMLEY, A.V. 1965. Intrusive quartz latites in the Blaenau Ffestiniog area, Merioneth. Geol.J. 4, 247-256.

BROMLEY, A.V. 1968. A volcanic vent in the Tremadocian rocks southeast of Blaenau Ffestiniog, Merionethshire, North Wales. Geol.J. 6, 7-12.

BROMLEY, A.V. 1969. Acid plutonic igneous activity in the Ordovician of North Wales. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 387-408.

BRONDOS, M.D. & KAESLER, R.L. 1976. Diversity of assemblages of late Paleozoic Ostracoda. In Scott, R.W. & West, R.R. (eds.). Structure and classification of paleocommunities. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pennsylvania, 213-234.

BRONGERSMA-SANDERS, M. 1971. Origin of major cyclicity of evaporites and bituminous rocks : an actualistic model. Mar.Geol. 11, 123-144.

BROOKES KNIGHT, J. et al. 1960. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part I, Mollusca 1. Geological Society of America and University of Kansas Press, 351pp.

BULL, W.B. 1972. Recognition of alluvial-fan deposits in the stratigraphic record. In Rigby, J.K. & Hamblin, W.K. (eds.). Recognition of ancient sedimentary environments. Spec.Publ.Soc.econ.Paleontol. Mineral.Tulsa. 16, 63-83.

BULMAN, O.M.B. 1945-1947. A monograph of the Caradoc (Balclatchie) graptolites from limestones in Laggan Burn, Ayrshire. Monogr.palaeontogr.Soc.London. 430 (1945), 1-42;433 (1946), 43-58;439 (1947), 59-78.

BURNE, R.V. 1970. The origin and significance of sand volcanoes in the Bude Formation (Cornwall). Sedimentology. 15, 211-228.

BURRETT, C. 1973. Ordovician biogeography and continental drift. Palaeogeogr.Palaeoclimatol.Palaeoecol. 13, 161-201.

CALEF, C.E. & HANCOCK, N.J. 1974. Wenlock and Ludlow marine communities in Wales and the Welsh Borderlands. Palaeontology.London. 17, 779-810.

CAVE, R. 1965. The Nod Glas sediments of Caradoc age in North Wales. Geol.J. 4, 279-298.

CAVE, R. & DEAN, W.T. 1959. Four British Ordovician species of dalmanelloid brachiopod. Palaeontology.London. 1, 292-297.

CHAPMAN, V.J. 1962. The Algae. Macmillan, London, 472pp.

CHAVE, K.E. 1964. Skeletal durability and preservation. In Imbrie, J. & Newell, N.D. (eds.). Approaches to paleoecology. John Wiley, New York, 377-387.

*CHUANG, S.H. 1956. The ciliary feeding mechanisms of Lingula unguis (L) (Brachiopoda). Proc.zool.Soc.Lond. 127, 167-189.

CHURKIN, Jr., M. 1974. Paleozoic marginal ocean basin - volcanic arc systems in the Cordilleran foldbelt. In Dott, Jr., R.H. & Shaver, R.H. (eds.). Modern and ancient geosynclinal sedimentation. Spec.Publ.Soc. econ.Paleontol.Mineral.Tulsa. 19, 174-192.

CHURKIN, Jr., M., CARTER, C. & JOHNSON, B.R. 1977. Subdivision of Ordovician and Silurian time scale using accumulation rates of graptolitic shale. Geology. 5, 452-456.

CLARKSON, E.N.K. 1968. Structure of the eye of Crozonaspis struvei (Trilobita, Dalmanitidae, Zeliszkellinae). Senckenbergiana Lethaea. 49, 383-393.

CLIFTON, H.E. 1969. Beach lamination : nature and origin. Mar.Geol. 7, 553-559.

CLIFTON, H.E. 1971. Orientation of empty pelecypod shells and shell fragments in quiet water. J.sediment.Petrol. 41, 671-682.

CLIFTON, H.E. & BOGGS, Jr., S. 1970. Concave-up pelecypod (Psephidia) shells in shallow marine sand, Elk River Beds, southwestern Oregon. J.sediment.Petrol. 40, 888-897.

CLIFTON, H.E., HUNTER, R.E. & PHILLIPS, R.L. 1971. Depositional structures and processes in the non-barred high-energy nearshore. J.sediment.Petrol. 41, 651-670.

CLOOS, E. 1947. Oolite deformation in the South Mountain fold, Maryland. Bull.geol.Soc.Am. 58, 843-918.

COCKS, L.R.M. 1967. Depth patterns in Silurian marine coomunities. Mar.Geol. 5, 379-382.

COCKS, L.R.M. 1978. A review of British Lower Palaeozoic brachiopods, including a synoptic review of Davidson's Monograph. Monogr.palaeontogr.Soc.London. 549, 1-256.

COCKS, L.R.M. & McKERROW, W.S. 1978. Ordovician. *In* McKerrow, W.S. (ed.). *The ecology of fossils*. Duckworth, London, 62-91.

COLEMAN, J.M. & GAGLIANO, S.M. 1965. Sedimentary structures : Mississippi River deltaic plain. *In* Middleton, G.V. (ed.). Primary sedimentary structures and their hydrodynamic interpretation. *Spec.Publ.Soc. econ.Paleontol.Mineral.Tulsa*. *12*, 133-148.

COMPTON, R.R. 1962. *Manual of field geology*. John Wiley, New York, 378pp.

COWPER-REED, W.H.C. 1920-1921. British Ordovician and Silurian Bellerophontacea. *Monogr.palaeontogr.Soc. London*. *345* (1920), 1-48;*347* (1921), 49-92.

COX, L.R. et al. 1969. *In* Moore, R.C. (ed.). *Treatise on invertebrate paleontology*, *Part N*, *Mollusca 6* (1 of 3). Geological Society of America and University of Kansas Press, 489pp.

CRAIG, G.Y. 1952. A comparative study of the ecology and palaeoecology of *Lingula*. *Trans.geol.Soc.Edinburgh*. *15*, 110-120.

CRAIG, G.Y. 1954. The palaeoecology of the Top Hosie Shale (Lower Carboniferous) at a locality near Kilsyth. *Q.J.geol.Soc.London*. *110*, 103-109.

CRAIG, G.Y. 1967. Size-frequency distribution of living and dead populations of pelecypods from Bimini, Bahamas, British West Indies. *J.Geol.Chicago*. *75*, 34-45.

CRAIG, G.Y. & HALLAM, A. 1963. Size-frequency and growth ring analysis of *Mytilus* *edulis* and *Cardium* *edule* and their palaeoecological significance. *Palaeontology. London*. *6*, 731-750.

CRAIG, G.Y. & JONES, N.S. 1966. Marine benthos, substrate and palaeoecology. *Palaeontology.London*. *9*, 30-38.

CRIMES, T.P. 1970. The significance of trace fossils in sedimentology, stratigraphy and palaeoecology with examples from Lower Palaeozoic strata. In Crimes, T.P. & Harper, J.C. (eds.). Trace fossils. Geol.J.Spec. Issue. 3, 101-126.

CROWE, B.M. & FISHER, R.V. 1973. Sedimentary structures in base-surge deposits with special reference to cross-bedding, Ubehebe Craters, Death Valley, California. Bull.geol.Soc.Am. 84, 663-682.

CROWELL, J.C., HOPE, R.A., KAHLE, J.E., OVENSHINE, A.T. & SAMS, R.H. 1966. Deep water sedimentary structures, Pliocene Pico Formation, Santa Paula Creek, Ventura Basin, California. Spec.Rep.California Div.Mines. 89, 40pp.

DAKYNS, J.R. 1900. First fruits of a geological examination of Snowdon. Geol.Mag. 37, 267-273.

DAKYNS, J.R. & GREENLY, E. 1905. On the probable pelean origin of the felsitic slates of Snowdon, and their metamorphism. Geol.Mag. 42, 541-549.

DAVIDSON, T. 1866-1884. The Fossil Brachiopoda. Monogr. palaeontogr.Soc.London.84 (1866), 1-88;87 (1867), 89-168;96 (1869), 169-248;108 (1871), 249-397;172 (1882), 1-134;177 (1883), 135-242;183 (1884), 243-476.

DAVIES, D.A.B. 1936. The Ordovician rocks of the Trefriw district (North Wales). Q.J.geol.Soc.London. 92, 62-90.

DAVIS, J.E. 1846. On the geology of the neighbourhood of Tremadoc, Caernarvonshire. Q.J.geol.Soc.London. 2, 70-75.

DEAN, W.T. 1958. The faunal succession in the Caradoc Series of south Shropshire. Bull.Br.Mus.nat.Hist. Ser.Geol. 3, 191-231.

DEAN, W.T. 1959. The stratigraphy of the Caradoc Series in the Cross Fell inlier. Proc.Yorkshire geol.Soc. 32, 185-228.

DEAN, W.T. 1960a. The Ordovician trilobite faunas of south Shropshire, I. Bull.Br.Mus.nat.Hist. Ser.Geol. 4, 71-143.

DEAN, W.T. 1960b. The use of shelly faunas in a comparison of the Caradoc Series in England, Wales and parts of Scandinavia. 21st.Int.geol.Congr.Norden. 7, 82-87.

DEAN, W.T. 1960c. The Ordovician rocks of the Chatwall district, Shropshire. Geol.Mag. 97, 163-171.

DEAN, W.T. 1961. The Ordovician trilobite faunas of south Shropshire, II. Bull.Br.Mus.nat.Hist. Ser.Geol. 5, 311-358.

DEAN, W.T. 1962. The trilobites of the Caradoc Series in the Cross Fell inlier of northern England. Bull.Br. Mus.nat.Hist. Ser.Geol. 7, 65-134.

DEAN, W.T. 1963a. The Ordovician trilobite faunas of south Shropshire, III. Bull.Br.Mus.nat.Hist. Ser.Geol. 7, 213-254.

DEAN, W.T. 1963b. The Ordovician trilobite faunas of south Shropshire, IV. Bull.Br.Mus.nat.Hist. Ser.Geol. 9, 1-18.

DEAN, W.T. 1963c. The Stile End Beds and Drygill Shales (Ordovician) in the east and north of the English Lake District. Bull.Br.Mus.nat.Hist. Ser.Geol. 9, 47-65.

DEAN, W.T. 1964. The geology of the Ordovician and adjacent strata in the southern Caradoc district of Shropshire. Bull.Br.Mus.nat.Hist. Ser.Geol. 9, 257-296.

DEAN, W.T. 1965. A shelly fauna from the Snowdon Volcanic Series at Twll Ddu, Caernarvonshire. Geol.J. 4, 301-314.

DEWEY, J.F. 1969. Evolution of the Appalachian/Caledonian orogen. Nature.London. 222, 124-129.

DICKINSON, K.A., BERRYHILL, Jr., H.L. & HOLMES, C.W. 1972. Criteria for recognising ancient barrier coastlines. In Rigby, J.K. & Hamblin, W.K. (eds.). Recognition of ancient sedimentary environments. Spec.Publ.Soc. econ.Paleontol.Mineral.Tulsa. 16, 192-214.

DICKINSON, W.R. 1974. Sedimentation within and beside ancient and modern magmatic arcs. In Dott, Jr., R.H. & Shaver, R.H. (eds.). Modern and ancient geosynclinal sedimentation. Spec.Publ.Soc.econ.Paleontol.Mineral. Tulsa. 19, 230-239.

DIGGENS, J.N. & ROMANO, M. 1968. The Caradoc rocks around Llyn Cowlyd, North Wales. Geol.J. 6, 31- 48.

DOTT, Jr., R.H. 1963. Dynamics of subaqueous gravity depositional processes. Bull.Am.Assoc.Petrol.Geol. 47, 104-128.

DURHAM, J.W. 1967. The incompleteness of our knowledge of the fossil record. J.Paleontol. 41, 559-565.

DZULYNSKI, S. & SMITH, A.J. 1963. Convolute lamination, its origin, preservation and directional significance. J.Geol.Chicago. 33, 616-627.

EATON, G.P. 1964. Windborne volcanic ash : a possible index to polar wandering. J.Geol.Chicago. 72, 1-35.

EKDALE, A.A. 1973. Relation of invertebrate death assemblages to living benthic communities in Recent Carbonate sediments along eastern Yucatan coast. Bull.Am.Assoc.Petrol.Geol. 57, 777. (Abstract).

ELLES, G.L. 1922. The Bala country : its structure and rock succession. Q.J.geol.Soc.London. 78, 132-175.

ELLES, G.L. 1939. Factors controlling graptolite successions and assemblages. Geol.Mag. 76, 181-187.

ELLES, G.L. 1940. The stratigraphy and faunal succession in the Ordovician rocks of the Builth-Llandrindod inlier, Radnorshire. Q.J.geol.Soc.London. 95, 383-445.

ELLES, G.L. & WOOD, E.M.R. 1901-1918. A monograph of British graptolites. Monogr.palaeontogr.Soc.London. 260 (1901), 1-54;265 (1902), 55-102;271 (1903), 103-134; 277 (1904), 135-180;288 (1906), 181-216;297 (1907), 217-272;305 (1908), 273-358;316 (1911), 359-414;323 (1913), 415-486;327 (1914), 487-526;339 (1918), cxlix-clxxi.

ELLIOTT, G.F. 1956. Post-Palaeozoic brachiopod ecology : a re-assessment. Geol.Mag. 93, 196-200.

EMERY, K.O. 1968. Positions of empty pelecypod valves on the continental shelf. J.sediment.Petrol. 38, 1264-1269.

*EMERY, K.O., MERRILL, A.S. & TRUMBULL, J.V.A. 1965. Geology and biology of the sea floor as deduced from simultaneous photographs and samples. Limnol.Oceanogr. 10, 1-21.

ENGELDER, T. & ENGELDER, R. 1977. Fossil distortion and décollement tectonics of the Appalachian plateau. Geology. 5, 457-460.

FAGERSTROM, J.A. 1964. Fossil communities in paleoecology : their recognition and significance. Bull.geol.Soc.Am. 75, 1197-1216.

FEARNSIDES, W.G. 1903. The Llanvirn Beds in Carnarvonshire. Rep.Meet.Br.Assoc.Adv.Sci. 73, 665.

FEARNSIDES, W.G. 1910a. North and central Wales. In Monckton, H.W. & Herries, R.S. (eds.). Geology in the field. The Jubilee volume of the Geologists' Association (1858-1908). Stanford, London, 786-825.

FEARNSIDES, W.G. 1910b. The Tremadoc Slates and associated rocks of south-east Carnarvonshire. Q.J.geol.Soc. London. 66, 142-188.

FEARNSIDES, W.G. & DAVIES, W. 1944. The geology of Deudraeth. The country between Traeth Mawr and Traeth Bach, Merioneth. Q.J.geol.Soc.London. 99, 247-276.

FERGUSON, L. 1962. Distortion of Crurithyris urei (Fleming) from the Viséan rocks of Fife, Scotland, by compaction of the containing sediment. J.Paleontol. 36, 115-119.

FERGUSON, L. 1963a. The paleoecology of Lingula squamiformis Phillips during a Scottish Mississippian marine transgression. J.Paleontol. 37, 669-681.

FERGUSON, L. 1963b. Estimation of the compaction factor of a shale from distorted brachiopod shells. J.sediment. Petrol. 33, 796-798.

FISHER, R.V. 1960. Classification of volcanic breccias. Bull.geol.Soc.Am. 71, 973-982.

FISHER, R.V. 1964. Maximum size, median diameter and sorting of tephra. J.geophys.Res. 69, 341-355.

FISHER, R.V. 1971. Features of coarse grained, high-concentration fluids and their deposits. J.sediment Petrol. 41, 916-927.

FISHER, R.V. 1977. Erosion by volcanic base-surge density currents : U-shaped channels. Bull.geol.Soc.Am. 88, 1287-1297.

FISHER, R.V. & WATERS, A.C. 1970. Base surge bed forms in maar volcanoes. Am.J.Sci. 268, 157-180.

FISKE, R.S. 1963. Subaqueous pyroclastic flows in the Ohanapecosh Formation, Washington. Bull.geol.Soc.Am. 74, 391-406.

FISKE, R.S. & MATSUDA, T. 1964. Submarine equivalents of ash flows in the Tokiwa Formation, Japan. Am.J.Sci. 262, 76-106.

FITCH, F.J. 1967. Ignimbrite volcanism in North Wales. Bull.Volcanol. 30, 199-219.

FITCH, F.J. 1971. The recognition of ignimbrites in North Wales. Proc. 1664, 280-282.

FITCH, F.J., FORSTER, S.C. & MILLER, J.A. 1976. The dating of the Ordovician. In Bassett, M.G. (ed.). The Ordovician System : proceedings of a Palaeontological Association symposium, Birmingham, September 1974. University of Wales Press and National Museum of Wales, Cardiff, 15-27.

FITTON, J.G. & HUGHES, D. 1970. Volcanism and plate tectonics in the British Ordovician. Earth planet. Sci.Lett. 8, 223-228.

FLOYD, P.A., LEES, G.J. & ROACH, R.A. 1976. Basic intrusions in the Ordovician of North Wales : geochemical data and tectonic setting. Proc.Geol.Assoc.London. 87, 389-400.

FOX, W.T. 1968. Quantitative paleoecologic analysis of fossil communities in the Richmond Group. J.Geol.Chicago. 76, 613-641.

FRANCIS, E.H. & HOWELLS, M.F. 1973. Transgressive welded ash-flow tuffs among the Ordovician sediments of NE Snowdonia, N.Wales. J.geol.Soc.London. 129, 621-641.

FREY, R.W. 1973. Concepts in the study of biogenic sedimentary structures. J.sediment.Petrol. 43, 6-19.

FREY, R.W. & HOWARD, J.D. 1970. Comparison of Upper Cretaceous ichnofaunas from siliceous sandstones and chalk, western Interior Region, U.S.A. In Crimes, T.P. & Harper, J.C. (eds.). Trace fossils. Geol.J.Spec. Issue. 3, 141-166.

FURSICH, F.T. 1977. Corallian (Upper Jurassic) marine benthic associations from England and Norway. Palaeontology.London. 20, 337-385.

FURSICH, F.T. & HURST, J.M. 1974. Environmental factors determining the distribution of brachiopods. Palaeontology.London. 17, 889-900.

GARSON, M.S. & MITCHELL, A.H.G. 1976. Mineralization at destructive plate boundaries : a brief review. In Volcanic processes in ore genesis. Spec.Publ.geol. Soc.London. 7, 81-97.

GARY, M., McAFEE, Jr., R. & WOLF, C.L. (eds.). 1972. Glossary of geology. American Geological Institute, Washington, D.C., 805pp.

GEIKIE, A. 1897. The ancient volcanoes of Great Britain. Vol.1, 207-218.

GEORGE, T.N. 1955. In discussion of Bassett, M.G. 1955.(The Silurian rocks of the Talerddig district, Montgomeryshire. Q.J.geol.Soc.London. 111, 239-264.) Q.J.geol.Soc.London. 111, 263-264.

GEORGE, T.N. 1963. Palaeozoic growth of the British Caledonides. In Johnson, M.R.J. & Stewart, F.H. (eds.). The British Caledonides. Oliver & Boyd, Edinburgh, 1-33.

GILL, W.D. & KUENEN, P.H. 1958. Sand volcanoes on slumps in the Carboniferous of County Clare, Ireland. Q.J.geol.Soc.London. 113, 441-460.

GREENWOOD, R. 1956. Submarine volcanic mudflows and limestone dikes in the Grayson Formation (Cretaceous) of central Texas. Trans.Gulf Coast Assoc.geol.Soc. 6, 167-177.

GREIG, D.C., WRIGHT, J.E., HAINS, B.A. & MITCHELL, G.H. 1968. Geology of the country around Church Stretton, Craven Arms, Wenlock Edge and Brown Clee. (Sheet 166). Mem. geol.Surv.G.B. 379pp.

HAAF, E. TEN. 1956. Significance of convolute lamination. Geol.Mijnbouw. 18, 188-194.

HAIRSTON, N.G. 1959. Species abundance and community structure. Ecology. 40, 404-415.

HALLAM, A. 1960. A sedimentary and faunal study of the Blue Lias of Dorset and Glamorgan. Philos.Trans.R.Soc. London. Ser.B. 243, 1-44.

HALLAM, A. 1965. Environmental causes of stunting in living and fossil marine benthonic invertebrates. Palaeontology.London. 8, 132-155.

HAMBLIN, W.K. 1961. Micro - cross-lamination in Upper Keeweenawan sediments of northern Michigan. J.sediment. Petrol. 31, 390-401.

HANCOCK, N.J., HURST, J.M. & FURSICH, F.T. 1974. The depths inhabited by Silurian marine communities. J.geol.Soc. London. 130, 151-156.

HANTZSCHEL, W. 1962. Trace fossils and problematica. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part W, Miscellanea. Geological Society of America and University of Kansas Press, W177-W245.

HARKER, A. 1889. The Bala Volcanic Series of Caernarvonshire and associated rocks. Cambridge University Press.

HARMS, J.C. & FAHNESTOCK, R.K. 1965. Stratification, bed forms, and flow phenomena (with an example from the Rio Grande). In Middleton, G.V. (ed.). Primary sedimentary structures and their hydrodynamic interpretation. Spec.Publ.Soc.econ.Paleontol.Mineral. Tulsa. 12, 84-115.

HARMS, J.C., MACKENZIE, D.B. & McCUBBIN, D.G. 1963. Stratification in modern sands of the Red River, Louisiana. J.Geol.Chicago. 71, 566-580.

HARPER, D.A.T. 1978. The occurrence of the Ordovician brachiopod *Heterorthis alternata* (J. de C.Sowerby) in the topmost Onnian of the type Caradoc area. *Geol.Mag.* *115*, 301-304.

HARPER, J.C. 1947. The Caradoc fauna of Ynys Galed, Caernarvonshire. *Ann.Mag.nat.Hist.London*. Ser.11, *14*, 153-175.

HARPER, J.C. 1956. The Ordovician succession near Llanystwmdwy, Caernarvonshire. *Liverpool Manchester geol.J*. *1*, 385-393.

HARPER, J.C. & RAST, N. 1964. The faunal succession and volcanic rocks of the Ordovician near Bellewstown, Co. Meath. *Proc.R.Irish Acad*. Sec.B. *64*, 1-23.

HARRINGTON, H.J. et al. 1959. *In* Moore, R.C. (ed.). *Treatise on invertebrate paleontology*, *Part O*, *Arthropoda 1*. Geological Society of America and University of Kansas Press, 560pp.

HASS, W.H. et al. 1962. *In* Moore, R.C. (ed.). *Treatise on invertebrate paleontology*, *Part W*, *Miscellanea*. Geological Society of America and University of Kansas Press, 259pp.

HAVLÍČEK, V. 1967. Brachiopoda of the suborder Strophomenidina in Czechoslovakia. *Rozpr.ustred. Ustavu geol*. *33*, 1-235.

HECKEL, P.H. 1972. Recognition of ancient shallow marine environments. In Rigby, J.K. & Hamblin, W.K. (eds.). Recognition of ancient sedimentary environments. *Spec. Publ.Soc.econ.Paleontol.Mineral.Tulsa*. *16*, 226-286.

HEINBERG, C. 1970. Some Jurassic trace fossils from Jameson Land (east Greenland). *In* Crimes, T.P. & Harper, J.C. (eds.). Trace fossils. *Geol.J.Spec. Issue*. *3*, 227-234.

HELM, D.G. & SIDDONS, A.W.B. 1971. Deformation of a slaty lapillar tuff in the English Lake District : Discussion. Bull.geol.Soc.Am. 82, 523-531.

HENDRY, H.E. 1972. Breccias deposited by mass flow in the Breccia Nappe of the French pre-Alps. Sedimentology. 18, 277-292.

HENNINGSMOEN, G. 1960. The Middle Ordovician of the Oslo Region, Norway. 13. Trilobites of the family Asaphidae. Nor.geol.Tidsskr. 40, 203-257.

HENNINGSMOEN, G. 1975. Moulting in trilobites. In Martinsson, A. (ed.). Evolution and morphology of the Trilobita, Trilobitoidea and Merostomata. Fossils and strata. 4, 179-200.

HOBBS, B.E. & TALBOT, J.L. 1966. The analysis of strain in distorted rocks. J.Geol.Chicago. 74, 500-513.

HOBBS, B.E., MEANS, W.D. & WILLIAMS, P.F. 1976. An outline of structural geology. John Wiley, New York, 571pp.

HOLLINGWORTH, S.E. 1954. The geology of the Lake District - a review. Proc.Geol.Assoc.London. 65, 385-402.

HOOKE, R.L. 1967. Processes on arid-region alluvial fans. J.Geol.Chicago. 75, 438-460.

HOWARD, J.D. 1971. Comparison of the beach-to-offshore sequence in modern and ancient sediments. In Howard, J.D., Valentine, J.W. & Warme, J.E. (eds.). Recent advances in paleoecology and ichnology. American Geological Institute, Washington, D.C. 148-183.

HOWARD, J.D. 1972. Trace fossils as criteria for recognizing shorelines in stratigraphic record. In Rigby, J.K. & Hamblin, W.K. (eds.). Recognition of ancient sedimentary environments. Spec.Publ.Soc.econ.Paleontol. Mineral.Tulsa. 16, 215-225.

HOWARD, J.D. & REINECK, H.-E. 1972. Georgia coastal region, Sapelo Island, U.S.A. Sedimentology and biology. IV. Physical and biogenic sedimentary structures of the nearshore shelf. Senckenbergiana Maritima. 4, 81-123.

HOWELLS, M.F. 1977. The varying pattern of volcanicity and sedimentation in the Bedded Pyroclastic/Middle Crafnant Volcanic formations in the Ordovician of central and eastern Snowdonia. J.geol.Soc.London. 133, 404.

HOWELLS, M.F., LEVERIDGE, B.E. & EVANS, C.D.R. 1971. The Lower Crafnant Volcanic Group, eastern Snowdonia. Proc. 1664, 284-285.

HOWELLS, M.F., LEVERIDGE, B.E. & EVANS, C.D.R. 1973. Ordovician ash flow tuffs in eastern Snowdonia. Rep.Inst.geol.Sci.London. 73/3, 33pp.

HOWELLS, M.F., FRANCIS, E.H., LEVERIDGE, B.E. & EVANS, C.D.R. 1978. Capel Curig and Betws-y-Coed : Description of 1:25000 sheet SH 75. Classical areas of British geology, Institute of Geological Sciences. Her Majesty's Stationery Office, 73pp.

HUGHES, C.P. 1970. Statistical analysis and presentation of trinucleid (Trilobita) fringe data. Palaeontology. London. 13, 1-9.

HUGHES, C.P., INGHAM, J.K. & ADDISON, R. 1975. The morphology, classification and evolution of the Trinucleidae (Trilobita). Philos.Trans.R.Soc.London. Ser.B. 272, 537-607.

HURST, J.M. 1975. Wenlock carbonate, level bottom, brachiopod dominated communities from Wales and the Welsh Borderland. Palaeogeogr.Palaeoclimatol.Palaeoecol. 17, 227-255.

IMBRIE, J. & BUCHANAN, H. 1965. Sedimentary structures in modern carbonate sands of the Bahamas. In Middleton, G.V. (ed.). Primary sedimentary structures and their hydrodynamic interpretation. Spec.Publ.Soc.econ. Paleontol.Mineral.Tulsa. 12, 149-172.

JAMES, G.W. 1971. Depositional environment of widespread Pennsylvanian black shale (Excello). Bull.Am.Assoc. Petrol.Geol. 55, 345. (abstract).

JEANS, P.J.F. 1973. Plate tectonic reconstruction of the southern Caledonides of Great Britain. Nature (phys.Sci.). 245, 120-122.

JENKINS, D.A. & BALL, D.F. 1964. Pumpellyite in Snowdonian soils and rocks. Mineralog.Mag.London. 33, 1093-1096.

JENNINGS, A.V. & WILLIAMS, G.J. 1891. Manod and the Moelwyns. Q.J.geol.Soc.London. 47, 368-383.

JOHNSON, J.H. 1952. Ordovician rock building algae. Q.Colorado Sch.Mines. 47, 29-56.

JOHNSON, J.H. & KONISHI, K. 1959. Part I - A review of Silurian (Gotlandian) algae. Part III - Some Silurian calcareous algae from northern California and Japan. In Johnson, J.H., Konishi, K. & Rezak, R. (eds.). Studies of Silurian (Gotlandian) algae. Q.Colorado Sch.Mines. 54, Part I, 1-115;Part III, 131-158.

JOHNSON, R.G. 1957. Experiments on the burial of shells. J.Geol.Chicago. 65, 527-535.

JOHNSON, R.G. 1960. Models and methods for the analysis of the mode of formation of fossil assemblages. Bull.geol.Soc.Am. 71, 1075-1086.

JOHNSON, R.G. 1964. The community approach in paleoecology. In Imbrie, J. & Newell, N.D. (eds.). Approaches to paleoecology. John Wiley & Sons, New York, 107-134.

*JOHNSON, R.G. 1970. Variations in diversity within benthic marine communities. Am.Nat. 104, 285-300.

JOHNSON, R.G. 1971. Animal-sediment relations in shallow water benthic communities. Mar.Geol. 11, 93-104.

JOHNSON, R.G. 1972. Conceptual models of benthic marine communities. In Schopf, T.J.M. (ed.). Models in paleobiology. Freeman, San Francisco, 148-159.

JONES, O.T. 1938. On the evolution of a geosyncline. Q.J.geol.Soc.London. 94, lx-cx.

JOPLING, A.V. 1966. Some deductions on the temporal significance of laminae deposited by current action in clastic rocks. J.sediment.Petrol. 36, 880-887.

KARIG, D.E. 1970. Ridges and basins of the Tongo-Kermadec island arc system. J.geophys.Res. 75, 239-254.

KARIG, D.E. 1971. Origin and development of marginal basins in the western Pacific. J.geophys.Res. 76, 2542-2561.

KARIG, D.E. 1972. Remnant arcs. Bull.geol.Soc.Am. 83, 1057-1068.

KARIG, D.E. & MOORE, G.F. 1975. Tectonically controlled sedimentation in marginal basins. Earth planet.Sci. Lett. 26, 233-238.

KELLING, G. & WILLIAMS, B.P.J. 1966. Deformation structures of sedimentary origin in the Lower Limestone Shales (basal Carboniferous) of south Pembrokeshire, Wales. J.sediment.Petrol. 36, 927-939.

KELLING, G. & WILLIAMS, P.F. 1967. Flume studies of the reorientation of pebbles and shells. J.Geol.Chicago. 75, 243-267.

KESLING, R.V. 1966. Cyclocystoids. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part U, Echinodermata 3 (1 of 2). Geological Society of America and University of Kansas Press, U188-U210.

KING, W.B.R. 1923. The upper Ordovician rocks of the south western Berwyn Hills. Q.J.geol.Soc.London. 79, 487-507.

KLEIN, G. de V. 1967. Comparison of recent and ancient tidal flat and estuarine sediments. In Lauff, G.H. (ed.). Estuaries. American Association for the Advancement of Science, publication no. 83, 207-218.

KLEIN, G. de V. 1970. Tidal origin of a Precambrian quartzite - the lower fine-grained quartzite (middle Dalradian) of Islay, Scotland. J.sediment.Petrol. 40, 973-985.

KOBLUK, D.R. & RISK, M.J. 1977. Algal borings and framboidal pyrite in Upper Ordovician brachiopods. Lethaia. 10, 135-143.

KORNICKER, L.S. & ARMSTRONG, N. 1959. Mobility of partially submersed shells. Publ.Inst.Mar.Sci. 6, 171-185.

KRUMBEIN, W.C. 1960. The geological population as a framework for analyzing numerical data in geology. Liverpool Manchester geol.J. 2, 341-368.

KUENEN, P.H. 1953. Significant features of graded bedding. Bull.Am.Assoc.Petrol.Geol. 37, 1044-1066.

LAKE, P. 1919. The Cambrian Trilobites. Part V. Monogr. palaeontogr.Soc.London. 343, 89-120.

LAKE, P. 1943. Restoration of the original form of distorted specimens. Geol.Mag. 80, 139-147.

LAMING, D.J.C. 1966. Imbrication, paleocurrents and other sedimentary features in the lower New Red Sandstone, Devonshire, England. J.sediment.Petrol. 36, 940-959.

LAMONT, A. 1934. Lower Palaeozoic Brachiopoda of the Girvan district : suggestions on morphology in relation to environment. Ann.Mag.nat.Hist.London. Ser. 10, 14, 161-184.

LAMONT, A. 1946. B.B.Bancroft's work on Caradocian lavas and sediments in the Capel Curig district, Caernarvonshire. - 1. Quarry Managers J.London. 30, 235-239.

LAMONT, A. 1948. B.B.Bancroft's geological work in the Cross Fell inlier. Quarry Managers J.London. 32, 416-418, 466-469.

LAPWORTH, C. 1879a. On the tripartite classification of the Lower Palaeozoic rocks. Geol.Mag. 16, 1-15.

LAPWORTH, C. 1879b. On the geological distribution of the Rhabdopora. Ann.Mag.nat.Hist.London. Ser.5, 3, 245-257, 449-455; 4, 333-341, 423-431.

LAWRENCE, D.R. 1968. Taphonomy and information losses in fossil communities. Bull.geol.Soc.Am. 79, 1315-1330.

LAWSON, J.D. 1975. Ludlow benthonic assemblages. Palaeontology.London. 18, 509-525.

LEVER, J. 1958. Quantitative beach research : I - The "left-right" phenomenen : sorting of lamellibranch valves on sandy beaches. Basteria. 22, 21-51.

*LEVER, J. & THIJSSEN, R. 1968. Sorting phenomena during the transport of shell valves on sandy beaches studied with the use of artificial valves. Symp.zool.Soc.Lond. 22, 259-271.

LINDSTROM, M. 1953. On the Lower Chasmops Beds in the Fagelsang district (Scania). Forh.geol.Foren.Stockholm. 75, 125-148.

LOWE, D.R. 1975. Water escape structures in coarse grained sediments. Sedimentology. 22, 157-204.

MacGREGOR, A.R. 1961. Upper Llandeilo brachiopods from the Berwyn Hills, North Wales. Palaeontology.London. 4, 177-209.

MacGREGOR, A.R. 1962. Upper Llandeilo trilobites from the Berwyn Hills, North Wales. Palaeontology.London. 5, 790-816.

MARGALEF, R. 1968. Perspectives in ecological theory. University of Chicago Press, Chicago, 111pp.

MARR, J.E. 1925. Conditions of deposition of the Stockdale Shales of the Lake District. Q.J.geol.Soc.London. 81, 113-136.

MARTIN, R.C. 1959. Some field and petrographic features of American and New Zealand ignimbrites. N.Z.J.Geol.Geophys. 2, 394-411.

MARTIN-KAYE, P. 1951. Sorting of lamellibranch valves on beaches in Trinidad. Geol.Mag. 88, 432-434.

MATSUDA, T. & UYEDA, S. 1971. On the Pacific-type orogeny and its model - extension of the paired belts concept and the possible origin of marginal seas. Tectonophysics. 11, 5-27.

MATTHEWS, P.E., BOND, R.A.B. & VAN DEN BERG, J.J. 1976. Strain analysis of symmetric folds using slaty cleavage. Tectonophysics. 34, 199-217.

McALESTER, A.L. 1968. Type species of Paleozoic nuculoid bivalve genera. Mem.geol.Soc.Am. 105, 1-143.

McALESTER, A.L. & RHOADS, D.C. 1967. Bivalves as bathymetric indicators. Mar.Geol. 5, 383-388.

McGOWEN, J.H. & GARNER, L.E. 1970. Physiographic features and stratification types of coarse grained point bars : modern and ancient examples. Sedimentology. 14, 77-111.

McKEE, E.D. 1957. Primary features in some recent sediments. Bull.Am.Assoc.Petrol.Geol. 41, 1704-1747.

McKEE, E.D. & WEIR, G.W. 1953. Terminology for stratification and cross-stratification in sedimentary rocks. Bull.geol.Soc.Am. 64, 381-390.

McNAMARA, K.J. 1978. Symbiosis between gastropods and bryozoans in the late Ordovician of Cumbria, England. Lethaia. 11, 25-40.

MENARD, H.W. & BOUCOT, A.J. 1951. Experiments on the movement of shells by water. Am.J.Sci. 249, 131-151.

MIDDLETON, G.V. 1967. The orientation of concavo-convex particles deposited from experimental turbidity currents. J.sediment.Petrol. 37, 229-232.

MITCHELL, A.H.G. & READING, H.G. 1969. Continental margins, geosynclines and ocean floor spreading. J.Geol.Chicago. 77, 629-646.

MITCHELL, A.H.G. & READING, H.G. 1971. Evolution of island arcs. J.Geol.Chicago. 79, 253-284.

MITCHELL, W.I. 1977. The Ordovician Brachiopoda from Pomeroy, Co.Tyrone. Monogr.palaeontogr.Soc.London. 545, 1-138.

MOORE, D.G. & SCRUTON, P.C. 1957. Minor internal structures of some recent unconsolidated sediments. Bull.Am.Assoc.Petrol.Geol. 41, 2723-2751.

MOORE, J.G. & PECK, D.L. 1962. Accretionary lapilli in volcanic rocks of the western continental United States. J.Geol.Chicago. 70, 182-193.

MOORE, R.C. 1939. The use of fragmentary crinoidal remains in stratigraphic paleontology. J.sci.Lab.Denison Univ. Ohio. 33, 165-250.

MOORE, R.C. & JEFFORDS, R.M. 1968. Classification and nomenclature of fossil crinoids based on studies of dissociated parts of their columns. Paleontol.Contrib. Kansas Univ. 46, Echinodermata, Article 9, 1-86.

MOORE, R.C., JEFFORDS, R.M. & MILLER, T.H. 1968. Morphological features of crinoid columns. Paleontol. Contrib.Kansas Univ. 45, Echinodermata, Article 8, 1-30.

MOREL, P. & IRVING, E. 1978. Tentative paleocontinental maps for the early Phanerozoic and Proterozoic. J.Geol.Chicago. 86, 535-561.

MORTON, R.A. 1978. Large scale rhomboid bed forms and sedimentary structures associated with hurricane washover. Sedimentology. 25, 183-204.

MOSELEY, F. 1977. Caledonian plate tectonics and the place of the English Lake District. Bull.geol.Soc.Am. 88, 764-768.

MUGGË, A. 1893. Unterschungen uber die Lenneporphyre in Westfalen. Beilage Band. Neues Jahrb.Mineral.Geol. Palaeontol. 8, 713-714.

MULLINEAUX, D.R. & CRANDELL, D.R. 1962. Recent lahars from Mount St.Helens, Washington. Bull.geol.Soc.Am. 73, 855-870.

MURCHISON, R.I. 1834. On the structure and classification of the Transition rocks of Shropshire, Herefordshire and parts of Wales, and on the lines of disturbance which have affected that series of deposits, including the Valley of Elevation of Woolhope. Proc.geol.Soc.London. 2 (for 1833-1838), 13-18.

MURCHISON, R.I. 1839. The Silurian System founded on geological researches in the counties of Salop, Hereford, Radnor, Montgomery, Caermarthen, Brecon, Pembroke, Monmouth, Gloucester, Worcester and Stafford : with descriptions of the coal-fields and overlying formations. Murray, London, 768pp. (2 vols.).

MUTTI, E. 1965. Submarine flood tuffs (ignimbrites) associated with turbidites in Oligocene deposits of Rhodes Island (Greece). Sedimentology. 5, 265-288.

NAGLE, J.S. 1967. Wave and current orientation of shells. J.sediment.Petrol. 37, 1124-1138.

NEUMAN, R.B. 1964. Fossils in Ordovician tuffs, northeastern Maine. Bull.U.S.geol.Surv. 1181-E, E1-E38.

NEWTON, R.S. 1968. Internal structure of wave-formed ripple marks in the nearshore zone. Sedimentology. 11, 275-292.

NICHOLS, J.A., ROWE, G.T., CLIFFORD, C.H. & YOUNG, R.A. 1978. In situ experiments on the burial of marine invertebrates. J.sediment.Petrol. 48, 419-425.

OERTEL, G. 1970. Deformation of a slaty, lapillar tuff in the Lake District, England. Bull.geol.Soc.Am. 81, 1173-1188.

OLIVER, R.L. 1954. Welded tuffs in the Borrowdale Volcanic Series, English Lake District, with a note on similar rocks in Wales. Geol.Mag. 91, 473-483.

OWENS, R.M. 1973. British Ordovician and Silurian Proetidae (Trilobita). Monogr.palaeontogr.Soc.London. 535, 1-98.

PACKHAM, G.H. & FALVEY, D.A. 1971. An hypothesis for the formation of marginal seas in the western Pacific. Tectonophysics. 11, 79-109.

PAINE, R.T. 1970. The sediment occupied by recent lingulid brachiopods and some palaeoecological implications. Palaeogeogr.Palaeoclimatol.Palaeoecol. 7, 21-31.

PAUL, C.R.C. 1973. British Ordovician cystoids. Monogr. palaeontogr.Soc.London. 536, 1-64.

PERRIER, R. & QUIBLIER, J. 1974. Thickness changes in sedimentary layers during compaction history : methods for quantitative evaluation. Bull.Am.Assoc.Petrol.Geol. 58, 507-520.

*PETERSEN, C.G.J. 1911. Valuation of the sea. I. Animal life of the sea bottom, its food and quantity. Rep.Dan.biol.Stn 20, 1-81.

PETERSEN, C.G.J. 1913. Valuation of the sea. II. The animal communities of the sea bottom and their importance for marine zoogeography. Rep.Dan.biol.Stn 21, 1-44.

PETTIJOHN, F.J. 1975. Sedimentary rocks. (3rd.edition). Harper & Row, New York, 628pp.

PETTIJOHN, F.J., POTTER, P.E. & SIEVER, R. 1972. Sand and sandstone. Springer-Verlag, Berlin, 618pp.

PHILLIPS, J. 1843. On certain movements in the parts of stratified rocks. Rep.Meet.Br.Assoc.Adv.Sci. 13, 60-61.

PHILLIPS, W.E.A., STILLMAN, C.J. & MURPHY, T. 1976. A Caledonian plate tectonic model. J.geol.Soc.London. 132, 579-609.

PIA, J. 1927. Thallophyta. In Hirmer, M. (ed.). Handbuch der Palaobotanik. Band I : Thallophyta - Bryophyta - Pteridophyta. Munchen und Berlin, Druck und Verlag von R. Oldenburg, 31-136.

PICKERILL, R.K. 1973. *Lingulasma tenuigranulata* - palaeoecology of a large Ordovician linguloid that lived within a strophomenid - trilobite community. Palaeogeogr.Palaeoclimatol.Palaeoecol. 13, 143-156.

PICKERILL, R.K. 1974. Geology of the south Berwyn Hills, North Wales, with particular reference to Upper Ordovician marine benthic communities. Unpublished Ph.D. thesis, University of Liverpool. (2 vols.).

PICKERILL, R.K. 1977. Trace fossils from the Upper Ordovician (Caradoc) of the Berwyn Hills, central Wales. Geol.J. 12, 1-16.

PICKERILL, R.K. & BRENCHLEY, P.J. 1979. Caradoc marine benthic communities of the south Berwyn Hills, North Wales. Palaeontology.London. 22, 229-264.

PLATT, J.W. 1976. Volcanogenic mineralization at Avoca, Co. Wicklow, Ireland, and its regional implications. In Volcanic processes in ore genesis. Spec.Publ.geol.Soc. London. 7, 163-170.

POTTER, P.C. & PETTIJOHN, F.J. 1963. Paleocurrents and basin analysis. Springer-Verlag, Berlin, 296pp.

PUGH, W.J. 1923. The geology of the district around Corris and Aberllefenni (Merionethshire). Q.J.geol.Soc. London. 79, 508-541.

RAAF, J.F.M. de & BOERSMA, J.R. 1971. Tidal deposits and their sedimentary structures. Geol.Mijnbouw. 50, 479-504.

RAMSAY, A.C. 1853. On the physical structure and succession of some of the Lower Palaeozoic rocks of North Wales and part of Shropshire. Q.J.geol.Soc.London. 9, 161-179.

RAMSAY, A.C. 1866. The geology of North Wales. Mem.geol.Surv.G.B. 3, 381pp.

RAMSAY, A.C. 1881. The geology of North Wales (2nd.edition). Mem.geol.Surv.G.B. 3

RAMSAY, J.G. 1967. Folding and fracturing of rocks. McGraw-Hill, New York, 568pp.

RAMSAY, J.G. & WOOD, D.S. 1973. The geometric effects of volume change during deformation processes. Tectonophysics. 16, 263-277.

RAMSBOTTOM, W.H.C. 1961. British Ordovician Crinoidea. Monogr.palaeontogr.Soc.London. 492, 1-37.

RANKIN, D.W. 1960. Paleogeographic implications of deposits of hot ash flows. 21st.Int.geol.Congr.Norden. 12, 19-34.

RAST, N. 1961. Mid-Ordovician structures in south-western Snowdonia. Liverpool Manchester geol.J. 2, 645-652.

*RAST, N. 1962. Ordovician volcanoes of north and central Wales. Part II. Volcanic rocks and their environment. Nature Wales. 6, 111-116.

RAST, N. 1969. The relationship between Ordovician structure and volcanicity in Wales. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 305-335.

RAST, N., BEAVON, R.V. & FITCH, F.J. 1958. Subaerial volcanicity in Snowdonia. Nature.London. 181, 508.

RAW, F. 1927. The ontogenies of trilobites, and their significance. Am.J.Sci. 5th.Ser. 14, 7-35,131-149,240.

REINECK, H.-E. 1967. Layered sediments of tidal flats, beaches and shelf bottoms of the North Sea. In Lauff, G.H. (ed.). Estuaries. American Association for the Advancement of Science, publication no.83, 191-206.

REINECK, H.-E. 1972. Tidal flats. In Rigby, J.K. & Hamblin, W.K. (eds.). Recognition of ancient sedimentary environments. Spec.Publ.Soc.econ.Paleontol. Mineral.Tulsa. 16, 146-159.

REINECK, H.-E. & SINGH, I.B. 1972. Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud. Sedimentology. 18, 123-128.

REINECK, H.-E. & SINGH, I.B. 1975. Depositional sedimentary environments. Springer-Verlag, Berlin, 439pp.

RHOADS, D.C. 1967. Biogenic reworking of intertidal and subtidal sediments in Barnstaple Harbour and Buzzards Bay, Massachusetts. J.Geol.Chicago. 75, 461-466.

RHOADS, D.C. & MORSE, J.W. 1971. Evolutionary and ecologic significance of oxygen deficient marine basins. Lethaia. 4, 413-428.

RICH, J.L. 1951. Probable fondo origin of Marcellus - Ohio - New Albany - Chattanooga bituminous shales. Bull.Am.Assoc.Petrol.Geol. 35, 2017-2040.

RICHARDS, R.P. 1972. Autecology of Richmondian brachiopods (late Ordovician of Indiana and Ohio). J.Paleontol. 46, 386-405.

RICHTER, R. 1942. Die Einkippungsregel. Senckenbergiana. 25, 181-206.

ROBERTS, B. 1969. The Llywd Mawr ignimbrite and its associated volcanic rocks. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 337-356.

ROLFE, W.D.I. 1960. A fine air-heave structure from the Old Red Sandstone of Lanarkshire, Scotland. Geol.Mag. 97, 133-136.

ROMANO, M. & DIGGENS, J.N. 1969. Longvillian shelly faunas from the Dolwyddelan area, North Wales. Geol.Mag. 106, 603-606.

ROSS, C.A. 1978. Distortion of fossils in shales. J.Paleontol. 52, 943-945.

ROSS, C.S. & SMITH, R.L. 1961. Ash-flow tuffs : their origin, geologic relations and identification. Prof.Pap.U.S.geol.Surv. 366, 81pp.

ROSS, Jr., R.J., NAESER, C.W. & IZETT, G.A. 1976. Apatite fission-track dating of a sample from the type Caradoc (middle Ordovician) Series in England. Geology. 4, 505-506.

RUDWICK, M.J.S. 1965. Ecology and paleoecology. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part H, Brachiopoda (1 of 2). Geological Society of America and University of Kansas Press, H199-H214.

RUDWICK, M.J.S. 1970. Living and fossil brachiopods. Hutchinson, London, 199pp.

RUEDEMANN, R. 1925. Origin of black shales of Cincinnatian. In Ruedemann, R. The Utica and Lorraine formations of New York. Part I. Bull.New York State Mus. (nat.Hist.). 258, 73-84.

RUEDEMANN, R. 1926. Faunal facies differences of the Utica and Lorraine shales. Bull.New York State Mus.(nat. Hist.). 267, 61-77.

SALTER, J.W. 1864 - 1883. A monograph of the British trilobites from the Cambrian, Silurian and Devonian formations. Monogr.palaeontogr.Soc.London. 67, (1864) 1-80; 72, (1865), 81-128; 77, (1866), 129-176; 86 (1867), 177-214; 175, (1883), 215-224.

*SANDERS, H.L. 1958. Benthic studies in Buzzards Bay. I. Animal - sediment relationships. Limnol.Oceanogr. 3, 245-258.

*SANDERS, H.L. 1960. Benthic studies in Buzzards Bay. III. The structure of the soft-bottom community. Limnol.Oceanogr. 5, 138-153.

SANDERS, J.E. 1965. Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms. In Middleton, G.V. (ed.). Primary sedimentary structures and their hydrodynamic interpretation. Spec.Publ.Soc.econ.Paleontol.Mineral. Tulsa. 12, 192-219.

SANDERSON, D.J. 1976. The determination of compactional strains using quasi-cylindrical objects. Tectonophysics. 30, T25-T32.

SCHAFER, W. 1972. Ecology and palaeoecology of marine environments. Translated by I.Oertel. Edited by G.Y.Craig. Oliver & Boyd, Edinburgh, 568pp.

SCHEIDEGGER, A.E. & POTTER, P.E. 1968. Textural studies of grading : volcanic ash falls. Sedimentology. 11, 163-170.

SCHIENER, E.J. 1970. Sedimentology and stratigraphy of three tuff horizons in the Caradocian sequence of the Bala area (North Wales). Geol.J. 7, 25-46.

SCHMINKE, H.-U. 1967. Graded lahars in the type sections of the Ellensburg Formation, south central Washington. J.sediment.Petrol. 37, 438-448.

SCHMINKE, H.-U., FISHER, R.V. & WATERS, A.C. 1973. Antidune and chute and pool structures in the base surge deposits of the Lacher See area, Germany. Sedimentology. 20, 553-574.

SCHOLZ, C.H., BARAZANGI, M. & SBAR, M.L. 1971. Late Cenozoic evolution of the Great Basin, western United States, as an ensialic inter-arc basin. Bull.geol.Soc.Am. 82, 2979-2990.

SDZUY, K. 1966. An improved method of analysing distortion in fossils. Palaeontology.London. 9, 125-134.

SEDGWICK, A. 1838. A synopsis of the English series of stratified rocks inferior to the old red sandstone - with an attempt to determine the successive natural groups and formations. Proc.geol.Soc.London. 2 (for 1833-1838), 675-685.

SEDGWICK, A. 1841. Supplement to Sedgwick 1838. Proc.geol.Soc.London. 3, 549.

SEDGWICK, A. 1843. Outline of geological structure of North Wales. Proc.geol.Soc.London. 4, 212-224.

SEDGWICK, A. 1847. On the classification of the fossiliferous slates of North Wales, Cumberland, Westmoreland and Lancashire. Q.J.geol.Soc.London. 3, 133-164.

SEILACHER, A. 1964. Biogenic sedimentary structures. In Imbrie, J. & Newell, N.D. (eds.). Approaches to paleoecology. John Wiley & Sons, New York, 296-316.

SEILACHER, A. 1967. Bathymetry of trace fossils. Mar.Geol. 5, 413-428.

SHACKLETON, R.M. 1954. The structural evolution of North Wales. Liverpool Manchester geol.J. 1, 261-297.

SHACKLETON, R.M. 1959. The stratigraphy of the Moel Hebog district between Snowdon and Tremadoc. With a note on the Caradoc shelly faunas by J.C.Harper. Liverpool Manchester geol.J. 2, 216-252.

SHARPE, D. 1843. On the Bala Limestone. Proc.geol.Soc. London. 4, 10-14.

SHARPE, D. 1846. Contributions to the geology of North Wales. Q.J.geol.Soc.London. 2, 283-316.

SHARPE, D. 1847. On slaty cleavage. Q.J.geol.Soc.London. 3, 74-105.

SHEEHAN, P.M. 1977. Ordovician and Silurian brachiopods from graptolitic shales and related deep-water argillaceous rocks. Lethaia. 10, 201-203.

SHEEHAN, P.M. 1978. The hinging mechanisms of brachiopods - taphonomic considerations. J.Paleontol. 52, 748.

SHERLOCK, R.L. 1918. The geology and genesis of the Trefriw pyrites deposit. Q.J.geol.Soc.London. 74, 106-114.

SHIRLEY, J. 1931. A redescription of the known British Ordovician species of Calymene (s.l.). Mem.Proc.lit.phil.Soc.Manchester. 75, 1-35.

SHIRLEY, J. 1936. Some British trilobites of the family Calymenidae. Q.J.geol.Soc.London. 92, 384-422.

SHROCK, R.R. 1948. Sequence in layered rocks. McGraw-Hill, New York, 507pp.

SIMONS, D.B., RICHARDSON, E.V. & NORDIN, C.F. 1965. Sedimentary structures generated by flow in alluvial channels. In Middleton, G.V. (ed.). Primary sedimentary structures and their hydrodynamic interpretation. Spec.Publ.Soc.econ.Paleontol.Mineral. Tulsa. 12, 34-52.

SKEVINGTON, D. 1969. The classification of the Ordovician System in Wales. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 161-179.

SMITH, A.G., BRIDEN, J.C. & DREWRY, G.E. 1973. Phanerozoic world maps. In Hughes, N.F. (ed.). Organisms and continents through time. Spec.Pap.Palaeontol.London. 12, 1-42.

SOOT-RYEN, H. & T. 1960. The Middle Ordovician of the Oslo region, Norway. 11. Pelecypoda. Nor.geol.Tidsskr. 40, 81-121.

SORBY, H.C. 1853. On the origin of slaty cleavage. Edinburgh new philos.J. 55, 137-148.

SORBY, H.C. 1908. On the application of quantitative methods to the study of the structure and history of rocks. Q.J.geol.Soc.London. 64, 171-233.

SPEDEN, I.G. 1966. Palaeoecology and the study of fossil benthic assemblages and communities. N.Z.J.Geol.Geophys. 9, 408-423.

SPJELDNAES, N. 1957. The Middle Ordovician of the Oslo region, Norway. 8. Brachiopods of the Suborder Strophomenida. Nor.geol.Tidsskr. 37, 1-214.

SPJELDNAES, N. 1961. Ordovician climatic zones. Nor.geol.Tidsskr. 41, 45-77.

*SPJELDNAES, N. 1967. The palaeogeography of the Tethyan region during the Ordovician. In Adams, C.G. & Ager, D.V. (eds.). Aspects of Tethyan biogeography. Publs Syst.Ass. 7, 45-57.

SPJELDNAES, N. 1976. Ordovician climates. In Bassett, M.G. (ed.). The Ordovician System : proceedings of a Palaeontological Association symposium, Birmingham, September, 1974. University of Wales Press and Natural Museum of Wales, Cardiff, 67-69.

SPJELDNAES, N. 1978. Faunal provinces and the Proto-Atlantic. In Bowes, D.R. & Leake, B.E. (eds.). Crustal evolution in northwestern Britain and adjacent regions. Geol.J.Spec.Issue. 10, 139-150.

STANLEY, D.J. 1963. Vertical petrographic variability in Annot Sandstone turbidites : some preliminary observations and generalisations. J.sediment.Petrol. 33, 783-788.

STANTON, R.J. & EVANS, I. 1972. Community structure and sampling requirements in paleoecology. J.Paleontol. 46, 845-858.

STEVENSON, I.P. 1971. The Ordovician rocks of the country between Dwygyfylchi and Dolgarrog, Caernarvonshire. Proc.Yorkshire geol.Soc. 38, 517-548.

STEWART, A.D. 1963. On certain slump structures in the Torridonian sandstones of Applecross. Geol.Mag. 100, 205-218.

STORMER, L. 1953. The Middle Ordovician of the Oslo region, Norway. 1. Introduction to stratigraphy. Nor.geol.Tidsskr. 31, 37-141.

*STRAATEN, L.M.J.U. VAN 1952. Biogene textures and the formation of shell beds in the Dutch Wadden Sea. Proc.K.ned.Akad.Wet. 55, 500-516.

STRAATEN, L.M.J.U. VAN 1954. Composition and structure of Recent marine sediments in the Netherlands. Leidse geol.Meded. 19, 1-110.

STRAATEN, L.M.J.U. VAN 1959. Minor structures of some recent littoral and neritic sediments. Geol.Mijnbouw. 21, 197-216.

STRAATEN, L.M.J.U. VAN 1960. Marine mollusc shell assemblages of the Rhone Delta. Geol.Mijnbouw. 39, 105-129.

STRAATEN, L.M.J.U. VAN 1961. Sedimentation in tidal flat areas. J.Alberta Soc.Pet.Geol. 9, 203-226.

TERWINDT, J.H.J. 1971. Litho-facies of inshore estuarine and tidal-inlet deposits. Geol.Mijnbouw. 50, 515-526.

*THAYER, C.W. 1975. Morphologic adaptations of benthic invertebrates to soft substrata. J.mar.Res. 33, 177-189.

THORSON, G. 1957. Bottom communities (sublittoral or shallow shelf). In Hedgpeth, J.W. (ed.). Treatise on marine ecology and paleoecology. Vol. 1. Ecology. Mem.geol.Soc.Am. 67(1), 461-534.

TILLMAN, C.G. 1960. Spathacalymene, an unusual new Silurian trilobite genus. J.Paleontol. 34, 891-895.

TIPPER, J.C. 1976. A method for the quantitative estimation of the faunal content of well cemented fossiliferous rocks. J.Paleontol. 50, 175-179.

TITUS, R. & CAMERON, B. 1976. Fossil communities of the Lower Trenton Group (Middle Ordovician) of central and northwestern New York State. J.Paleontol. 50, 1209-1225.

TOBISCH, O.T., FISKE, R.S., SACKS, S. & TANIGUCHI, D. 1977. Strain in metamorphosed volcaniclastic rocks and its bearing on the evolution of orogenic belts. Bull.geol.Soc.Am. 88, 23-40.

TOMKEIEFF, S.I. 1962. Unconformity - an historical study. Proc.Geol.Assoc.London. 73, 383-417.

TOOTS, H. 1965a. Orientation and distribution of fossils as environmental indicators. In DeVoto, R.H. & Bitter, R.K. (eds.). Sedimentation of late Cretaceous and Tertiary outcrops, Rock Springs uplift. Wyoming geol.Assoc.guideb., 19th. field conference, 219-229.

TOOTS, H. 1965b. Random orientation of fossils and its significance. Contrib.Geol.Univ.Wyoming. 4, 59-62.

TREMLETT, W.E. 1962. The geology of the Nefyn - Llanaelhaiarn area of North Wales. Liverpool Manchester geol.J. 3, 157-176.

TURPAEVA, E.P. 1957. Food interrelationships of dominant species in marine benthic biocoenoses. In Nikitin, B.N. (ed.). Trans.Inst.Oceanol.Mar.Biol. U.S.S.R. Academic Science Press, 20, 137-148.

TWENHOFEL, W.H. 1939. Environments of origin of black shales. Bull.Am.Assoc.Petrol.Geol. 23, 1178-1198.

VOLL, G. 1960. New work on petrofabrics. Liverpool Manchester geol.J. 2, 503-567.

WALKER, K.R. 1972a. Trophic analysis : a method of studying the function of ancient communities. J.Paleontol. 46, 82-93.

WALKER, K.R. 1972b. Community ecology of the Middle Ordovician Black River Group of New York State. Bull.geol.Soc.Am. 83, 2599-2624.

WALKER, K.R. & LAPORTE, L.F. 1970. Congruent fossil communities from Ordovician and Devonian carbonates of New York. J.Paleontol. 44, 928-944.

WARME, J.E. 1969. Live and dead molluscs in a coastal lagoon. J.Paleontol. 43, 141-150.

WATERS, A.C. & FISHER, R.V. 1971. Base surges and their deposits : Capelinhos and Taal volcanoes. J.geophys.Res. 76, 5596-5614.

WATKINS, R. & BERRY, W.B.N. 1977. Ecology of a late Silurian fauna of graptolites and associated organisms. Lethaia. 10, 267-286.

WELLMAN, H.W. 1962. A graphical method for analysing fossil distortion caused by tectonic deformation. Geol.Mag. 99, 348-352.

WHITTARD, W.F. 1955-1967. The Ordovician trilobites of the Shelve Inlier, west Shropshire. Monogr.palaeontogr.Soc. London. Part I, 470 (1955), 1-40; Part III, 478 (1958), 71-116; Part IV, 487 (1960), 117-162; Part VII, 501 (1964), 229-264; Part IX, 516 (1967), 307-352.

WHITTINGTON, H.B. 1938a. The geology of the district around Llansantffraid ym Mechain, Montgomeryshire. Q.J.geol.Soc.London. 94, 423-457.

WHITTINGTON, H.B. 1938b. Fauna of the Lluest quarry, Llanfyllin (Wattsella horderleyensis super-zone) and its correlation. Proc.Geol.Assoc.London. 49, 49-54.

WHITTINGTON, H.B. 1938c. New Caradocian brachiopods from the Berwyn Hills, North Wales. Ann.Mag.nat.Hist.London. Ser. 11, 2, 241-259.

WHITTINGTON, H.B. 1962-1966. The Ordovician trilobites of the Bala area, Merioneth. Monogr.palaeontogr.Soc. London. Part I, 497 (1962), 1-32; Part II, 504 (1965), 33-62; Part III, 512 (1966), 63-92.

WHITTINGTON, H.B. 1966b. Phylogeny and distribution of Ordovician trilobites. J.Paleontol. 40, 696-737.

WHITTINGTON, H.B. 1968. The Ordovician trilobites of the Bala area, Merioneth, part IV. Monogr.palaeontogr.Soc. London. 520, 93-138.

WHITTINGTON, H.B. & HUGHES, C.P. 1972. Ordovician geography and faunal provinces deduced from trilobite distribution. Philos.Trans.R.Soc.London. Ser.B 263, 235-278.

WHITTINGTON, H.B. & WILLIAMS, A. 1955. The fauna of the Derfel Limestone of the Arenig district, North Wales. Philos.Trans.R.Soc.London. Ser.B 238, 397-429.

WHITTINGTON, H.B. & WILLIAMS, A. 1964. The Ordovician period. In Harland, W.B., Smith, A.G. & Wilcock, B. (eds.). The Phanerozoic Time-scale. Q.J.geol.Soc. London. 120S, 241-254.

WILLIAMS, A. 1949. New Lower Ordovician brachiopods from the Llandeilo - Llangadock district. Parts I and II. Geol.Mag. 86, 161-174; 226-238.

WILLIAMS, A. 1962. The Barr and Lower Ardmillan Series (Caradoc) of the Girvan district, south west Ayrshire, with descriptions of the Brachiopoda. Mem.geol.Soc.London. 3, 1-267.

WILLIAMS, A. 1963. The Caradocian brachiopod faunas of the Bala district, Merionethshire. Bull.Br.Mus.nat.Hist. Ser.Geol. 8, 327-471.

WILLIAMS, A. 1969a. Ordovician faunal provinces with reference to brachiopod distribution. In Wood, A. (ed.). The Pre-Cambrian and Lower Palaeozoic rocks of Wales. University of Wales Press, Cardiff, 117-154.

WILLIAMS, A. 1969b. Ordovician of the British Isles. In Kay, M. (ed.). North Atlantic - geology and continental drift : a symposium. Mem.Am.Assoc.Petrol. Geol. 12, 236-264.

WILLIAMS, A. 1973. Distribution of brachiopod assemblages in relation to Ordovician palaeogeography. In Hughes, N.F. (ed.). Organisms and continents through time. Spec.Pap.Palaeontol.London. 12, 241-269.

WILLIAMS, A. 1974. Ordovician Brachiopoda from the Shelve district, Shropshire. Bull.Br.Mus.nat.Hist. Supplement Ser. 11, 1-163.

WILLIAMS, A. 1976. Plate tectonics and biofacies evolution as factors in Ordovician correlation. In Bassett, M.G. (ed.). The Ordovician System : proceedings of a Palaeontological Association symposium, Birmingham, September 1974. University of Wales Press and Natural Museum of Wales, Cardiff, 29-66.

WILLIAMS, A. & WRIGHT, A.D. 1963. The classification of the "Orthis testudinaria Dalman" group of brachiopods. J.Paleontol. 37, 1-32.

WILLIAMS, A., STRACHAN, I., BASSETT, D.A., DEAN, W.T., INGHAM, J.K., WRIGHT, A.D. & WHITTINGTON, H.B. 1972. A correlation of Ordovician rocks in the British Isles. Spec.Rep.geol.Soc.London. 3, 1-74.

WILLIAMS, A. et al. 1965. In Moore, R.C. (ed.). Treatise on invertebrate paleontology, Part H, Brachiopoda. Geological Society of America and University of Kansas Press, 927pp.

WILLIAMS, D. 1930. The geology of the country between Nant Peris and Nant Ffrancon (Snowdonia). Q.J.geol.Soc. London. 86, 191-233.

WILLIAMS, D. & RAMSAY, J.G. 1959. Geology of some classic British areas : Snowdonia. Geol.Assoc.Guide. 28, 1-20.

WILLIAMS, E. 1960. Intra-stratal flow and convolute folding. Geol.Mag. 97, 208-214.

WILLIAMS, H. 1922. The igneous rocks of the Capel Curig district (North Wales). Proc.Liverpool geol.Soc. 13, 166-206.

WILLIAMS, H. 1927. The geology of Snowdon (North Wales). Q.J.geol.Soc.London. 83, 346-431.

WILLIAMS, H. & BULMAN, O.M.B. 1931. The geology of the Dolwyddelan syncline (North Wales). Q.J.geol.Soc. London. 87, 425-458.

WILLIAMS, P.F. 1976. Relationships between axial-plane foliations and strain. Tectonophysics. 30, 181-196.

WINDLEY, B.F. 1977. The evolving continents. John Wiley & Sons, New York, 385pp.

WINKLER, H.G.F. 1976. Petrogenesis of metamorphic rocks. Springer-Verlag, New York, 334pp.

WOOD, D.S. 1974. Ophiolites, melanges, blueschists, and ignimbrites : early Caledonian subduction in Wales ? In Dott, Jr., R.H. & Shaver, R.H. (eds.). Modern and ancient geosynclinal sedimentation. Spec.Publ.Soc. econ.Paleontol.Mineral.Tulsa. 19, 334-344.

WOOD, D.S. & HARPER, J.C. 1962. Notes on a temporary section in the Ordovician at Conway, North Wales. Liverpool Manchester geol.J. 3, 177-186.

WORSLEY, D. 1971. Faunal anticipation in the lower Llandovery of the Oslo Region, Norway. Nor.geol.Tidsskr. 51, 161-167.

WRIGHT, A.D. 1963. The fauna of the Portrane Limestone. I. The inarticulate brachiopods. Bull.Br.Mus.nat.Hist. Ser.Geol. 8, 221-254.

WRIGHT, A.D. 1964. The fauna of the Portrane Limestone. II. Bull.Br.Mus.nat.Hist. Ser.Geol. 9, 157-256.

WRIGHT, J.V. & COWARD, M.P. 1977. Rootless vents in welded ash-flow tuffs from northern Snowdonia, North Wales, indicating deposition in a shallow water environment. Geol.Mag. 114, 133-140.

WUNDERLICH, F. 1972. Georgia coastal region, Sapelo Island, U.S.A. Sedimentology and biology. III. Beach dynamics and beach development. Senckenbergiana Maritima. 4, 47-79.

*YELTYSHEVA, R.S. 1956. Stebli morskikh liliy i ikh klassifikatsiya (Crinoid stems and their classification). Vestn.Leningr.Univ. Ser.Geol.Geogr. 12, 40-46.

ZANGERL, R., WOODLAND, B.G., RICHARDSON, Jr., E.S. & ZACHRY, Jr., D.L. 1969. Early diagenetic phenomena in the Fayetteville Black Shale (Mississippian) of Arkansas. Sediment.Geol. 3, 87-119.

ZIEGLER, A.M. 1965. Silurian marine communities and their environmental significance. Nature.London. 207, 270-272.

ZIEGLER, A.M., COCKS, L.R.M. & BAMBACH, R.K. 1968. The composition and structure of Lower Silurian marine communities. Lethaia. 1, 1-27.