THE TRACE FOSSIL STRATIGRAPHY OF SOME SHALLOW-MARINE CAMBRO-ORDOVICIAN ROCKS FROM BRITTANY, N.W. SPAIN AND THE UNITED KINGDOM.

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy.

by

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The material presented in this thesis represents the results of original research carried out under the supervision of Dr. T.P. Crimes, Department of Geology, University of Liverpool. Material from other sources is fully acknowledged.

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ABSTRACT.

Details are presented of the distribution of lithofacies and trace fossils within a continuously exposed 4.4 km thick sequence of Cambro-Ordovician rocks (The Cabos Series) located on the north coast of Spain. From facies data a sedimentological and palaeoenvironmental model is developed which demonstrates the depositional continuity of the sequence. As a result, the trilobite trace fossil stratigraphy derived from this sequence permits both minor refinement and broad verification of those existing trace fossil stratigraphies which are largely derived from geographically remote, essentially composite, basic data. Wider and more general applicability of these conclusions are tested on contemporaneous sequences in the Cambrian Mountains (Barrios Formation) and Western Brittany (Crozon Formation). Results confirm the conclusions derived from the Cabos Series.

. Within north-west Spain, correlations based on trace fossil data demonstrate that the upper 250 m of the relatively thin Cambro-Ordovician sequence present in the Cantabrian Zone is a condensed equivalent of the much thicker sequences of the West Asturian Leonese Zone. The erection of classical geosynclinal models to account for these differences are shown to be unnecessary.

Shelf, barrier bar and tidally influenced near shore are the dominant environments recorded in the clastic Cambro-

Ordovician rocks of both north-west Spain and Western Brittany. The lower 3800 m of the Cabos Series is composed of a complex transgressive sequence which commenced in late middle Cambrian and attained a maximum during Arenig times. A brief regressive phase characterises the next 500 m of the Series before a return, in the final 100 m, to transgressive conditions which culminated in deposition of the graptolitic muds of the overlying Llanvirnian Luarca Shales. Markov Chain analysis of facies is shown to provide a useful test of the intuative palaeoenvironmental model developed for the Cabos Series.

In Brittany a similar but entirely Arenig two part transgression is noted with the upper barrier bar dominated phase being examined in detail.

Trilobite trace fossils, particularly Cruziana rugosa collected from Spain, Brittany and the U.K. and specimens studied at the Museum of Natural History, Nantes, France provide material for a discussion of the production and preservation of these traces. The component parts (dig marks) of C.rugosa are shown to have considerable morphological stability and should be described in detail in systematic descriptions. A vertical gradient in the bearing capacity of excavated sediment is shown to strongly influence the quality of morphological detail preserved on trace fossils. From X-ray evidence it is concluded that the majority of Cruziana and Rusophycus were produced at the sediment/water interface.

Finally, in a palaeogeographical synthesis it is proposed that northern Spain, Brittany and the southern U.K. formed a broadly contiguous province founded on continental crust which deformed by slow warping along linear troughs. The faulting and associated volcanic activity in Wales is shown to mark the boundary of an area which in Cambro-Ordovician times behaved in a fundamentally different manner.

ACKNOWLEDGEMENTS

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I am grateful to Dr. H.D. Johnson and Dr. R.K. Pickerill for reading and criticizing parts of this manuscript; also to Dr. A. Marcos for logistical assistance during field work in Spain.

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GENERAL INTRODUCTION

Palaeozoic trilobite trace fossil stratigraphies developed from geographically discrete sections in the United Kingdom (Crimes, 1968, 1970a, 1970b and 1975), because of their composite nature, are potentially problematical in the area of facies control of trace fossil assemblages. This thesis is directed towards verification and refinement of the UK ichnostratigraphies. This is achieved by use of a continuous stratigraphic section of determined facies.

In the UK late Cambrian to Lower Ordovician trilobite trace fossil assemblages contain relatively few morphologically distinct individuals (see Seilacher, 1970 and Crimes, 1975). Their identification was considered relatively simple so that a combined facies and trace fossil analysis could be completed in the available field seasons. Further, a detailed trilobite trace fossil stratigraphy of the Upper Cambrian and Lower Ordovician rocks of the UK had been presented by Crimes (1970, 1975). These two works provided a paradigmatic model which could be further tested and refined within a wider European context.

Continuous, well exposed Lower Palaeozoic sections were sought in which lithofacies controls could be identified and isolated from the stratigraphic analysis. The coast of Asturias, N.W. Spain (Fig. 1) contains in continuously exposed cliff sections a sequence of sedimentary rocks ranging in age from Lower Cambrian to Middle Ordovician. Recent stratigraphic work in this region (Marcos, 1973) reaffirmed a Middle Cambrian to Lower Ordovician age range of a sequence of sandstones, quartzites and shales named the Cabos Series (Lotze, 1958). This series forms the major study of this thesis and a summary of facies and trace fossil distributions within it are given in the paper 'The stratigraphy of the Cabos Series in the section between Cadavedo and Luarca, Province of Oviedo, N.W. Spain'.

In order to ensure that data derived from the Asturian section was not parochial, two additional, apparently broadly contemporaneous but subordinate sections were considered from the Cantabrian Mountains, N.W. Spain (Fig. 2) and from Western Brittany. In the former, lithofacies data was available from recent Dutch work (van den Bosch, 1966;

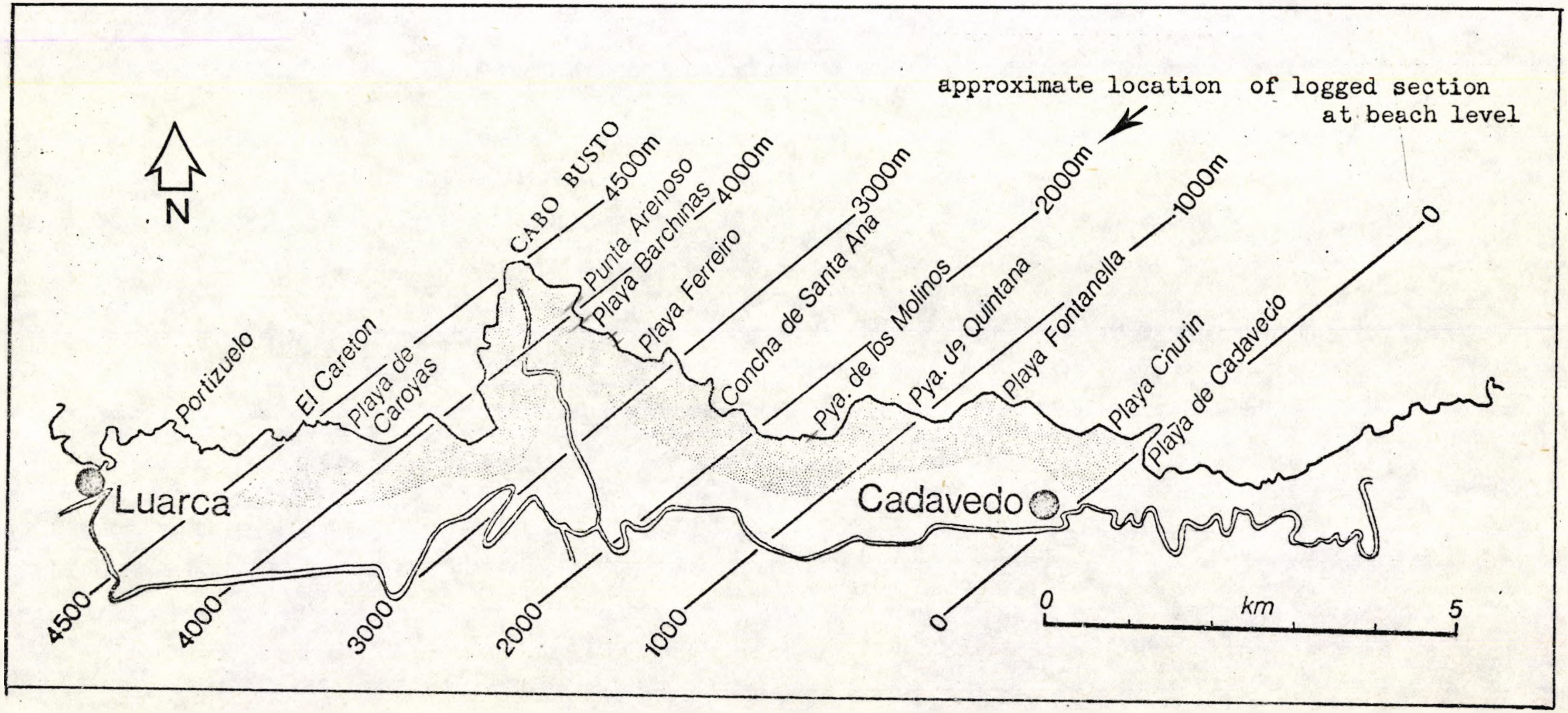

Figure 1

The Cambro-Ordovician Cabos Series in the section between Cadavedo and Luarca, Province of Oviedo, N.W. Spain'.

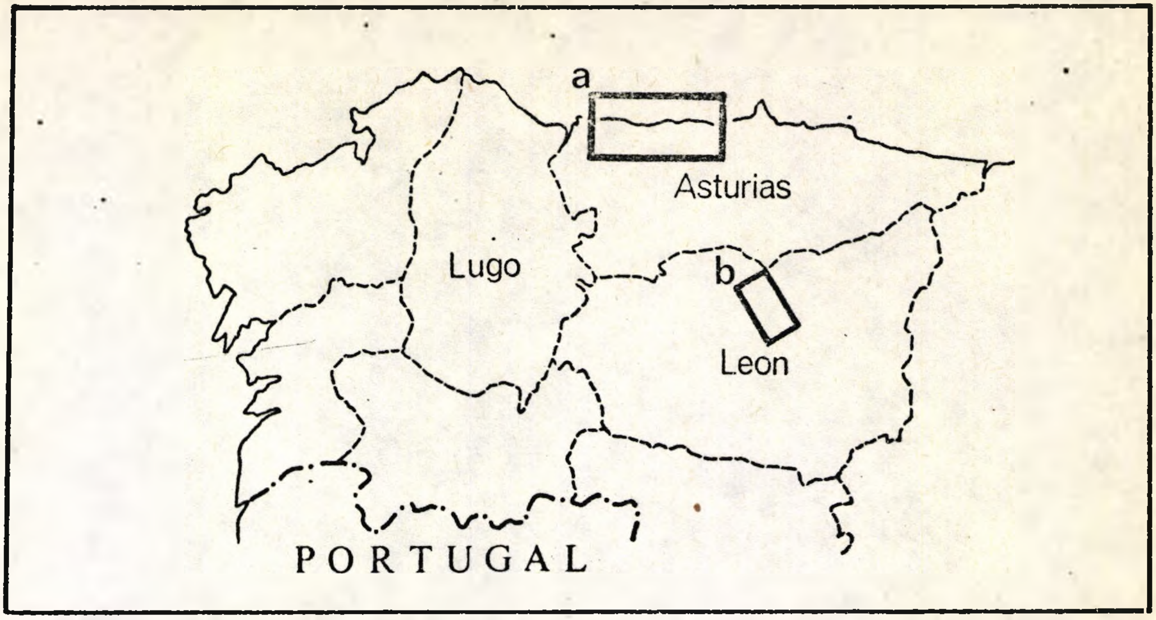

Figure 2 Locations of the two principle study areas. a = Luarca-Cadavedo coastal section; b = Cantabrian, Luna-Sil area.

Geitelink, 1973). A comparison of the trace fossil stratigraphies of this and the Asturian area is given in the manuscript 'A comparison of the stratigraphy and depositional processes in the Cambro-Ordovician rocks of the Cantabrian and West Asturian-Leonese Zones, N.W. Spain'. (This paper is accepted for publication in a review of the geology of north-west Spain to be published in memory of Professor Parga Pondal.) In Brittany analysis of lithofacies was necessary and details of these are presented in the paper 'A storm influenced barrier bar and lagoonal transgressive sequence from the Gres Armoricain of the Crozon Peninsula (Finistere)'. (In press: Proc. Geol. Assoc.)

As originally conceived this project included analysis, similar in detail to those undertaken in Brittany and Iberia, of the Stiperstones Quartzite of Shropshire. Reconnaissance field work carried out during Autumn 1971 indicated the absence of detail in the fine grained lithotopes. Facies analysis of the type required became effectively meaningless in this situation. As a result stratigraphic information from this area was confined to that published by Crimes (1970a).

Collections of trace fossils from known medium and high energy facies stimulated consideration of trilobite trace production and preservation. Some conclusions derived from this work are presented in the paper 'Internal structures of trilobite trace fossils indicative of an open surface furrow origin'. (In press: Palaeo^3.) A detailed discussion of a new species of Cambro-Ordovician resting trace in which appendage morphology is preserved is given in '*Rusophycus morgati*: an asaphid produced trace fossil from the Cambro-Ordovician of Brittany and N.W. Spain'. (In press: Journ. Paleontol.)

This thesis is in five parts. The first part deals with the Spanish sections, trace fossils and stratigraphic synthesis. The second part follows a similar format, but presents facies and trace fossil data derived from the Brittany sections. Part three considers trace production and preservation. Part four is an attempt at a broad palaeogeographical synthesis of Iberia, Brittany and the UK within the context of a plate tectonics setting. Finally, part five is a micro film appendix of the detailed logs and facies interpretation of the Asturian coastal section.

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VOLUME 1.

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VOLUME 2.

PART ONE

NORTH SPAIN

CHAPTER 1

LITHOFACIES ANALYSIS AND ENVIRONMENTAL INTERPRETATION

1. INTRODUCTION.

a. General.

The northern coast of Spain trends east/west and, in the province of Asturias, cuts at a high angle the north or north-north-east regional strike of the Lower Palaeozoic sediments (Fig. 1). The east Asturian coastline, formed from bays and capes, provides good two dimensional, but less adequate three dimensional exposure of the rock sequence. From such a section the sequential development of sedimentation can best be studied through an analysis of the vertical arrangement of facies. Unfortunately, the spatial distribution of facies can only be inferred from their vertical relationships and few direct observations of lateral transitions can be made in the field.

Lithofacies groups are identified and described from what appears to be a tide dominated, shallow marine environment. This strong tidal influence to the Cabos Series has stimulated the discussion of tidal sedimentation and general tidal processes operative in such environments.

b. Regional stratigraphic context of the Cabos Series.

Previous work on the regional stratigraphy and delimitation of the Cambrian/Ordovician boundary is discussed in Chapter 3.

In summary, the Cabos Series, of approximately 4500m total thickness in the study area, extends in age from low Middle Cambrian up to the base of the Llanvirn.

c. Sections.

The main study section, from Luarca to Cadavedo is shown in Figure 2. An additional coastal section, north of La Caridad, was studied during the first period of field work in 1971, but was found to be less complete and less accessible than the Cadavedo/Luarca section. It does, however, provide checks which may be applied to some of the conclusions derived from the main section.

Inland exposures along strike from the Cadavedo/Luarca section were studied, but interpretation of data derived from these sections has been treated with extreme caution. Sampling in such areas is biased in favour of the thicker sandstones and anything other than palaeocurrent data from these sand dominated facies is of little use in facies interpretation. The interpolation and correlation of the type of detail derived from analysis of the coastal section is considered unsafe with facies groups which seem, intrinsically, so variable. As a result, the southward development of the north coast sedimentary model is considered only briefly.

d. Access and continuity of section.

Care was taken in the field to avoid any erroneous duplication of parts of the section. At only one point (area west of El Carreton) was a 'long range' (<500m) correlation required and by walking the section could be made with reasonable certainty. Most bays along the section are accessible by paths and access could be gained to all other bays at low tide. Two small headlands composed of uniform quartzite (on a macro scale) could not be reached for detailed study and these were checked visually from the cliff top.

e. Structure.

The structure of the west Asturian region has been discussed by Marcos (1973). Folds within the study area are open flexures with wavelengths of hundreds of metres and the section is essentially composed of a tilted sequence dipping westwards at between 40 and 70^{0} (Fig. 1). Repetition on small scale folds occurs only at two points in the section and could be recognized with ease so that due allowance could be made in logging the section. Plunges of the few small scale folds and of the major regional structures do not exceed 10^{0} locally (Marcos, op. cit.), so that palaeocurrent measurements could be rotated without need for plunge compensation.

The Lower Palaeozoic stratigraphy of Asturias is repeated by north/south trending thrusts, the transport on which is westwards (Marcos, 1973, Fig.33, p.65) (see Fig. 1 herein). In selecting the section, care was taken to ensure that field data was taken from a single thrust unit so that the effect of large scale spatial variation in facies was not included in the resultant analysis. Faulting within the thrust boundaries is insignificant and does not adversely affect the logging.

f. Petrology.

Jaritz and Walter (1970) described some details of the petrography of the Cabos Series and their modal analyses, relevant to the Luarca-Cadavedo section, are presented in Figure 3 . The number of samples recorded is so small that little idea of the petrographic evolution is possible. Their lowest sample (Fig. 3, sample 5) falls well into the quartzite arenite field (Classification of Dott, 1964). Samples 6, 7 and 8, from the two immediately overlying members of Jaritz and Walter (op. cit.), are subarkoses. However, the next member (samples 1 and 2) contains both quartz arenites and subarkoses. The topmost member of the Cabos Series (sensu Jaritz and Walter, op. cit.) contains pure quartz arenites (samples 9 and 10), but the immediately underlying member has subarkoses (sample 3).

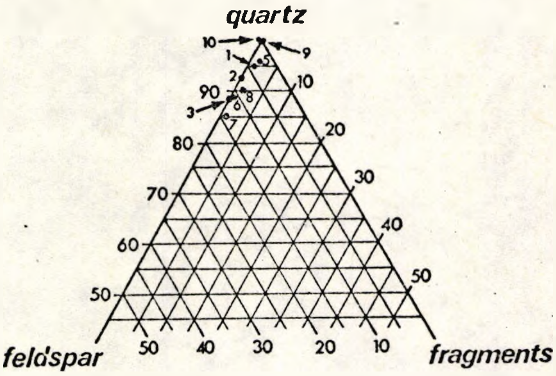

Figure 3
Petrography of the Cabos Series in the section between Cadavedo and Luarca (figure from Jaritz and Walter, 1971; sample numbers as Jaritz and Walter, op.cit.).

Thus no simple pattern is developed and more extensive programmes of analysis are required before conclusions can be drawn regarding petrographic evolution. Geitelink (1973) is at present completing a petrographic analysis of the Cambro-Ordovician rocks of the western Cantabrian and Asturias regions.

g. Data collection.

Field sections were logged on a scale of 1:100, the symbols and format employed by Shell Petroleum (Shell Manual, 1964) being utilised as far as possible. Logged data was derived from integration of all available information for a given level and not, for example, by simply selecting a single sample line such as the beach/cliff junction. Additional detailed information was recorded on prepared data blanks which involved the 'checking off' of sedimentological and biogenic information.

h. Data presentation.

The logged sections are presented on microfilm in the appendix and facies interpretation are included in the data sheets. Interpretation of the lithofacies and the facies model are discussed below. Summaries of the distribution of facies are shown in Figures 1* & 2* of the paper 'The stratigraphy of the Cabos Series in the section between Cadavedo and Luarca, Province of Oviedo, N.W. Spain'. (See appendix.)

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*References to these two figures will be differentiated by asterisk.

2. FACIES DESCRIPTION AND INTERPRETATION

1. Foreshore (Proximal) Magnafacies.*

Facies 1A. Sand flat/beach.

Facies 1A is formed from the combination of two lithotopes which may be differentiated by style of large scale stratification and by overall bed geometry characteristics. Differences in actual lithology and small scale structures are less significant. The degree of intermixing of the two lithotopes within individual facies groups is such that their separation into formal sub-facies does not appear appropriate. The two lithotopes will be described under essentially geometrical headings (viz. tabular and lenticular sands) leaving their environmental interpretation to the end of the section.

Description.

Tabular sands: The tabular component of facies 1A is dominated by medium and fine well sorted sandstones with subordinate intercalations of silts and muds. Pure mud and mud/fine silt lithologies are rare, but where present are wave and interference rippled and display wavy and ripple lamination in section. Bed thicknesses range from a few mm to over 2.5m with the majority of beds falling within the range of 0.2m to 0.5m. (Most are parallel sided, with sharp or rapidly transitional upper and lower contacts.) Beds occur in bundled sets, up to 12m in thickness (Pl.46.1). These form sandstone bodies of pronounced tabular geometry (Pl.47.1). These beds are dominantly evenly laminated (Reineck and Singh, 1973, p. 105), the lamination occurring either as low angled ($<15^o$) dipping layers (Pl.43.2) or horizontal bedding. Laminae are commonly less than 2mm thick, both continuous and discontinuous, and differentiated by variable proportions of dark heavy minerals. In the thicker laminae, both simple and reversed grading are present and primary current lineation is commonly preserved on bedding and lamina surfaces (Pl.47.2). Low angle planar discordances, dipping both north-west and south-east are present throughout many of the low angle cross-bedded units, but

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*Magnafacies - Caster, 1934.

these surfaces cannot usually be traced for more than 3 or 4m before they are reorientated to merge parallel with the adjacent units.

Apparently massive beds, often with evenly laminated tops and bases (Pl.46.2) are associated with some of the thicker parallel and low angle cross-laminated beds. No appreciable change in grain size or lithology is present at these types of contacts, but textural modification derived from the close spaced, better sorted laminae tends to promote a weathering difference which visually accentuates the contacts.

Lenticular sands: Associated with the tabular sands are occasional units of medium sands with lenticular geometries which are characterised by both high angle planar and trough, large scale cross-bedding. In most cases the cosets rest on broadly undulating erosion surfaces with a relief of up to 3m (Pl.42.1) and the toe sets are normally tangential to the local topography. Spoon-shaped fills are common, often composed of sigmoidal co-sets which drape the basinal form (Pl.43.3). Such units can rarely be traced for more than 15-20m before they pinch out, usually into an irregular or undulating rippled surface which generally merges with adjacent parallel sided units. Small scale wave bed forms are associated with the cross-bedded units of the facies. Asymmetric current ripples are common, so are large and small scale linguoid ripples. Wave ripples (determined from internal laminae), modified by post-constructional phase flow to more or less symmetrical forms are present. Flat topped ripples with a relief of less than 4mm indicate a similar two stage genetic process (Pl.45.2). More intense local erosion is indicated by large open flute casts (Pl.45.1) on the sole of a single fine to medium sandstone which cuts down into the top of a parallel laminated sandstone.

Continuous erosion surfaces composed of irregular hummocks (Pl.41.1) of laminated sand are present in a number of places in this facies. The rounded, hummocky surfaces may have a relief of more than 1m and the erosive nature of these surfaces is indicated by the truncated laminae present within the hummocks (Pl.41.1). In most cases these surfaces are draped with thin bedded and rippled sand, silts and occasional flasered muds, which, within less than 1.5m, pass again into strongly parallel laminated medium sands which lack any rippled bed forms.

Associated structures indicating similar erosional processes are lenticular, sigmoidally cross-bedded sand stringers (Pl. 44.4) with mud pellets on the foresets (Pl. 44.2). Tangential bottom sets suggest that these are depositional structures detached by some distance from the mud pellet source. Possible reactivation surfaces and the mud pellets probably indicate almost coeval erosion. Soft-sediment deformation is present, but only the larger scale structures are recognised with ease, there being only poor markers for the small scale load and slump structures. Large bulbous load casts of sand in sand are commonly associated with the thicker units of parallel laminated and particularly with the massive sandstone units (Pl . 41.1). Load casts tend to be roughly boat or hemispherical in shape, but the elongate forms give no regular orientation pattern. Underlying sand beds may be pinched up into the overlying loading bed and, in one case, lenses of sand derived from the underlying loaded bed are completely isolated by the closing together of the lateral margins of the large load structures. Rarely do the structures of the loading bed become isolated or detached and loading beds with an under-surface relief of up to 0.75m may pass up in less than 1m to a parallel laminated or massive bed with a flat upper surface.

Palaeocurrents.

The palaeocurrent patterns derived from the large scale, high angle cross beds present throughout the outcrop of facies 1A show a major transport direction towards the north and north-west (Fig. 4). Subordinate modes demonstrate flows towards the east, through south to due west. The general flow pattern is essentially trimodal with a north to north-west/south, 180^{0} bimodal pattern dominating a weaker westward transport mode (Fig. 5).

The low angle cross beds, measured dominantly from the tabular lithotopes of the upper 2500m of the section give widely dispersed flow patterns (Fig. 4). A slight north-west/south-east bimodal pattern dominates and shows marginally greater transport towards the south-east.

Flow patterns derived from ripples and ripple lamination of both the upper and lower halves of the section (Fig. 4) show a 180^{0} bimodal pattern, dominated by north-west/south-east modes. The inte-

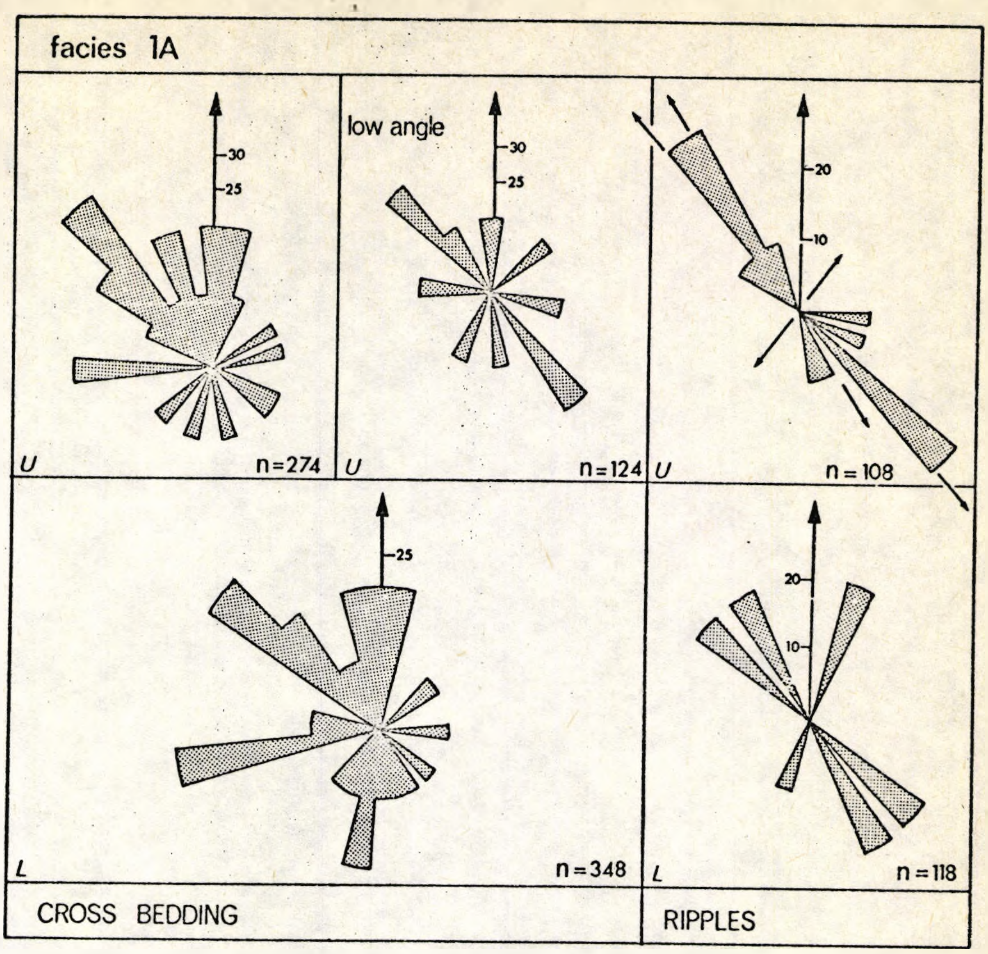


Figure 4
Palaeocurrent patterns of Foreshore Sand Facies. U - samples from upper transgressive part of section; L - samples from lower transgressive part of section. Arrows in upper ripples rose indicate channel trends. Absolute scale to roses.

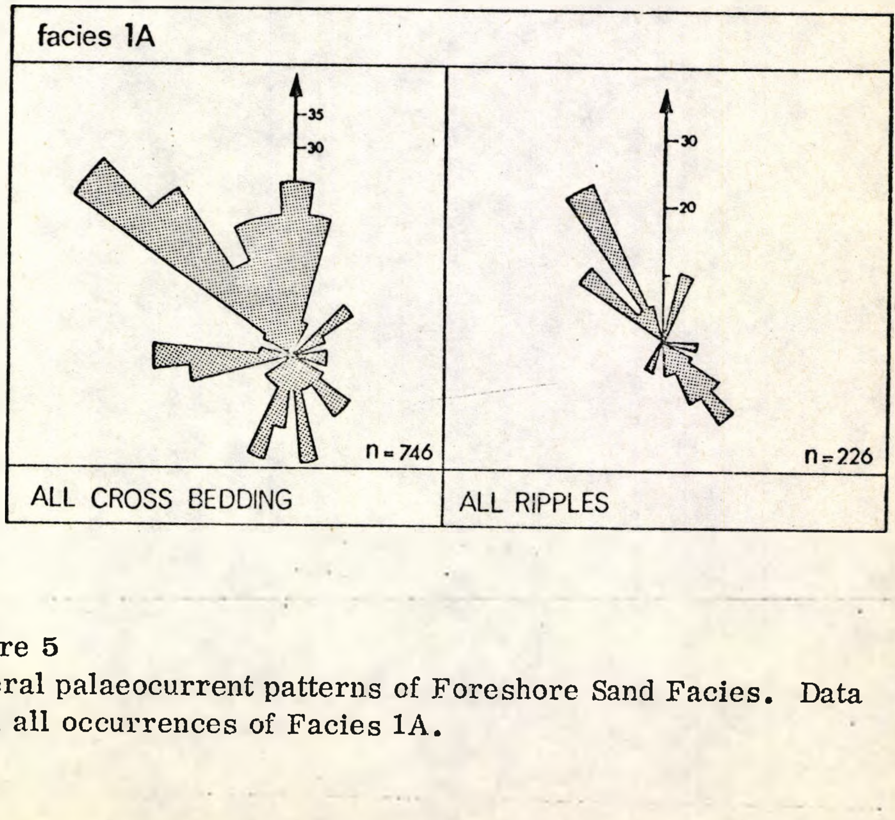


Figure 5
General palaeocurrent patterns of Foreshore Sand Facies. Data from all occurrences of Facies 1A.

gration of both groups of data (Fig. 5) shows little dispersal of south-eastward flows: flows directed to the north-west, while quantitatively greater, are more dispersed. A weak north-east/south-west bimodal couplet is also present.

Bioturbation.

Bioturbation and destratification levels (Reineck, 1963) are characteristically low in this facies, rarely exceeding 25%.

Discussion.

Evenly laminated sands are characteristic of modern shallow marine environments in which perturbations in grain transporting systems permit the hydrodynamic sorting of available sediment. Bogardi (1965) and Guy *et al* (1966) suggest that sand transport in the 'plane bed without movement' phase of the lower flow regimes (Simons *et al*, 1965) could, provided there was sufficient sand input, produce this type of lamination, but these conditions would probably require long term, uni-directional currents to produce other than relatively thin sedimentation units. Deposition of sand during the plane bed phase of the higher flow regime may produce an indistinct type of parallel lamination (Jopling, 1967). Bed load segregation produces *en echlon* ridges and hollows (primary current lineation) which tend to show a size sorting with coarser grains in the ridges (Schlichting, 1960; Allen 1964). This sorting and the regular spacing of the ridges has been interpreted as resulting from tubular, corkscrew vortices present in the flow (Allen, *op. cit.*). The discontinuity of the current lineations tends to preclude continuous laminae (Reineck and Singh, 1973, p. 106) and a streaky type of lamination is produced. Allen (1964 & 1968, p. 34) indicates that water flows of large stream power and high Froude numbers (>0.3) are required for the production of these structures and he suggests that backwash flows from breaking waves may generate these upper flow regime conditions. Davis *et al* (1972) demonstrated from both tidal and non-tidal environments that variations in water depth above berms and welded beach faces could, at certain water stages, produce plain bed conditions resulting in parallel laminated, current lineated units.

Evenly laminated sands in which primary current lineation is relatively uncommon are described from low angled beach lamination by Reineck (1963). He interprets the alternating laminae, often characterised by reversed graded lamina, as resulting from swash and backwash action of waves. Grains transported up the beach face by the swash are sedimented through the retreating backwash so that both grain size and specific gravity differences tend to be accentuated during sorting (Sanders, 1965; Clifton, 1969). This leads particularly to heavy mineral segregations which visibly define lamination (Clifton, op. cit.).

The low angle cross-bedded units of the tabular sands of this facies are similar to beach deposits described by Thompson (1937). The low angle, planar erosion surfaces represent variations in local beach slope and geometry, possibly derived from beach stripping and subsequent accretion following local or regional weather changes (Kraft, 1971; Davis et al, 1972).

The cross-bedded, lenticular members of the facies are similar to the scour and fill structures described from the Arenicola sand flats of the Wash (Evans, 1965). In the Wash environment the scours are derived from abandoned, slumped and modified creeks which can be differentiated from the active creeks by the absence of lateral accretion deposits. Such scours may be up to 1.3m deep which is slightly greater than any seen in the Cabos Series. Allen (1968) describes spoon-shaped scour pits, approximately 0.5m deep, in association with large scale lunate ripples from various sand flats and sand bars in England and Wales. These have a relief and form in common with many of the cross-bedded lenses present in this facies. Various forms of channel fill have been described by McKee (1957), and the asymmetrical fill (Fig.6 c) would be similar to many of the spoon-shaped cross-bedded units of the 1A facies. The sigmoidal form of the filling cosets may derive from a combination of high levels of suspended and load sediment in a flow relatively deeper than the relief of the scour. Similar processes were discussed by Jopling (1965) for the formation of cosets in laboratory deltas.

Channel forms and characteristic lateral accretion deposits (van Straaten, 1952) appear to be relatively uncommon in this facies, a feature which is at variance with many modern intertidal sand flat environ-

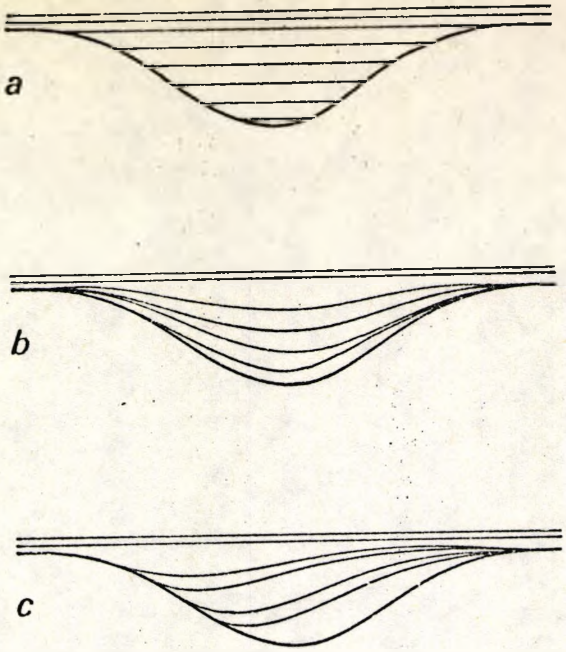


Figure 6
Cross-sectional form of channel fills. a) truncated margins; b) symmetrical drape; c) asymmetrical drape (from McKee, 1957).

ments (cf. van Straaten, 1952, 1954a; Reineck, 1958; Klein, 1965). Klein (1970a) noted a similar difference in his study of Dalradian tidal deposits of Islay, Scotland. Klein (*op. cit.*, p. 982) compares his Dalradian environment with the Recent non-chanelled tidal sand flats of the Wash (Evans, 1965), but proposes no mechanism to account for such absence. Walker and Harms (1971) suggest that very low tidal ranges (*c.* 2m) may be the cause of the absence of channels from Devonian tidal deposits. In this case the volume of water covering the tidal flats during high tide periods was so low that most could be drained off during ebb by sheet-like runoff which was unable to develop confined channel flows. The tidal range operative during the period of deposition of the Cabos Series (see p.41) is much greater than that suggested by Walker and Harms (*op. cit.*) so that this tidal mechanism may not represent the only controlling factor. Local shoreline geometry, particularly the presence or absence of offshore bars and intervening lagoons may have influenced drainage characteristics of the foreshore zone.

An additional reason for the low incidence of channels may in fact stem from difficulty of recognition of such forms in what is an essentially two-dimensionally exposed section. Channels exposed in the vertical cliff-

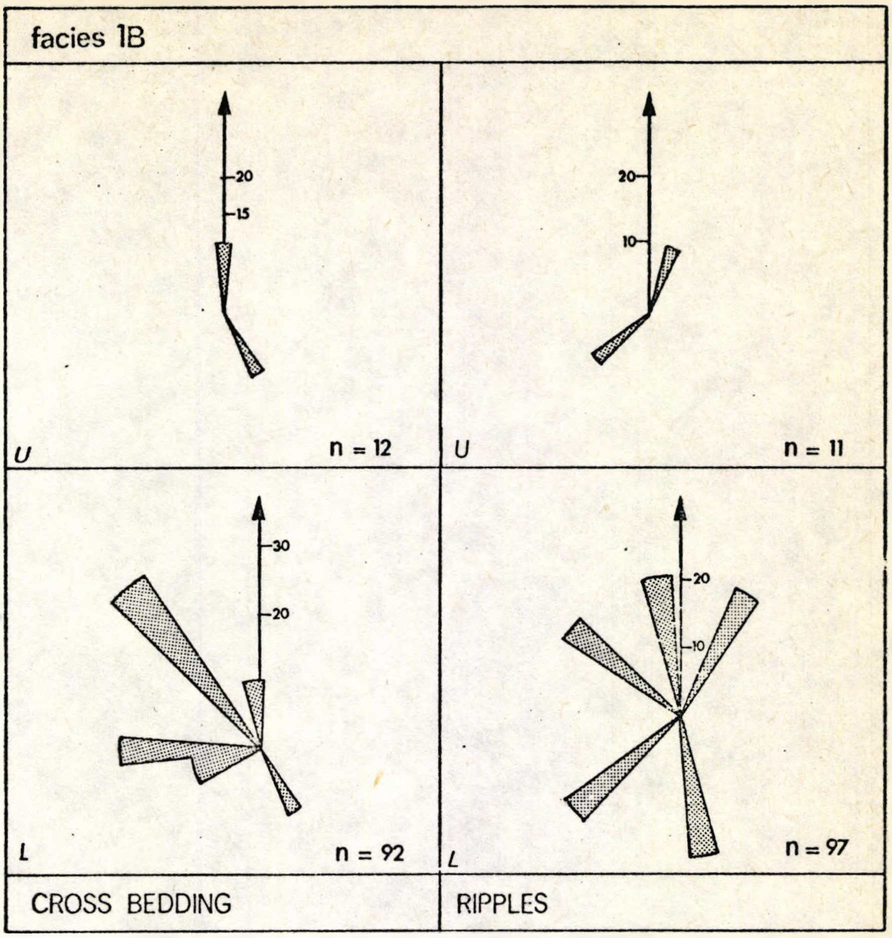


Figure 7
Palaeocurrent patterns of Foreshore Mud Facies.
Other details as for Figure 4 .

line would only be visible when trending at high angles to the local dip, but would be more easily identified in the wave-cut platform. Unfortunately, due to intervening shingle beaches and access controlled by tides, platform and cliff exposure could not always be studied together.

It appears that for intermittent periods processes involving local erosion were operative. This stripping of adjacent mud layers is in keeping with a foreshore/sand flat model, but the absence of mud pellet concentrates from the basal layers of scour fill structures suggests that these clasts do not represent lateral accretion components. Mud pellets have a limited transport potential (Smith, 1972), and their incorporation in cross-bedded sand fills and low amplitude wave forms appear to reflect tidal or storm induced incursions into the low topography areas of tidal flats and high beaches.

Large scale load casts of sand into sand have been reported from beach foreshore areas at or above the breaker zone (Zenkovich, 1967). Geitelink (1973) specifies the same position for similar large bulbous load structures in the Barrios Formation and supposes that these structures are related to foundering processes operating in water saturated sands.

The thin and discontinuous fine grained rippled beds which comprise only an insignificant proportion of the facies may represent runnel or sand flat depression sediments. Ponding of water in topographic lows has been described from tidal flats in the North Sea (van Straaten, 1954; Reineck, 1958; Reineck and Singh, 1973) and similar thin drapes of fine grained sediments over sands were discussed by Parker (1971) from foreshore areas of the west Lancashire coast, marginal to Mersey Bay.

Bradshaw (1966) interpreted the sand mounds of Finistere as the products of local gully erosion and envisaged a tidal marsh or sand flat environment for their development.

Interpretation.

The repeated mixing of two sedimentologically and bathymetrically related environments is suggested for facies 1A. The tabular and lenticular components appear to represent respectively beach and tidal sand flat environments, but the degree of intermixing and the completely transitional relationships of both the components suggest neither marked spatial or temporal separation of the environments. Rather, the two components are the end members of a spectrum of micro-environments all of which were developed in similar sediments and at similar positions in a marginal marine area.

The immediate juxtaposition of beach and tidal flat and the absence of intervening lagoonal facies appears to preclude protective barrier bar development offshore from the area of facies 1A. In this case, high energy beach facies could margin lower energy tidal sand flats and the preserved sediments perhaps reflect the constant but irregular shifting of energy zones leading to the thorough mixing of these environments. Thus a beach/sand flat or alternatively backshore/foreshore facies is proposed in which berm and beach accretion, possibly related to relatively higher energy conditions (syn- or post-storm?), was followed by a reduction of foreshore slopes and the redistribution of sands in a tidal sand flat environment.

Facies 1B. Mud and mixed tidal flat.

Description.

Facies 1B has dominantly gradational relationships with other members of magnafacies 1, but commonly displays erosive or abrupt contacts with the sand dominated members of magnafacies 2.

The facies is composed of silts and muds with subordinate medium and fine sandstones. Bedding contacts are commonly gradational and irregular or undulating (Pl.48). The coarser sandstone lithologies have sharp but not erosive lower contacts and tend to drape the mud and silt topography (Pl.49.1). Upper contacts of the sands may be similarly sharp and undulating with preserved wave bed forms determining the overall shape of the sandstone beds. Internal, as well as some upper surface, contacts are wavy and lenticularly bedded (Pl.48.3) and merge by both diffuse and rapidly gradational contacts with the surrounding finer lithologies. Most of the medium sands are cross-bedded, with high angle tabular and trough cross-beds (Pls.49.2, 3). Both tangential and high angle bottom-sets are preserved. Rare mud pellets may be present as thin, discontinuous concentrates at the base of the cross-bedded units, but most commonly they are dispersed throughout the foresets (Pl.50.3).

The muds and silts are dominantly flaser and linsen bedded with less common parallel and even bedded silts (Pl.49.3). Ripple lamination present in the silt and fine sand lenses and the rare rippled surfaces preserved in the facies indicates straight crested wave ripple forms with rounded - depositional and rounded - truncated crests. Flaser and linsen bedded units rarely exceed 0.5m in thickness and are characterised by internal, undulating discontinuity surfaces which, as the flasers and lamination are not cross-cut, but more commonly amalgamate, appear to be of depositional rather than erosional origins. The 'fills' of these shallow undulating forms drape or bank up against the pre-existing topography, this again leading to amalgamation of the lower four or five flasered sets (Pl.50.3).

Palaeocurrents.

Only twelve palaeocurrent determinations were possible in this facies from the upper 2500m of the section (Fig. 7). More data is available from the lower half of the section, the contrast reflecting variations in proportions of the facies in each half of the section.

Cross-bedding indicates a palaeoflow pattern similar to that of facies 1A. A north and north-west/south-east 180° bimodal pattern dominates a secondary westward transport direction. Again the pattern is essentially trimodal (Figs. 7 , 8).

Flow directions derived from ripples and ripple lamination are diverse, but a south-west/north-east trend dominates (Fig. 8).

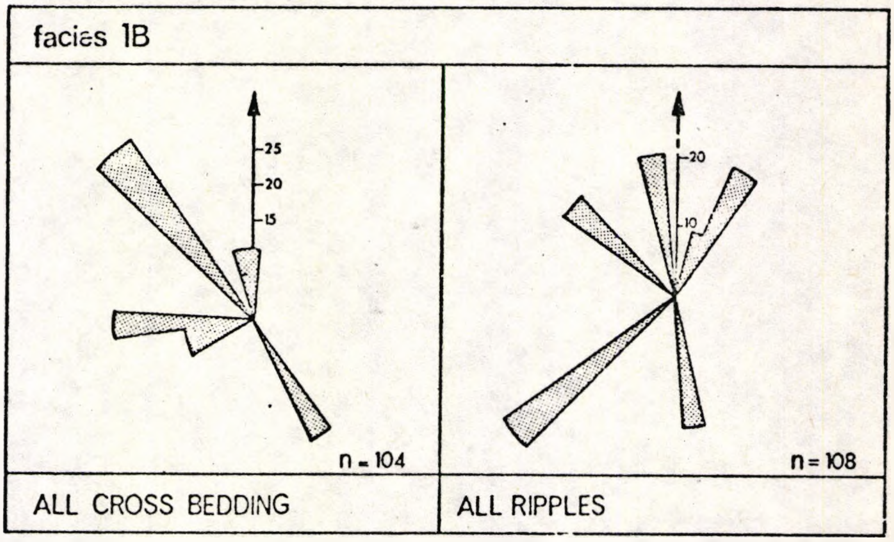


Figure 8
General palaeocurrent patterns of Foreshore Mud Facies. Data from all occurrences of Facies 1B.

Bioturbation.

Bioturbation levels rarely exceed 35% to 40% (Pl.50.1), but occasional thin beds of silts may be heavily destratified (70%) near their surfaces (Pl.50.2). Meandering small bilobate trails and Planolites are the most common trace fossils. Rare vertical U and Skolithos are confined to the thicker sand intercalations.

Discussion.

There exists an extensive literature on various types of modern tidal flat environments, perhaps the best known study areas being located around the North Sea (e.g. Dutch Wadden Zee - van Straaten, 1961; The Wash, England - Evans, 1965; north-west Germany - Hantzschel, 1939; Jade Bay - Linke, 1939; Gadow, 1970; general North Sea areas - Reineck, 1970). Other areas in various parts of the U.S.A. are similarly documented (e.g. Bay of Fundy - Klein, 1963, 1970b; Gulf of California - Thompson, 1968). The Gulf of Gaeta, southern Italy provides an even more up to date study (Reineck and Singh, 1971).

In the Jade Bay tidal flats, small scale ripple cross-bedding exhibits herringbone relationships in sections normal to the ripple crests and such beds are interbedded with wavy, flaser and linsen bedded units. Mud layers contain scattered sand grains which were deposited with mud aggregates of similar hydraulic properties (Reineck and Singh, op. cit., p. 359). Interbedded sands with megaripple bedding are preserved in broad tidal channels where high current velocities are able to construct megaripple, giant ripple and sand wedge bodies (Luders, 1929; Hantzschel, 1938; van Straaten, 1950, 1954; Hulseman, 1955; Reineck, 1963). These megarippled, wave-form sands may be interdigitated with lateral accretion deposits formed from longitudinal cross-bedded point bar deposition (Reineck and Wunderlich, 1969).

It is in the channel areas that van Straaten (1954) and Reineck (1958) consider the main depositon of tidal flats take place. There is, however, net accretion in shallow morphological depressions of the relatively high areas marginal to the channels. Evans (1965) describes similar mud and silt draped deposits from his high mud flat facies of the Wash. Walker and Harms (1971) have suggested that the absence or reduced occurrence of tidal channels and creeks from tidal flat environments may be related to low tidal ranges (c. 2m) which do not require channel systems for the efficient removal of ponded flood tidal waters. Ebb flows are drained as sheet flows or along shallow, open linear depression.

Bioturbation levels are variable on modern tidal flats and bear a direct relationship to the relative volume of muds and fine silts in a given flat. Faunas tend to be restricted, but abundant, where protection from wave action is afforded (Hertweck, 1970; Schäfer, 1973).

Interpretation.

Sedimentary structures, bedding types and patterns of bioturbation preserved in facies 1B are similar to those displayed in modern mixed tidal flat environments. The cross-bedded sands with wavy laminated tops appear to represent sand incursions into a mud/silt dominated environment and their wavy form suggests channel megaripple or sand wedge bodies which were redistributed by wave and local topographically controlled currents. Lateral accretion deposits are however rare, so that deep relatively meandering channels seem to have been of minor importance in this environment. The majority of the sedimentation appears to have taken place in the shallow depressions of the undulating surface of the mud flat and in this case an environment comparable with Evans 'high mud flat' is envisaged.

Periods of sand flat dominance periodically seem to have eclipsed the mud dominated environment and this may relate to sediment supply, possibly ultimately related to macro-geometry of the shoreline area. Barrier bars may have effectively blocked sand inputs to the high flat area and thus permitted the fuller development of mud and mixed flat facies.

2. Inter Bar Magnafacies.

Facies 2B. Inter bar low.

Description.

In a vertical sequence facies 2B often separates sand bar facies from the more proximal onshore sand and tidal flat facies (Fig. 2), but it also interdigitates with either of these sand dominated facies.

The facies is composed of interlaminated muds and silts in thin, medium and thick beds and subordinate sands and silts in thin and medium-thick beds (Pls. 51, 1 - 4). The sand interbeds are wavy and parallel laminated when thin, but tend to appear massive when thicker than 0.25m. Lower contacts are usually flat, weakly erosive and abrupt, whereas the upper surfaces tend to be strongly laminated, diffuse and more gradational with the immediately overlying silts and muds (see Pls. 52, 53). The sands are usually continuous and of even thickness for distances greater than 20m, but may terminate suddenly by pinching together of the upper and lower bedding surfaces. Such terminations may be accomplished in distances of less than 0.75m. Beds mostly have the geometries of thin sand sheets, but some examples occupy shallow (0.2m) channel forms which may be up to 15m wide. Few deeply erosive or steep sided channel forms were recorded and where they are present the facies group occupies a position adjacent to beach or sand flat facies. Some of the thicker, massive sand interbeds have wave forms of 1 to 2m wavelength bounding their upper surfaces. Cross-bedded fills are rare, as are multi-stacked composite or amalgamated sands. Most are single beds.

The range of structures preserved in the mud/silt beds is shown in a sequence of plates (Pls. 52 - 54). Many forms of flaser and linsen bedding are preserved and the available cliff and foreshore exposure in the Luarca-Cadavedo study area (Fig. 2) permitted the detailed recording

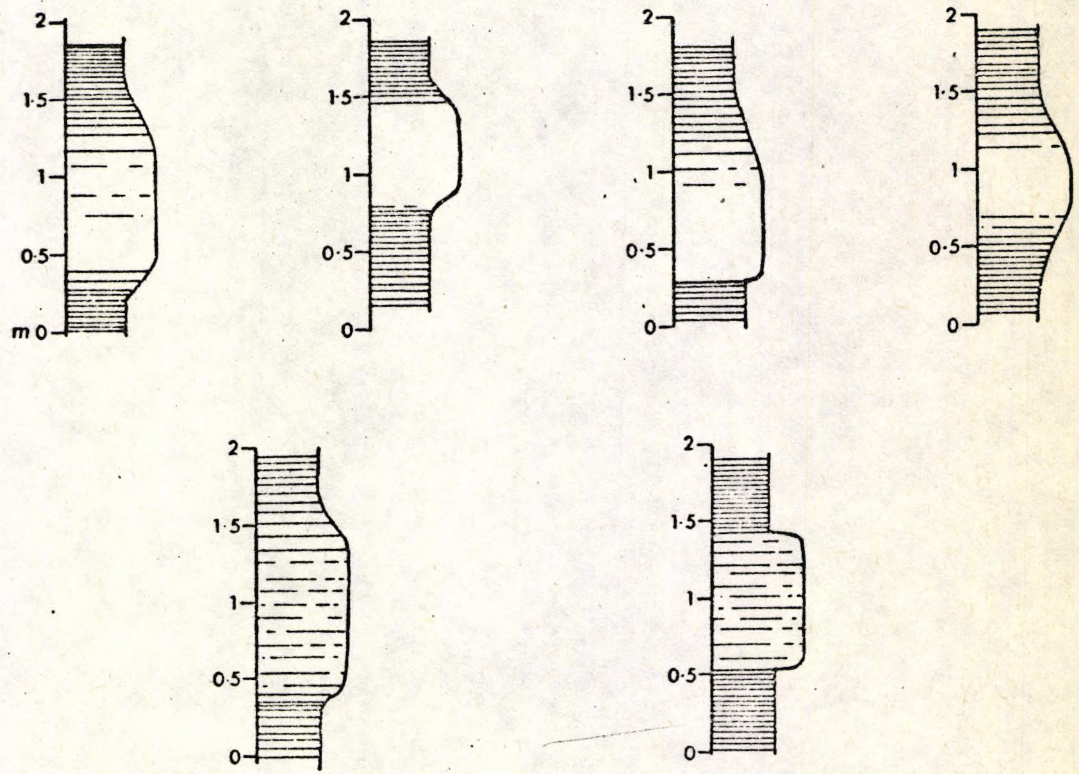


Figure 9
Representative examples of sands and laminated interbeds present in Facies 2 B . Strength of lamination and grain size variations given in relative terms only.

scheme of Reineck and Wunderlich (1967) to be followed. Simple, bifurcated and wavy forms of flaser bedding, wavy bedding and linsen bedding with both connected and isolate lenses are preserved. Good examples of isolate linsen (Pl.56.3) are preserved low in the section where bioturbation is at a minimum.

From the sequence of plates (Pls. 52 - 54) which record individual beds of flasered and linsen units, a complex history of accretion is recognised. Each of these small scale multiple sedimentation units (Otto, 1938) is composed of silt and mud lenses (Fig. 16) which are themselves composite and composed of separate, individual laminae. The lamination of these small scale units is locally wavy and irregular, but the individual units can be traced along the limit of exposure (c. 30m). Over this length they may change appreciably in thickness and form, but they still maintain their individuality and coherence. The strongly wavy laminated and flasered sedimentation units alternate with weakly laminated or structureless muds which are similarly laterally continuous.

The most striking feature of the facies is the apparent regularity of spacing of the sandstone interbeds (Pls. 51, 52). Within individual silt/mud beds a degree of consistency of both spacing and numbers of the small scale sedimentation units (viz. the strongly flasered and non-laminated components) forming the major sedimentation unit is apparent. It is noticeable that the laminated small scale units slightly increase in the proportion of the total sediment by a gradual reduction of the spacing of the laminae immediately above and below the sandstone interbeds (Pls.53.2 53.3) (Fig. 9).

Palaeocurrents.

The few cross-bedded sandstones of facies 2 indicate a variable flow pattern. Four separate modes show transport towards the north-west, north, east and south-east (Fig. 10), with a higher incidence of northward and southward flows.

Ripples (Fig. 10) suggest the combination of two 180^{o} bimodal patterns, one on a north-west/south-east trend (transport to the north-west dominant) and the second on an east/west trend (transport to the east dominant).

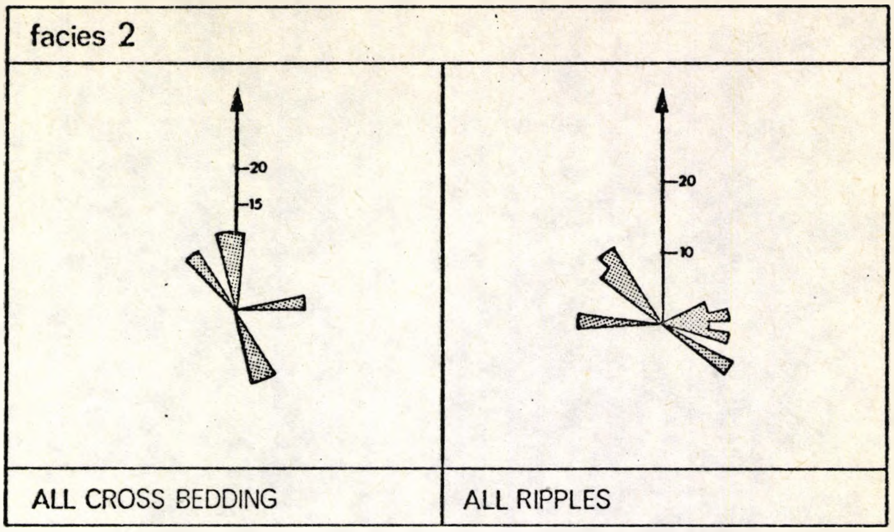


Figure 10
General palaeocurrent patterns of Lagoonal Magnafacies. Data from all occurrences of Magnafacies 2.

Bioturbation.

Bioturbation is variable and heavily destratified beds may be adjacent to non-bioturbated units. There is, however, a noticeable pattern of bioturbation when the total 4,500m section is considered. The lower 2000m to 2500m are characterised by low levels of bioturbation (30%). Units with much higher values are present within this part of the section, but they are more or less isolated and usually less than 5m thick. Above approximately 2000m there is a marked increase in bioturbation. Thick (10m - 15m) units of facies 2B may be destratified by more than 60% and thin units may be completely destratified (Pl. 57).

The facies contains the bulk of the trace fossils recovered from the section. The ichnospectrum is narrow, being dominated by trace fossils of trilobite origin. Cruziana are common as are indeterminate shallow horizontal and inclined burrow systems. Skolithos and other vertical tube structures are rare.

Discussion.

Reineck (1960a & b) and Reineck and Singh (1973) discussed the origins of flaser and lenticular bedding and demonstrated that these types of bedding are dependent on the alternation of currents or waves which deposit sands and silts with slack water periods during which muds and fine silts are sedimented. The sands are formed into ripples so that in section they are seen to be composed of small scale foreset laminae. The mud layers drape the ripple lenses and in some cases completely enclose them. Therefore, a spectrum of structures dominated by either sand or mud is recognised and this may be subdivided and used to develop a classificatory system of nomenclature of flaser and linsen bedding (Reineck and Wunderlich, 1968).

Reineck (1963), Reineck et al (1968), Terwindt (1971) and Terwindt and Breusers (1972) described most forms of flaser and linsen bedding from subtidal zones. Hantzschel (1936) and van Straaten (1954) reported the same structures from intertidal zones. In both areas bed form genesis is controlled by the tidal rhythm (Reineck and Singh, 1973), but the actual rate and mechanics of accretion is uncertain. Terwindt's and Breusers' (op. cit.) experimental work has demonstrated that early consolidation of muds leads to their retention as draped layers and also accounts for the discrete boundaries between muds and sands. The mechanism of mud sedimentation is as yet unclear. McCave (1970) has suggested that mud layers may in fact be deposited by ejection of fluids from a thick viscous mud sub-layer and not sedimented by simple fall-out from the water column. Such a process permits an increase in the period over which mud can be deposited. Rhoads (1970) and Oertel (1973) have reported important depositional processes in which mud, in the form of sand sized faecal pellets, is rapidly deposited by traction currents. Again the slack water period during which mud deposition is possible is effectively extended so that relatively thick mud layers can accrete.

Warme (1966, 1967, 1969a & b, 1971) described the facies relationships in and around the Magu lagoon of southern California. The lagoon is connected to the open sea only at certain stages of the tide. Due to variations in the heights of the diurnal tides, the lagoonal area is subjected to oscillating wave and tidal current activity. Various forms of flaser, lenticular and alternating mud/silt bedding are described from the intertidal, so-called 'barren zone', which is situated between the lowest, non-vegetated intertidal levels and extends up to the vegetated parts of the intertidal marsh (Warme, 1971). Variations in sand, silt and mud proportions reflect various positions of the barren zone relative to tidal inlets, creeks and barrier bar environments. The muddy portions characteristically flank the tidal creeks and mud flats whereas the sandy sediments are located inside the barrier sand bars and adjacent to the tidal inlets. Sediment dispersal patterns inside the lagoon are complex. Algal mats are important agents in fixing thin mud layers.

Storm washover sands which appear similar to some of the sandstone stringers of facies 2B have been described from Holocene barrier bar sequences of coastal Georgia (Kraft, 1971). Similar deposits have been described from the Gres Armoricain of Finistere (Baldwin, in press). These are all characteristically 'scoopy' in geometry and more strongly erosive than the majority of the sands in facies 2B, which are flat bedded and only gently erosive. Amalgamated and bunched beds are more typical of the storm sands and these again contrast with the dominance of isolated sands of facies 2B.

Interpretation.

Areas inshore from barrier bars and intertidal sand bars may provide the types of environments for thick intercalations of flasered muds and silts. Such zones in the Cabos Series were probably subject to tidal and immediate sub-tidal influences for much of their existence and did not become true isolated lagoons characterised by long duration of sub-aerial exposure. The interdigitation of facies 2B with both proximal and distal sand facies suggests an intermediate position between these two environments. Sands may have been spread by high and storm tidal events from both sand environments.

Storms, in most cases, ultimately controlled the distribution of inter bar lows and intervening sand bars, but it appears that offshore bars remained sufficiently stationary for thick inter bar low sediments to accumulate.

Facies 2B is dominated by tidal effects and it is possible that some sedimentary structures reflect spring tidal events. These and other details of tidal control to sedimentation will be discussed at greater length below (p.41).

3. Sand Bar (Distal) Magnafacies.

Facies 3A(i). Bar crest.

Description.

Sub-facies 3A(i) is commonly gradationally associated with high shoreface, bar flank and beach/berm (Fig. 2*), but the higher energy members of these facies (beach, shoreface and even some inter bar low facies) may overlie the bar crest on shallow, non-channelled erosive surfaces.

The sub-facies is dominantly composed of well sorted medium sands with subordinate, less well sorted silt interbeds. Muds are rare

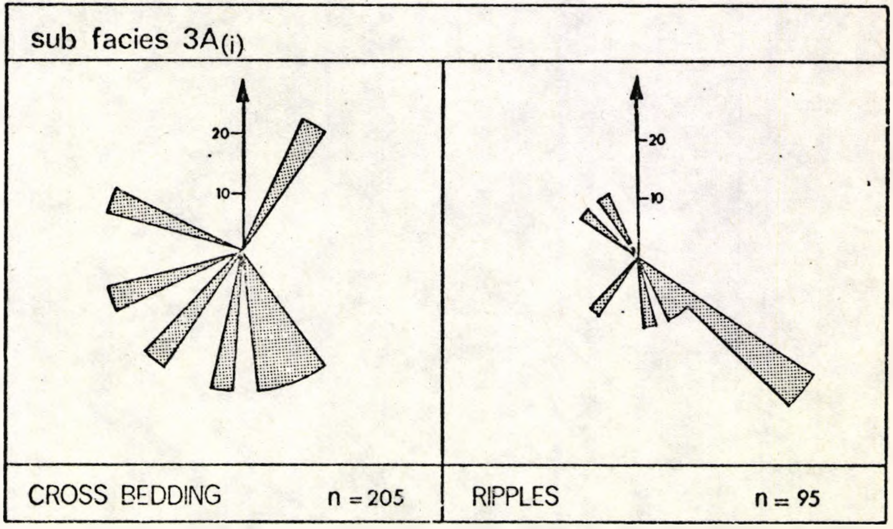


Figure 11
Palaeocurrent patterns of Sand Bar Crest sub-facies. Data from all occurrences of sub-facies 3A(i).

and present only with discontinuous, lenticular flaser and ripple laminated interbeds. Bed thicknesses rarely exceed 0.4m and beds normally have tabular geometries (Pl.59.1) with flat, sharp or rapidly gradational contacts. Gently inclined, sharp discontinuity surfaces are present which merge with gently undulating or flat beds over distances of less than 10m (Pl. 59.2)

There is a characteristic sequence of sedimentary structures preserved. Many of the medium sandstones either contain diffuse even and parallel lamination or appear to be structureless (Pl.58.5). Some of these sands are cross laminated with flat, tangential foresets resting on erosive but planar surfaces (Pl.59.2). Lower contacts of the sands are dominantly sharp and some exhibit shallow (<50mm) scours. The upper contacts pass by gradation into silts which in nearly all cases are strongly parallel or evenly laminated. Some examples of this type of laminated boundary show that the lamination present in the silt and fine sand interbed gradually develops from the massive (?) or diffusely laminated sands (Pl.58.3). The laminated interbeds may be up to 0.25m thick and terminate at the upper surface more rapidly than they develop in the lower part (Fig. 12). However, not all interbeds are overlain by a strongly erosive contact and the strength, if not the actual presence, of lamination in the lower parts of the sand beds gradually declines to give a homogeneous sand at the centre (Pls.58.5)

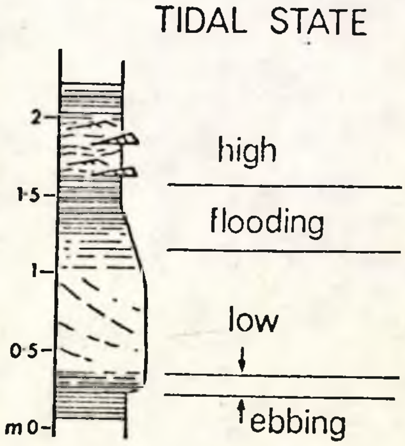


Figure 12
A tidal model for the separation of rippled sedimentation units of the interbeds from the massive or weakly laminated medium sandstones in Facies 3A(i).

Associated with the relatively simple, essentially parallel laminated bedded units are sands and silts with subordinate muds, which alternate on a similar scale, but which have more undulating contacts and, particularly in the fine interbeds, have slightly lenticular geometries (Pl.58.4). The coarser sands and silts are still either massive or weakly laminated. The finer silts and more common muds are wavy or irregularly laminated (Pl.58.1) with some diffuse bifurcating flasers. Multiple, evenly laminated sedimentation units approximately 30mm thick alternate with massive fine silts and muds and wavy and ripple laminated units of equal thickness (Pls.58.4 ,64.3). Thin, laterally continuous strongly laminated fine sand beds may be present (Pls.64.4,59.4) which separate packets of multi-laminated fine lithologies. In these groups with flaser and rippled fine interbeds, the rippled sedimentation units are without exception isolated from the massive sands by units of parallel lamination (Fig. 12). Many of the silts are normally graded.

Palaeocurrents.

The palaeocurrent pattern determined for cross-beds from the complete section (Fig. 11) shows a number of modes spanning the sector from west-north-west, through west to south-south-west, all of which contain approximately the same number of recordings. A single mode indicating more consistent transport towards the south-east forms the only major grouping in the pattern. A single mode indicates some transport to the north-east.

Ripples indicate that the predominant flow was towards the south-west (Fig. 11) with subordinate north-westward directed modes producing a 180^0 bimodal pattern. A third mode, directed to the south-west, introduces an overall trimodality to the palaeocurrent pattern.

Bioturbation.

Levels of bioturbation and destratification rarely exceed 10% and most of this is confined to the few mud and silt interbeds. The parallel laminated sands show no evidence of bioturbation and the absence of discernable structures in the massive sand beds appears to be the result of primary depositional processes, as no mottling or biogenically altered bed contacts are present.

Discussion.

Davis et al (1972) discusses the sequential development of ridge and runnel structures in beach and inner nearshore environments (Fig. 13) and they show that ridge topography is developed during periods of high wave and tidal energy following storm events. The ridges developed in the nearshore zone migrate onshore during 'normal' low energy weather conditions and eventually weld to the beach as berm structures. During onshore migration, crests of successive ridges approach the MLW level and in some cases eventually become exposed. During periods of near exposure wave generated currents in combination with sufficiently shallow water levels cause the development of upper flow regime conditions.

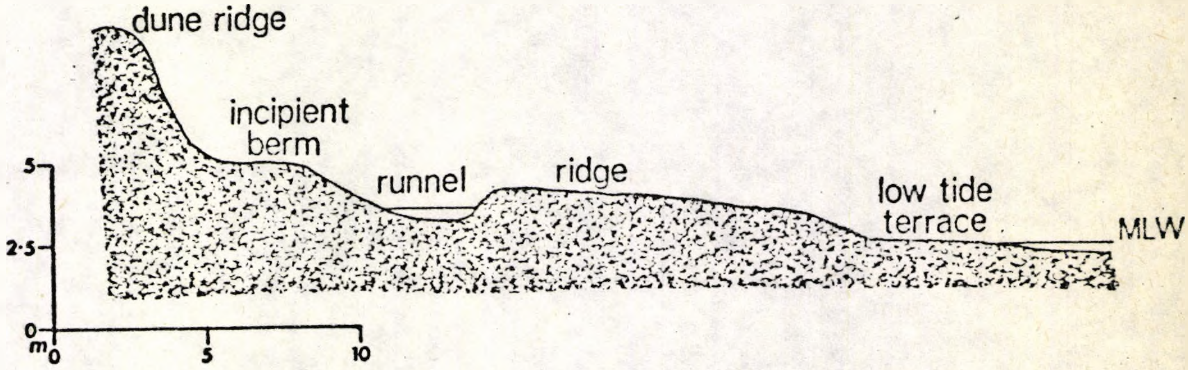


Figure 13
The development of a generalised ridge and runnel beach profile (from Davis et al, 1972).

This results in upper flow regime plain bed deposition (Davis et al, op. cit., p. 417) over the bar crest for limited periods.

Klein (1970b) described the dynamics of intertidal sand bars in Bay of Fundy, U. S. A. and demonstrated that the bulk of ripple and wave bedforms developed during periods when tidal currents had tranquil turbulent flows characteristic of lower flow regime conditions. Such conditions were punctuated briefly at certain tidal stages by rapid turbulent flow conditions of the upper flow regime. These followed from water depths of 0.2m or less during tidal exposure of bar crests and were associated with the highest Froude numbers in the bottom currents. Longitudinal and rhombic ripples developed and bar crests become planed-off during these intermittent exposure periods.

In 'the thin and thick bedded sandstones and siltstones facies' described by Banks (1973) from the late Precambrian Enerlev Member of Finnmark, parallel laminated and rippled silts are interbedded with massive, evenly laminated and cross-laminated sandstones and siltstones. Parallel lamination is confined to the lower parts of the beds and passes upwards into cross-laminated divisions. Both type A and B_1 climbing ripples (Allen, 1970a) are preserved and primary current lineation is absent from the associated parallel laminated beds.

Banks (op. cit.) considers that the couplets of parallel laminated silts and sands overlain by ripple lamination indicates deposition by waning currents (cf. Walker, 1965). Banks (op. cit.) notes the absence of primary current lineation from these parallel laminated beds and follows Goldring (1966) in suggesting that the grain size would probably exclude such longitudinal structures, while still allowing the generation of the parallel lamination by upper flow regime flows. A storm surge influenced offshore channel termination model is envisaged by Banks (op. cit., Fig. 14, p. 23) as the major control of his facies.

Interpretation.

The regularity of spacing of massive sand beds and laminated interbeds is the most noticeable macroscopic feature of the sub-facies and some regularly recurring mechanism must be found which will account for it. The adjacent facies all indicate tidal control and consequently the features of facies 3A(i) may be similarly controlled by the tidal cycle. The interbedded laminated components probably represent periods of higher flow regime deposition developed during the emergence or submergence of sand bar crests. The progressive increase in the intensity of lamination may indicate the gradual development of the upper flow regime conditions during falling and rising stages, a regime which is maintained until flow depth and associated Froude numbers are changed. This could then lead to the development of rippled beds produced lower flow regime conditions. The apparent asymmetry of the laminated divisions above and below the massive sands may result from differences in the overall pattern of flow around the bars during ebb and flood periods. Reineck and Singh (1973, p. 356) have shown from tidal flat areas that flood tide ingress is controlled by water level differences, whereas ebb flow patterns tend to be controlled more strongly by emergent areas. In this case ebb and flood periods of bar crest reworking can have different durations.

The presence of cross-bedding in some of the thick sandstones suggests sediment transport in dune or wave structures. The lamination developed at the top of the sands may represent the flooding tidal period which, over the period of maximum water depth, allowed wave and current reworking of silts and muds to form the flasered and rippled divisions (Fig. 12)

The rate of ingress of the flooding tide must have been slower than the ebb: the plane bed phase was passed through and flooded out much more slowly (Fig. 12) so that the lamination developing from the dune migration conditions tends to appear thicker.

The thicker, lenticular and flasered interbeds, while still showing the same sequence of massive or cross-bedded sands through parallel lamination to ripples, may represent a slight difference in the environment to that involved with the massive/laminated alternations. Approach of the sand bars to mixed tidal flats without the intervention of other bars and associated runnels may have allowed correspondingly greater amounts of mud and sand to be entrained and deposited on the low relief of the flattened bars. The massive sands and mud dominated interbeds may therefore represent periods of nearer to shore development of sand bars, whereas the massive/laminated sands represent the earlier stage of bar construction and reworking in a distal offshore/nearshore location.

3A(ii). Bar flank.

Description.

The sub-facies is formed dominantly from well sorted medium sandstones in lenticular and tabular beds up to 3m thick. Bedding contacts are characteristically sharp but not deeply channelling. Amalgamated sandstone units, up to 25m thick, form tabular sandstone bodies which often have abrupt, shallowly scouring relationships with underlying inter bar low (Pl.64.1) and beach dominated facies.

Large scale cross-bedding is the most common sedimentary structure preserved in the sub-facies (Pls.64.2 ,63.1). Planar and trough sets with foresets dipping at up to 35° form the bulk of the cross-bedded units, but many other varieties are preserved. Sigmoidal and concave-up tangential sets (Pl.64.1) are present in the lower part of some of the thick amalgamated sandstone bodies, and these pass upwards into angular planar foresets resting on irregular erosive bases and with truncated angular tops. The thick sandstones may either persist, in which case the cross-lamination becomes gradually more diffuse and eventually disappears altogether leaving massive beds approximately 0.75m thick, or the cross-beds pass up into units of facies 3A(i). Herringbone sets (Pl.62.1) are relatively uncommon, but where present tend to occur as packets (Pl.63 1) up to 7 or 8m thick. In these units, in nearly all cases, one flow direction is dominant, but the herringbone sets do not show scale differences between either of the pairs forming the set. Reactivation surfaces (Collinson, 1970) are common throughout the sub-facies (Pl 63.2), most flattening and opening out pre-existing wave forms with wave lengths of 5 or 6m.

Linguoid, interference and both current and wave ripples (Pls.61.3, 4) and small scale cross-bedding are associated with the more common large scale sets and in places these small scale structures are present in interbeds of medium sandstone. They rarely exhibit current flow directions different to those indicated by the large scale cross-beds. Examples of small scale cross-bedding superimposed on much larger scale cross-bedding and sandwave-form structures have been recorded (Pl.62.4). The large scale cross-bedded sands form lenticles and pinching out units which either amalgamate with underlying beds or are condensed in relatively thin laminated sandstone interbeds. Small scale cross-beds, with set heights of approximately 50mm, can be seen to climb up the pre-existing topography of the sand waves (Pl.62.4).

Some examples of the sand facies have gradational relationships with the underlying inter bar low facies. In these cases the bar facies is characteristically finer grained, being composed of thin, often rippled and cross-bedded medium sands with flaser and lenticular bedded silts and muds and massive or parallel laminated fine sands and coarse silts (Pl.61.1). Bed contacts of the medium sands are usually sharp at the base but more diffuse at the top (Pl.61.2). This grouping of lithologies usually passes up into the more thickly bedded, cross laminated members of the facies.

Transitions from the dominant large scale cross-bedded members into beds similar to those of the bar crest sub-facies (3A(i)) is accomplished by general thinning of cross-beds and often the complete suppression of visible internal structures. These massive or homogeneous beds are interspersed with occasional lenticular and tabular high angled cross-beds. Bedding contacts in these portions of the facies are difficult to distinguish and some massive units up to 4 or 5m thick may be composed of amalgamated or merged beds.

Palaeocurrents.

The palaeocurrent pattern determined from the large scale cross-beds of the lower 2000m of the section shows (Fig. 14) a pronounced mode indicating flow towards the north-east with subordinate 180° bimodal components on north-west/south-east and north/south trends. The pattern of flow from the upper half of the section provides a different pattern with a spread of current modes almost boxing the compass (Fig. 14). However, north-westward transport dominates an otherwise weakly 180° bimodal pattern with the subordinate transport

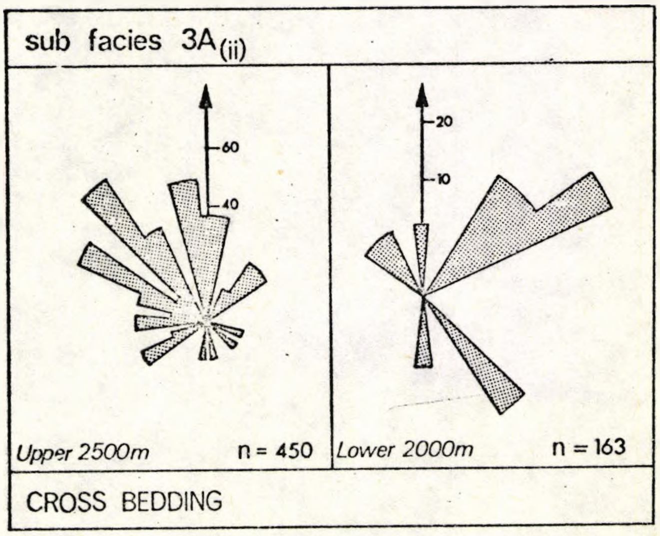


Figure 14
General palaeocurrent patterns of Sand Bar Flank sub-facies. Data from all occurrences of sub-facies 3A(ii).

to the south-east.

Palaeocurrents determined from ripples and ripple cross-bedding (Fig. 14) indicate a trimodal control to water movement which matches the north-west/south-east bimodal pattern with the third north-east mode at right angles seen in the large scale cross-beds of the sub-facies.

The integration of all cross-bedding data from facies 3 again indicates an approximately trimodal pattern (Fig. 15). North-westward flows dominate the strong northward flow, these directions being matched by a numerically smaller but still pronounced south-eastward mode to form an approximately 180^{0} bimodal set. The third mode indicates flow towards the north-east, more or less at right angles to the main bimodal couplet.

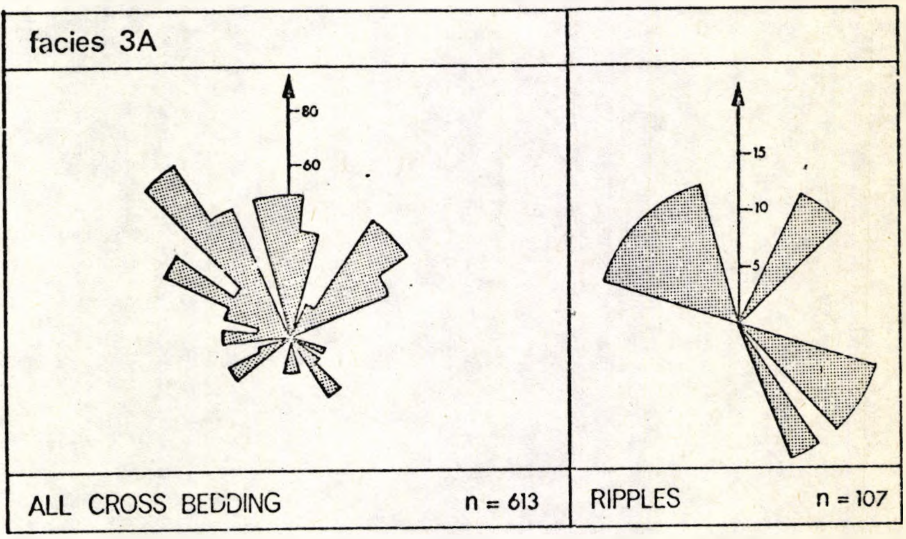


Figure 15
Palaeocurrent patterns of Sand Bar Flank sub-facies.
Subdivision of data as indicated.

Bioturbation.

Bioturbation levels are extremely low (<10%) in the thickly bedded portions of the facies and even in the occasional laminated and flasered interbeds destratification rarely exceeds 25%. However, in the thinly bedded lower units of the facies, transitional with the inter bar low facies, bioturbation in the silt and mud beds may exceed 50%. The sands of this part of the facies are rarely affected by burrowing, but they do quite commonly have Cruziana and similar cast trace fossils on their soles which indicate passive filling of mud surface excavations.

Discussion.

Klein (1970) has shown the complexity of the dynamics of intertidal sand bar development in his study of actively migrating sand bars in the Minas Basin of Nova Scotia. The key factor in the morphological development of these bars is the variation of flow patterns and velocities of the ebb and flood tidal events: currents which are characterised by so-called asymmetric time velocity profiles. There is however a spatial variation in the velocities of each of these currents which leads to 'ebb and flood dominated zones' on each of the several bars present in the basin.

Dunes, sand waves and ripples superimposed on the large sand bar features move only during that period of current flow which characterises that particular part of the bar (either ebb or flood) and accordingly analysis of flow directions indicated by internal stratification produces unimodal patterns in any single given area. It is only with a total synthesis of complete dune fields on quite separate parts of the same bar and on different bars that the ebb and flood separation can be identified.

As with tidal sand and mud flats discussed by Reineck and Singh (1970), the separation of ebb and flood flows is particularly strong during periods of exposure of the local topography (i.e. largely during flood flows and the latter part of ebb flows), and it is this factor which particularly determines patterns and orientations of small scale ripple and dune features. This leads to the superimposition and oblique orientation of small scale structures on large. In the Minas Basin examples of large scale dunes indicate flows parallel to the long margins of the sand bars and basin, whereas the small scale structures are oriented at right angles to this elongation.

Klein (op. cit.) suggests a set of criteria characteristic of tide dominated sand bars. These include sharp erosional contacts between cross-stratified sets, reactivation surfaces within thick cross-bedded units. Orientation of foresets are complex, but unimodal and bimodal distributions are less common. Small scale ripple and wave features are often superimposed at 90° or 180° to the orientation of the larger dune and wave structures. Above all, the internal stratification of such units is complex and reflects the secular complexity of flow patterns over the sand bar topography.

Interpretation.

The features of sub-facies 3A(ii) accord with many of the features considered by Klein (op. cit.) to be characteristic of tidal sand bar environments. The weak bimodality of palaeocurrents determined from the large scale cross-beds suggests a similar ebb and flood separation as that described from the Minas Basin.

The sub-facies appears capable of being subdivided further, and high, middle and low sub-environments can be recognised. The low bar flank is transitional between the inter bar low facies or sub-tidal shoreface environment and the sand wave dominated environment characterised the mid bar flank facies. A similar transition exists between the beach like bar crest facies and the mid bar flank.

The repeated association of each of the three sub-environments appears best to be treated as a single facies grouping, as at all stages temporary switches from one to the other appear to have been made without any long term establishment of that sub-environment.

Large offshore bars which migrated onshore at certain times appear to be the types of structures involved in the Cabos Series. However, it is difficult to know the spatial separation or overall orientation of these bar features. They may have been oriented with their long axes normal or parallel to the coast.

4. Shore face (Proximal/Distal) Magnafacies.

Description.

Where a full sequence of facies is developed representing the bathymetric range of intertidal or tidal out to shelf environments, facies 4 separates the sub-tidal facies from the others (Fig.2 *). Similarly, this facies shows a close vertical relationship with lower foreshore and beach environments of facies 1A.

Facies 4 is composed of thin, medium and thickly bedded fine sandstones and siltstones with subordinate thin bedded muds (Pl.65.1). Medium sandstones are relatively rare, occurring as continuous and discontinuous isolated stringers with medium to low angle long planar cross-bedding on undulating sharp lower surfaces (Pl.65.4). The upper surfaces of the same sands are usually gradational with dominant medium coarse silt and fine sand lithologies.

Bedding contacts are commonly indistinct in the fine sand and coarse siltstone lithologies, but, where they can be traced, most beds are more or less laterally continuous over the limit of available exposure (c. 30m). Where beds do terminate or change their thickness, they do so on essentially planar, gently cross-cutting surfaces which eventually merge tangentially with the normal flat bedding surfaces. Inclined, planar lamination dipping at approximately 20^{o} north or north-westwards, wave and current ripple lamination and diffuse wavy, parallel and curved lamination are the most common internal structures (Pl.65.4). Normally graded silt and fine sand beds are common in the more thinly bedded parts of the sequence.

At two points, the shore face facies intergrades with over and underlying facies. The transition with the open shelf mud facies is marked by a gradual decline in the volume of coarse silt, combined with the near absence of medium sandstones. The transition to the shallower bar flank and foreshore facies is marked by gradual increases in the number of sedimentary structures which reflect time tidal velocity asymmetry, particularly flaser bedding, and by the increase in thickness and volume of medium sandstones.

Palaeocurrents.

Due mainly to the poor three dimensional exposure of the facies, palaeocurrent data is scant.

Wave ripples indicate flow trends oriented both north-west/ south-east and north-east/south-west with a possible third trend of east/ west. Rare current ripples and ripple lamination indicates flows towards the north-west. Shallow angled, large scale cross-bedding similarly indicates flows towards the north-west and north-north-west.

Bioturbation.

Bioturbation is variable in amount in the facies, most trace fossils being horizontal (Planolites) or inclined, sometimes spreite bearing, feeding systems (Pl.65.3), such as Teichichnus rectus, Phycodes palmatum. Less commonly, small poorly preserved Cruziana are present. Vertical tubes are absent. In those parts of the facies transitional with the shelf mud facies, bioturbation levels may reach 75% to 80% (grade 4 bioturbation of Reineck, 1963). Bioturbation grades away upwards to levels below 20% (grade 1) and reaches a minimum where the facies intergrades with the foreshore and beach facies.

Discussion.

Facies with a predominance of evenly laminated fine sands and silts and small scale ripples similar to those in facies 4 have been described from a number of studies of modern coastal environments. Howard and Reineck (1972 a & b) carried out a survey of litho and bio facies of the Pleistocene and Holocene Sapelo Island barrier of the coastal plain of Georgia. Can, vibro and box cores permitted the description of sedimentary structures, associated biogenic structures and the contained fauna (Howard and Reineck, op. cit. a & b; Frey and Howard, 1972; Hertweck, 1972; Dorjes, 1972). The shore face facies of Sapelo Island is characterised by fine sands and subordinate silts with parallel and even lamination in the upper part of the facies, while wave ripple lamination is more characteristic of that part of the facies immediately above and transitional with the offshore facies (Howard and Reineck, 1972b). Dorjes (op. cit.) in his transect studies of the same environments reports both restricted species diversity and small absolute numbers in comparison with other facies. Hertweck (1972) discussed the trace fossils of the Sapelo Island section and concluded that the shore face zone lacked distinct traces both as a result of organism absence and high rates of wave reworking masking ephemeral biogenic structures.

A facies study of the Licola region, Gulf of Gaeta, Italy, similar to that conducted on Sapelo Island, was carried out by Reineck and Singh (1971) who reported similar lithological, bioturbation and faunal patterns to those of the Georgia area. In Reineck's and Singh's study area the shore face facies is greatly expanded in comparison with the Sapelo Island sections and greater variation in relief and micro topography modified the simple Sapelo derived model. The lower shore face is characterised by strong bioturbation and the preserved primary sedimentary structures are composed in distinct evenly bedded and laminated fine sands and silts. The middle and upper shore face mark a gradual increase in the volumes of medium sands and a similar increase in cross-bedding and ripple lamination. Bioturbation increases upwards and is almost absent in the upper shore face. The middle shore face is characterised by medium bioturbate, laminated fine and subordinate medium sands with gentle, planar asymptotic discordances.

The graded beds of facies 4 possibly originate from a stirring of foreshore or upper shore face sediments during periods of increased water level which resulted from landward moving storms (cf. Hayes, 1964, 1967; Hayes and Boothroyd, 1969). Wave action erodes and suspends sands and silts (Reineck and Singh, 1971, 1972, 1973; Hobday and Reading, 1972; Banks, 1973) and these are sedimented after storms have passed to form parallel laminated and evenly bedded fine sands (Reineck and Singh, 1972, 1973). Banks (op. cit.) described shallow scoop-like scours filled with 'flat laminated' sediments from 'black laminated siltstone' shelf facies of the late Precambrian Innerelv member of east Finnmark, Norway. The shallow, tangential discontinuity surfaces present in facies 4 of the Cabos Series may reflect similar storm erosion processes and the discete medium sandstone stringers with sharp bases and diffuse tops perhaps represent high shore face or barrier sands shot into deeper water as a result of storm action.

Interpretation.

The details of facies 4 conform to many of the features of well documented modern examples of shore face facies. The juxtaposition of facies 4 between shelf mud and barrier sand facies tends to support the shore face interpretation. Storms appear to have shaped the local topography of the environment and also, to some extent, determined short duration changes in grain size away from the normal fine sands and silts. An environmental model in which the normal shore face was dominantly controlled by storm events is proposed.

5. Shelf Magnafacies.

Facies 5. Shelf/offshore transition.

Description.

Facies 5 is difficult to study in the field due to marked weathering producing a fretted and slightly careous surface to exposures (Pl.65.1).

Accordingly, the fine lamination and small scale structures which appear to be characteristic of the facies are identified only with difficulty.

The facies is composed of units of black and dark grey, sometimes pyritic, shales with indistinct, wavy and ripple lamination defined by fine silts (Pl.65.4). Discrete and continuous bedding contacts within the silts are rare and only where occasional silts and thin, wave rippled sandstone stringers intervene can the precise bedding be defined. The sandstones are normally sharp based with more gradational tops which are often wave rippled. Some amalgamated sands, up to 2.5m thick are present. Most beds exhibit weak parallel lamination.

The magnafacies grades into low bar flank facies, the transition being marked initially by a slow increase in the proportions of discrete silt interbeds and subsequently by an increase in the proportions of medium sandstones.

Wave ripples are quantitatively the most important primary sedimentary structure of the facies. Current directions in the bulk of the facies are highly variable with ripple crests, even on the sandstone stringers, being oriented in three different directions in succeeding beds (Pl.65.2). At the upper transition with the sand bar facies, more uniformly north/south trending ripples are preserved in thick rippled silt units.

Palaeocurrents.

Palaeocurrent data is so poor in this facies group that no meaningful conclusions can be drawn.

Bioturbation.

Bioturbation is variable in amount but increases in intensity upwards in the facies. Horizontal, spreite bearing (e.g. Teichichnus, Phycodes) and radiating spreite bearing (Teichichnus stellatus) are the most common forms of trace fossils preserved. Planolites and other inclined simple burrows are common. Arches and strings of pyrite cubes define pre-existing burrow systems which were probably filled with faecal material.

Discussion.

A number of beach/shelf profiles of various ages have been discussed (Reineck and Singh, 1973, pp. 311-349). Almost without exception the shelf members, due particularly to sampling problems in modern examples, are only sketchily known. Both ancient and modern open shelf areas are characterised by dark, dominantly structureless black shales and muds, with intercalated storm sand layers. Reineck et al (1967, 1968), Gadow and Reineck (1969), Goldring (1971) and Goldring and Bridges (1974) have discussed the transport of fine and medium sands from the coastal areas by post-storm ebb currents. The sands form laterally extensive thin sand sheets which may be weakly laminated, diffusely graded or massive and which thin away from the coast. Escape structures are characteristic of these sands (Hertweck, in Reineck et al, 1968; Goldring and Bridges, op. cit.), and the tops of the sands are often overlain by non-bioturbate graded muds and fine silts which are considered to represent sedimented fines (Reineck and Singh, 1970, 1973).

The width of modern transition zones is dependent on the energy characteristics of the coastline: the greater the energy, the greater the width of the zone (Reineck and Singh, 1973). Most modern transition zones form in depths of water varying from 2 to 30m (Reineck and Singh, op. cit.) and are situated below normal wave base. Rippled sands, interpreted as storm layers, are more common than in the deeper shelf environments, and wave ripples indicate the greater depth of wave orbits during storm periods.

Bioturbation usually has its maximum development in the transition zone. Values of over 76% have been described from the North Sea area (Reineck and Singh, in Dorjes et al, 1970) and ancient examples exhibit similar high levels of destratification resulting from diverse trace fossil assemblages (e.g. Cretaceous Mesaverde Group, Masters, 1965, 1967; Cretaceous Book Cliff, Howard, 1966).

Interpretation.

Facies 5 appears to represent the intergradation of both shelf and transition zone sediments. Interrelated sandstones accord well with storm generated sands of both ancient and modern offshore face and shelf environments.

3. FACIES DISTRIBUTION AND EVOLUTION.

The detailed distribution of each facies and sub-facies group is shown in the appendix and summarized in Figure 1*. Characteristics of each facies are tabulated in Figure 2*.

The logged section indicates a predominance of tidal flat facies in the lower half of the section with a gradual increase in offshore bar and associated inter bar low facies in the middle of the section (c. 2200 - 3100m). These gradually pass upwards into increasingly distal facies characterised by the distal shore face, transition and shelf facies at approximately the 3000 to 4000m level. This part of the section therefore constitutes a complexely fining-up sequence composed of an intermixing of numerous transgressive and regressive couplets which form a major transgressive phase in the evolution of the Asturian Arc basin (Julivert et al, 1972).

Above the offshore and shelf facies, distal sand, sand bar and inter bar low facies initially predominate but give way in the succeeding 500m to dominantly tidal flat facies including mud, mixed and sand dominated types. Thus, the upper 600 to 700m of the Cabos Series appears to represent a regressive phase of the basin development. As such, the gradational relationship between the Cabos Series and the overlying Luarca Shales described by Marcos (1973) must indicate a termination of the regressive phase and a return to the quantitatively more important transgression. Marcos (op. cit.) suggests a 'medium euxinic' environment for the Luarca Shales, but no bathymetric interpretation is proposed. The presence of graptolites near to the base of the Shales suggests at least some connection with the open sea, even if the environment did not itself constitute a fully open marine one. Thus, considering the bathymetric evidence derived from the Cabos Series, the basal parts at least of the Luarca Shales may have been deposited in a shallow basin of restricted circulation which, while gradually deepening, did not receive appreciable sediment until the turbiditic input of the Agueira Formation (Llandeilo-Caradoc).

The transition at the base of the section between the Cabos Series and the underlying limestones and dolomites of the Vegadeo Formation is difficult to interpret due to the shattered state of the exposure. Marcos (op. cit.) briefly discussed the Vegadeo Formation, but obtained little petrographic and hence environmental information from the heavily recrystallised limestones. Oolitic structures and stromatolites found in the Asturian region (Lotze, 1961; Marcos, 1973) suggest shallow water conditions, probably above wave base. The widespread development of correlatable very shallow marine limestones in the Cantabrian Zone to the east and south-east of Asturias (Zamarreno & Julivert, 1967; Meer Mohr, 1969; van den Bosch, 1969; Zamarreno, 1972) may support a similar interpretation for those of the north coast. If this shallow marine origin for the Vegadeo Formation is correct, the terrigenous facies of the Cabos Series, which appear to be similarly shallow marine, reflect a change in the input of clastic material and not a fundamental change of bathymetric environments.

The palaeocurrents of the Cabos Series do not provide a simple sequential palaeogeographical model. The domination of the tidal flat facies in the lower part of the section provides variable flow pattern. As a generalisation, the north-eastward flows are the strongest in this part of the section, but north-west/south-east bimodal patterns are a constant feature here and in the rest of the section.

The change to more distal facies in the middle of the section is associated with a decline in the importance of north-eastward flows coupled with a much stronger and more uniform bimodal north-west/south-east pattern. Even so, north-east, east and westward flows are still common.

Above the shelf facies, a more pronounced change in the palaeocurrents is apparent. Northward flows predominate, but, given the tidal flat environment, the general flow pattern is again complex.

The dominant north-west/south-east transport pattern and its associated secondary modes, orientated more or less at right angles, suggests that the Cabos Series was deposited in an area with a shore zone trending north-east/south-west or at the most east/west. Longshore transport both eastward and westward may partly reflect the general water circulation of the basin, but it may also indicate flow around local depositional topographic features.

The strong northward and north-westward transport direction which dominates most of the palaeocurrent patterns of the Cabos Series represents the offshore transport, away from the Narcea and Cantabrian Zone (cf. Julivert _et al_, 1972, Fig. 1, p. 2). Thus, from this area at least, the probable arcuate form of the Asturian basin was probably developed prior to the deposition of the Cabos Series, and may in fact have tightened late in this period to give the northward flows at the top of the Cabos Series.

4. TIDAL INFLUENCES TO DEPOSITION OF THE CABOS SERIES.

As discussed in section 2 above, magnafacies 1,2 and sub-facies 3A(i) contain small and large scale sequences which appear to be _regularly_ repeated in time. In the context of the shallow marine environment suggested for the deposition of the bulk of the Cabos Series, it appears possible that some form of tidal mechanism may have been the regulating influence of these sequences.

a. Tidal theory: resume.

Tide generating forces are complex and include the elliptical orbits of the Earth and Moon, their variable attitudes of orbital planes, changes of declination of the Sun and Moon throughout their orbital cycles and the effects of rotation of the Sun and Earth about their own axes. Combined with these factors, local basin size and shape are of major importance in determining tidal periodicity and range (Allen, 1970, p. 162; Tricker, 1964, pp. 1-23).

The equilibrium tide generating forces of the Sun and Moon (i. e. the simple theoretical gravitational tides predicted for a water covered globe) are combined or reinforced at fortnightly intervals by their recurrent 'in line' position, such that at periods of full and new Moon higher tides than normal are produced. These are known as _spring tides._ This principle of 'reinforcing' of tide generating forces to produce higher than normal tide heights operates on cycles of much greater periodicity than the bimensual periodicity of the normal springs discussed above. Due to the elliptical orbits of the Earth, Moon and Sun, the distance between the Earth and the other two is not fixed but varies in a complex fashion (Tricker, op. cit.). The maximum tides are produced when the Moon is at a position of closest approach to the Earth (Perigee) and intermediate tides are produced during periods of closest approach of the Sun (Perihilion). It is then possible for three separate tide generating forces to be combined: the normal spring tides are reinforced by the perigee (the most important) and perihilion tide so that at two periods during the year the so-called perigee springs are operative. At the present time perigee springs add approximately 10% to the height of the normal springs (pers. comm., Dr. David Pugh, Tidal Institute, Bidston Observatory). This figure, though relatively small, may have important influences in barrier bar and coastal lagoon environments (see below for further discussion). Because of the complexities of the orbits the perigee springs are not evenly spaced biannually, but oscillate in time around the more or less fixed times of Spring and Autumn. The two perigee springs may be further reinforced by declination effects of the Sun. The declination tends to reduce tide heights, so that tides developing at equinoxial periods, when declination of the Sun is at a minimum, tend to be the greatest (Tricker, op. cit.).

The complex variation in time of the combination of numerous tide generating forces becomes resolved into single maximum lunar perigee spring tides which recur for approximately three months in succession during the Autumn (Tricker, op. cit., p. 15). Thus, a hierarchy of tides exists: single, major perigee tides during the Autumn form the main class and these are separated by bimensual springs. Normal daily and diurnal tides form the lowest orders and these, due to basin geometry, are often of variable magnitudes.

A more or less regularly recurring cycle of variations of water depth and hence wave and tide energy may underlie the time-variable parameters such as storm effects and wind variation which are important in shaping marginal environments.

b. Lithological cyclicity: the role of tidal influences.

In two of the facies groups described from the Cabos Series (facies 2 and 3A) bedding is characterised by alternations of thick, sometimes massive and medium sandstones, with either more intensely laminated sand (3A) or wavy interlaminated mud/silt (2) interbeds. The regularity of spacing of the sandstone ribs of both facies is most striking and intuitively it would appear that some regulating mechanism must have influenced the depositional process.

The sedimentation unit. Otto (1938) in defining the 'sedimentation unit' proposed a hierarchical system of causes of variation in sedimentary rocks. Such variations of the depositional process could be reflected by an individual lamina, a bed or groups of beds and so on to complete members and formations, all being characterised by a high degree of uniformity of lithology and geometry. Events for which causes of variation could be determined (these could be of any scale - e.g. from local prevailing winds to global wind patterns) were designated sedimentation units with assignable causes of variation. These could be 'mapped' and to some extent predicted. The other events, charcterised by so-called unassignable causes of variation, were usually of small scale and appeared largely random.

It seems probable that causes of variation can be assigned to the alternating beds of facies 2 and 3. In facies 2 (Fig. 16), the individual laminae of the alternating bedding (Reineck and Singh, 1973, p. 102), composed of flaser and linsen sub-units may be accounted for by tidal variation (Reineck and Wunderlich, 1968). Hence an assignable cause of variation is identified. The individual form-sets and wavy laminae are grouped (Fig. 16) so that laminae rich zones alternate with practically non-laminated zones. The regularity of spacing of these sub-sets appears too great for a storm mechanism to apply and a more regularly recurring mechanism is required. The bimensual spring tides discussed above may form an appropriate mechanism. Slightly increased wave and tide activity within barrier bar chains could permit silt and fine sand to develop rippled bed forms. Eventually the hydrodynamic conditions appropriate for these bedforms would decay and be replaced by neap tidal conditions during which wave and current energy would be insufficient to transport sediment other than mud and some fine silts. The sequence of events discussed here could be even more effective with a barrier and inter bar low geometry similar to that of the Magu Lagoon of southern California. The lagoon inlet permits only the higher parts of each high tide to enter

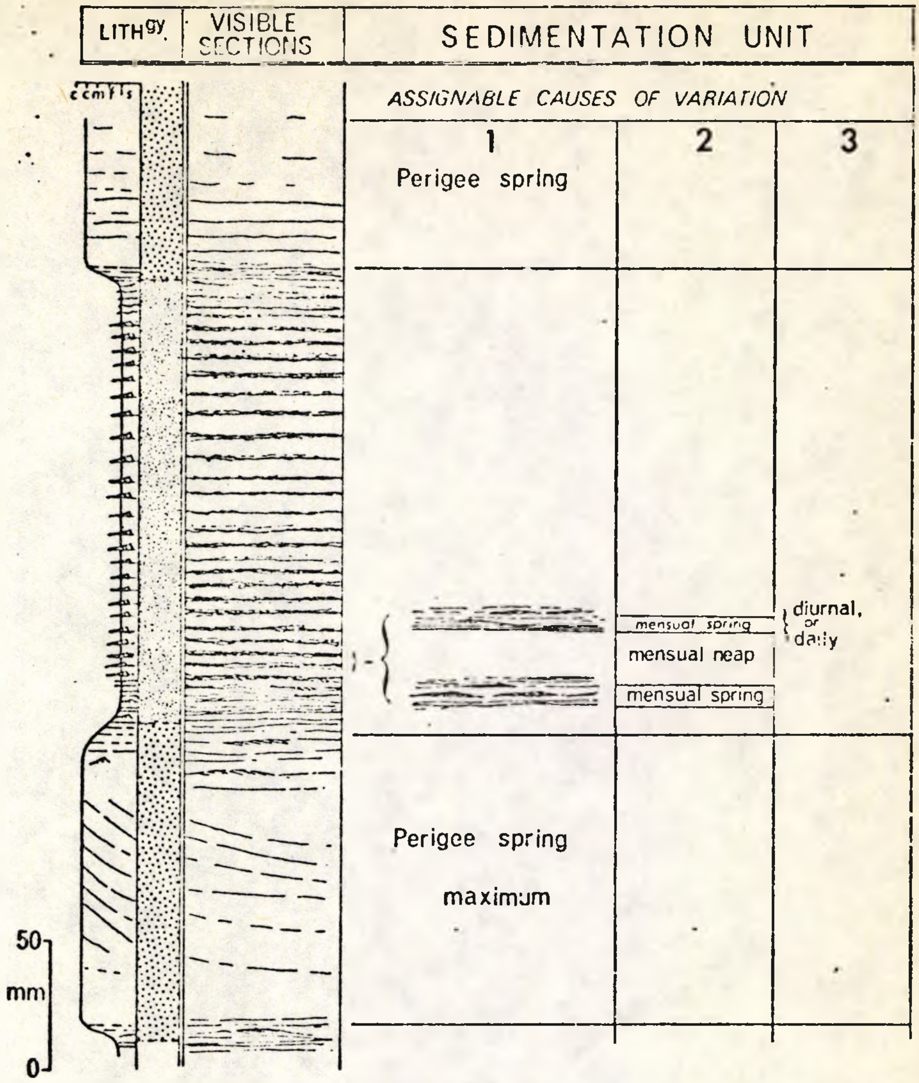


Figure 16
Tidal control model of sedimentation units in Facies 2B. Rank order of causes of variation increase from left to right.

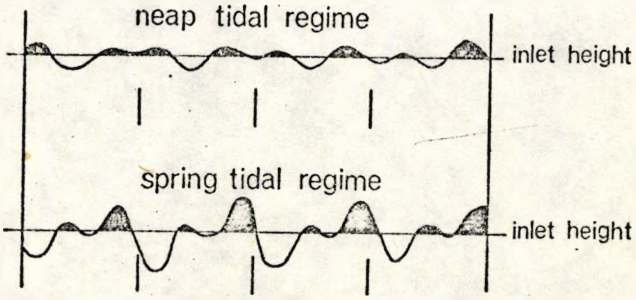


Figure 17
The affects of inlet height and tidal regime on the circulation of Magu Lagoon, Gulf of California. Areas in black indicate time when tide was above inlet height. (From Warme, 1971.)

the lagoon and neap and spring tidal regimes exhibit markedly different circulation patterns (Fig. 17).

Continuing the tidal analogy for the facies 2 sediments, the sandstone interbeds (Fig. 16) possibly represent perigee spring tide deposits. Coastal lagoons (cf. inter bar lows) isolated from the open sea by barrier sand bars (either exposed but of low topography, or submerged in which case they would form wave baffles) would probably be influenced in a critical fashion by a 10% rise in high tide level. Wave and current energy would be increased across the crest of submerged bars; exposed bars could be transgressed so bar crest sands would be carried over into the lagoon or runnel. The normal inter bar low circulation controlled by tidal channel influences during flooding tides would be temporarily suspended and wave energy within the low during high tide periods. Hence, the resultant ebb tidal currents would be increased.

The maintenance of the perigee spring tides over an effective period probably extending to one month or more (pers. comm., Dr. D. Pugh) could lead to the amalgamation of a number of relatively thin sand beds. The power of the ebb currents during this period could exclude muds and fine silts so that laminated and flasered layers would not form.

The flooding through of barrier bars by the mechanism proposed would not represent a 'catastrophic' event, and the resultant sand beds would not directly correspond to the storm washover fan deposits described from the Georgia coast of the U.S.A. (Kraft, 1971; Kraft et al, 1973). The absence of markedly erosive bases to the sands contrasts with the scooped and scoured bases of storm deposits (Kraft, 1971; Banks, 1973).

The termination of the alternating beds of facies 2 and the irregularities which certainly are present in the alternating pattern may have resulted from storm periods which interrupted the regular tidal pattern.

The alternations of the massive sands and laminated interbeds of facies 3A seem in keeping with a similar tidally controlled model. Because no single tidal event (e.g. a single flaser or linsen) can be identified it is difficult to know the time scale that the sedimentary variation represents. The laminated interbeds probably represent normal tidal variation, but the possibility exists that these too represent perigee spring sequences.

The thickness of massive and laminated sands which are separated by strongly laminated interbeds appear homogeneous and of sufficient thickness (0.2 - 0.45m) to have been deposited during single tides given a sand bar environment.

c. Palaeotidal range.

Various schemes have been developed which purport to indicate the tidal ranges operative during the deposition of ancient sedimentary and biosedimentary rocks. In most cases, these tidal schemes are derived from direct observation of present day tidal processes and deposits, but they also recognise the inherent variations in the Earth/Moon tide generating system.

Logan (1961) described Recent stromatolites from the hypersaline barred bay of Hamelin Pool which forms part of Shark Bay, Western Australia. Here the growth relief of the stromatolites equals the local tidal amplitude. Cloud (1968) discussed palaeotidal ranges, and through this the evolution of the Earth/Moon system viz a viz the relief of ancient stromatolite dome structures which, following Logan's basic premise, Cloud considered to similarly represent the approximate palaeotidal range.

The broader application of any direct relationship between stromatolite relief and tidal range to ancient rocks, as developed by Cloud (op. cit.), has however been questioned by a number of workers. Playford and Cockbain (1969) were able to determine the bathymetric position of growth of columnar stromatolites from Devonian reef complexes in western Australia. From palaeontological data, correlations of age equivalent parts of inter-reef, fore-reef, reef and back-reef facies could be established and the actual topographic relief of the reef structure could be determined. Fixing the reef crest at or about sea level, Playford and Cockbain (op. cit.) found stromatolites in growth positions down to depths in excess of 45m. They therefore concluded that Cloud's unqualified uniformitarian application of stromatolites was not always valid. While the significance of the deep water position of Playford's and Cockbain's stromatolites is important, it so far serves only to qualify the application of some stromatolites as palaeotidal indicators. If the intertidal position of ancient stromatolites can be established by other means, then Cloud's approach may be found to be valid. As an example of this, Playford and Cockbain (op. cit., p. 1009) described probable intertidal stromatolites and oncoliths from their back-reef facies, but unfortunately they give no indication of the relief of these algal structures.

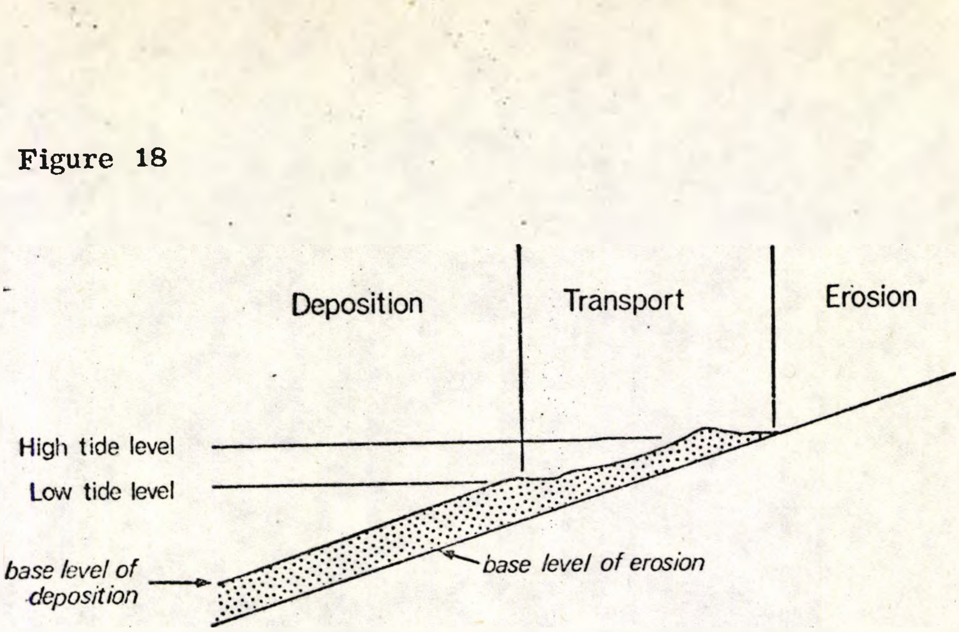
Walter (1970) effectively reiterates the criticisms of Playford and Cockbain of Cloud's tidal range model. In so doing, he reviews some independent evidence which may lend support to the validity of Cloud's model. There appears to be high tidal ranges as indicated by late Precambrian and Cambrian stromatolite domes (Nechaeva, 1945), and independently derived information suggesting that increased tide generating forces were operative over approximately the same period (Alfven and Arrhenuis, 1969).

Littoral gravels.

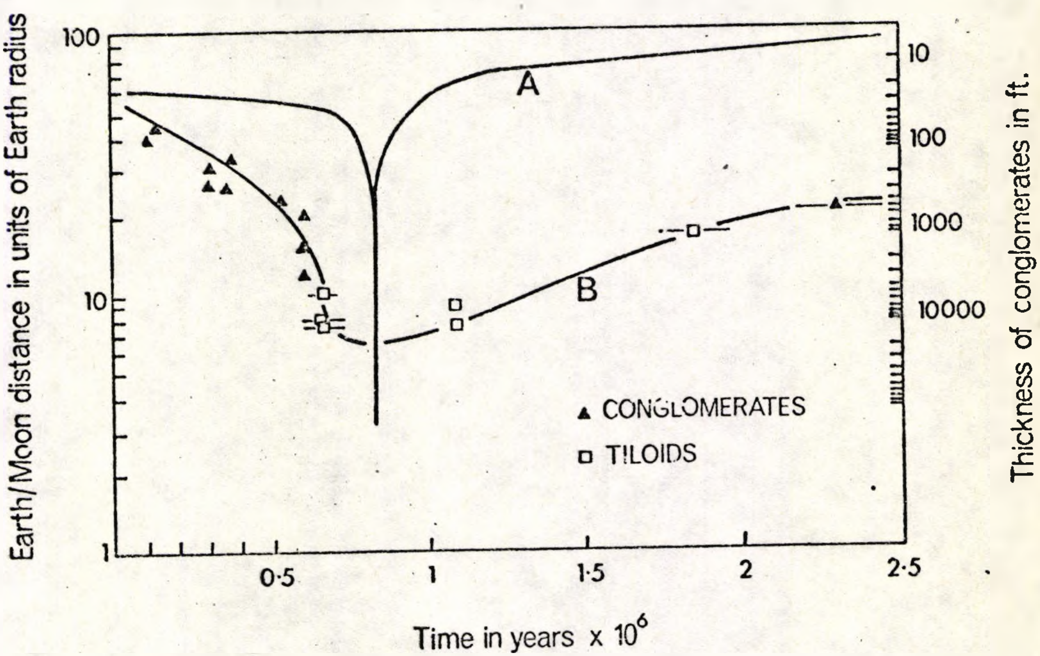
The relationship between the thickness of intertidal and tidally generated marine gravels and actual tidal ranges has been discussed by Olson (1970) who concluded, following Twenhofel (1926, 1936), that the upper limit for thicknesses of littoral gravels equals the tidal range (Fig.18a) (Olson, *op. cit.*, p. 223, Fig. 17). Throughout this discussion Olson stresses the problems, and hence the need for caution in differentiating littoral gravels (modern) and littoral conglomerates (ancient) from deposits of other environments, and he specifically mentions marine conglomerates deposited in deep water.

Olson (*op. cit.*, Table 1, p. 226) showed from a sequence of gravels, the neritic origin of some of which is open to question, a gradual increase in tidal amplitude from the Holocene as far back as the Huronian (Precambrian). He goes further to suggest that some of the late Precambrian tilloids may in fact be 'hypertidal' (derived from tidal ranges 300m) in origin rather than related to glacial events. Olson's (*op. cit.*, Fig. 3, p. 230) (Fig.18b herein) plot of conglomerate thicknesses versus geological age shows a gradual increase throughout the Proterozoic to a maximum at about 750 x 10^6 years BP. There then follows a more rapid decrease throughout the late Precambrian and early Palaeozoic followed by a more gentle decrease into the Mesozoic. The match of Olson's conglomerate curve with a curve showing the variation of Earth/Moon distance over

Figure 18



a. Model of gravel deposition on a transgressive shoreline (after Olson, 1971, Figure 2, p.223).



b. Comparison of thicknesses of conglomerates with variation of Earth/Moon distance.

Curve A. Shows variation in Earth/Moon distance over geological time (after MacDonald, 1965).

Curve B. Shows variation in thickness of conglomerates over geological time (figure after Olson, 1971, Figure 3, p.230).

geological time (and hence, as tide generating forces are inversely related to Earth/Moon separation, the curve indicates probable tidal amplitudes) derived by MacDonald (1965) appears to support the general hypothesis.

Lamb (1968), Smith (1969) and Klein (1970b) described recent gravel littoral deposits and in all three cases they are formed dominantly from relic, Pleistocene sediments. Gravels, derived directly from bed rock erosion are present in some parts of the Minas Basin (Klein, 1970b) and become mixed with the exhumed relic gravels and deposited at the high water line. Klein (1971) states that he is 'unaware of any coincidence between thickness of Holocene littoral gravel deposits and tidal range', but the situation in the Minas Basin with gravels limited to the upper extent of the tidal range conforms to at least half of the process specified by Twenhofel (1926, 1936) and developed further by Olson (1970).

Intertidal facies.

Walker and Harms (1971) described transgressive fining-up sequences from the Upper Devonian Catskill Formation of central Pennsylvania. Each sequence is composed of a number of facies groups and the term 'motif' is employed for the repeated occurrence of these facies members. A typical complete motif (Fig. 19I) contains at its base an unrestricted marine fauna which gradually diminishes in importance upwards to be eventually replaced by rare brachiopods and abundant bioturbation structures. Cross-bedded sands and silts give way to occasional rippled sands in burrowed silts and muds which in places have abundant desiccation cracks. At this level, root traces are present and the motif becomes dominated by alluvial facies.

Walker and Harms (op. cit.) suggest that the part of the motif below the rootlet bearing beds and immediately above the marine fauna represent intertidal deposition and hence gives a direct indication of maximum tidal range. Problems exist in the application of this type scheme. In particular, the marine faunas may be sub-tidal in origin in which case an inflated value for the tidal range would be derived (Klein, 1971, p. 2586), or, alternatively, the marine fauna could be drifted into the intertidal environment giving the appearance of a considerably reduced tidal range.

Klein (1971) attempted to overcome some of the difficulties of Walker's and Harms' (op. cit.) tidal range indicator by excluding from his scheme information which was not itself directly genetically related to tidal processes. All the features utilised by Klein are primary sedimentary structures, incapable of being drifted or transported, and relate directly to the energy gradient of tide dominated areas.

The sediments and sedimentary structures deposited in the intertidal zone Klein (op. cit.) calls 'tidalities', and an extensive 'tidalite process-response model' is presented (Klein, op. cit., Table 1). A graded, fining-up sequence (Fig. 19. m) is developed in prograding areas, the grading reflecting various transport processes and energy zones of intertidal flats. The lowest zone is composed of herringbone cross-stratified sands with current and interference ripples superimposed at 90° or 180° to underlying large scale cosets. Reactivation surfaces and the orientation and distribution of dune and ripple bedforms indicate that the facies was deposited in areas (transport domain, Klein, op. cit.) characterised by time velocity asymmetry of tidal currents and reversing bottom traction currents followed by emergence run-off (cf. Klein, 1970b). A low tidal flat environment is proposed for these deposits. The second part of the sequence is formed from interbedded sands and muds, dominantly in various forms of tidal bedding (Wunderlich, 1970) such as flaser and lenticular bedding, wavy bedding, etc., and considered to have formed from alternating bedload sand transport and mud suspension sedimentation. A mud tidal flat environment is proposed.

The top of the mud flat facies grades into massive, silty clays which are usually strongly bioturbated. This facies Klein (op. cit.) interprets as the product of suspension deposition in a high tidal flat environment.

The fining-up sequence is considered to directly reflect tidal range, the lower sands with emergence run-off features marking the limit of low tide and the top of the massive muds the upper limit of high tide. Klein recognises potential discrepancies in the application of this model. Compaction, particularly of the muds, would tend to introduce low values of tidal range, but Klein (op. cit.) argues that compaction is probably accomplished at the relatively early diagenetic stage. This notion is supported by Terwindt's and Breusers' (1972) determinations of ratios of 'initial consolidation', particularly of mixed muds and sands, from both Recent intertidal areas and experimental data. Similarly, deposition of muds as sand sized faecal pellets further enhances the rate of compaction due to reduced water contents of the pellets. A number of examples of this process have been described from shallow marine environments (Haven and Morales-Alamo, 1968, 1973; Rhoads, 1970; Rhoads and Young, 1970). McCave (1971) has discussed the problems of assigning a time scale to the accretion of tidal bedding deposits and has noted the very high water contents and hence high potential compaction of muds sedimented as individual clay grade particles. Undoubtedly some reduction in thickness of the ancient sedimentary sequence will be involved due to superincumbent material and tectonic effects and the tidal range derived from such sequences probably only give an order of magnitude idea of the actual operative tidal range.

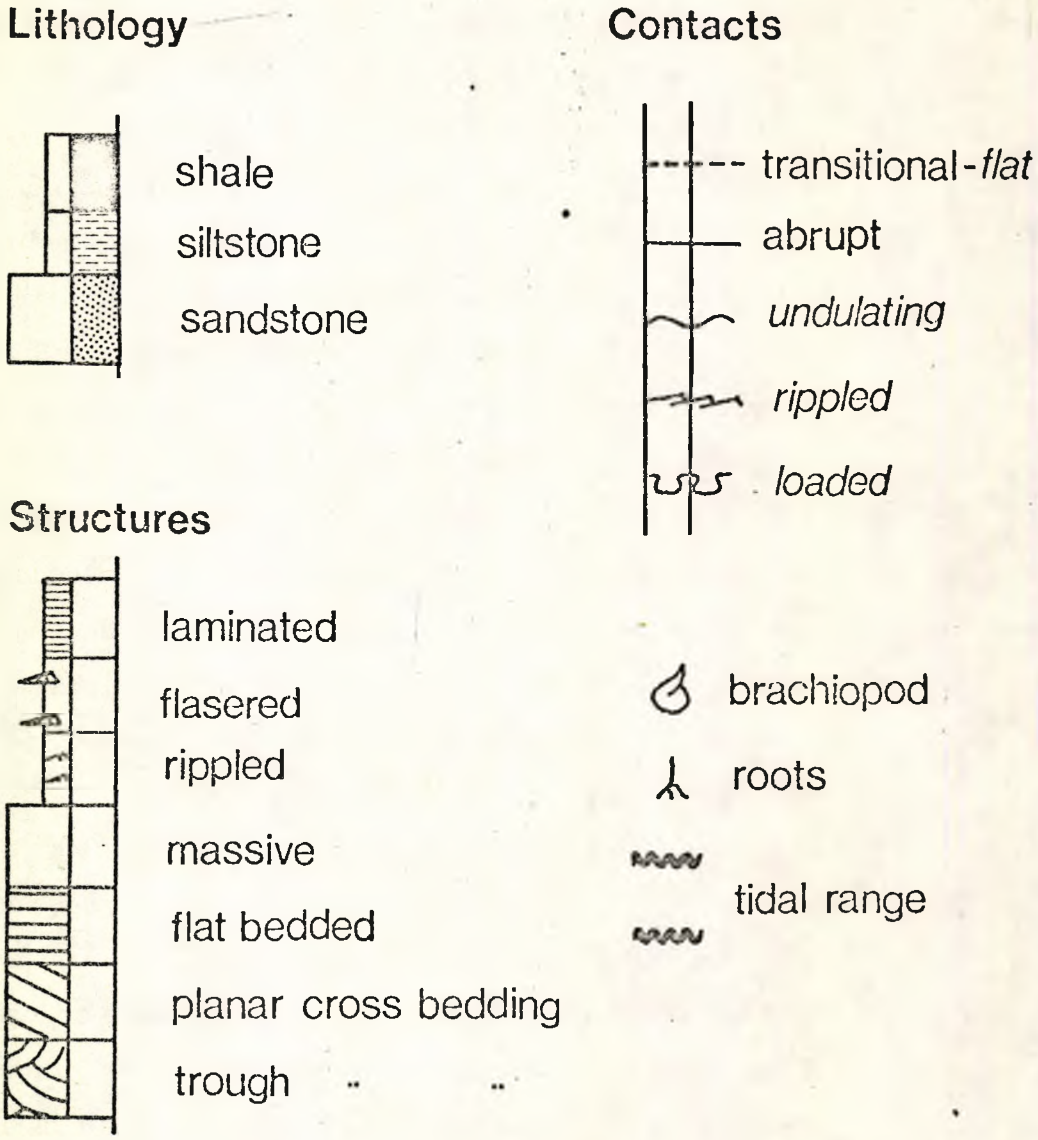
The erosion of any of the members of a tidalite sequence would be more easily accounted for and incomplete sequences should be recognised. However, the internal thinning of any of the three facies groups without the development of strongly discordant surfaces must be borne in mind, and the sampling of a number of sequences would probably negate any major discrepancies.

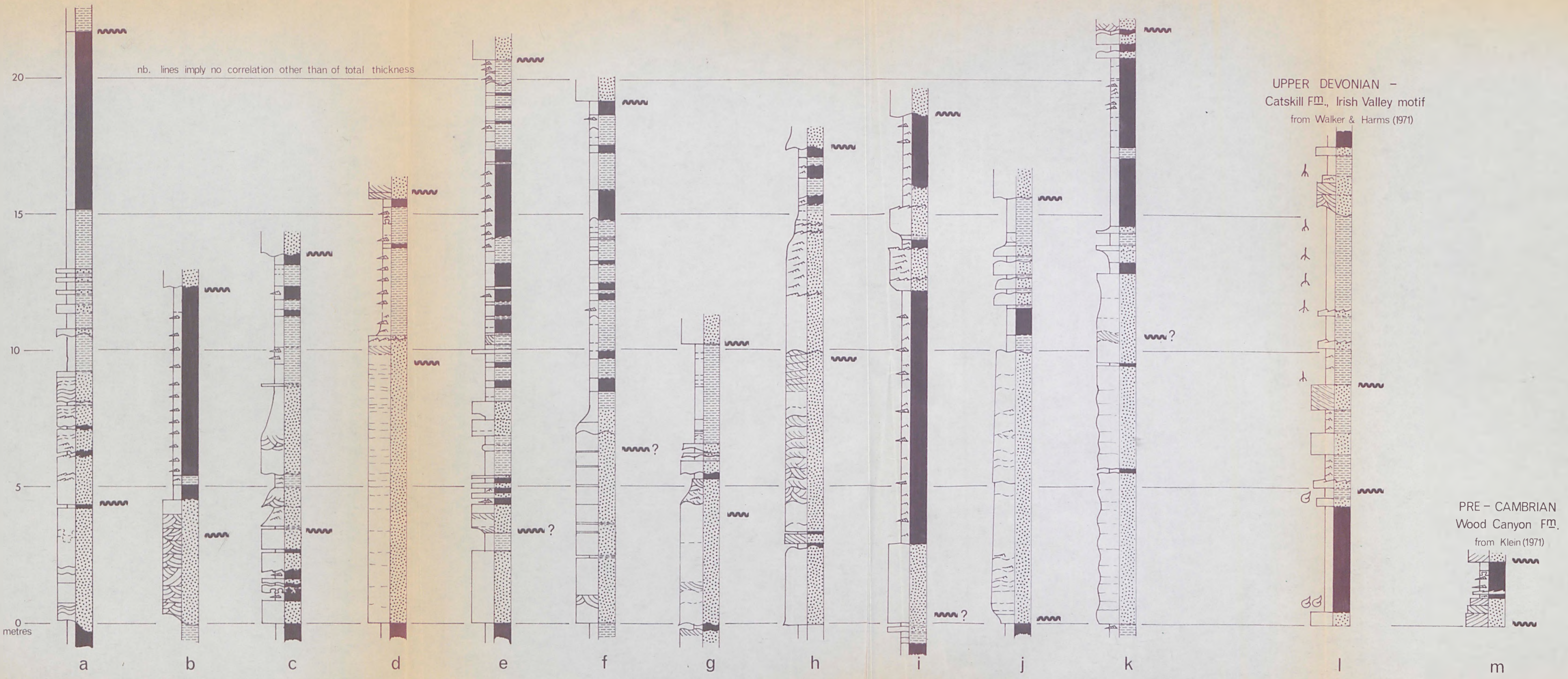
The final point is probably the most difficult to identify in ancient sediments. Klein's (op. cit., Fig. 1) model envisages a simply prograding coastline with little or no basin subsidence. Accordingly, the actual recorded thickness of this tidalite sequence more or less equals the tidal range. Boyd and Dyer (1966) described from part of the Oligocene Frio Sand a static shoreline sequence in which a delicate balance existed between rates of sedimentation and rising sea level. In this example, some facies groups developed only in a vertical sense and the tidalite sequence did not always form. The Frio Sand is an exceptional case, but the coastal progradation combined with some basin deepening is probably more common (cf. van Straaten, 1964; Thompson, 1968; Reineck, 1970b).

Again the values derived from the application of Klein's model must be considered to indicate orders of magnitude of tidal range rather than absolute values.

Figure 19

A comparison of tidal 'motifs' from the Cabos Series (a - k) with others from the Catskill Formation (l) (from Walker and Harms, 1971) and the Wood Canyon Formation (m) (from Klein, 1971). For detailed discussion see text.




20
15
10
5
0
metres
nb. lines imply no correlation other than of total thickness
UPPER DEVONIAN –
Catskill Fm., Irish Valley motif
from Walker & Harms (1971)
PRE – CAMBRIAN
Wood Canyon Fm.
from Klein (1971)
?
a
b
c
d
e
f
g
h
i
j
k
l
m

The tidal range of the Cabos Series: the application of the Klein (1971) model.

Eleven selected examples of fining-up sequences from various parts of the Cabos Series are shown in Figure 19. Most include some but not all of the diagnostic elements and ordering of Klein's (*op. cit.*) tidalite model. The integration of all sequences into a single model would produce a motif (*sensu* Walker and Harms, 1971) strikingly similar to that proposed by Klein.

Three particularly good motifs are recorded in (d), (g) and (h) of Figure 19. Motif (d) commences with 10.5m of massive, medium bedded sands, resting on a planar erosive base, which becomes cross-bedded towards the top of the unit. Wave and current ripples are superimposed over the undulating bedding surfaces which comprise the top 1m of the sandstone facies. The sands grade into a flaser, linsen and laminated, tidally bedded facies group composed of silts and mudstones. Wave and interference ripples are preserved in this part of the sequence. Load cast and isolation structures indicating extensive soft sediment deformation are present in the upper part of the sequence where non-laminated muds gradually replace the laminated lithologies. The muds are terminated above by the erosive base of the next thick cross-bedded sand facies.

Motif (g) is much thinner than most of the other motifs, but it still includes an apparently complete tidalite sequence. The lower sand facies is thick bedded with some dune scale tabular cross-stratification present. Towards the top of the sands tabular and trough cross-stratified sets with undulating and gently scoured bases have current ripples superimposed on the upper sand wave surfaces. Ripple lamination is preserved on reactivation and scour surfaces within massive and weakly cross-laminated sets. The sands pass abruptly into evenly laminated muds and silts and eventually into structureless fine silts. Three sand beds with undulating scoopy bases are present within the silt facies and probably represent storm input sands.

Motif (h) is formed from thicker and more obviously cross-stratified medium sands. Complexly arranged sets of cross and tabular cross-bedding pass up into more regular dune bedded sands which become strongly current rippled towards the top. Reactivation surfaces are present towards the top of the cross-bedded facies. The rippled sands pass gradually into rippled silts and muds which, upwards, give way to evenly laminated and eventually massive mudstones at the top of the motif.

Tidal range.

The sample of eleven motifs indicates a spread of tidal range values from 5.5m to 21.5m with a mean of 14.5m. The less equivocal motifs provide the lowest values and range 5.5m to 9.0m.

There exists little data with which to check the validity of these values. Olson's (1970) conglomerate curve (Fig. 18b) predicts tidal ranges for the Cambro-Ordovician of over 40m.

Markov Chain analysis of facies distribution in the Cabos Series.

1. Introduction.

A number of statistical techniques exist which assist in the identification of cyclicity in sedimentary sequences. Recently published applications of some of these methods (e.g. Selley, 1970; Miall, 1973) have produced results, which, due to relatively small samples (i.e. analysis of sequences of the order of 10^0 to 10^1m thick), tend to develop and refine the statistical techniques rather than serve any useful purpose in assisting in environmental analysis.

The continuity of exposure and the 4.5km thickness of the Cabos Series in the Asturias study area provides a suitable sequence for statistical analysis. Thus, intuitively derived sedimentary models can be tested by independent statistical techniques.

2. Markovian systems: definition.

Markov process models fall within a conceptual spectrum which at its extremes is delimited by (1) purely random models in which all events are independent of each other, and (2) by directly deterministic models in which all future states or results can be predicted from any preceding state (Krumbein, 1967). A first-order Markov model includes elements of both the independent and deterministic models and permits the prediction of only immediately succeeding events or states and so demonstrates a system of partial dependence. Markovian processes, therefore, are those 'in which the probability of the process being in a given state at a particular time may be deduced from knowledge of the immediately preceding state' (Harbaugh and Bonham-Carter, 1970, p. 98). Krumbein (op. cit.) equates the dependency of the random, deterministic and intervening Markovian models with the concept of 'memory': the former having no memory, the second a long memory and the Markovian process a short memory.

Repetition of short-term memory events (i.e. single step variations) within sequences of sedimentary rocks can impart a cyclic pattern, the identification of which may assist in environmental interpretation.

3. Analysis of sedimentary successions - conceptual framework.

In most statistical treatments of sedimentary sequences which identify Markovian processes (e.g. Carr et al, 1966; Gingerich, 1969; Selley, 1970; Doveton, 1971; Miall, 1973), the analysis centres on lithological cyclicity. In these cases lithology is directly transposed as an index for a given environment; a technique which appears to have its greatest relevance in coal measure cyclothem analysis (cf. Read, 1969; Selley, 1970; Doveton, 1971) where small scale, well-documented and theoretically 'safe' environmental models are available. The validity of naive application of the same method to other lithological/environmental 'twins' appears questionable.

Selley (op. cit., discussion, p. 576) argues for the analysis of 'raw data' in order to produce sampling techniques which minimize potential operator bias or subjectivity. Reading (in discussion of Selley, op. cit.) criticized the 'non-geological', largely non-interpretative approach which seems to follow from Selley's and others' sampling methods, and stresses the need for inclusion of much more information than simple lithology. The nature of bedding plane contacts Reading considers to be of fundamental importance in this context.

In the following analysis of the Cabos Series an attempt has been made to minimize the problems which follow from considering only lithological information by discussing possible Markovian properties in the succession of facies groups. In this case, the various parameters which define a given environment are included in the original designation of each facies so that the geological requirements of Reading are satisfied. However, problems of the recognition of types of contacts between facies remain, possibly obscuring some of the true Markovian components of the sequence. (See page 58 for further discussion of this point.)

4. Methods of analysis.

a. Transition count matrix: Following statistical terminology all changes of state are called 'transitions' regardless of the form of that transition. Thus the geological connotation of 'gradual change' is not involved. The first step in analysis is the tabulation of all transitions in the given succession. A two dimensional data array or matrix is drawn up which records the number of times each state (facies) passes into all others (e.g. Table 1). The lower bed involved in each transition is given by the horizontal row number and the upper bed by the vertical column number. Elements of the matrix are referred to as fij, where i = row value and j = column value.

b. Probability matrices: From the transition count matrix two types of probability matrices may be derived. The independent trials probability matrix (rij) represents the probability of the given transition occurring randomly and two methods are available for its determination. In the simplest case the probability of a given state i being succeeded by another state j is dependent only on the proportions of the states present in the matrix. Thus:

$$rij = (si.\,sj)/t, \qquad \text{Eqn. 1}$$

where t = total number of recordings = $\sum_{y}^{n} fij$, si = sum of fij for the ith row and sj = sum of fij for the jth column. This formula is only applicable to transition count matrices where zeros do not appear on the major diagonal (i.e. where i = j = multi-storey lithologies) (Selley, 1970; Miall, 1973).

In transition count matrices which do have zeros on the principal diagonal the independent trials probability matrix (rij) must exclude i = j values. Thus the predicted or theoretical proportions of the remaining $i \neq j$ values must be increased proportionately while remaining the same relative to each other. (See Selley, 1970, Fig. 2, p. 568 for a simplified worked example.) The formula for the independent trials probability then becomes:

$$rij = sj/(t - si). \qquad \text{Eqn. 2}$$

The second matrix (pij) indicates the probabilities of the given transition occurring in the section and is derived from:

$$pij = fij/si. \qquad \text{Eqn. 3}$$

d. Difference matrix: As the statistical analysis involves the comparison of observed transition values with those of a theoretically derived random model, the final matrix shows these differences.

In Selley's (op. cit.) method the observed and predicted values are compared directly, a process which appears empirically viable but statistically simplistic. Thus:

$$dij = fij - rij. \qquad \text{Eqn. } 4$$

Miall's (op. cit.) method is statistically more sophisticated and accomodates the proportional variations involved with no recorded multi-storey lithologies. In this case the difference matrix is derived from:

$$dij = pij - rij. \qquad \text{Eqn. } 5$$

In both cases, positive values of dij represent those transitions which occur more commonly than would be expected given randomly controlled systems.

5. Sampling methods.

Two sampling methods are available for determining values of fij. In the first a set sample interval is decided upon and only transitions at the sample points are recorded. A problem arises in deciding on the sample interval, as too widely spaced samples would miss thinly interbedded states, while too narrow an interval would produce such high values on the $i = j$ diagonal that all Markovian properties would be obscured (Miall, op. cit.). An interval which approximates to mean state thickness appears to be the most appropriate (Selley, op. cit.; Miall, op. cit.). Results derived from fixed interval sampling tend to amplify thickness variations in the sample states and thus indicate duration of the state (i. e. maintenance of a given sub-environment in the Cabos Series). The other sampling procedure requires that all transitions from one state into another are recorded. Multi-storey lithologies are not recognized and the method stresses the sequential evolution of the succession.

6. Test of significance.

The values of the dij matrix may represent the results of random chance events so that some form of test must be applied to check for significance. The chi-squared test is suitable for this purpose and the formula given by Billingsley (1961) is applied to all matrices in which values of $i = j$ were not recorded. For this test:

$$X^2 = \sum_{ij}^{n} (fij - si.\, rij)^2/si.\, rij \qquad \text{Eqn. 6}$$

and the null hypothesis is that the vertical succession of states (facies) follows from some randomly controlled mechanism of deposition.

Two different fixed-interval sample analyses (intervals of 5 and 10m) were applied to various parts of the Cabos Series, but in both cases the i = j values were so high in comparison with all other values of fij that without more refined analysis involving consideration of Markov dependency of states separated by more than a single transition, the chi-squared test is of little value. The matrices and corrected facies relationship diagrams (see below) are presented for this data, but will be considered further only briefly.

7. Results of analysis of the Cabos Series.

The matrices derived from analysis of various parts of the Cabos Series are presented in tabular form (Tables 1 to 25). Data from the fij matrix may be summarised in a facies relationship diagram (De Raaf et al, 1965) and this can be compared with a 'corrected' facies relationship diagram (Selley, 1970) derived from the dij matrix and which shows only the non-random transitions. Both diagrams show the main transitions in the form of arrows to which can be added the values of dij so that the relative importance of each transition can be read directly from the diagram.

Matrices and associated facies relationship diagrams are presented for data derived from analysis of the complete succession. Other data is considered from the two major transgressive and regressive sequences derived from the empirical facies analysis presented in this chapter. Thus, this latter data more directly corresponds to a test of the proposed empirical model.

Table 1 Transition count matrix, transgressive sequence.

Facies		1A	1B	2	3	4	5	Row sum
Sand flat/beach	1A	0	115	5	25	6	0	151
Mud flat	1B	108	0	7	14	1	0	130
Inter bar low	2	5	3	0	62	0	0	70
Sand bar	3	34	11	59	0	3	0	107
Shore face	4	3	0	0	2	0	1	6
Shelf	5	0	0	0	0	0	0	0
						Total		464

Table 2 Independent trials probability matrix, transgressive sequence.

Facies	1A	1B	2	3	4	5
1A	0.00	0.41	0.23	0.33	0.03	0.00
1B	0.45	0.00	0.21	0.31	0.03	0.00
2	0.38	0.31	0.00	0.26	0.02	0.00
3	0.42	0.36	0.20	0.00	0.03	0.00
4	0.33	0.28	0.15	0.22	0.00	0.00
5	0.32	0.28	0.15	0.22	0.02	0.00

= rij

Table 3 Transition probability matrix, transgressive sequence.

Facies	1A	1B	2	3	4	5
1A	0.00	0.76	0.03	0.16	0.04	0.00
1B	0.83	0.00	0.05	0.10	0.00	0.00
2	0.07	0.04	0.00	0.88	0.00	0.00
3	0.32	0.10	0.55	0.00	0.03	0.00
4	0.50	0.00	0.00	0.33	0.00	0.17
5	0.00	0.00	0.00	0.00	0.00	0.00

= pij

Table 4 Difference matrix, transgressive sequence.

Facies	1A	1B	2	3	4	5
1A	0.00	+0.35	-0.20	-0.17	+0.01	0.00
1B	+0.38	0.00	-0.16	-0.21	-0.03	0.00
2	-0.31	-0.27	0.00	+0.62	-0.02	0.00
3	-0.10	-0.26	+0.35	0.00	0.00	0.00
4	+0.27	-0.28	-0.15	+0.11	0.00	+0.17
5	-0.32	-0.28	-0.15	-0.22	-0.02	0.00

= dij

Table 5 Test of significance, transgressive sequence.

Test equation from	X^2	d.f.	Limiting value
Billingsley (1961)	410	20	31

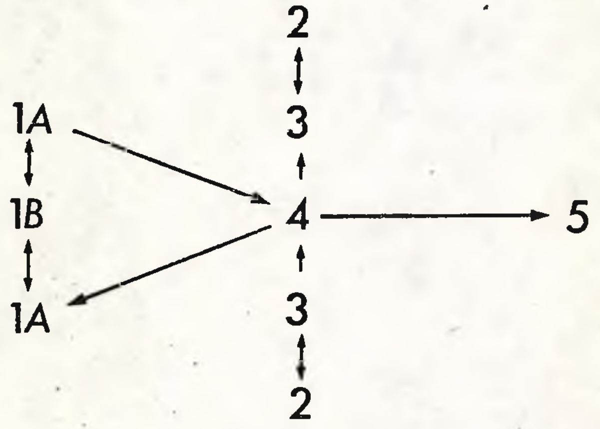


Fig. 20 Facies relationship diagram, transgressive sequence.

Table 6 Transition count matrix, total section.

	1A	1B	2	3	4	5	
1A	0	127	5	28	6	0	166
1B	115	0	7	21	1	0	144
2	7	3	0	66	0	0	76
3	41	13	65	0	3	0	122
4	3	0	0	3	0	1	7
5	0	0	0	0	1	0	1
					Total		516

Table 7 Independent trials probability matrix, total section.

	1A	1B	2	3	4	5
1A	0.00	0.40	0.22	0.33	0.03	0.00
1B	0.44	0.00	0.20	0.31	0.02	0.00
2	0.37	0.32	0.00	0.26	0.02	0.00
3	0.47	0.40	0.22	0.00	0.03	0.00
4	0.32	0.28	0.15	0.23	0.00	0.00
5	0.32	0.27	0.14	0.22	0.02	0.00

= rij

Table 8 Transition probability matrix, total section.

	1A	1B	2	3	4	5
1A	0.00	0.76	0.03	0.17	0.04	0.00
1B	0.80	0.00	0.05	0.14	0.01	0.00
2	0.09	0.03	0.00	0.87	0.00	0.00
3	0.33	0.10	0.53	0.00	0.02	0.00
4	0.43	0.00	0.00	0.43	0.00	0.14
5	0.00	0.00	0.00	0.00	1.00	0.00

= pij

Table 9 Difference matrix, total section.

	1A	1B	2	3	4	5
1A	0.00	+0.36	-0.19	-0.16	+0.01	0.00
1B	+0.36	0.00	-0.15	-0.17	-0.01	0.00
2	-0.28	-0.29	0.00	+0.61	-0.02	0.00
3	-0.14	-0.30	+0.31	0.00	-0.01	0.00
4	+0.11	-0.28	-0.15	+0.20	0.00	+0.14
5	-0.32	-0.27	-0.14	-0.22	+0.98	0.00

Table 10 Test of significance, total section

Test equation from	X^2	d.f.	Limiting value
Billingsley (1961)	404	20	31

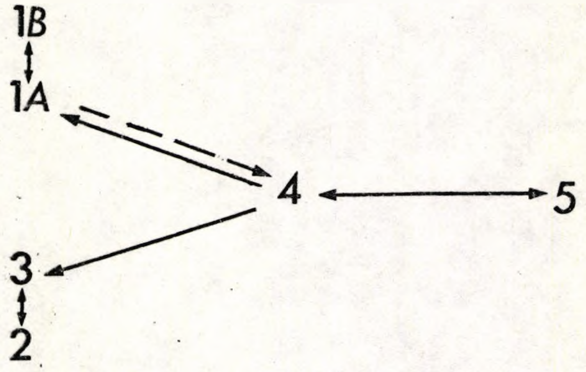


Fig. 21 Facies Relationship Diagram, Total Section.

Table 11 Transition count matrix, regressive sequence.

	1A	1B	2	3	4	5	
1A	0	12	0	3	0	0	15
1B	7	0	0	7	0	0	14
2	2	0	0	4	0	0	6
3	7	2	6	0	0	0	15
4	0	0	0	1	0	0	1
5	0	0	0	0	1	0	1
					Total		52

Table 12 Independent trials probability matrix, regressive sequence.

	1A	1B	2	3	4	5
1A	0.00	0.38	0.16	0.41	0.03	0.00
1B	0.42	0.00	0.16	0.40	0.03	0.00
2	0.35	0.30	0.00	0.33	0.02	0.00
3	0.43	0.38	0.16	0.00	0.03	0.00
4	0.31	0.27	0.12	0.29	0.02	0.00
5	0.31	0.27	0.12	0.29	0.02	0.00

= rij

Table 13 Transition probability matrix, regressive sequence.

	1A	1B	2	3	4	5
1A	0.00	0.80	0.00	0.20	0.00	0.00
1B	0.50	0.00	0.00	0.50	0.00	0.00
2	0.33	0.00	0.00	0.67	0.00	0.00
3	0.47	0.13	0.40	0.00	0.00	0.00
4	0.00	0.00	0.00	1.00	0.00	0.00
5	0.00	0.00	0.00	0.00	1.00	0.00

= pij

Table 14 Difference matrix, regressive sequence.

	1A	1B	2	3	4	5
1A	0.00	+0.42	-0.16	-0.21	-0.03	0.00
1B	+0.08	0.00	-0.16	+0.10	-0.03	0.00
2	-0.02	-0.30	0.00	+0.34	-0.02	0.00
3	+0.04	-0.24	+0.14	0.00	-0.03	0.00
4	-0.31	-0.27	-0.12	+0.71	-0.02	0.00
5	-0.31	-0.27	-0.12	-0.29	+0.98	0.00

Table 15 Test of significance, regressive sequence.

Test equation from Billingsley (1961)	X^2	d.f.	Limiting value*
	78.42	21	32

*From table of chi-square values with correct number of degrees of freedom at 95%

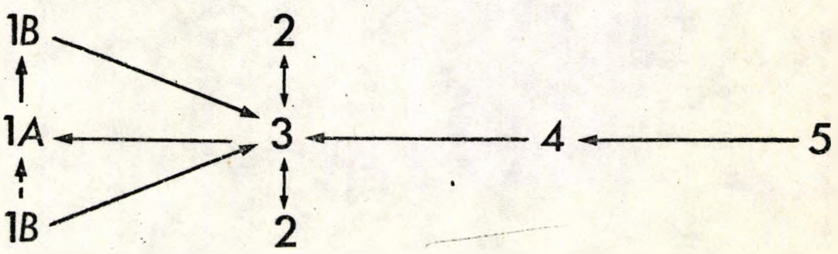


Fig. 22 Facies relationship diagram, regressive sequence.

Table 16 Transition count matrix, transgressive sequence.
Fixed interval sampling (= 5m).

	1A	1B	2	3	4	5	
1A	118	59	9	21	3	0	210
1B	51	62	3	15	2	0	133
2	7	3	12	31	0	0	53
3	25	14	30	247	2	0	318
4	3	0	0	3	4	1	11
5	0	0	0	0	0	17	17
					Total		742

Table 17 Predicted matrix, transgressive sequence.

	1A	1B	2	3	4	5
1A	58	39	15	90	3	5
1B	37	25	10	57	2	3
2	15	10	4	23	1	1
3	87	59	23	136	5	8
4	3	2	1	5	0	0
5	5	3	1	7	0	0

= rij

Table 18 Difference matrix, transgressive sequence.

	1A	1B	2	3	4	5
1A	+60	+20	-6	-69	0	-5
1B	+14	+37	-7	-42	0	-3
2	-8	-7	+8	+8	-1	-1
3	-62	-45	+7	+111	-3	-8
4	0	-2	-1	-2	+4	+1
5	-5	-3	-1	-7	0	+17

= dij

Table 19 Transition count matrix, upper 2500m
10m sample interval.

	1A	1B	2	3	4	5	
1A	25	9	3	7	0	0	44
1B	2	14	2	6	1	1	26
2	3	0	5	13	0	0	21
3	13	3	11	81	1	0	109
4	2	0	0	1	5	0	8
5	0	0	0	0	1	8	9
					Total		217

Table 20 Predicted matrix assuming a random arrangement.

	1A	1B	2	3	4	5	
1A	9	5	4	22	2	2	
1B	5	3	3	13	1	1	
2	4	3	2	10	1	1	= rij
3	23	13	11	54	4	5	
4	2	1	1	4	0	0	
5	2	1	1	4	0	0	

Table 21 Difference matrix, total section.
10m sample interval.

	1A	1B	2	3	4	5
1A	+16	+4	-1	-15	-2	-2
1B	-3	+11	-1	-7	0	0
2	-1	-3	+3	+3	-1	-1
3	-10	-10	0	+27	-3	-5
4	0	-1	-1	-3	+1	0
5	-2	-1	-1	-4	+1	+8

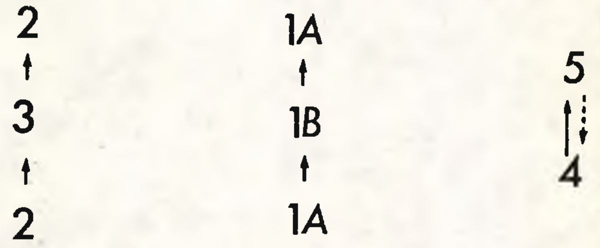


Fig.23a Facies relationship diagram, transgressive sequence, 5m sample interval.

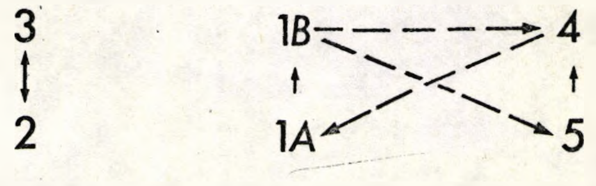


Fig.23b Facies relationship diagram, upper 2500m, 10m sample interval.

Table 22 Transition count matrix, upper 2500m

	1A	1B	2	3	4	5	
1A	0	28	2	13	0	0	43
1B	19	0	2	11	0	1	33
2	1	0	0	46	0	0	47
3	23	5	44	0	2	0	74
4	2	0	0	0	0	1	3
5	0	0	0	0	1	0	1
					Total		201

Table 23 Independent trials probability matrix, upper 2500m.

	1A	1B	2	3	4	5
1A	0.00	0.20	0.30	0.44	0.02	0.01
1B	0.27	0.00	0.28	0.42	0.02	0.01
2	0.29	0.21	0.00	0.44	0.02	0.01
3	0.35	0.26	0.38	0.00	0.02	0.01
4	0.22	0.17	0.24	0.35	0.00	0.01
5	0.22	0.16	0.24	0.35	0.01	0.00

= rij = sj

Table 24 Transition probability matrix, upper 2500m.

	1A	1B	2	3	4	5
1A	0.00	0.65	0.05	0.30	0.00	0.00
1B	0.57	0.00	0.06	0.33	0.00	0.03
2	0.02	0.00	0.00	0.98	0.00	0.00
3	0.31	0.07	0.59	0.00	0.03	0.00
4	0.67	0.00	0.00	0.00	0.00	0.33
5	0.00	0.00	0.00	0.00	1.00	0.00

= pij = si

Table 25 Difference matrix, upper 2500m.

	1A	1B	2	3	4	5
1A	0.00	+0.45	-0.25	-0.14	-0.02	-0.01
1B	+0.30	0.00	-0.22	-0.09	-0.02	+0.02
2	-0.27	-0.21	0.00	+0.54	-0.02	-0.01
3	-0.04	-0.19	+0.21	0.00	+0.01	-0.01
4	+0.45	-0.17	-0.24	-0.35	0.00	+0.32
5	-0.22	-0.16	-0.24	-0.35	+0.99	0.00

= dij
= pij - rij

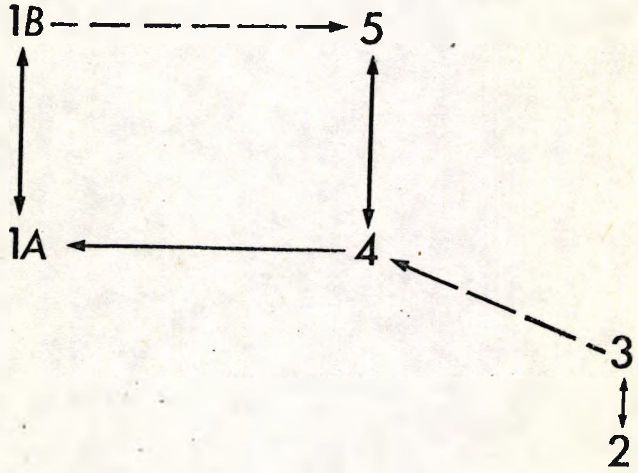


Fig.24 Facies relationship diagram, upper 2500m.

8. Discussion and comparison with the intuitive facies model.

The fixed interval samples (Tables 16 to 21) indicate from the corrected facies relationship diagrams only isolated couplets of two linked facies (Fig. 23). Thus the tidal sand/beach and mud flat environments change between themselves, but change to other facies less often than would be accounted for by randomly controlled processes. This model may be correct, in which case it does not indicate any 'preferred direction' of transition (viz. transgressive or regressive). Alternatively the $i = j$ transitions, the high number of recorded transitions between magnafacies pairs (e.g. 1A - 1B, 2 - 3, 4 - 5) and the relatively small and restricted samples of states 4 and 5 possible obscure any meaningful results.

Samples of all transitions applied to test the transgressive/regressive model of Chapter 1 give results which seem to agree with the proposed model. The corrected facies relationship diagram for the transgressive sequence shows (Fig. 20) a tendency of the facies states to move from proximal (facies 1A and 1B) towards distal (magnafacies 5) through the intermediate shore face facies (4). The tidal flat facies can alternate with the shore face, but the barrier bar facies (3) once developed from the shore face only returns with difficulty. There appears to be little regular exchange between the proximal and barrier bar facies and such transitions may possibly be accounted for by storm processes which are effectively randomly controlled. The logged section does in fact support this idea in that many of the lower contacts of units of facies 3 are erosive or sharp where they overlay units of facies 1.

The results of Markov analysis of the upper regressive sequence (Fig. 22) again support the empirical model. The facies move from distal towards proximal, but in this case facies 3 intervenes between the tidal flat and shore face facies.

9. Summary.

The statistically determined facies model accords with the empirical model only when the sequential development of the succession is considered. Fixed interval sampling appears to involve too much 'noise' (derived dominantly from $i = j$ transitions) and results appear inconclusive. These statistical analyses seem to provide useful, partially objective tests which can be applied to facies models derived from more subjective analytical techniques.

CHAPTER 2

TRACE FOSSIL SYSTEMATIC DESCRIPTIONS

SYSTEMATICS OF TRACE FOSSILS: SPAIN

Ichnogenus CRUZIANA d'Orbigny 1842

Cruziana semiplicata Salter 1853

Plates
1,2,3,4

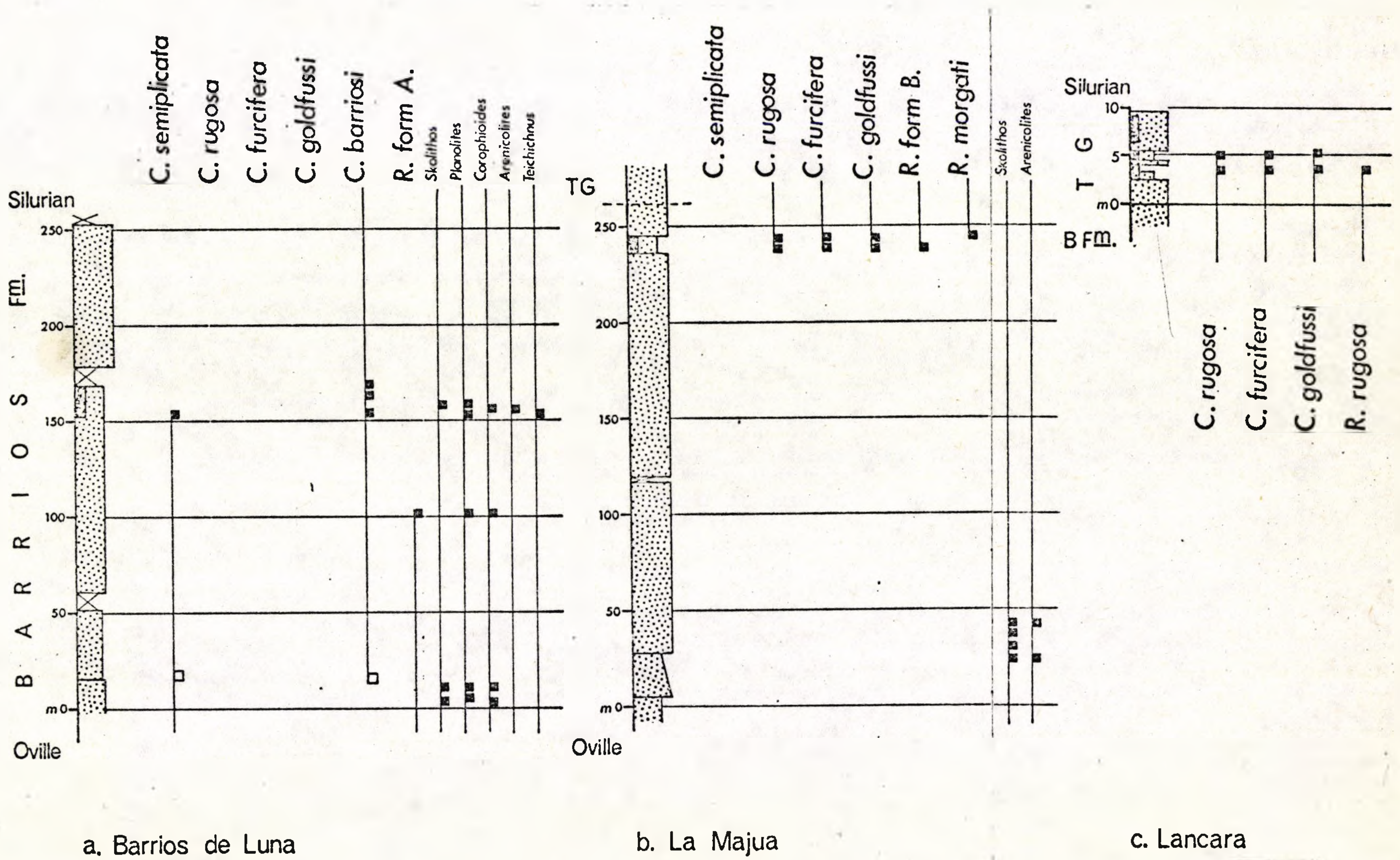
Material.

Over 50 specimens of varying quality of preservation collected from Luarca-Cadavedo section (= Asturian) below 3300m level, most from within zone 2800-3300m (Fig. 1*). Four traces from 153m level, Barrios de Luna section (= Cantabrian) (Fig.25). Additional material studied in situ. Most specimens recovered as casts on the soles of medium or fine sand and coarse siltstone beds. No original furrows from tops of sand beds were found, but two well-preserved examples of furrows in mud were recovered. The grain size and induration of both casting and excavated sediments appears to have been too similar for the preservation of very fine detail on many specimens from the lower 1500m of the Asturias section.

Description.

C. semiplicata usually occur grouped (Pl.1.1), with both straight and gently curved forms present on the same surface. Continuous traces, over 3.5m long, were recorded in the field. Widths vary from 19mm to 56mm with a mean of 36mm. Depths rarely exceed 5-6mm.

Deeply dug V-patterns, both extending fully to the margins (Pl.2.1) and confined to the central half of the trace (Pl.1.3), are present. Most traces have continuous genal welts running along the two outside margins and these represent the maximum width in all those traces in which they are preserved. The medial digging impressions are grouped in sets of up to a maximum of three and are considered to represent the



a. Barrios de Luna

b. La Majua

c. Lancara

Figure 25
Distribution of trace fossils in three Luna-Sil region sections. Stratigraphically useful trilobite trace fossils are shown in heavy print. TG = Transition Group. BF$^{\underline{m}}$ = Barrios Formation. Open squares indicate uncertain observations.

digging activity of a digited appendage (Seilacher, 1962, 1970; Crimes, 1970a, 1970b, 1975). The V-angle (the angle subtended by the limbs of the V-patterned digging strokes) varies from 50° to 130° with a mean of 90° (cf. Crimes, 1970a, p. 5). Variations in number of grooves and ridges within and between the V sets, but on the same Cruziana, suggests such variability is the result of variation in appendage attitude during the digging stroke and not to differences in appendage morphology (Pls.22, 23). In fully preserved specimens a 'claw form' composed of one central digit flanked by a pair of shorter digits (Pl.23) appears to be the complete morphological form and this type recurs throughout the upper 500m of C. semiplicata bearing strata in the Asturian section.

The indifferent preservation of the bulk of the material allows little information on the form of the scratch marks of the two relatively flat zones which separate the genal welts from the digging impressions (V-markings). Feint wisps, at lower angles to the median axis than the digging impressions, are preserved only poorly in only seven specimens (Pl.13). In one specimen from the Cantabrian section a tridigitate claw form is indicated for the central excavation impressions and a similar claw morphology may be indicated in the impressions on the outer lobe (Pl.23). However, the lateral continuity of the two sets cannot be traced with certainty (cf. Crimes, 1975, Fig.5).

Discussion.

An Upper Cambrian age for C. semiplicata is now widely accepted (Crimes, 1970a, 1970b; Seilacher, 1970; Radwanski and Roniewicz, 1963). Crimes (1974b) has recently suggested that the range may be further extended to include also the Lower Tremadoc.

This Spanish material differs little from Seilacher's formalised description (Seilacher, 1970, p. 461) and close similarities are found between many of the features of British C. semiplicata described by Crimes (1970a, 1975) and Spanish specimens.

Cruziana furcifera d'Orbigny 1842

Plates
5,8,9,15

Material.

Over 100 specimens collected from the Cadavedo-Luarca coastal section (above 2880m, Fig. 1*) and 28 specimens from the La Majua and Lancara de Luna sections (Cantabrian Zone). Additional material from section north of La Caridad, Asturias (Fig. 1). Most are extremely well-preserved, occurring as casts on the underside of medium and fine grained sandstones. The Cantabrian material occurs both as shallow and very deeply dug casts which are considered transitional with Rusophycus. Shale pellets are preserved in the sand fills of some of the deeply dug specimens. Three moulds on the top of sandstone beds were recorded in the field and two large specimens of mud moulds have been recovered.

Description.

Traces over 4.0m long have been recorded in the field, but recovered specimens rarely exceed 100mm in length. Variations in depth of excavation are common along the length of individuals, but width rarely varies sympathetically. Widths vary from 21mm to 211mm with a mean of 52mm. Most specimens from the upper beds of the Barrios Formation at the roadside near Lancara de Luna are over 35mm deep and, being more or less discontinuous, represent forms transitional with Rusophycus (Pl.9.1) A single Cruziana, wider than any yet recorded in the literature (211mm), was recovered from the La Majua section (@ 234m) where at least two other examples of similar size were observed in situ. (Pl. 5)

Scratch markings usually define a V-pattern, the limbs of the V always extending to the full width of the two lobes and formed from both straight and siculate patterns. V-angles vary considerably both between and along the length of individual specimens (Pl.5 1). A range from 23° to 180° has been measured from recovered Asturian material with a mean of 77°. In the Cantabrian material the range is from 20^{o} to 131^{o}, mean 50^{o}. On the longer specimens the V-pattern is complex, two distinct sets of impressions on each lobe being superimposed so that a diamond pattern results (Pl.5.2).

The component scratch marks are arranged in multiple sets which appear to vary in number from a minimum of two to a maximum of eight per set. Again variation in numbers within an individual trace and even within separate sets indicates that such numerical variations are behaviourally controlled. Appendage profile indicated by scratch morphology suggests a gently curved or in some cases practically straight edge. Individual scratches indicate digits with an asymmetrical profile. Scratches may become retroversely directed at the lateral margins of some deeply dug specimens.

Periodic swellings modify the V-form of some specimens of C. furcifera so that an appearance approaching that of C. rugosa is is produced. Dimorphism of limb impressions is also present, mostly including elements of both C. rugosa and C. furcifera.

In all cases, the appendage impressions extend fully to the lateral margins of the traces. In the most deeply dug examples these are aligned vertically and normal to the median axis. Only on the relatively flat surfaces of each lobe do these impressions change to more normal oblique orientations (Pl.9.1).

In most specimens genal welts are absent, but in a number of specimens, both deeply and shallowly dug, sections of genal welt absent trace pass laterally into welt present sections. Appendage morphology appears to remain constant in both forms and presumably reflects behavioural variation during furrowing (cf. Crimes, 1970a; Seilacher, 1970, p.453).

Discussion.

The superimposed V-appendage pattern which is typical of the larger specimens of C. furcifera suggest the digging action of at least two pairs of broad, multi-digited anterior appendages. This is in contrast with typical examples of C. rugosa in which a single pair of anterior appendages - apparently with the same general claw morphology -

produces dig marks which remain separate and for the most part undisturbed by successive excavation strokes. The significant morphological difference between *C. rugosa* and *C. furcifera* is the form of the anterior margin of the two species. *C. rugosa* typically have steep, sometimes vertical anterior and lateral margins whereas *C. furcifera* more typically have gently sloping margins. *C. furcifera* therefore appears, in most cases, to represent a shallower and possibly more rapidly advancing form of furrowing than the deeper and hence slowly progressing technique employed in *C. rugosa*. The exceptionally deep Cantabrian specimens of *C. furcifera* are atypical in that the normal oblique/postro-medially directed digging strokes are retained on vertical walled traces.

The behaviourally controlled relationship between *C. furcifera*, *C. goldfussi* and *C. rugosa* suggested by Seilacher (1970) and Seilacher and Crimes (1969) is confirmed by the lateral continuity of two or more of these species. However, this does not entirely preclude the production of these traces by more than one trilobite species or genus.

C. furcifera is of cosmopolitan distribution in Cambro-Ordovician strata (see Seilacher, 1970, p. 464). Crimes (1970b) suggests an age range from Upper Tremadoc and throughout the Arenig. Seilacher (*op.cit.*) suggests a similar age range from Tremadoc to Llandeilo.

In Spain, *C. furcifera* was reported from possible Tremadocian rocks of the Iberian Series by Schmitz (1973) where it occurs with *C. semiplicata*. A similar overlap in the ranges of *C. furcifera* and *C. semiplicata* is present in the Cabos Series of Asturias (Fig. 1*) but is not demonstrable in the Cantabrian sections.

Cruziana goldfussi (Rouault) 1850

Plates
3, 7, 8

Material.

Over 50 specimens from Luarca-Cadavedo section (above 3400m, possibly down to 2920m, Fig. 1*) and 7 specimens from the La Majua and Lancara sections (Fig. 26). Preservation as *C. furcifera*.

Description.

No large examples of C. goldfussi were recorded and lengths of recovered material are similar to C. furcifera. Widths vary from 15mm to 101mm, mean 48mm.

C. goldfussi has all the features and lateral variability exhibited by C. furcifera but with the addition of two lateral genal welts (Pls.7.2 ,3.1 8.2). Such welts are usually of the order of 1mm wide and may either merge mediolaterally with the excavated lobes or stand separate with a gap of up to 1. 5mm.

Two distinct forms of appendages appear to have been used for

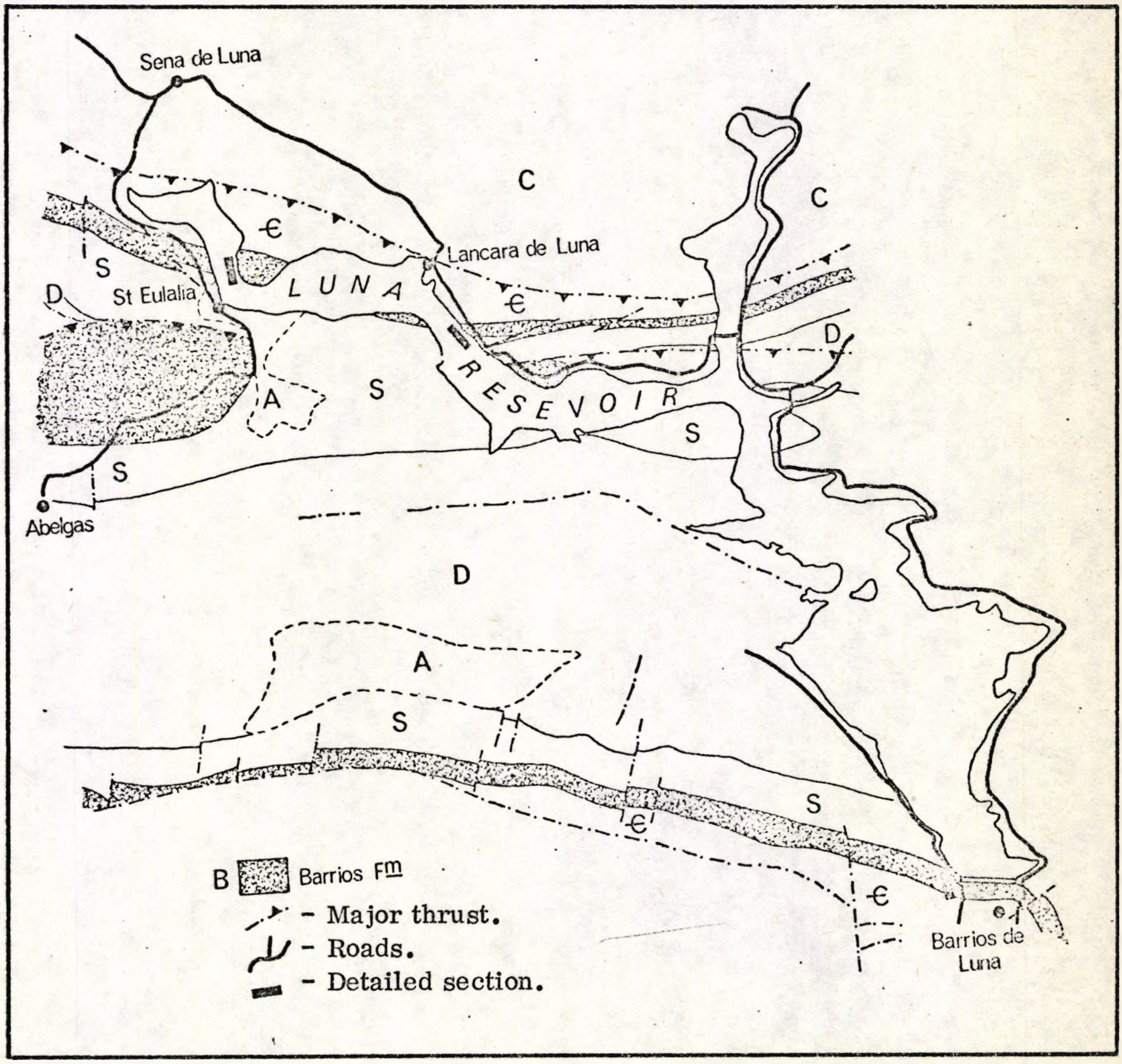


Figure 26
Locations of detailed sections of the Barrios Formation in the Luna Resevoir area. A - Drift; C - Carboniferous; D - Devonian; S - Silurian; Barrios Formation stippled; € - Oville, Lancara and Herreria Formations.

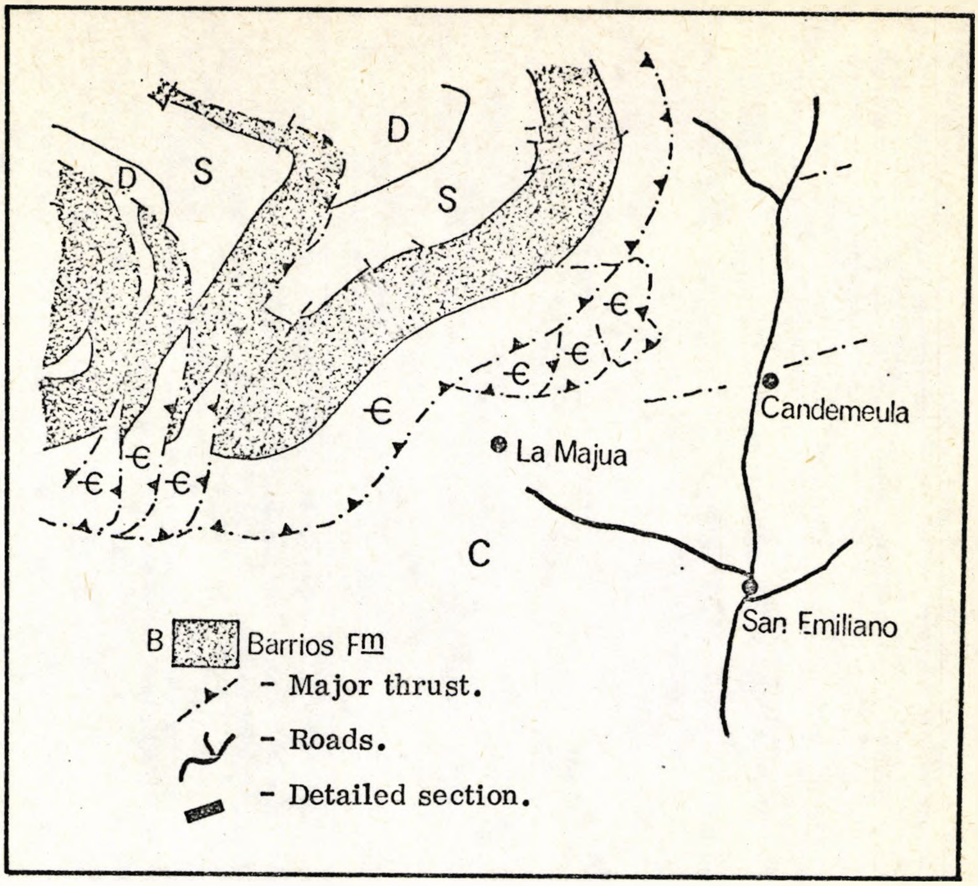


Figure 27
Location of La Majua section of the Barrios Formation.
C - Carboniferous; D - Devonian; S - Silurian; Barrios Formation stippled; Є - Oville, Lancara and Herreria Formations.

the excavation of these traces: the two rarely appearing on a single Cruziana. The multi-digited broad forms described for C. furcifera and a second type composed of three digits, the anterior of which was longer than the two equal length posterior ones. Appendage rotation during the digging stroke leads to changes in scratch morphology (Fig. 28)and the appearance of medial convergence. Appendage V-impressions are simple, with V-angles varying from 28° to 79°, mean 52°.

Discussion.

The two morphologies of appendage impressions appear to be sufficiently different to indicate separate appendage forms rather than behavioural variations in the use of a single appendage. Therefore, these differences may be either related to production by two separate trilobites with differentiated appendages or by the overall behavioural control of a single trilobite in which exite excavation (multi-digited) and endite (tri-digitate) activity could be selected.

The restriction of C. goldfussi to the same stratigraphic range as C. furcifera (Seilacher, 1970) and the demonstrable lateral continuity

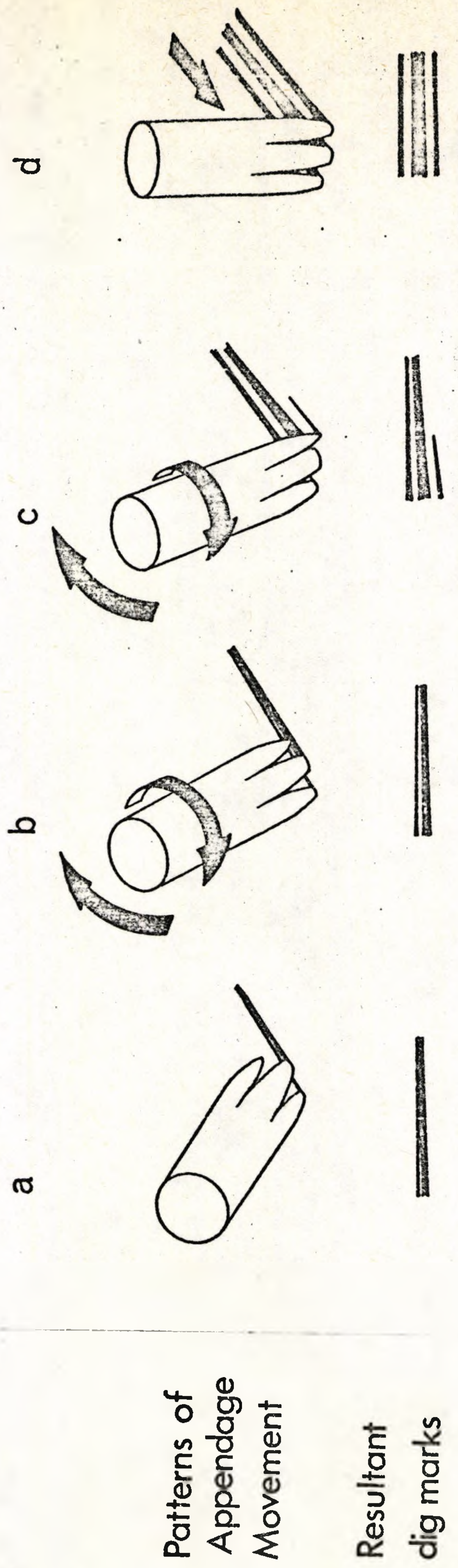


Figure 28
The affects of appendage attitude on dig mark morphology. (a) Oblique axis. (b) and (c) Rotation and straightening. (d) Vertical, full-face attitude.

of these two species suggests behavioural control of gross morphology. Hence, the proposal of variation in exite and endite use appears, in the context of demonstrable ethological variation, to be a viable explanation of more detailed variations in excavation impressions.

Cruziana rugosa d'Orbigny 1842

Plates
6,7,8,9,10,11,12,19

Material.

Over 50 specimens from the Luarca-Cadavedo section where all occur over 3300m from the base (Fig. 1*). Preservation as C. furcifera and C. goldfussi. A similar number of specimens from the La Majua (@ 226-238m) and Lancara sections. The La Majua material occurs as casts on the soles of medium to fine red sandstones which are interference rippled. The Lancara specimens are mostly deep, wall-like casts on the base of white, low-angle cross laminated and rippled orthoquartzitic medium sandstones. Mud pellets are associated with a number of these specimens.

Description.

C. rugosa over 1.0m long were recorded in the La Majua section where also the wider specimens occur. In the Lancara section, short discontinuous traces, rarely exceeding 150mm, are the most common, and many represent forms transitional with Rusophycus. The Asturian section demonstrates the relationship of C. rugosa with C. furcifera. Forms of C. rugosa which are transitional with C. furcifera are common at lower levels (c. 3300m-3450m), but towards the top of the section forms become wider and have a slightly different morphology (usually more deeply and coarsely dug) while still retaining all the diagnostic features of C. rugosa. Transitional forms are absent from these higher levels.

Widths vary from 12mm to 115mm, mean 44mm and V-angles vary from 0° to 87°, mean 50°. Depths vary from less than 5mm to over 35mm.

Appendage impressions are grouped in sets with a maximum of eight digits per set (cf. 12 of Seilacher, 1962, 1970). Individual sets vary in angle from the lateral margins to the median line of many traces. Rotation of the multi-digited appendage about its own axis during the digging stroke results in appendage impression sets which broaden towards the median line. (See Chapter 6 for fuller discussion of the details of production of *C. rugosa.*) Only close to the central axis is the full form of the appendage preserved.

In very deeply excavated specimens from the Lancara road section many of the appendage impressions lie more or less parallel to the axis of the trace. This is particularly so at the final withdrawal portion of the digging stroke which produces the low corrugations oriented normal to the long axis, and which are diagnostic of *C. rugosa*. Impressions of the genal or pleural margins of the trilobite are preserved along the steep lateral walls of some of these deeper specimens (Pl.113).

Specimens of *C. rugosa* transitional, and passing into *C. furcifera*, are common from both the Asturian and Cantabrian localities (Pl.9.1). In all cases the *C. rugosa*-like form is preserved on sections with steeper margins, but which are NOT necessarily more deeply excavated than the *C. furcifera*-like sections.

Discussion.

C. rugosa is demonstrably a behavioural variant of *C. furcifera*, but these two species have distinct and partially separate stratigraphic ranges. In south, north-central and north-west Spain *C. furcifera* always appears below *C. rugosa*, the two species occurring together only at higher levels (Schmitz, 1971; Scheuplein, 1970). *C. rugosa* has been recorded from very low Arenig rocks of south Wales by Crimes (1970b). From adjacent U.K. sections, *C. rugosa* appears to be absent from beds stratigraphically below the Arenig.

The subdivisions of the Rugosa Group appear to represent distinct changes in behaviour of one form of trilobite: deep posteriorally directed digging techniques only being developed during the Arenig. Causes of such variation are not directly determinable, but the marked increase in bioturbation in the Arenig presumably determined changes in the trilobite coenosis, possibly leading to increasing predation on endobiota located further from the surface during the Arenig than at any time prior to this period.

Cruziana barriosi ichnosp.nov.

Plates
12 , 13

Species name.

Barriosi = from the village of Barrios de Luna which gives its name to the Barrios Formation from which the specimens were collected.

Material.

Five specimens (nos. T940, T941, T942, T943) collected from the Barrios Formation (@ 28.5m, 106m and 172m, Fig.25), western abutment of Barrios de Luna dam, Luna Valley, Leon Province, Cantabrian Mountains, north-west Spain. Additional well-preserved and fragmentary material (collected by T. P. Crimes) from the Barrios Formation, La Vid valley section (Fig. 1), 26km south of Puerto Pajares.

Holotype.

The best preserved specimen (T943).

Diagnosis.

Casts of trilobite furrows, normally with wide, flat topped lobes and no genal welts. Appendage digging impressions run more or less parallel with the long axis of the traces and are grouped in sets with at least 5 digits per set. Often a wide median groove separates the two lobes.

Description.

The type specimen is 123mm wide and continuous for over 300mm without axial termination. The depth of the trace, relative to the adjacent bedding plane, is less than 5mm and the lateral and medial margins of each lobe slope steeply. The central depression between the two lobes is flat bottomed and featureless and separates the two lobes by 9mm.

The appendage impressions are variable in orientation along the length of each lobe but at no point does the V-angle exceed 20°.

Over much of the trace these grooves lie parallel to the central axis.

At a number of points the appendage impressions are interrupted and a surface morphology similar to that of C. rugosa is produced. These interrupted sections pass into otherwise continuously striated sections in which no termination can be seen.

The other complete specimens collected from the Barrios de Luna vary in width from 82mm to 116mm, the narrowest specimen being markedly less flat topped than the others but still retaining the wide lobe separation.

Fragmentary material from the La Vid section is largely composed of 'pad-like' sandstone casts which are comparable with parts of the individual lobes of the full Cruziana. In none of this material can the limits of individual digging strokes be recognized, the preserved striae being continuous over the length of each specimen. Similarly no C. rugosa-like corrugations are present which may suggest an interrupted digging stroke.

In both the Barrios de Luna and La Vid sections C. barriosi occurs at a level a few metres below the top-most very thickly bedded, white quartzite (Member BF, Geitelink, 1973, Fig. 15). Below this level in the La Vid section Cruziana and also Rusophycus typical of the Middle Cambrian (Crimes, pers.comm.) occur, the two localities being separated by less than 25m vertical thickness. In the Barrios de Luna section C. barriosi possibly overlaps and occurs within less than 18m of C. semiplicata.

Discussion.

A number of specimens of C. furcifera and C. goldfussi collected from the Cambro-Ordovician Cabos Series of Asturias and the Grès Armoricain of Brittany have very low V-angles ($<25^{\circ}$). In these specimens careful tracing of individual scratches indicates that apparently very long appendage impressions are in fact composite and composed of shorter, discontinuous grooves which appear almost perfectly aligned (Pl.29.5). In deeply excavated examples of C. rugosa an axis parallel digging stroke may be demonstrated from the preserved multi-digited appendage impressions (= dig mark) but these are always short and markedly discontinuous.

In the case of *C. barriosi* the digging impressions are commonly interrupted and for most of the specimens it appears that multi-digited appendages were dragged passively across the mud surface at the base of the excavated furrow. This process may also be supported by the typical flat topped form of the full *Cruziana*. Passive dragging of posterior appendages behind weakly active anterior appendages may have practically smoothed out the more normal curved form of each lobe.

A precise age for *C. barriosi* is difficult to determine, there being no faunal control in either of the sections studied. The upper part of the Barrios Formation is undoubtedly of Arenig age (contains all members of the Rugosa Group) but the more thinly bedded and mixed lithologies below contain no specific (as yet defined) ichnofaunas. The size range of *C. barriosi* is comparable with Upper Tremadoc and Arenig species but the association of *C. semiplicata* almost certainly excludes an Arenig age. A Tremadoc age for at least the middle part of the Barrios Formation seems probable (see Ch. 3 for further discussion).

Cruziana aff. *semiplicata* Salter 1854

Material.

Two specimens from Luarca-Cadavedo section at 2870m. Preserved as casts on the sole of fine sandstones.

Description.

Cruziana with indistinct lateral margins, 47mm wide and symmetrical. Claw impressions appear to be single and remain separate and distinct along their length. Shallow excavation of the two lobes is characteristic of typical *C. semiplicata*. V-angle = 28°.

Discussion.

The simplicity of the individual claw impressions and the low V-angle are similar to features normally associated with *C. furcifera* and C. goldfussi, but the shallow excavation of the lobes and the general appearance of the traces suggest C. semiplicata associations. This trace may represent a form transitional between C. semiplicata and members of the Rugosa Group.

Cruziana cf. (?)semiplicata Salter 1854

Plate 4

Material.

One complete, well preserved specimen and one well preserved fragment from Luarca-Cadavedo section. Occur at 2940m and 3105m respectively. Preserved as casts on the soles of thin-bedded fine sandstones.

Description.

Asymmetrical form of Cruziana with different styles of claw impressions on each lobe. Left lobe of the complete trace bears continuous, slightly curved claw impressions which are broad and imbricate at the lateral margin but which become narrow and relatively simple towards the centre of the trace. Claw impressions suggest a bi or tridigitate appendage, inclined towards the central axis so that the outer part of the excavation was made by the outer flank of the appendage and the inner by the extreme tip. The right lobe is entirely composed of scratch marks similar to the outer part of the left lobe. In this case the scratches are strongly curved and lie almost normal to the central axis for most of their length, only changing to medio-posterior orientation at the central margin of the lobe. The total width of the full trace is 38mm, with the left lobe 17mm and the right 21mm. The whole trace is straight.

The fragmentary specimen has only one lobe preserved and is similar in many respects to the right lobe of the complete specimen. Discontinuous, asymmetrical claw impressions cross-cut the long axis of the lobe at right angles. A crude linear, repeated pattern is produced by the distribution of these impressions but this is made increasingly diffuse by the bi-digitate form of the individual impressions which tend to merge the separate bands.

Discussion.

This form of Cruziana appears to include features of C. semiplicata, the bi or tri-digitate claw forms being similar. The differences with typical C. semiplicata may well indicate slight behavioural control. If the distal ends of the appendages of the excavating trilobite were turned in towards the central axis, the outer margins may intersect the sediment surface at a low angle. Only where the tips of the appendages encountered the ridge of sediment situated between the two sets of active limbs would the relatively simple claw form associated with C. semiplicata be imprinted.

The inter and intra-lobe variability of structure present on this and some other examples of Cruziana draws attention to the need for fairly broad samples if such traces are to be useful as strain indicators in structural/tectonic analysis (cf. Crimes, 1975).

Cruziana sp.

Material.

A single specimen from the Barrios de Luna section (22.5m).

Description.

Small (20mm wide) trace, weakly bilobate with individualised rounded claw impressions cross-cutting multiple sets of impressions. V-angle of the former impressions vary considerably along the trace, producing strongly cross-cutting impressions. The 3 or 4 claw multiple sets present at the more gently sloping anterior end of the trace lie at a lower angle to the median axis than more deeply impressed, single claw impressions.

Discussion.

The appearance of the multiple sets of claw impressions suggest possible affinities with *C. furcifera* or *C. rugosa*, but the highly irregular individual claw impressions are more typical of Lower or Middle Cambrian species of *Rusophycus* such as *R. parallelum* Bergström (1970).

Ichnogenus FRAENA Rouault 1850

Fraena lyelli (Rouault) 1850

Plates
18 , 19

Material.

Two specimens on the same slab and a single specimen associated with a large *Arthrophycus* (?) from the Lancara road section and numerous well preserved specimens from high in the Luarca-Cadavedo section (above 4300m). Preserved as casts continuous with the overlying fine sandstones and as isolate, full relief filled burrows.

Description.

Continuous uni and bilobate traces up to 38mm wide. Bilobate forms have a very shallow medial groove on the ventral side, separating the two lobes. No claw impressions are preserved on the lobes which may be up to 20mm deep (cf. Crimes, 1970a). No indication of genal welts. In cross-section the full relief specimens are roughly of an inverted heart shape, the low central groove being absent from the upper surface.

All specimens occur with *C. rugosa* (Pl.19).

Discussion.

F. lyelli has previously been recorded from the Arenig (Lessertisseur, 1955; Hantzschel, 1962) and this Arenig age is supported by its association with *C. rugosa* in both the Asturias and Cantabrian sections.

Rouaultia, considered an invalid synonym of *Fraena* (Hantzschel, 1962) was described by Crimes (1970a) from the Upper Cambrian. In Crimes' material *Rouaultia rouaulti* Lebesconte exhibits faint V-markings, so that a link with *Cruziana* and *Fraena* and hence a trilobite origin for the latter may be proposed (Crimes, *op. cit.*). Some of the full relief specimens of *Fraena* may therefore represent true trilobite burrow structures.

Ichnogenus DIMORPHICHNUS Seilacher 1955

Dimorphichnus sp.

16 , 17 19

Material.

12 specimens collected from Luarca-Cadavedo section. Additional material studied *in situ*. They occur as shallow casts on the soles of fine and medium sandstones. No upper surface moulds found. Present

intermittently throughout the total thickness of the section.

Description.

Parallel, paired series of dots and wedge or elongate drop-shaped imprints (terminology of Osgood, 1970, p. 354) forming discontinuous but repeated patterns. In most specimens the individual imprints are featureless and vary in shape from small circular mounds to elongate forms. In two of the best preserved specimens (Pls.16.3,17.2)a marked difference is apparent between the two rows of imprints: repeated dots on one side (= Stemmsiegel, Seilacher, 1955) while elongate, wedge shaped and slightly curved imprints (= Harksiegel, Seilacher, op. cit.) are present on the other. At least four parallel grooves are present on one of the elongate imprints (Pl.16.3), indicating formation from a quadridigitate appendage (cf. Seilacher, 1955, p. 347). In some other specimens a maximum of eight pairs of imprints in each series is preserved, these being repeated three times. It appears that the trace maker jumped or floated from place to place so that a staggered pattern of series was preserved.

Discussion.

Seilacher (1955) described a number of Dimorphichnus from the Lower Cambrian of the Salt Range of Pakistan and proposed the species D. obliquus for forms with imprints of dot and sigmoidal shapes. The Spanish material collected is of insufficient quality and quantity to allow the proposal of a new species but the longer imprints are all more or less straight and certainly lack the pronounced sigmoidal form of Seilacher's figured material. The indication of four digits is comparable with Seilacher's D. obliquus.

Dimorphichnus from other Cambrian rocks have been reported by Martinsson (1965), Radwanski and Roniewicz (1963) and Crimes (1970a), also from the Cambro-Ordovician (Lower Silurian sensu lato) of Portugal by Delgado (1910).

No information on the feeding process suggested by Seilacher (1955) to be the cause of this type of trace may be derived from this material.

Ichnogenus MONOMORPHICHNUS Crimes 1970

Monomorphichnus sp.

9 , 4

Material.

Over 60 specimens recorded in situ and six specimens recovered from Luarca-Cadavedo section. Additional 2 specimens from section north of La Caridad. 6 poorly preserved specimens from the Barrios de Luna and Lancara sections. All preserved as casts on the soles of fine sand and coarse silt beds. No upper surface moulds recorded.

Description.

Isolate or grouped imprints which do not form pairs. Up to eight digit impressions may be present on each imprint but lower numbers of 3-6 (Pl.9.3) are more common. Imprints vary considerably in length, ranging from a little over 2mm to approximately 50mm. Both sigmoidal and straight forms occur, sometimes on the same slab. Monomorphichnus may pass laterally into and be indistinguishable from Dimorphichnus, the dot like imprints of the latter making the only taxonomic difference.

No precise stratigraphic order may be determined for the variants of this trace, low numbers of digits being associated with high. Multi-digited forms are, however, absent from at least the lower 3000m of the section.

Discussion.

Monomorphichnus have been described from the Middle Cambrian (Martinsson, 1965) and the Upper Cambrian (Hecker and Zharkov, 1966; Crimes 1970a). Martinsson (op. cit.) suggested that they represent the action of a current propelled trilobite raking the sediment surface with endopodite claws. This general idea is supported particularly by evidence of passage from Monomorphichnus to Dimorphichnus exhibited in studied material. The similarity of form of many Monomorphichnus with the parts of C. rugosa leads to the conclusion that the two are related through appendage morphology - presumably exites (Bergström, 1973).

The stratigraphic distribution of Monomorphichnus in the Asturian section is comparable with that of Dimorphichnus.

Ichnogenus DIPLICHNITES Dawson 1873

Diplichnites sp.

Plate 17

Material.

Four specimens collected from the Luarca-Cadavedo section. 3 specimens recorded in situ. All occur as casts on the soles of fine sandstones.

Description.

Specimens are composed of paired rows of small (< 0. 5mm diam.) dot like imprints (Pl.17·1). The pairs of imprints remain separated and evenly spaced for part of the length of the trace but may become merged and confused in other parts. One specimen seen to pass laterally into Dimorphichnus.

Discussion.

The absence of detail makes stratigraphic interpretation impossible. 'Tip-toeing' on the points of appendages, possibly only endites, presumably accounts for the simplicity of these traces.

Ichnogenus RUSOPHYCUS Hall 1852

Material.

Rusophycus are relatively rare in the section from Luarca to Cadavedo, only 5 specimens being collected and 27 other poorly preserved specimens recorded in situ. All occur as casts on the soles of medium or fine sandstones.

Although rare, Rusophycus occur throughout the total thickness of the section and the levels of occurrence of three Forms - A, B and C - of the total of four Forms described by Crimes (1970) are shown in Figure 1* .

Description.

Form A: Simple featureless bilobate traces with pronounced gap separating the parallel sided lobes. No claw impressions preserved. All specimens less than 20mm long with a shape factor (length : breadth, Crimes, 1970, p. 114) of 1.4 (cf. 1.5, Crimes, op. cit.).

Form B: Slightly divergent lobes separated by a shallow groove. Specimens larger than Form A (maximum length approximately 150mm). Shape factor = 1.8-2.0. One small specimen has faint claw impressions only on the mediolateral margins of the lobes.

Form C: One specimen recorded which is similar to Form B but includes a margin of sediment around the two lobes. Interpreted by Crimes (op. cit.) as the impression of the doublure of the trilobite which made the trace.

Form E: Rounded traces, only weakly bilobate with obvious fine appendage scratch marks passing fully to the lateral margin of the trace. Occur grouped on the same slab, with individuals merging to form a more continuous Cruziana type of trace. Shape factor = 1.8-2.0. The claw impressions and open V-pattern are similar to those found on C. semiplicata, but the shape factor and general form of the traces is more like Arenig forms of Rusophycus and Cruziana. Claw impressions may be grouped in fours.

Discussion.

Crimes (1970) discussed the stratigraphic range of the Forms of Rusophycus and his results are summarised in Table 26.

A similar pattern of increase in absolute size of specimens of Rusophycus from bottom to the top of the section appears to be present (cf. Crimes, 1970, Fig. 5), but insufficient material is available to conclusively separate size populations.

The new Form described above has features in common with both Upper Cambrian (= C. semiplicata) and Arenig (C. furcifera) forms of Rusophycus and Cruziana and possibly reflects transitional features similar to those of C. tortworthi and C. breadstoni described from Tremadoc strata (Crimes, 1974b).

Rusophycus morgati sp. nov.

Plate 18

The systematics of R. morgati is presented in the form of a complete paper entitled 'Rusophycus morgati: an asaphid produced trace fossil from the Cambro-Ordovician of Brittany and north-west Spain.' This paper is now in press with the Journal of Palaeontology.

RUSOPHYCUS MORGATI: AN ASAPHID PRODUCED TRACE FOSSIL FROM THE CAMBRO-ORDOVICIAN OF BRITTANY AND NORTH-WEST SPAIN

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ABSTRACT: A new species of trilobite resting trace, *Rusophycus Morgati*,is described from the upper part of the Gres Armoricain (Arenigian: Lower Ordovician) of Finistere, Brittany, France and from the top of the Barrios Formation, Cantabrian Mountains, north-west Spain. In both areas it occurs with *Cruziana rugosa*, *C. furcifera* and *C. goldfussi* . The morphologies of impressions of appendages, podomeres, hypostome and pygidial doublure differ from similar features in previously described *Rusophycus* and suggest an isotelinid-asaphid, possibly *Plesiomegalaspis*, as the trace maker. The Gres Armoricain and Barrios trilobite coenoses may have included both asaphids and asaphaceans.

INTRODUCTION

Rusophycus are trilobite excavations which involve little or no forward movement and ethological interpretations suggest either resting (Crimes, 1970a), protection and hunting (Bergström, 1973) or less likely nest making (Fenton and Fenton, 1937).

Appendages and other structures of the ventral surface of the trilobite trace makers may be impressed on the surface of the Rusophycus and afford a rare opportunity to study this little known part of trilobite morphology.

An undescribed form of Rusophycus was collected from a heterolithic group of shales, siltstones and thin quartzites near to the top of the Grès Armoricain on Cap de la Chevre, Presqui'ile de Crozon, Finistere, France and from similar lithologies near to the top of the Barrios Formation, Cantabrian Mountains, Spain. Associated with these traces are many large Cruziana rugosa, C.furcifera and C. goldfussi, which in Wales (Crimes, 1970b) and north-west Spain (Seilacher, 1970) indicate an Arenig age. The detail preserved allows possible identification of the trace maker.

SYSTEMATIC PALEONTOLOGY

Rusophycus morgati ichosp. nov.

PL 1, figs. 1 and 2.

Entymology - From the town of Morgat which is situated 2km north of the French collection area.

Material - One very well preserved specimen (Holotype No. T977 British Museum)
occurring as a cast on the sole of a thinly bedded fine sandstone, Crozon Formation (Bishop et al. 1969), north of Pte. de St. Herno [- 4°31': 48° 12'], Cap de la Chevre, Finistere, France. Two specimens on a single slab (No. T978 British Museum) from the upper 100m of the Barrios Formation (Comte, 1959; van den Bosch, 1969), west of La Majua [5°81': 43°00'], Leon Province, Cantabrian Mountains, Spain

Diagnosis - Trilobite resting trace with impressions of hypostome, coxae and most of the length of the appendages which show a pronounced bent 'knee" between the second the third podomere. Cast, roughly pear shaped, wider at the anterior end with impression of the pygidial margin around the posterior edge.

Description - The type specimen (Fig. 1) is 63m long overall and 47m wide at the broadest point, but the zone which bears the impression of the ventral morphology is 59mm long and 37mm wide. Within this zone is a roughly bilateraly symetrical pattern of linear, weakly annulated ridges, less than 1mm in relief, which individually are of a pronounced siculate form. Each ridge, inserting along the medium axis of the trace, commences with a slightly more pronounced and elongate annulation (maximum length 3.5mm) which is oriented more or less normal to the median axis of the trace (Fig. 1c). These annulations appear to insert alternately on either side of the median line so that a zig-zag suture separates the two rows. Extending from the distal end of the central annulation are four or possibly five less pronounced annulations which exhibit a pronounced 'knee' at the junction of the second and third (Fig. 1k).

The second annulation is the longest and is directed antero - laterally at 45° to the central axis. The third, fourth and (?) fifth are directed posterio -laterally. The maximum length of any single annulated ridge, including the large medial impression is 17mm. Approximately half this length comprises the posterio - laterally directed portion.

The posterior margin of the trace (Fig. 1 pd) is defined by an evenly curved, relatively smooth feature which extends both posteriorally and laterally to the central ridged zone. On its right hand side this smooth welt (Fig. 1 t/pj) curves back sharply towards the median axis to approximately coincide with the third or fourth posterior central annulations.

Towards the anterior end the central zig-zag suture passes into a slightly raised or domed area (Fig. 1h) which though poorly defined appears to be indented on each margin by weak linear troughs or folds (Fig. 1f). These run antero - laterally at approximately 45° to the central axis and define at least 3 indistinct pillow shaped lobes.

Around the posterio - lateral margin of the central ridged zone is a crudely v-shaped raised welt, up to 4.5mm deep, more prominant on the left side (Fig. 1w). This exhibits no detailed surface morphology and the central ridged portion of the trace blurrs against its inside edge.

Remarks - Rusophycus morgati is effectively a trilobite ventral surface impression complete with impressions of appendages, pygidial doublure and hypostome. The detail of appendage morphology is similar to that shown on a cast of the ventral surface of Isotellus maximus Locke figured by Osgood (1970, pl. 57, Fig. 5) from the Upper Ordovician of the Cincinnati area, U.S.A., but the pronounced 'knee' to the appendage impressions, hypostome and pygidium are significantly different.

R. carleyi James (Rusophycus of Isotellus) from the same beds (Osgood 1970., Pl. 57, Fig. 1) bears impressions of coxae, hypostome, doublure and genal spines but lacks all but the proximal first or second podomeres of the appendages. A similar pattern of coxal impressions is present in R. polonicus (Orlowski, et al. (1971, Pls. 2 - 6), but differ from R. morgati in the shortness and greater width of individual impressions.

A further feature worthy of note is the pattern of coxal impressions along the median line. Individual impressions appear slightly offset or staggered either side of the median line, so that a weakly sinuous line separates the two pairs of impressions. A similar offset pattern is indicated in at least two spedimans of R. polonicus (Orlowski et al. 1971, Pl. 3 (7) and Pl. 6(2)). In the latter speciman a distinct honey-comb pattern is generated by the offset of at least four rows of raised impressions. In this case the style and quality of preservation suggests that the offset pattern reflects morphological features of the undersurface of the trilobite trace maker, more or less unmodified by behavioural or preservational variants.

A case for a similar 'morphological' interpretation of the offset of coxal impressions in R. morgati is by no means as strong but the possibility might be borne in mind that the locomotory mechanisms of the trace maker were not restricted to a simple bilaterally symetrical configuration.

The exact morphology of the hypostome is indeterminate but Bergström (pers. comm.) feels that a wide raised doublure may be indicated.

The raised v-shaped welt of sediment around the margin of the posterior appendages (Fig. 1w) may represent the cast of an excavation made at the time the trilobite vacated the trace and therefore represents a potential behavioural variant of little taxonomic significance. Load casting appears to have produced a slight twisting of the trace after formation.

The detail preserved allows proposals to be made as to potential trace makers. The presence of possibly seven to nine pairs of thoracic appendages (allowing three or four for the cephalon) does not exclude any major group of trilobites. The regular curve to the pygidial doublure suggests an isopygous trilobite and in the context of the Arenigian age this limits the choice to members of Asaphacea or Illaenida. The possibility of a raised cephalic doublure supports an asaphacean origin rather than a illaenid and the similarity with *R. carleyi* indicates little phylogenetic distance between trace makers, so that an asaphid or an asaphacean, perhaps an isotelinid-asaphid such as *Plesiomegalaspis,* could have been the trace maker.

CAMBRO-ORDOVICIAN TRACE MAKERS

Rusophycus morgati is associated with typical examples of *C. rugosa*, *C. goldfussi* and *C. furcifera* (Rugosa Group of Seilacher, 1970), species for which Bergström (1973, p. 58) postulates a taihungshaniid-dikelokephalinid type of asaphacean origin. The Gres Armoricain and Barrios Formation trilobite coenoses of Brittany and Spain may therefore have included both asaphids and asaphaceans.

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PLATE CAPTIONS

Plate 1 *Rusophycus morgati* showing impressions of coxae (c), 11 or 12 pairs of appendages, hypostome (h) with folds (f) and pygidial doublure (pd). Thorax/pygidial junction coincides with the posterior coxal impression and may be traced out to the notched antero-lateral corner of the pygidium on the right hand side (t/pj). The appendage impressions indicate a pronounced 'knee' (k) at the junction of the 2nd. and 3rd podomere. Holotype No. T977, British Museum: Pte. de St. Herno, Cap de la Chevre, Finistere, France.

Plate 2 Less deeply impressed examples of *R. morgati*. Note the retention of the pronounced 'knee' (k) in the appendage impressions. No. T978, British Museum: La Majua, Leon Province, Cantabrian Mountains, Spain.

Ichnogenus ARTHROPHYCUS Hall 1852

Arthrophycus alleghaniensis (Harlan) 1831

Plate 22

Material.

Over 30 extremely finely preserved specimens from above the lake wall, north-east of the drowned village of St. Eulalia de las Manzanas (Fig. 26). Preserved as full relief, cylindrical burrows and wall-like casts on the sole of thin and medium bedded, rippled sandstones.

Description.

Straight, meandering, branching and bunched low wall-like and cylindrical traces with regularly spaced transverse annulations at right angles to the main elongation. Spacing of the annulations bears a direct relationship to the width (diameter) of the individual traces (Fig. 29). A low depression along the centre of the traces intensifies the general angularity of the cross section. Widths vary from less than

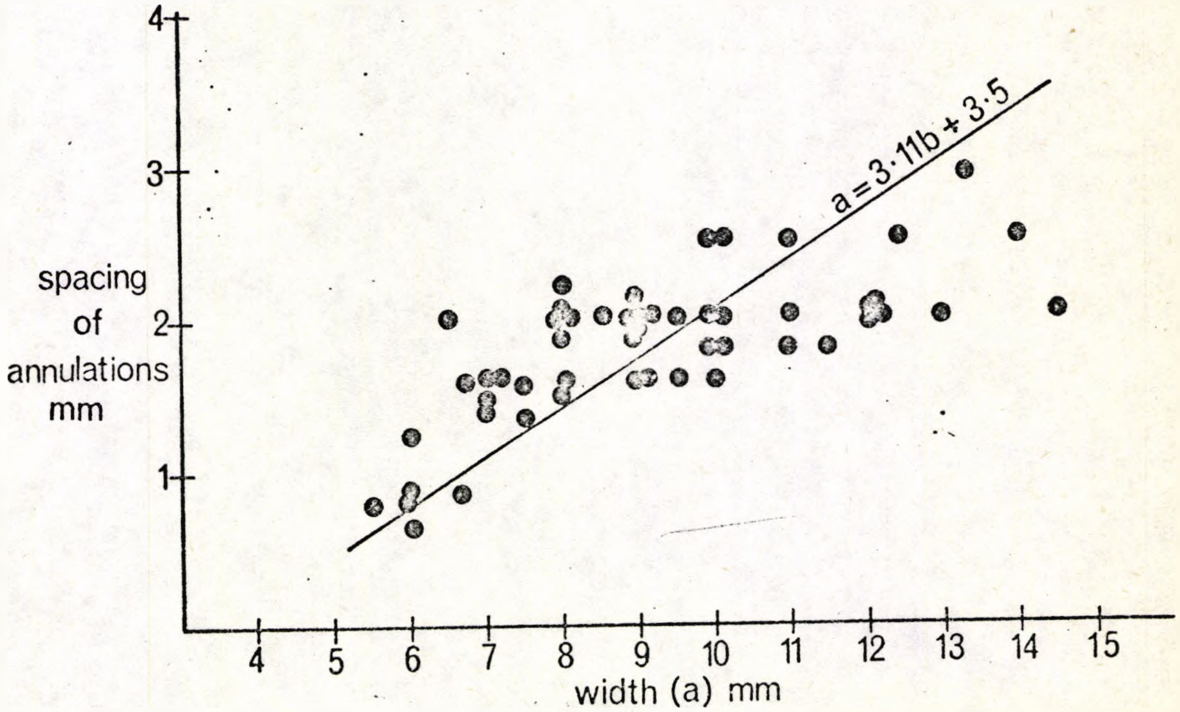

Figure 29
Correlation of width of individual Arthrophycus and spacing of annulations.

5mm to approximately 25mm, the wider portions representing the joining of a number of narrower individuals (Pl. 22.3). Continuous but strongly curved individuals can be traced for over 0.4m but most recovered material is continuous for less than 0.2m.

Sectioning of specimens indicates a crude protrusive spreite fill (Osgood, 1970, Fig. 7), similar to that described from Buthopteris palmata by Seilacher (1953, Fig. 3).

Discussion.

Arthrophycus Hall has wrongly been considered a synonym of Harlania Goepert (1852), the latter being excluded on grounds of priority (Hantzschel, 1965, p. 10). Seilacher (1955) considered Arthrophycus to be a junior synonym of Phycodes Reinhardt Richter (1850). However the differences in overall size of Arthrophycus (c. 0.6m long) versus Phycodes (c. 0.2m), the much coarser annulations and common bilobate form of Arthrophycus are considered sufficient to maintain the separation of these two genera (Hantzschel, 1962; Osgood, 1970).

Interpretations of Arthrophycus have developed from algal (de Saporta, 1879; Schimper, 1869; Delgado, 1886) to trace fossil origins (Romer, 1880; Nathorst, 1887; Sarle, 1906; Douville, 1907; Lessertisseur, 1953). Abel (1935) suggested that the bundled appearance of Arthrophycus resulted from the drifting together of sedentary annelid worm tubes. Seilacher (1955), while discussing the genesis of Phycodes (he included Arthrophycus in this discussion), described the sequence of feeding gallery extension from serially sectioned material. Potential trace makers were not discussed. (See section on Arthrophycus sp. for further discussion of trace maker.)

Most of the recovered material is similar in size and form to a specimen from the Lower Silurian (?) figured by Hantzschel (1962, Fig. 111. 3) and ascribed to Fucoides (nomen invalididum) allegheniensis Harlan (1931). Similar and larger sized specimens of Arthrophycus have been recorded from near the top of the Grès Armoricain (Crozon Formation) of Finistere, France, which on the basis of C. rugosa and an immediately overlying shelly fauna is of Arenig age (see Chapter 4). A similar age is indicated for the St. Eulalia section which can be traced laterally to the approximate level of C. rugosa bearing beds, south of Lancara de Luna (see van den Bosch, 1969 - Geological map of the Southern Cantabrian Mountains).

Arthrophycus sp.

Material.

A single specimen (No. E64) from the Lancara road section.

Description.

Cylindrical cast, 36mm in diameter with pronounced annulations cross cutting the axis at right angles. Annulations are spaced at 5mm intervals at the end at which they are most deeply impressed but increase to spacings of approximately 10. 5mm along most of the rest of the length of the trace. Very faint ridges running parallel to the axis of the trace cross cut the crests of each of the annulations.

The end of the trace with the more weakly impressed annulations appears to expand while terminating, to form a partial hemispherical shape, 55mm in diameter. Crude annulations or ridges form a weak radial pattern on this section of the trace. (N. B. Checking the width: annulation spacing ratio of this specimen of Arthrophycus against the computed values of the regression line of the plotted data of A. alleghaniensis (Fig. 29), the wider spaced annulations of Arthrophycus sp. exhibit an almost perfect fit, viz.

Slope of regression line: $a = 3.11b + 3.5$,

where $b = 10.5$mm, a (calculated) = 36. 1, vs. 36 (measured).

On the flank of the trace, at the opposite, less flared end, is a rusophyciform trace, 34mm wide by at least 33mm long. Weakly impressed bi or tridigitate appendage impressions are preserved on one lobe of the trace. A single specimen of Fraena lyelli cross cuts the end of the Arthrophycus and a low amplitude, 29mm Cruziana sp. intersects one margin.

Discussion.

The diameter of this specimen is far in excess of the 10mm considered typical for most Arthrophycus (Hantzschel, 1962), and the absence of any bilobate form is similarly different. However the strength of the annulations and the general form of the trace is similar to that preserved on some specimens of A. alleghaniensis from laterally equivalent beds in the Barrios Formation. The fitting of the two sets of annulation: width ratio data reinforces the Arthrophycus designation.

The ridges on the deeply impressed annulations are reminscent of the digited ridges (effectively dig marks) typical of well preserved specimens of C. rugosa. As the specimen was recovered from beds adjacent to C. rugosa bearing beds this association is perhaps more significant. The rusophyciform trace preserved at the flank of the Arthrophycus is of similar width and may be the product of the same organism which excavated the Arthrophycus.

It would appear possible that this Arthrophycus represents the true burrowing activity of a trilobite which most commonly produced surface furrows preserved as C. rugosa.

Ichnogenus SKOLITHOS Haldeman 1840

Skolithos linearis Haldeman 1840

Plates
23 , 24

Material.

Numerous grouped examples studied in situ in Asturias, Barrios de Luna and La Madua sections. For occurrence see Fig.1* & appendix. Two well preserved specimens were recovered.

Description.

Vertical, unbranched, infilled tubes, circular in cross section, which stand out on the upper and lower bedding planes of the sandstones through which they pass as short (<3mm long), cylindrical or dome shaped extensions. In some examples a shallow ring like depression surrounds the end of the cylindrical extensions. Lengths are variable, many recorded individuals exceeding 150mm. These may be closely associated with much shorter individuals.

In sandstones, most Skolithos are less than 4mm in diameter, but appear to thicken when the same burrow is traced into interbedded pelites. In all cases the central core filling the burrows differs in colour and texture from the surrounding beds; in most cases the trace fossils lack dark minerals and appear more densely cemented.

Sand filled Skolithos within a fine silt and mudstone bed were recorded at two localities in the Luarca-Cadavedo section (Pl. 23, 24). In one recovered specimen from 2412m the S. linearis can be traced through from the pelite into both the underlying and overlying sandstone beds. At the upper surface of both sandstones pronounced pits, approximately 5mm deep, are present at each point where the Skolithos intersects the bedding surface. Concentric rings of finely cominuted, phosphate rich (?) shell material surrounds a quartz rich core of the burrow fill. The two sandstones contain high levels of phosphate (4-7%) - almost entirely derived from particulate material distributed throughout the sediment. Sectioning of specimens reveals no conically depressed laminae around the termination of these burrows.

Discussion.

Haldeman (1840) and other early workers considered that Skolithos represented the casts of stems and roots of marine plants. Later, various forms of burrow origin were proposed, including brachiopod pedicle perforations (Perry, 1872). The absence of rootlets or any form of branching led to the suppression of the plant hypothesis, and the considerable length (>1.0m, Hallam and Swett, 1966) which single specimens can attain did not support the brachiopod interpretation. Polychaet worm burrow origins found the widest support (Richter, 1920, 1921; McNair and Read, 1929) and Fenton and Fenton (1934) suggested that Skolithos could be the tubes of phoronids. In these burrows the walls of the excavation are maintained by the secretion of parchment like tube linings or by the addition of mucus to the sand around the tube.

The operation of the phoronid type of support process may be indicated by some aspects of S. linearis morphology. The depressed ring around the margins of the burrows as they intersect the bedding surfaces may represent the modified (? aglutinated) burrow margin. The examples with phosphate rich margins possibly indicate the concentration of cominuted brachiopod or trilobite skeletal material cemented to form a similar supporting wall. Reineck (1958) suggested that such coatings could be of two types: 1) coatings due to internal instincts of the burrower found mainly in feeding burrows, and 2) coating as a reaction to external factors such as wall collapse. The coatings of type 1) tend to be more regular than type 2). Due to diagenetic effects, even in sectioned material, it is difficult to determine the exact nature of the burrow walls but on a number of specimens the markedly altered margins do have abrupt limits with the unchanged sediment on the outside and the burrow fill on the inside, so that type 1) may be indicated.

Osgood (1970) developed the ideas of marginal support to account for the precipitation of sparry calcite as the fill of Skolithos delicatus. In this process, the upper part of the tubes may have been blocked by sediment after the burrow was vacated, leaving a void below in which the spar could develop. The textural and mineralogical differences between the fill of S. linearis and that of the host sediment may have resulted from similar causes but due to diagenetic alteration the sparry fill (if ever present) has been annealed and resolved to give an irregular mosiac of quartz crystals differing from the surrounding sandstones in the absence of dark heavy mineral components.

An age range from late Precambrian to the present permits little stratigraphic use to be made of these trace fossils. However, the restriction of S. linearis to shallow, tidal and intertidal marine environments in both the Barrios Formation and the Cabos Series conforms to the bathymetric facies model proposed by Seilacher (1964, 1967).

Ichnogenus TEICHICHNUS Seilacher 1955

Teichichnus stellatus sp. nov.

Plate 21

Species name.

Stellatus = referring to the star shape of the complete trace.

Material.

Two well preserved specimens collected from the coastal section (Schiefer von Viavelez, Farber and Jaritz, 1964), north of the village of Grandadisla, La Caridad, Asturias Province, north-west Spain. Additional extensive material studied in situ, Luarca-Cadavedo section (@ 3900m-4100m level, Fig. 1*). Preserved as full relief traces in ripple laminated fine siltstones and shales.

Syntypes.

The two well preserved specimens (Nos. T979, T980 - British Mus.)

Diagnosis.

Retrusive spreite-filled, wall like galleries, radiating from a single central point to form a more or less symmetrical stellate pattern.

Description.

The wall like limbs of the traces are approximately 12mm wide, 11 or 12mm deep and in both specimens approximately 80mm long. 5 limbs are present on one specimen (T980) and 7 or possibly 8 on the other specimen (T979). Retrusive spreite form the fill and in cross section each limb approximates to a rotated D, the flat surface uppermost (Fig. 30). The limbs radiate from a central point and distally appear to plunge away gently. No spreite is present at the central point of the stars and in no specimens was any form of central boss present. Small, weathered pyrites crystals are distributed throughout all the limbs, but are absent from the surrounding sediment. In both recovered specimens the limbs are located on or just above a ripple-laminated, fine silt layer.

Discussion.

Seilacher (1955) suggested the designation of Teichichnus 'for all wall shaped, elongate spreite constructions'. The type specimen, T. rectus Seilacher, was straight and unbranched and formed from retrusive spreite which were considered by Seilacher (op. cit.) to be typical of the genus. Branched and bunched forms were figured by Seilacher (op. cit. , Fig. 5) but not named.

T. stellatus is constructed from retrusive spreite and while radiating is composed of unbranched limbs. The location of both recovered specimens immediately above a white silt layer suggests a shale preference and in conjunction with the retrusive spreite supports an ethological interpretation of T. stellatus as a shallow feeding structure. The presence of pyrites in the fill of the trace suggests the incorporation of faecal material during the filling and moving process.

T. stellatus is facies specific, being confined to a silt/shale dominated member of the Cabos Series which is interpreted as a shelf or distal off-shore deposit.

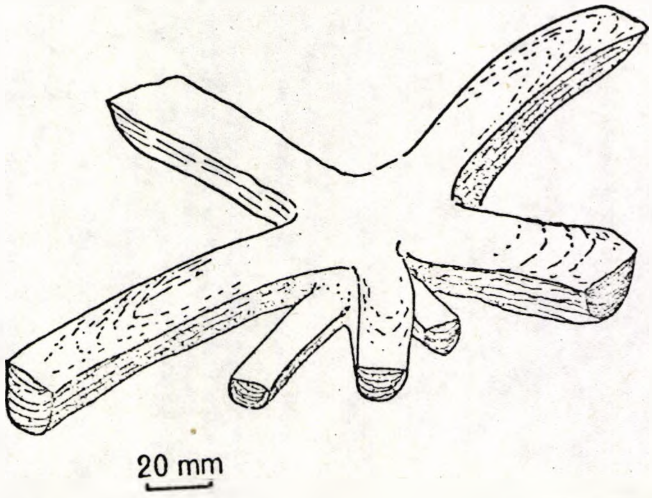

Figure 30
Reconstruction of Teichichnus stellatus sp.nov. Note retrusive spreite which intersect upper surface of three 'arms'. Drawn from actual specimen.

Teichichnus cf. rectus Seilacher 1955

Material.

Two recovered specimens, one from Luarca-Cadavedo section and one well preserved specimen from the Lancara road section. Preserved as full relief casts of fine sand in medium to fine silts. Additional extensive material studied in situ in the Luarca-Cadavedo section.

Description.

Wall like, crudely banana shaped casts, composed of distinct protrusive and retrusive spreite. The bulk of each trace lies parallel to bedding with only one end inclined and actually breaking the bedding plane surface. Lengths vary from less than 5mm to approximately 100mm and widths from 2 or 3mm to 8mm. Depths of walls vary from approximately 3mm to over 20mm.

Discussion.

Seilacher (1955) suggested that all Teichichnus were feeding burrows. Stratigraphic range extends from Lower Cambrian to Tertiary (Hantzschel, 1965).

The following four genera are of limited stratigraphic value and occur in insufficient numbers to warrant more than brief discussion. Occurrence and distribution details are given in the Appendix.

Ichnogenus ARENICOLITES Salter 1857

Arenicolites sp.

Description.

U-shaped tubes, normal to the bedding plane. Either simple or with concentric laminae (? tube linings) around the margin of the tube. No spreite joining the limbs of the U.

Occurrence.

Asturias, Barrios de Luna.

Ichnogenus DIPLOCRATERION Torrel 1870

Diplocraterion (?) *parallelum* Rudolf Richter 1926

Description.

U-shaped tubes, normal to bedding, with flared or funnelled expansions at the point of intersection of the tubes and the bedding planes. Diffuse, retrusive spreite are present between the two limbs of the U.

Occurrence.

Asturias.

Ichnogenus COROPHIOIDES John Smith 1893

Corophioides biclavata (Miller) 1875

Description.

Dumbell shaped casts with the bar separate or connected to the shallow bell ends. Casts may be traced into the immediately overlying sand bed as verticula U tubes. Represent the interface termination of a psamophagus (?) filter feeder. The two bell ends are considered to correspond to extension of the vertical limbs of the U (Fig. **31**) while the central bar represents the base of the U (cf. Osgood, 1970, Fig. 9, p. 324).

Occurrence.

Asturias.

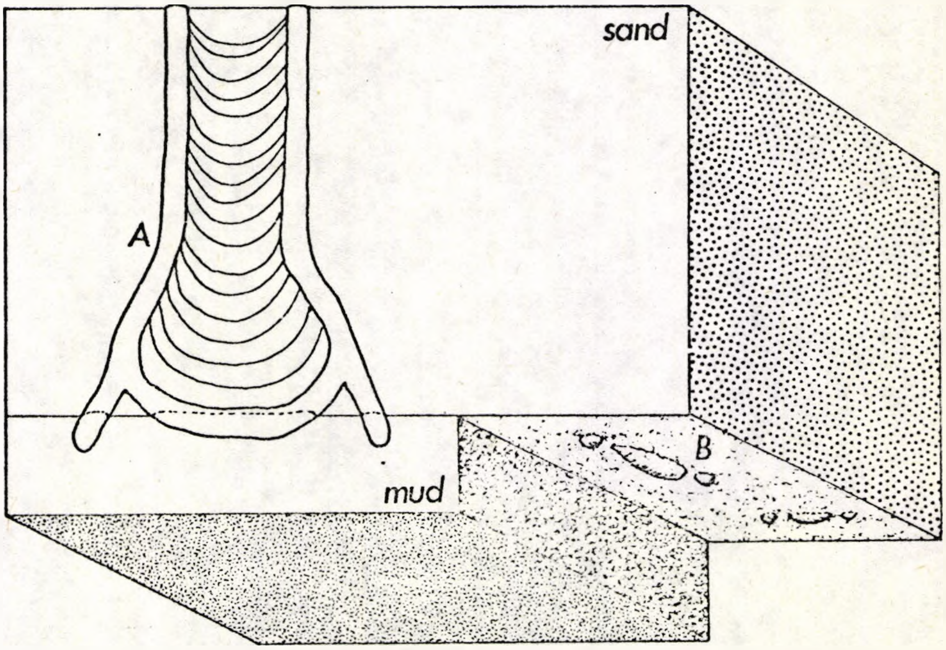

Figure **31**
Reconstruction of Corophioides biclavata.
A - full cross-section burrow which penetrates sand layer only as far as the top of the underlying mud.
B - dumb-bell shaped casts on the sole of the sand bed.

Corophioides luniformis Blanckenhorn 1902

Description.

Simple arched or crescent shaped casts on the soles of fine sandstones. Can be traced into the immediately overlying beds as simple U-tubes with diffuse retrusive spreite. Represent the termination of downward extension of psamophagus, sessile filter feeders.

Occurrence.

Asturias, Barrios de Luna, La Majua, St. Eulalia.

Ichnogenus PHYCODES Rudolf Richter 1850

Phycodes cf. *circinatum* Magdefrau 1934

Description.

Shallow casts of branched tubes and walls up to 3mm in diameter and radiating from a single, slightly larger diameter master shaft. Form an asymmetrical 'broom' shape composed of a maximum of five branches and of a total length of less than 40mm. No structure to the fill can be determined without X-radiogrography.

Occurrence.

Asturias.

Ichnogenus PLANOLITES Nicholson 1873

Planolites sp.

Description.

Simple, unbranched, cylindrical, sediment stuffed tubes up to 14mm in diameter. Always parallel to bedding.

Occurrence.

All sections.

CHAPTER 3

STRATIGRAPHIC ANALYSIS

The following chapter has been accepted for publication in a volume in memory of Professor Parga Pondal to be published by the University of Oviedo, Spain.

A comparison of the stratigraphy and depositional processes in the Cambro-Ordovician rocks of the Cantabrian and West Asturian-Leonese Zones, N.W. Spain.

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1. INTRODUCTION

The clastic shallow marine facies of the Cambro-Ordovician of Europe, North Africa and Arabia typically contain few, if any, stratigraphically useful body fossils. However, they do provide abundant trace fossils, some of which are of stratigraphic use. In Iberia, clastic sequences of this age vary in thickness from approximately 50 m to over 4000 m and, with few exceptions, only the upper and lower boundaries are precisely defined and correlated palaeontologically.

The Cambro-Ordovician sedimentary rocks in the western end of the Cantabrian Mountain chain and in Asturias, north-west Spain crop out on either side of an inticlinorial fold core of Precambrian metamorphics (= Narcea Anticlinorium) (Fig. 1). Variations in tectonic style, igneous and metamorphic suites and local stratigraphy have prompted subdivision of the Iberian Hercynian Orogen into six homogeneous zones (Lotze, 1945, 1966, 1968) (Fig.32). The Narcea Anti-

Figure 32. Structural and stratigraphic Zones of the Hercynian core of the Iberian Peninsula (after Parga, 1970). 1 = Cantabrian Zone; 2 = Asturian-Leonese Zone; 3 = Galician-Castilian Zone.

Figure 33. Distribution of the Cambro-Ordovician rocks of the Iberian Peninsula. (Adapted from Lotze & Sdzuy, 1961.)

clinorium separates two of these zones: the Cantabrian Zone in the northeast and the West Asturian-Leonese Zone in the west and south. Major changes in thickness of the Cambro-Ordovician between the two zones have been noted by Lotze and Sdzuy (1961), Matte (1968), and Marcos (1973). Lotze and Sdzuy (op.cit.) interpreted the greater thickness of sediment in the West Asturian-Leonese Zone as the product of orthogeosynclinal deposition, while the Cantabrian Zone was a shelf of varying stability.

Continuous exposure of a complete sequence of Cambro-Ordovician rocks in the West Asturian-Leonese Zone (the Cabos Series, Lotze, 1957) and cropping out along the coast of Asturias (Fig. 3.1) has furnished nearly 1000 trilobite produced trace fossils as well as material of non-trilobite origin. The stratigraphic history of this area will be compared with a similarly well exposed area, the Luna-Sil region (van den Bosch, 1969) of the Cantabrian Mountains, Cantabrian Zone

(Fig. 2b).

On the basis of morphological changes in the trace fossils from these two areas, the Cambro-Ordovician rocks can be subdivided and approximate boundaries of the Cambrian and Ordovician proposed. Criteria for the tentative recognition of the limits of the Tremadocian are also discussed.

For the moment the accepted 'British' positioning of the Cambro-Ordovician boundary at the base of the Arenig (Whittington and Williams, 1964) will be followed. However, the arguments of Henningsmöen (1973) for placing the boundary between the Upper and Lower Tremadoc have been borne in mind but the lack of stratigraphic precision so far developed with trace fossils mitigates against the adoption of the 'Scandinavian' junction.

2. TRILOBITE TRACE FOSSILS

Trace fossils are produced and preserved <u>in situ</u> and thus provide a totally non-drifted assemblage. Unfortunately, they suffer from a number of drawbacks which detract from their stratigraphic utility (see Seilacher, 1970). To a large extent they reflect the activity of the trace maker and, as this is conditioned by external stimuli, variability is to be expected. However, <u>stable</u> and hence stratigraphically useful morphological detail (cf. 'fingerprints', Seilacher, 1970) is preserved on many trace fossils ascribed to the activity of trilobites. Crimes (1968, 1969, 1970a & b, 1975), Seilacher (1970) and Seilacher and Crimes (1969) have discussed the stratigraphic usefulness of such information.

Production and Preservation

Trilobite trace fossils fall into three broad morphological groups, the definition of which do not require ethological interpretations. They are: (i) more or less continuous band like traces bearing scratches and other small-scale taxonomically useful features = <u>Cruziana</u>; (ii) discontinuous traces only slightly longer than wide, with similar detailed morphology to (i) = Rusophycus; (iii) discontinuous, isolate or grouped impressions, rarely bilaterally symmetrical, and broadly corresponding to the 'components' of (i) and (ii) = Dimorphichnus-Diplichinites-Monomorphichnus. These traces are usually excavated in mud, either at the sediment/water interface (Crimes, 1974 ; Baldwin, in press) or burrowed with or without a sand cover (Seilacher, 1970; Birkenmajer and Bruton, 1971) and are mostly recovered as casts on the soles of sand beds.

Taxonomically useful information

While the behavioural control of the general forms of Cruziana and Rusophycus must be borne in mind, the form and distribution of the 'component parts' of these trace fossils do have taxonomic stability. Both these forms of trace were excavated dominantly by appendages, either endites or exites, and thus reflect in part the profile of the edge of the digging 'tool' which in some cases was a form of claw (Seilacher, 1962). Thus, the detail of the component scratches of the trace are directly related to the morphology of the appendage of the trilobite which carried out the excavation and would in consequence be expected to show the same degree of taxonomic variability.

The presence or absence of genal or pygidial welts produced by the passive dragging of spines may partly reflect morphology of the trace maker, although differences in furrowing attitude (Seilacher, 1970) could account for some variability.

The patterns and distributions of the stable component parts of Cruziana and Rusophycus retain a degree of uniformity which has led to the identification of morphologically distinct species of both these genera (e.g. Seilacher, 1970).

The third group of trilobite trace fossils, Diplichnites, Dimorphichnus and Monomorphichnus, are composed of the more or less isolate components of Cruziana and Rusophycus and analysis of detail of the form of individuals may provide taxonomic information comparable with that derived from the larger traces.

3. ESTABLISHED TRILOBITE TRACE FOSSIL STRATIGRAPHIES

Trilobite trace fossil stratigraphies *per se* allow simple correlations to be made between successions (cf. Seilacher and Crimes, 1969), but due to the paucity, so far, of specific trilobite/trace fossil pairings, biostratigraphic conclusions are formed only with great difficulty. The need, therefore, is to correlate the trace fossil stratigraphies with acceptable body fossil data (Seilacher, 1970). So far, few areas where body and trace fossil bearing strata interdigitate have been studied in detail. Crimes (1968, 1969, 1970a & b, 1975) studied trace fossils in the faunally dated Cambrian to Ordovician rocks of Wales and Gloucestershire, England; the long history of palaeontologic and stratigraphic research of these rocks provided a stratigraphic framework within which to consider the trace fossils. It is largely from the background of this work that the stratigraphy of the Cambro-Ordovician of Spain will be compared. The general validity of applying detailed results from the British Isles to Iberian rocks has been demonstrated by Seilacher and Crimes (1969), who considered the British Isles and Iberia as well as Central Europe and Newfoundland to have occupied a 'European trilobite province' during the Cambro-Ordovician period.

British Isles

Crimes (1968, 1969) noted the stratigraphic separation of two species of *Cruziana* in the rocks of Snowdonia and the Lleyn Peninsula, north Wales. In this area *Cruziana semiplicata* (Salter) is confined to the Upper Cambrian (Ffestiniog) and does not range into the Arenig, whereas *C. furcifera* (d'Orb.) is present only the Arenig. Unfortunately, in parts of Lleyn the succession is incomplete, the Arenig resting with angular unconformity on the Cambrian (Crimes, 1968, p. 362), while in Snowdonia to the east, a lithofacies change in the Tremadoc leads to an absence of *Cruziana*. Later, Crimes (1970b, 1975) incorporated *Cruziana* of Tremadocian age into his British stratigraphy and showed transitional morphologies between Upper Cambrian, Tremadoc and Arenig species.

Cruziana goldfussi Rouault and *C. rugosa* d'Orb. appear to be confined to the Arenig in the British Isles (Crimes, 1970b), but *Cruziana* with *C. furcifera* affinites may range into the Upper Tremadoc (Crimes, *op.cit.*, p.112).

As well as *Cruziana*, Crimes (1970b) suggested a tentative *Rusophycus* stratigraphy based on both shape and length:width ratio. Crimes (*op.cit.*) did not propose formal binomial species names, but designated four different forms as A, B, C and D. The former (A), with length:width ratio = *c* 1.5, is confined to the Upper Cambrian and Lower Tremadoc, while form B is largely Arenig but may extend to the Lower Tremadoc. Both forms C and D are entirely Arenig.

In his most recent work Crimes (1975) has formally described *Cruziana* transitional between *C. semiplicata* and *C. furcifera*, named them *C. tortworthi* and *C. breadstoni* and demonstrated their Lower Tremadoc age range (see Table 1).

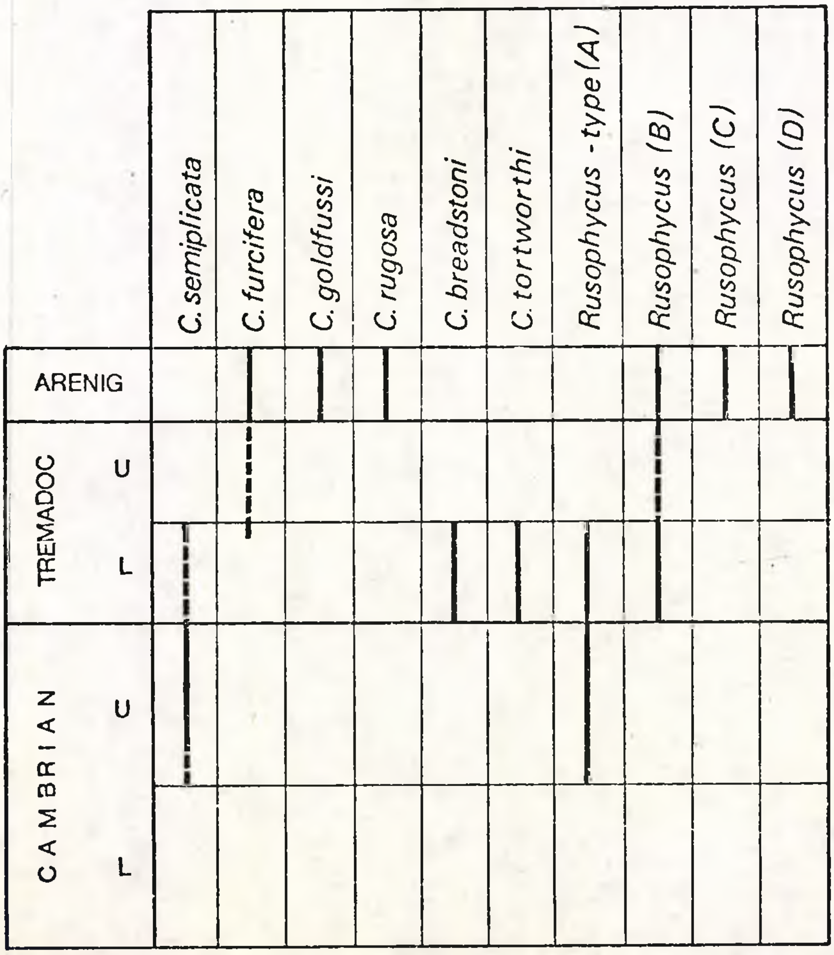

Table 26

Stratigraphic ranges of English and Welsh trilobite trace fossils. (Data from Crimes 1970b & 1975).

Northeastern Spain Fig. 32

Schmitz (1971) described a probable Tremadoc to Middle Cambrian Cruziana-bearing clastic sequence from Iberian Mountains, north-east Spain. This sequence is lithostratigraphically correlatable with the Cabos Series of Asturias (Lotze, 1961). Both C. semiplicata and C. furcifera occur together in the lower half of the series (Tables 27&28a) whereas C. furcifera occurs alone in the upper half.

Scheuplein (1970), working in the same area, found C. rugosa, C. goldfussi and C. furcifera in the Skolithos Quartzite (Tremadocian), but suggested that C. rugosa is absent from the overlying Amoricain Quartzite (of suggested Arenig age) (Table28b). It will be noted that this ichnological succession is at variance with Crimes' (1970b) and Seilacher's and Crimes' (1969) stratigraphies in north Wales and Asturias.

			trace fossils	*body fossils*
TREMADOC	IBERIAN SERIES	Espino Schiefer	C. furcifera	*Shumardia sp* *Geragnostus sp* *Asaphellus sp*
		Dere Wechelfolge	C. furcifera	*Lingulobus cf affinis* *Ectenoglossa cf lesueri*
		Corzas Schiefer	C. furcifera C. semiplicata	*Ectenoglossa n sp*
U		Barrera Quartzite	C. furcifera C. semiplicata	
M €		Acon Schichten		*Bailiella grifei* *Ctenocephalus bergeroni* *Solenopleuropsis cf pustalosa*
L €		Murero Schichten		

Table 27
Occurrence of Cruziana in the faunally-controlled stratigraphy of the Iberian Series, Iberian Mountains, North-East Spain (from Schmitz, 1971).

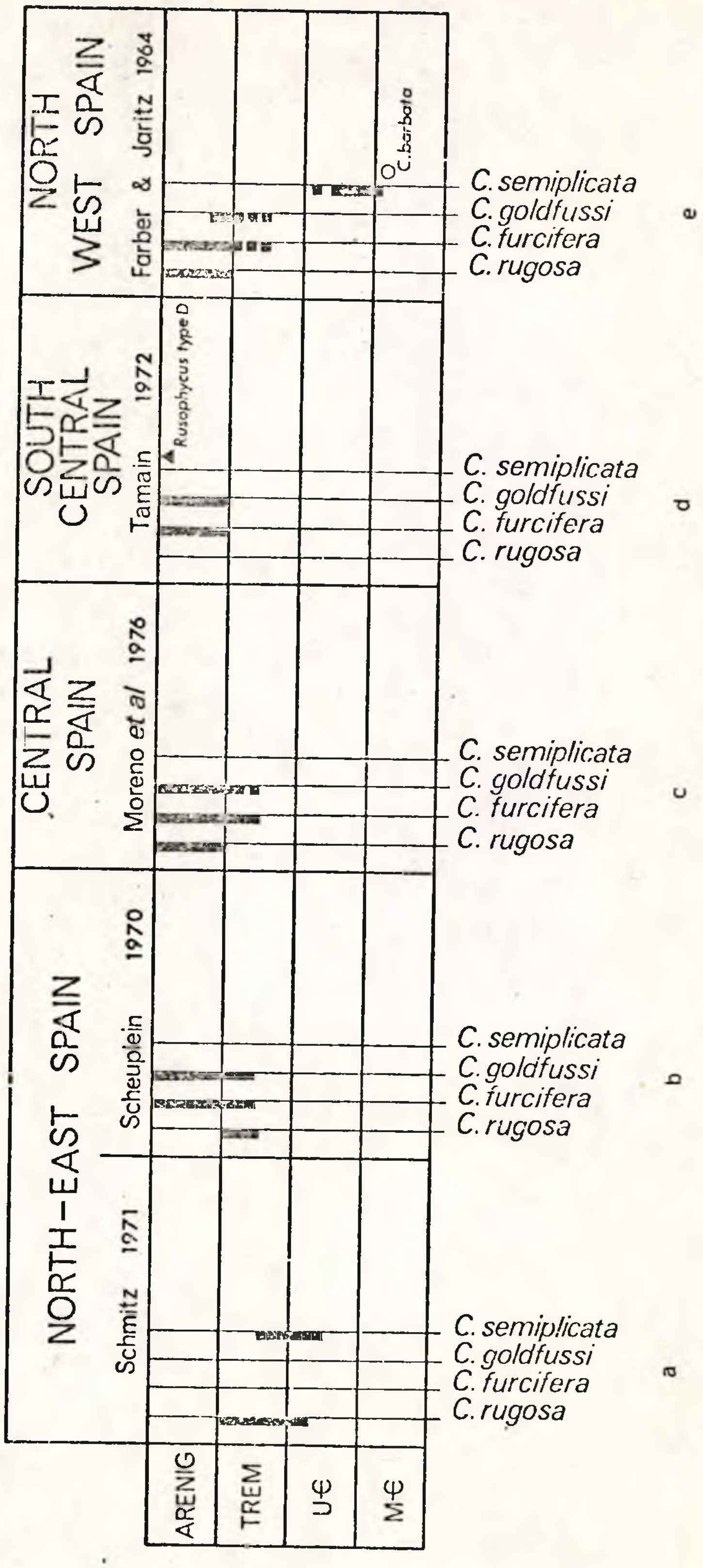

Figure 28
Trilobite trace fossil stratigraphies of various regions in Spain.

Central Spain Fig. 32

Moreno, Vegas & Marcos (1976) have described a clastic sequence of probably Tremadoc and Arenig age in Montes de Toledo, Central

Spain. This sequence is unconformable on rocks of Lower Cambrian age. In this area, *C.rugosa* is limited to the overlying Armoricain Quartzite while *C. furcifera* and *C. goldfussi* are widespread in all the clastic sequence. An Arenig age for the Armoricain Quartzite (based on the coexistence of the three species of the Rugosa Group) and a Tremadoc age for the underlying rocks have been suggested by the authors above mentioned. In addition, the lack of other species of *Cruziana* (i.e. *C. breadstoni*, *C. tortworthi* or *C. semiplicata*) exclude the Lower Tremadoc as well as the Upper Cambrian in this sequence.

Southern Spain (Fig. 32)

Tamain (1972(, working to the south in the Sierra Morena, recorded *C. furcifera* and *C. goldfussi* from the Middle Armoricain Quartzite and *C. goldfussi* and *Rusophycus* Form D (= Arenig - cf Crimes, 1970b, pl. 3e & f) from the overlying Pochicho Beds (Table 28d). *C. semiplicata* was not found by Tamain in any part of the section and on the evidence of *Lingulella* sp. it was concluded that the base of the section is Tremadocian (Bouyx, 1969, 1970), while the top of the Quartzites are overlain by the Llanvirn.

4. THE WEST ASTURIAN-LEONESE ZONE: THE CABOS SERIES

4a. Existing biostratigraphy of the Cambro-Ordovician of Asturias

The absence of faunal information has made stratigraphic subdivision of the Lower Palaeozoic rocks of Asturias difficult. An Ordovician fauna (fauna 2^a = Silurian, *sensu* Murchison) was recognised from the Luarca shales by Prado (1857) and later Barrois (1877) described a Cambrian fauna (1^a) from the lowest carbonates and dolomites in the succession, now named the Vegadeo Group (Table 29). A Middle Cambrian trilobite fauna has been described from the green shales which underlie, with gradational contact, the base of the Cabos Series (Farber and Jaritz, 1964; Sdzuy, 1968; Ruiz, 1971; Marcos, 1973). Sempelayo, in a long series of papers between 1914 and 1942 (Hernandez-Sempelayo, 1914, 1915a & b, 1916, 1924, 1931, 1933, 1935, 1942),

U O ı M O	AGÜEIRA FORMATION		greywackes black shales	3000m	*Aegiromena aff. aquila*
M O	LUARCA SHALES		black shales	300 - 1200m	*Neseuretus tristani* *D. murchisoni* *D. cf. stabilis*
LO ı M €	U M L	CABOS SERIES	sandstones quartzites sand – shale alternations	3000 - 4500m	*Cruziana* *Rusophycus* *Conocoryphe herberti* *C. pseudooculata* *Paradoxides pradoanus* *P. brachyrachis* *Solenopleuropsis simula*
L €	VEGADEO LIMESTONE		limestone dolomites	100 - 300m	
	CANDANA QUARTZITE		arkose quartzites	1000 - 2000m	*Metadoxides sp* *Astropolithon*
P €	NARCEA SHALES		greywackes shales		

Table 29
The Lower Palaeozoic stratigraphy of the West Asturian-Leonese Zone, north-west Spain (after Marcos, 1973).

refined and extended Barrois' stratigraphy and described Didymograptus (=Ordovician) from the Luarca shales which crop out in Lugo Province to the south-west of Asturias (Fig. 2).

Lotze (1945a & b, 1956a & b, 1957, 1958, 1961) was concerned with the Precambrian/Cambrian boundary in eastern Asturias and Galicia and latterly with regional correlations of the Cambrian of Spain. This work has refined the known Cambrian stratigraphy and has been extended by his students who considered the whole of the Lower Palaeozoics of north-west Spain (Farber and Jaritz, 1964; Farber, 1964; Jaritz, 1958; Jaritz and Walter, 1970; Walter, 1962, 1963, 1968), this more recent work adding to the stratigraphic framework and contributing details of palaeogeography and facies distribution.

Recently, Marcos (1973) mapped and described the rocks of western Asturias, and his stratigraphic collation (Table 29) is used here as a basis for further detailed discussion of the Cambrian-Ordovician boundary.

The shales immediately underlying the base of the Cabos Series are dated as Middle Cambrian (Farber and Jaritz, 1964; Sdzuy, 1968; Ruiz, 1971; Marcos, 1973), and the lower part of the Luarca shales, which conformably overlie the Cabos Series are of Llanvirn age (D.murchisoni Zone, Marcos, 1973). Thus the boundaries of the Arenig, Tremadoc and Upper Cambrian could all lie within the unfossiliferous clastic Cabos Series.

4c. Stratigraphic levels of trilobite trace fossils

The positions of various trace fossils are shown on a continuously logged section (Fig.2*) and for convenience the critical zone of mixing of the species is enlarged (Fig.34).

C. semiplicata is present from the base of the section to 3300 m. Above this it occurs with all three members of the Rugosa Group. C. rugosa occurs at and above 3300 m. and apart from the one occurrence C. rugosa and C. semiplicata are mutually exclusive. C. furcifera and C. goldfussi extend to a level lower than C. rugosa and overlap with C. semiplicata. C. furcifera is absent below 2875 m.

Rusophycus Form A occurs intermittently throughout most of the range of C. semiplicata, but is absent above 2600 m. Form B appears above Form A, but within the zone of C. semiplicata and C. rugosa. A new Form described elsewhere occurs at the junction between Forms A and B.

Monomorphichnus and Dimorphichnus reinforce the separation of Cruziana species, multi-digited forms of both these species only being associated with members of the Rugosa Group (i.e. above 2800 m.). Due to the problems of preservation and ethological variability of production only the maximum numbers of digits indicated for each level may have stratigraphic meaning. Low digit numbers (twos and threes) coexist with high (sixes and sevens) throughout the whole of the upper half of the section, but the sudden increase at 2900 m correlates well with the first appearance of C. furcifera.

The forms of Cruziana transitional between the Rugosa Group and C. semiplicata appear at 2750 m and are absent above 3300 m, but the relatively small numbers of specimens do not permit accurate subdivision of this zone. C. tortworthi and C. breadstoni are absent from the section, but three specimens at 2887 m, 2913 m and 3175 m suggest the form of C. tortworthi but lack the pronounced angular claw impressions.

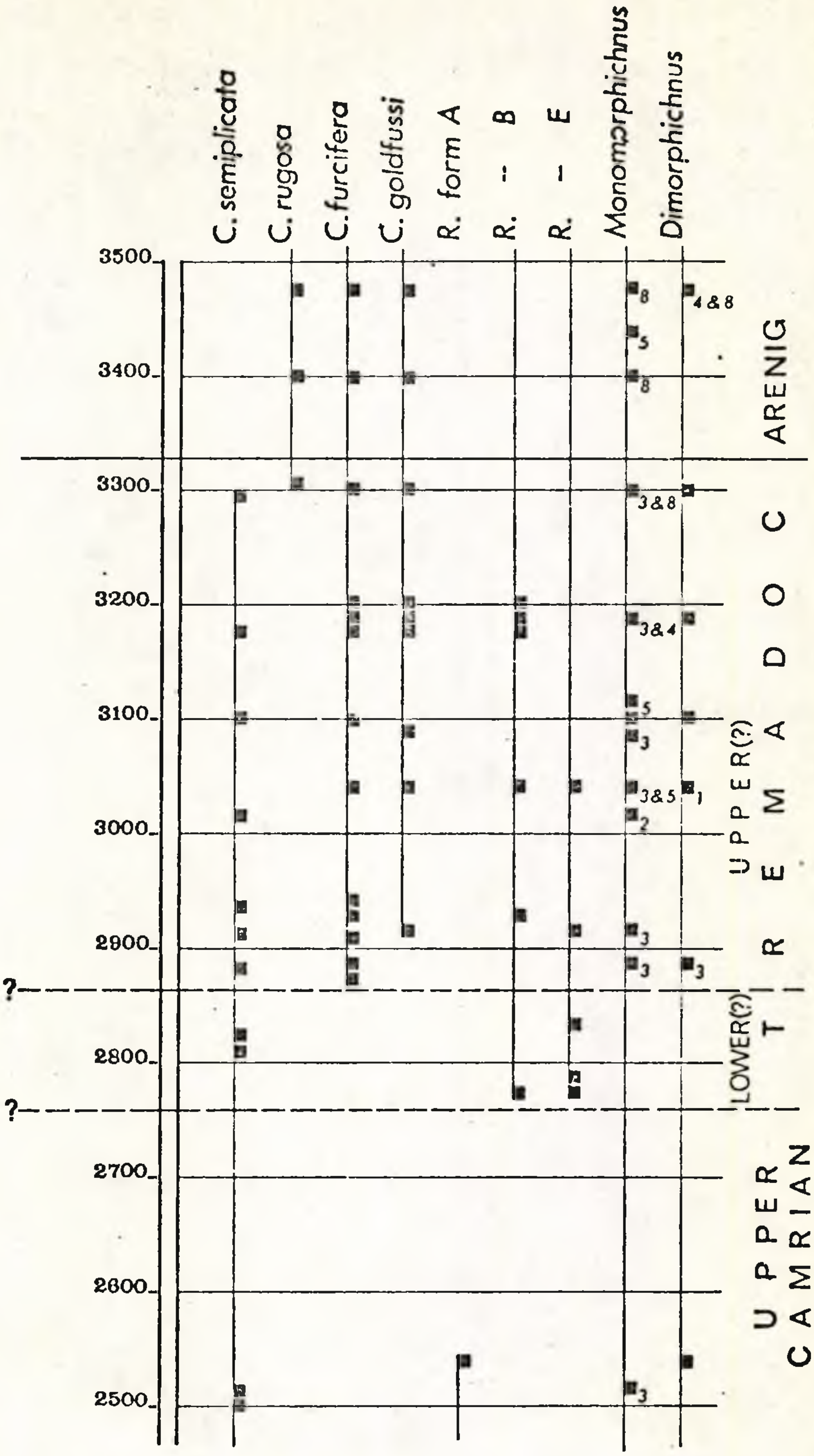

Figure 34

Ichnostratigraphic subdivision of the Cabos Series.
Detail of the zone 2500m to 3500m of Figure 1* showing the levels of occurrence and range of trilobite trace fossils. Figures on Monomorphichnus and Dimorhpichnus refer to number of digits indicated.

4d. Stratigraphic division of the Cabos Series

If circularity of argument is to be avoided, strict adherence to already established trace fossil stratigraphies for areas other than that under discussion must form the basis of stratigraphic subdivisions.

Two zones may be identified as the first stage of the stratigraphic subdivision (Fig.34). At 3300 m (approximately the middle of Playa Ferreiro, east of Cabo Busto) C. semiplicata disappears and C. rugosa appears. Crimes (1970, p.112) indicates that C. rugosa is present in 'very low Arenig' rocks at Trwyn Llwyd, south Wales, whereas C. semiplicata is absent. Consequently in Spain, it seems that C. semiplicata and C. rugosa almost coexist at one level (viz. c. 3300 m), so that in conformity with the British stratigraphy it appears most likely that the base of the Arenig must be above the highest C. semiplicata, possibly at approximately 3300 m where thick silts and muds overlie a 25 m thick-bedded quartzite.

Immediately below the suggested lower Arenig boundary is a 600 m thick zone with mixed ichnofaunas, including species which display elements of Cambrian and Ordovician morphology as well as typical Cambrian and Ordovician species (i.e. C. semiplicata, C. furcifera and C. goldfussi). Crimes (1975) described from the faunally dated Tremadocian rocks of Gloucestershire new species of Cruziana which appear to indicate Upper Cambrian/Arenig transitions of appendage morphology and particularly furrowing techniques. This work (Table 1) suggests C. furcifera has a range from Upper Tremadoc to Arenig, whereas the transitional species, C. breadstoni and C. tortworthi, are probably restricted to the Tremadoc, possibly only the lower division. Data from the Upper Tremadoc, however, is scant.

C. breadstoni and C. tortworthi are not present in the Cabos Series, but the ichnofauna from the beds above 2800 m (western side of unnamed bay, west of Concha Santa Ana) with C. semiplicata , C. furcifera, C. goldfussi and Rusophycus Form B conforms with some elements of Upper Tremadoc ichnofaunas (cf. Crimes, 1975 , Table 26). The immediately underlying 100 m with C. semiplicata and Rusophycus Form B and Form E may be Lower Tremadoc (Fig.34). Subdivisions of these Tremadoc (?) rocks are extremely tentative at this stage - further trace fossil data being required from faunally controlled sections elsewhere. However, the transitional nature of the complete 600 m unit is less equivocal and the proposed Tremadoc age appears reasonable.

Below 2800 m, the ichnofauna is restricted to C. semiplicata and Rusophycus Form A, both characteristic of Upper Cambrian (=sub-Tremadoc) strata (Crimes, 1970a; Radwanski and Roniewicz, 1963).

The preservation of trace fossils within the Upper Cambrian permits no sure subdivision of this lower 2800 m of the section. The beds immediately below the base of the Cabos Series (=Artedo Schichten, Farber and Jaritz, 1964) are faunally dated as high Middle Cambrian (Farber and Jaritz, op.cit.), and the lower few metres of the Cabos Series (= Churin Schichten, Farber and Jaritz, op.cit.) appear, on the basis of C. barbata (Seilacher, 1970), to be of similar age.

No ichnofaunal change was noted during the detailed recording of the section which would permit the identification of the Upper and Middle Cambrian boundaries, and this aspect of the stratigraphy must remain unresolved until further material can be collected from associated sections.

Summary

A trilobite trace fossil stratigraphy similar to Wales and England is found in the Cabos Series of Asturias, north-west Spain and the conclusions of Seilacher and Crimes (1969) are supported.

Details of this correlation are further refined by the similar distribution of trace fossils of proven Tremadocian age in both areas.

The range of C. rugosa suggested by Scheuplein (1970) appears open to question as does the too rigorous use of Seilacher's (1970) Rugosa Group, comprised of C. rugosa, C. furcifera and C. goldfussi. In both the United Kingdom and Asturias, C. furcifera and C. goldfussi have a longer range than C. rugosa, and it is possibly through furrowing action that the three species are linked, presumably the increasing use of exites as the excavation tool (Bergström, 1972, 1973) marking the Upper Tremadoc/Arenig boundary. Therefore, while in the Arenig the Rugosa Group may indicate a choice of endite and exite activity in furrowing, the Upper Tremadoc antecedents were possibly more restricted to endite activity, exite digging gradually appearing towards the top of the Upper Tremadoc.

The Cruziana stratigraphy from Asturias suggests that the upper 100 m of the Barrera Quartzite and the whole of the Corzas Schiefer of N.E. Spain described by Schmitz (1970) are both of Upper Tremadoc age (see Table27). The overlying beds with only C. furcifera may be Upper Tremadoc or Arenig, the former being supported by other faunal evidence. Further work may be required to delimit the upper boundary of the Upper Cambrian either in the Barrera Quartzite or perhaps even lower in the Acon Schichten.

5. THE CANTABRIAN ZONE: THE BARRIOS FORMATION

Most of the detailed aspects of this Zone are related only to the upper part of the Cambro-Ordovician (=Barrios Formation) of the Cantabrian Mountains, the Cambrian forming the subject of a separate study by Ian Legg (Ph.D. Thesis, University of Liverpool) and T.P. Crimes (Liverpool).

Four sequences in the Luna-Sil region (van den Bosch, 1969), Leon Province were logged on a scale of 1:100, note being taken of litho-facies and their associated trace fossils, most of which are trilobite produced.

5a. Existing stratigraphy of the Cambro-Ordovician of the Luna-Sil region

The Cambro-Ordovician Oville and Barrios Formations belong to the Lower Palaeozoic Luna Group (Brouwer, 1964), which is composed of five siliclastic and one carbonate formation. The lowest formation of the Group, the siliclastic Herreria Formation, rests unconformably on the Precambrian Mora Formation, the the upper part is dated as Lower Cambrian (Lotze and Sdzuy, 1961). This is progressively overlain by the carbonate Lancara Formation which includes limestone, dolomite and griotte members, and is dated low Lower Cambrian to lowermost Middle Cambrian (Comte, 1959; Sdzuy, 1968; Zamarreño, 1972).

The glauconitic Oville Formation has a gradational contact with the underlying griotte member of the Lancara, the progressive increase in siliclastic detritus eclipsing the carbonate lithologies. Gietelink (1973) divided the Oville into four members: Member A - shelf deposits consisting of flaser and lenticular, glauconitic sands and silts; Member B - littoral, mostly sub-beach deposits which become tidally influenced towards the top; Member C - shelf and deltaic deposits; Member D - tidal deposits which in different places within the Luna-Sil region have both gradational and erosive relationships with the overlying Barrios Formation. Gietelink (op.cit.) interprets Members A and B and the upper griotte member of the Lancara Formation as forming a regressive sequence developing from a prograding linear coastline. The second sequence composed of Members C and D include transgressive/regressive couplets derived from shelf and deltaic sedimentation.

The age range of the Oville is open to question. Lotze and Sdzuy (1961) suggest an age, based on a trilobite fauna, of upper Middle Cambrian (B) to uppermost Upper Cambrian, but the highest trilobites occur as drifted lenses of debris only 25-30 m above the base of the Formation (which around Barrios de Luna has a total thickness of just over 400 m) and are of Middle Cambrian age. Comte (1959) proposed an age of upper Middle Cambrian to Tremadoc, but so far only the age of the base of the Formation is dated with any degree of precision.

Age diagnostic trilobite trace fossils have been collected from the Oville of the La Vid area (30km east of the Luna-Sil region) by Dr. T.P. Crimes (pers.comm.), and these indicate a Middle Cambrian age for the base of the Oville, whereas the top contains _Cruziana_ species which show affinities with _C. furcifera_ which in the U.K. ranges down to Upper Tremadoc (Crimes, 1968, 1970b, 1975 ; Seilacher, 1970; Seilacher and Crimes, 1969). _C. semiplicata_ which is restricted to the Upper Cambrian (Crimes, 1968, 1970a; Seilacher, 1970) has not been found in this detailed recording of the La Vid section.

5b. Stratigraphy of the Barrios Formation

Established relationships

The Barrios Formation has locally both gradational and erosional relationships with the underlying Oville (van den Bosch, 1969; Geitelink, 1973), the boundary between the two being arbitrarily set at the base of the first thick, cross-bedded, major non-glauconitic quartzite beds (van den Bosch, _op.cit._). This datum corresponds to the base of Member A of the Barrios Formation as defined by Geitelink (_op.cit._). As with the upper part of the Oville Formation, the age of the Barrios has so far not been accurately determined, but an Upper Tremadoc or later age may be indicated for the base by the La Vid material of Crimes.

A major stratigraphic break separates the Barrios Formation from the overlying Formigoso Formation which is dated at its base as lowermost Upper Llandoverian (Comte, 1959; Truyols, Philipot & Julivert, 1974). With the exception of the Laviana thrust sheet (Pello & Philipot, 1971; Julivert, Marcos, Philipot & Henry, 1968) and the Cabos Peñas area (Julivert & Truyols, 1973) Middle Ordovician sediments are absent from the Cantabrian Zone.

Lithostratigraphy

An analysis of the lithofacies of the Barrios Formation was presented by Geitelink (1973) and in order to provide an environmental background for discussion of the trace fossils, this work can be considered. Comte (1959) introduced the name 'Quartzite de Barrios' and proposed a type section at the western end of the dam at Los Barrios de Luna. Oele (1964) described the petrology of the formation and van den Bosch (1969) reviewed its general stratigraphy and deposition.

5c. Stratigraphic levels of trilobite trace fossils

The levels of occurrence of the trace fossils are shown in separate, continuously logged sections (Fig.25). Apart from the Barrios de Luna section, trace fossils have been found mostly towards the top of the highest, thickly bedded member of the Formation and as such provide a limited range of ichnospecies. However the Barrios de Luna section contains a limited number of trace fossils lower down in the section, and it is from this section that most of the stratigraphic information is derived.

C. semiplicata is present at the 153 m level (Fig. 25) in the Barrios de Luna Section, but was unrecorded anywhere in the La Majua section. Associated with *C. semiplicata* at this same level are *Rusophycus* with a shape factor of 1.3-1.5, and *C. barriosi* sp.nov.

which is also present 22 m higher up the section as well as approximately 50 m below, at the 107 m level. Indeterminate species of *Cruziana* and (?) *Monomorphichnus* are present near the base of the Formation.

Two forms of *Monomorphichnus* are present at the 153 m level: bi or tridigitate forms with a longer medial digit flanked by shorter digits are comparable with the individual appendage impressions on *C. semiplicata*. The other forms have at least four, approximately equal length digits with rounded ends to each digit.

The seventy-five specimens collected from the upper part of the La Majua section (Fig. 25) includes all members of the Rugosa Group (*C. rugosa*, *C. goldfussi* and *C. furcifera*) as well as *Rusophycus morgati* sp. nov., indeterminate *Rusophycus* with a shape factor of approximately 2, and multi-digit produced *Monomorphichnus*.

The Lancara de Luna, Transitional Group section contains as rich a Rugosa Group ichnofauna as the La Majua section, differing only in the preponderance of rusophyciform species, (Fig. 26).

C. barriosi has been recovered from low in the Barrios Formation of the La Vid section: in the underlying Oville Formation Middle Cambrian forms of *Cruziana* are present (Crimes, pers. comm.). Elongate forms of *Rusophycus* (shape factor 2) have been found by Crimes in the thickly bedded unit of the Barrios Formation (pers. comm.).

5d. Stratigraphic divisions of the Barrios Formation

In the La Majua section, the upper part of the Barrios Formation and the immediately overlying Transition Group are, on the presence of *C. rugosa* and other members of the Rugosa Group, or Arenig age. Lithologically there appears to be no significant change in the La Majua section above approximately 62 m, until the thinner bedded *Cruziana* bearing facies at the 225 m level is encountered. The lack of a diagnostic ichnofauna below the 225 m level permits no stratigraphic subdivision of this section.

The Barrios de Luna section lacks trace fossils in the upper thickly bedded member (Member F, Geitelink, 1973), but both van den Bosch (1969) and Geitelink (op.cit.) consider this member to be conformable with the overlying Transition Group. If this is so, this thickly bedded member is likely to be equivalent to the upper part of the La Majua section (itself conformably overlain by the Transition Group) and therefore is probably of Arenig age. Lithologically and on style of bedding, the upper member of the Barrios de Luna section is comparable with almost all the Barrios Formation of the La Vid section (Crimes, pers. comm.). The presence of Arenig forms of Rusophycus (shape factor 2) low in the La Vid section reinforces the Arenig age for all the upper members of the Barrios Formation.

C. semiplicata is restricted to the Upper Cambrian (including the Tremadoc) and does not range into the Arenig of the United Kingdom or Poland (Crimes, 1970b; Seilacher, 1970). The presence of C. semiplicata less than 25 m below the base of the upper member of the Barrios Formation and the Rusophycus with shape factors of less than 1.5 suggests that the lower 180 m of the Formation is Upper Cambrian (Tremadoc) in age.

In the United Kingdom, C. furcifera is absent from below the Tremadoc (Crimes, 1968, 1970a) whereas C. semiplicata and Cruziana with C. furcifera affinities are present in the Tremadoc (Crimes, 1975). In the La Vid section, Cruziana with C. furcifera affinities occur at the top of the Oville Formation (Crimes, pers. comm.), and consequently, as it appears possible that the lower 180 m of the Barrios Formation in the Barrios de Luna section is Tremadocian, the overlying quartzites are probably Arenigian. In this case C.barriosi sp.nov. may have a similar transitional Tremadoc/Arenig range to C. furcifera.

6. STRATIGRAPHIC VARIATION BETWEEN THE CANTABRIAN AND WEST ASTURIAN - LEONESE ZONES

After the late Precambrian folding of the Narcea Shales and the Mora Formation, the sediments of the Lower Palaeozoic transgression evolved from dominantly fluviatile, arkosic sandstones into open marine silts, sandstones and shales and eventually, in the Lower Middle Cambrian, into the shallow marine carbonate facies of the Vegadeo and Lancara. Throughout this period the sedimentary history of the west Asturian-Leonese and Cantabrian Zones was more or less the same, (Lotze and Sdzuy, 1961; Matte, 1968; Marcos, 1973), and resulted in the deposition of approximately 1.25 km of sediment in both areas.

After the Lower Middle Cambrian, differentiation of sedimentation rates and possibly also erosion rates,but <u>not</u> sediment types, began to emerge in the two Zones (Fig.35). The Cabos Series of the west Asturian-Leonese Zone is comprised of over 4.5 km of paralic sediments which by and large are of tidal and immediately sub-tidal facies. In the Cantabrian Zone during the same period, less than 1 km of, similarly, shallow marine and deltaic sediments were deposited.

Ichnostratigraphic information from the two zones suggests that sedimentation rates and coeval erosion may largely account for the thickness differences. The ichnostratigraphy of the Cantabrian Zone is, in part, a condensed analogue of the west Asturian-Leonese Zone, and the thickness variation of, in particular, the Barrios Formation and its west Asturian-Leonese Zone equivalents derives from the lengthy reworking of high shelf facies (van den Bosch, <u>op.cit.</u>) during this period. However, in neither the Luna-Sil region nor in the La Vid section have any specific sub-Tremadoc, Upper Cambrian ichnocoenoses been found, whereas in the Cabos Series at least half of the 4.4 km is of Upper Cambrian (sub-Tremadoc) age. In the La Vid section 'space' for the Upper Cambrian may conceivably be found in a thirty metre thick (at maximum) zone at the top of the Oville (Crimes, pers. comm.), but careful examination of this section has furnished no trace fossils of diagnostic age.

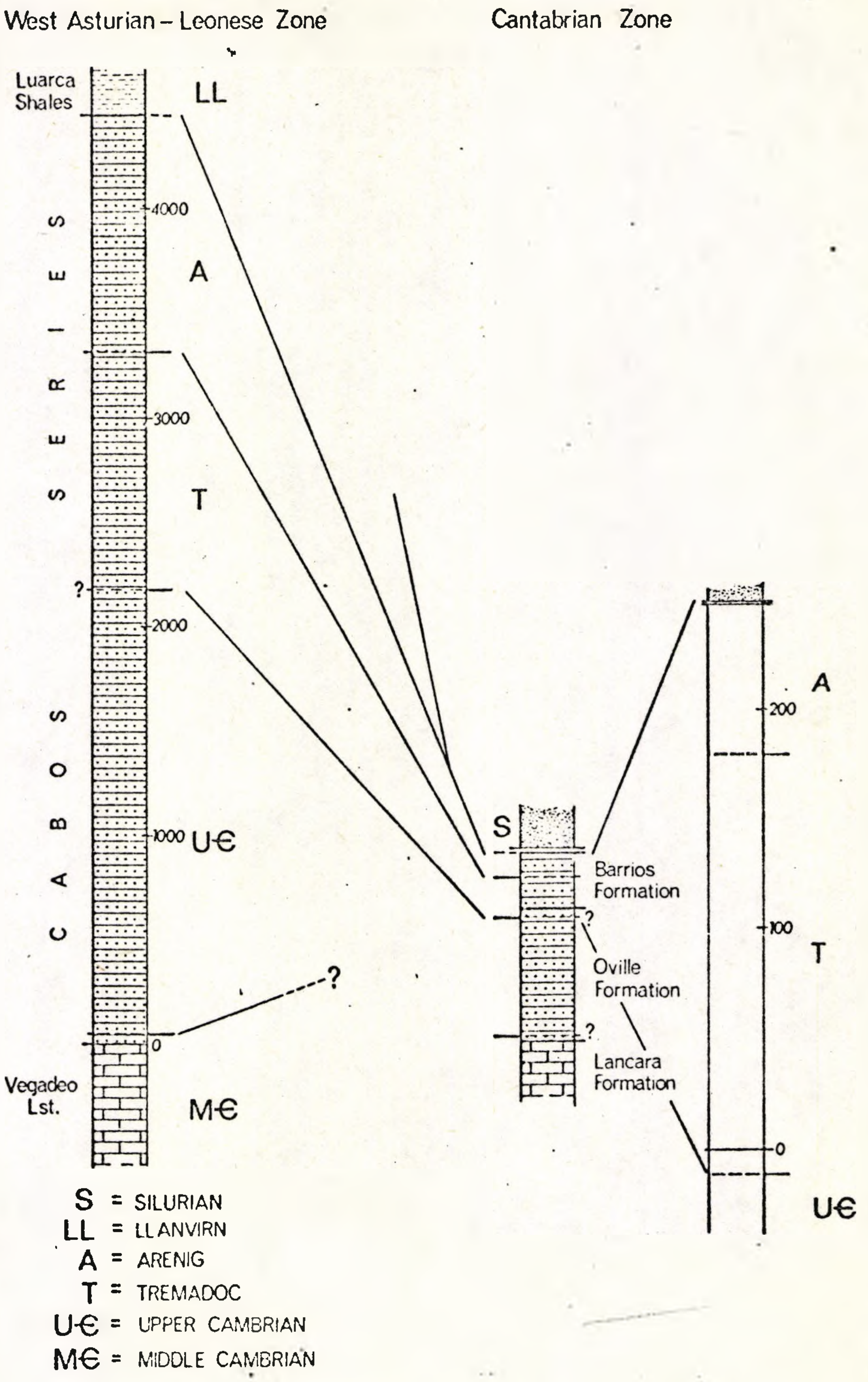

Figure 35
Comparison of the Cambro-Ordovician rocks of the West Asturian-Leonese and the Cantabrian Zones.

The beach, delta and tidal flat facies of the upper Oville and lower Barrios Formations are characterised by local and apparently temporary breaks in sedimentation (Geitelink, 1973), so that recognition of diastems or major periods of non-deposition are difficult. A potentially more important and continuous erosional surface is present low or at the base of the Barrios Formation (Member A, Geitelink, 1973) where it separates two transgressive phases. On ichnostratigraphic evidence it is possible that this break may be of 'higher rank' than the intraformational break derived from barrier bar front erosion during on-shore migration which is Geitelink's interpretation (Geitelink, op.cit., p. 139). The surface may, in fact, be more comparable with the Pre-Holocene erosion surfaces, typical of the transgressive sequences of coastal Delaware, U.S.A. (Kraft, 1971; Kraft et al., 1973), but the long -term existence of this surface (i.e. duration of the Upper Cambrian or the removal of all sediments deposited during that same period) is difficult to verify and further research may reveal more important breaks at high levels in the Oville Formation.

Conclusions

From ichnostratigraphic information it appears that the thickness variations of the clastic Cambro-Ordovician of the Cantabrian and west Asturian-Leonese Zones are derived both from slow sedimentation and local non-deposition or erosion in the Cantabrian Zone, while more continuous conditions prevailed in the west Asturian-Leonese Zone.

The eugeosynclinal interpretation of the west Asturian-Leonese Zone (Lotze and Sdzuy, 1961) seems improbable. Throughout the Cambrian and Lower Ordovician the sediments are of shallow marine aspect, and the whole arc shaped basin lacks any significant volcanic or igneous members (Julivert, 1971), and, in fact, the sequence of the two Zones are more comparable with the model of cratonic and miogeosynclinal sedimentation proposed by Pettijohn, Potter and Seiver (1972,p.548). Thus, a miogeosynclinal or even cratonic environment seems likely, in which case the interpretation of the Cantabrian Zone as the Geanticline (Matte, 1968) must be questioned. Similarly, the interpretation of the stratigraphic and structural evolution of N.W. Spain during the early Palaeozoic proposed by Wagner and Martinez-Garcia (1974) appears open to question. These authors (op.cit.) appear to have, in part, based their model on two pieces of incorrect information. The first is that the Cantabrian and West Asturian/Leonese Zones differ in facies development (Wagner and Martinez-Garcia, op.cit. p. 136). From observations this appears not to be the case: all facies are essentially shallow marine. The only facies "difference" exist with Llandeilo-Caradoc aged sediments. Turbidites are present in the West Asturian/Leonese Zone (Marcos, 1970; 1973; Crimes, Marcos & Perez-Estaun, 1974), whereas sediments of this facies are absent from the Cantabrians. Consequently meaningful comparisons of these two zones for this time period are not possible. The second problem lies in the apparently unfounded statement that "turbidites are common in the basal part of the Cambrian sequence" (Wagner & Martinez-Garcia, op.cit., p.136) of the West Asturian/Leonese Zone. Julivert, Marcos & Truyols, (1972) and Marcos (1973) have demonstrated that this is not so and that all Cambrian facies are of shallow marine aspect. Thus, the classical geosynclinal model proposed by Wagner and Martinex-Garcia (1974), at least during its early development, may require modification.

The centre of the Asturian Arc (Julivert, 1971), which corresponds more or less to the Cantabrian Zone, may in fact represent the shelf facies of the small craton which was margined in the south, west and north by a constantly subsiding arc shaped trough (Bard et al. , 1971) which remained shallow until the end of the Lower Ordovician.

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PART 2

WESTERN BRITTANY

CHAPTER 4

LITHOFACIES ANALYSIS

The following chapter has been accepted for publication in the Proceedings of the Geologists Association.

A storm influenced barrier bar and lagoonal transgressive sequence from the Grès Armoricain of the Crozon Peninsula (Finistere)

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ABSTRACT.

The Crozon Formation of the Grès Armoricain of the Presqu'ile de Crozon, Finistere, changes from featureless orthoquartzitic facies at the base into a unit of heterolithic facies and eventually into dark shales of Llanvirn age. Eight lithofacies are identified which reflect a normal transgressive sequence. During this transgression, barrier bar complexes provided calm conditions, allowing lagoonal facies to develop shoreward of the barriers. Storms caused occasional ingress of coarser lithologies into the protected lagoon and these deposits were redistributed by ebb flows. The barrier bar complexes migrated onshore and are replaced by tidal flats which were eventually transgressed by deeper water facies.

1. INTRODUCTION

The shallow marine clastic facies of the Grès Armoricain (Arenig) occurs throughout Europe and Iberia and extends southwards to the Arabian and North African shields.

The main purpose of this paper is to give a detailed sedimentological analysis of one section, and to use this to interpret the changing environment of deposition. It is hoped that this analysis might provide a template for further investigations elsewhere.

The section chosen for study occurs north of Camaret-sur-mer, Presqu'ile de Crozon, Brittany.

2. STRATIGRAPHY

Barrois (1876), in erecting a Paleozoic stratigraphy for the rocks of Brittany, divided the lower Ordovician into the Schistes Rouge de Monte forte, Gres Feldspathique, Schistes and Grès Armoricain. Chauvel and Corre (1971) interpreted the Grès Armoricain in terms of a lower sandstone member (>300m thick), a middle interbedded member (50 - 100m thick) and upper sandstones and transition beds (100 - 150m thick).

Pruvost (1949) was one of the earlier workers to discuss in detail the regional paleogeography of the Grès Armoricain of Brittany. His concept of the Fosse Armoricain, an east/west trending seaway which extended throughout Brittany, provided a framework in which to discuss patterns of early Paleozoic sedimentation.

Bradshaw (1963) gave a detailed analysis of the sedimentary history of the Crozon Peninsula and recognised that the Grès Armoricain is composed of two northward transgressive units. The lower of these - the Telgruc Formation - which overlies the Brioverian metasediments, commences with a coarse breccio-conglomerate and passes up into orthoquartzites. This Formation is overstepped northwards by the Crozon Formation, which also in places unconformably overlies the Brioverian, but with only a thin basal granule conglomerate. The transition to mature orthoquartzites is more rapid than in the Telgruc Formation and the quartzites are divided towards the top by a unit of shale/silt/sand alternations. The top of the

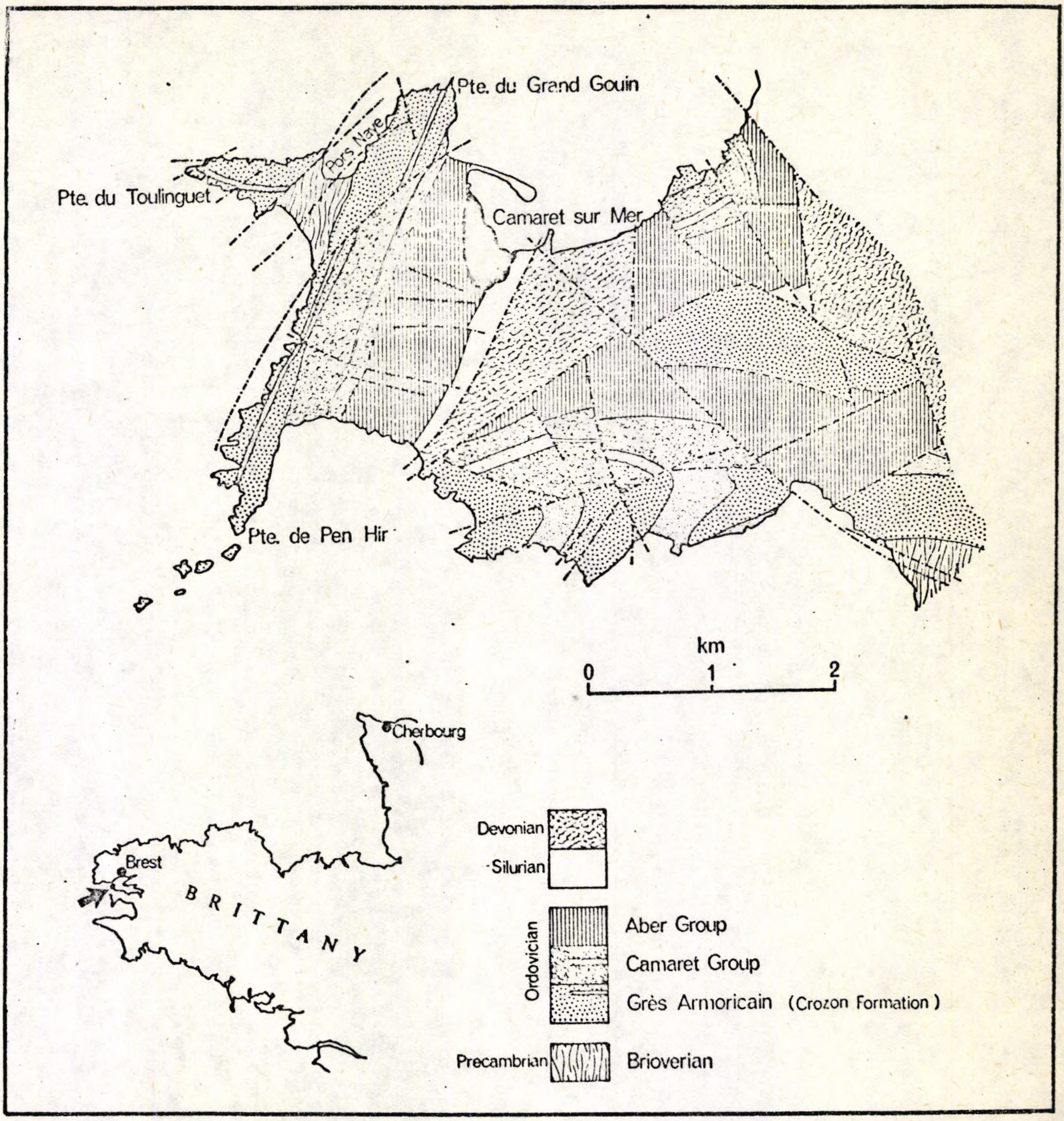

Figure 36 Location map.

Crozon Formation passes by gradual transition into dark shales of the Camaret Group (Bradshaw, 1963) which contain Didymograptus bifidus Hall, indicating a Llanvirn age.

3. FACIES

The Crozon Formation of the Pointe du Grand Gouin, north of Camaret-sur-mer (Fig.36), can be defined in terms of eight facies, the distribution of which is shown in (Fig.37). The lower two facies are poorly defined in the field and will be considered in less detail than the overlying facies.

Facies 1: Relict granule conglomerate.

Description.

The conglomerate, which is composed of yellow, white and subordinate pinkish quartz granules, rarely exceeds 0.3m in thickness within the small area studied in detail. The few silt and shale clasts present are usually elongate or discoid and always occur at the base of the bed. The conglomerate passes up by rapid transition into clean medium sandstones, and no marked separation is present.

Interpretation.

The small thickness of the basal conglomerate and its rapid transition to orthoquartzitic sandstones may be due to little or no erosive power of the transporting currents at this stage; the granule conglomerate representing a lag or residual deposit derived largely from the reworking of the top of the Telgruc Formation, and not by extensive erosion of the underlying Brioverian. A lack of good sedimentary contacts with the Brioverian makes this difficult to check but the nature of sedimentation seems to have changed little from that characterized by the main part of the Telgruc Formation and consequently no major environmental change is envisaged.

Facies 2: Massive sheet sands.

Description.

The bedding of facies 2 is indistinct in the field and appears to represent only slight textural changes rather than obvious lithological transitions. Thin films of grey green shale and fine silt are present (Bishop et al, 1969) but partings are rarely laterally continuous. The incorporation of clays at the contacts of otherwise clean sandstones may have led to a reduction of cementation in the manner suggested by Pittman and Lumsden (1968).

The apparently massive medium sandstones, up to 4m thick, are tabular with essentially planar contacts. Bed thickness decreases gradually upwards but rarely falls below 0.5m. Practically no internal sedimentary structures can be seen in the field but the presence of a few symmetrical wave ripples suggests occasional reworking of the tops of thicker beds.

Interpretation.

The mature sandstones and lack of lithological variability suggests derivation from an already mature source. Possible reworking of the top of the Telgruc Formation during the northward transgression of the Crozon Formation may have provided this type of maturity. Transport and deposition on a marine shelf, providing a long transport and sorting period, may have been involved.

The lack of major bed forms makes environmental interpretation difficult. Offshore shelf sands (Reineck, 1967, p. 203), littoral sand sheets (Goldring and Bridges, 1973) or sheet sands marginal to dune fields, similar to those in the southern and central North Sea (Stride et al, 1972) and Irish Sea (Belderson et al, 1971, 1972), would provide such extensive spreads of thick sands.

Water depths sufficiently shallow to allow wave base reworking, possibly during storm periods, existed only intermittently.

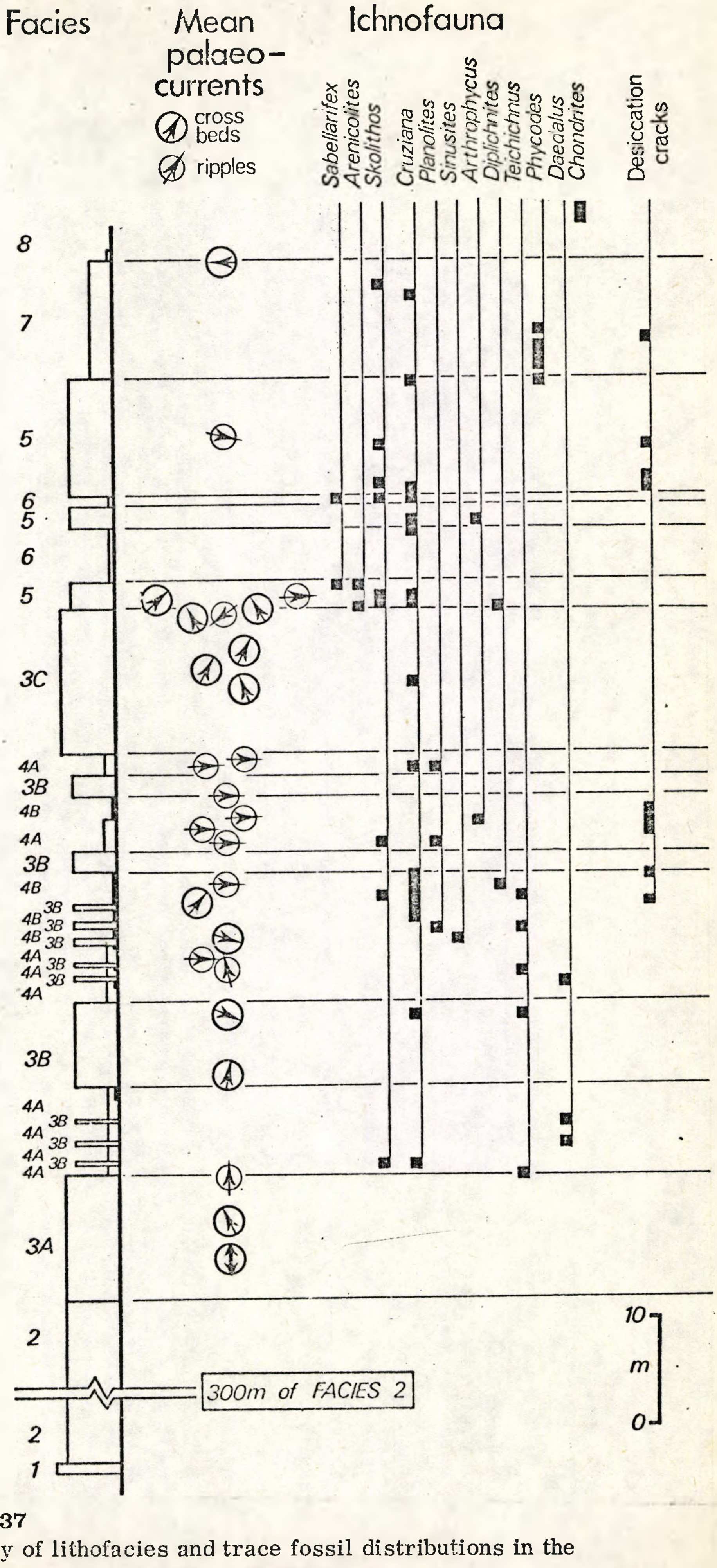

Figure 37
Summary of lithofacies and trace fossil distributions in the Crozon Formation, Pointe du Grand Gouin.

Facies 3: Nearshore barrier sands.

This facies may be divided into three sub-facies on the basis of sedimentary structures and relationship with other facies.

3A: Emergent barrier sands.

Description.

This sub-facies follows on by gradation from facies 2. The junction between the two facies is taken where the first parallel lamination appears in the medium sandstones. The lithology becomes gradually more variable upwards with the appearance of distinct, continuous mud interbeds. The lamination present in the lowest beds of the sub-facies is defined by medium sand grade, dark minerals, probably zircon or rutile (Chauvel and Corre, 1971). Immediately above the laminated beds, herring bone cross-bedded sets 10 - 20cm thick appear (Pl. 1A). The foresets are again defined by dark mineral bands. Thin undulating bedded sands with subordinate silts follow the herring bone sets and these are overlain by massive (?), thick (0.7 - 1.25m) bedded tabular medium sands. The top 1.5m is composed of slightly thinner bedded sands with steep planar cross-bedding and superimposed wave and current ripples. The cross-bedding overlies low relief erosional bases. Current directions in the planar sets indicate transport towards the north and north-west (Fig.37). The upper cross-beds are overlain by thin, parallel laminated and wavy-bedded sands. Upper surfaces of the cosets are erosive, curved and irregular and similar to the reactivation surfaces described by Collinson (1970) and figured by Klein (1970b, Fig. 27D).

The facies is overlain by facies 4, the contact between being either undulating or irregular and always abrupt.

Interpretation.

The gradual decrease in bed thickness, the increase in the heterolithic nature of the sediments and the presence of various types of cross-bedding and erosion surfaces all suggest increasing current activity and reworking by strong bottom traction currents.

Herring bone cross-stratification representing possible ebb and flood deposition, parallel lamination, erosive upper and lower contacts to cosets and subordinate smaller current ripples superimposed on planar cross-bedded units indicate inter or sub-tidal effects (Klein, 1970a, Table 2, p. 980; 1971, Table 1, p. 2586).

The weak bimodality of both the herring bone and planar cosets suggests one phase of the tidal cycle was dominant as the dune or bar constructing event. Klein (1970b) suggests that bedform migration is controlled by time velocity asymmetry of the bottom tidal currents and only with equality of power during both ebb and flood events may herring bone cross-stratification be formed. This structure is typical of European intertidal areas characterised by small to medium tidal ranges (Hulsemann, 1955; Reineck, 1963; Reineck and Wundelich, 1968; Evans, 1963; De Raaf and Boersma, 1971). Reactivation surfaces result from the superimposition of a destructional event after constructional dune migration. The change from herring bone cross-bedding near the base of sub-facies 3A may reflect a change in either tidal range (Klein, 1970b) or in the local geometry of the sand body (Davis *et al*, 1972). A further possibility may be a process similar to that described by Davis and Fox (1972) in which barometric pressure and wind variations induce changes in rip channel position, thus in effect altering bar geometry.

In the context of the overall northward transgression it would appear that the northerly paleocurrents were part of the flood tidal system and these were either matched or later modified by southerly and easterly ebb flows.

The erosive conditions indicated at the top of the facies suggest progressive emergence of a sand bar or barrier as it migrated onshore (northwards). The blocking or modification of ebb channels at this early stage of barrier development may have led to the ponded ebb flow passing back over and scouring the dune structures constructed during the flood phase.

3B: Storm input sands.

Description.

Sub-facies 3B is always interbedded with facies 4 and always displays erosional bases. Flat, planar, undulating and irregular lower contacts to the medium fine sands of this facies are all present but irregular and channel contacts predominate. Mud pellets and pebbles are present at the base of many of these sands.

Units of this sub-facies either commence with planar or trough cross-bedded sets 10 - 25cm thick or with massive or weakly wavy and parallel laminated sands (Pl. 1B). These grade upwards into coarse to medium silts with wavy lamination, wavy bedding and stronger parallel lamination with weak primary current lineation. The upper contacts of this sub-facies is normally gradational with facies 4 but amalgamated units may be piled up, making stratified units up to 5.0m thick.

Cross-bedding is variable in dip direction but most of the larger sets correspond to the northerly flood direction indicated for the top of sub-facies 3A. Other, thinner sets dip dominantly eastwards.

Interpretation.

The sandstones and siltstones were deposited by currents of similar or greater strength to those in facies 3A. Strong bottom shear is indicated by the erosion of the muds and fine silts of facies 4 into shallow scour and channel forms and by the presence of mud clasts in the base of the sand units. Declining current strength is indicated by the upward fining of each sub-facies unit. The change in primary structures towards those of facies 4 type suggests that sub-facies 3B events are atypical for the general environment and the gradation reflects the gradual change towards the more stable conditions characteristic of facies 4. Transition from massive to laminated sands may represent a change from sedimentation from a turbulent cloud, hence damping out grain traction and helical eddies (Allen, 1968; De Raaf and Boersma, 1971) to plane bed with movement conditions (Simons et al, 1965). A similar but smaller scale process has been described by Grant (1948), Duncan (1964) and Shidler (1973) for swash deposition.

The high initial energy and the conformity of paleocurrent directions with the flood directions of facies 3A suggests the ingress of powerful on-shore currents, possibly generated by northward moving storms which overtopped the barrier bar system. Hayes (1967), Gadow and Reineck (1969), Kraft (1971), Hobday and Reading (1972) and Davis and Fox (1972) have discussed the importance of storm events as depositional and erosional mechanisms of high preservation potential. In coastal Delaware sequences described by Kraft (1968, 1971) and Kraft et al (1973), storm events cause onshore transport of nearshore marine sands and the overtopping of the coastal barrier chain. These storm deposits form washover fans which interdigitate with lagoonal silts and muds. The current pattern of this facies would further correspond with the trimodal pattern described from runnels by Davis et al (1972, Fig. 11), except that the ebb lagoonal (= runnel) discharge is bimodal towards the north and east in the Crozon Formation. This indicates either the existence of an effectively permanent ebb channel some distance to the east or perhaps the complete termination of the barrier system in that direction. The latter would give a general paleogeometry to the environment similar to that proposed by Goldring (1971, Fig. 27) for the Devonian Baggy beds of north Devon. A modern example of this type of geometry is described by Kraft et al (1973) from the Holocene, Cape Henlopen Spit of Delaware.

The northerly dipping cross-bedded and current rippled sands are considered to represent the washover and initial spreading into the lagoon of storm input sands. The second, easterly paleocurrent mode indicated by smaller cross-beds and current ripples may represent the first stage of along lagoon redistribution of these storm sands.

3C: Barrier/berm sands.

Description.

This sub-facies has features in common with sub-facies 3A and 3B but the planar alpha and beta (Allen, 1963) and shallow, concave-up eta and theta cross-bedding (Allen, op. cit) is usually on a larger scale in this sub-facies. The sand fraction is composed dominantly of better sorted medium sands than those present in other members of facies 3.

Alpha and beta cross-stratified units are common at the base of the sub-facies. Both these types of cross-beds are homogeneous near the base but examples of more heterogeneous beta sets gradually appear and eventually give way to theta and eta types in the middle of the group. One example of theta cross-bedding exhibits, at the up-current end of the trough, recumbent folded, deformed foresets (Allen and Banks, 1972). Smaller scale alpha sets (10 - 20cm thick) are present near the top of the sub-facies group.

The base of the sub-facies is planar but appears to be fairly strongly erosive as an intraformational conglomerate of mud and silt pebbles along foresets. Only thin, laterally continuous silt interbeds are present in the middle of the facies, and many of these have interference and indistinct linguoid rippled surfaces.

Paleocurrents from cross-beds near the base of the unit are unidirectional towards the north while the smaller scale alpha sets show easterly flow directions.

Numerous current oriented Cruziana and Rusophycus are present wherever thick silt interbeds occur.

Interpretation.

Alpha and beta cross-stratified units suggest the fossilization of either forward building banks or migratory asymmetric dunes (Allen, 1963, p. 101). The eta and theta units, above the larger alpha and beta sets are probably both scour fills, similar in origin to that given as typical of theta sets by Allen (1963, p. 105). The eta units may be channel fills but appear to be formed in large spoon shaped depressions similar to those bounding theta types but differentiated from the latter by the heterogeneous fill.

A process of onshore dune building by flood tides, possibly in combination with storms, may have produced the lower large scale planar sets. The presence of the coarse intraformational conglomerate at the base of the facies indicates erosion of mud layers, probably as the dunes transgressed shorewards over the lagoonal facies. This may have been due to major storm breaching of an offshore protecting barrier so that the lower part of sub-facies 3C forresponds to a catastrophic example of sub-facies 3B. Due to the wiping out of the barrier, the lagoonal environment was not re-established.

After the phase of berm construction which followed the erosive transgression, the upper surface of the dunes was reworked and eroded into extensive scour pits. These were filled with medium sand and mud pellets. Large scour pits of this type have been described from the intertidal sand bars of the Minas Basin by Klein (1970). A similar type of topography is figured by Allen (1968) from the Barmouth estuary of Wales where deep pits with superimposed ripplefans are developed in the lee of large scale catenary and lunate ripples. The fill and general heterolithic nature of the scour fill possibly reflects a new stage of environmental instability when nearshore barriers were in a stage of rebuilding or entirely absent and thus affording little protection to inshore mud deposits. These would have been removed by relatively weak storms or strong tides and transported over the welded berm crest.

The tabular smaller scale alpha sets at the top of the facies group indicate easterly flow directions. This may represent an easterly longshore drift, possibly still controlled by the pattern of sub-tidal rip channels operative during deposition of facies 3B.

Facies 4: Lagoonal.

Facies 4 is divided into two sub-facies on the basis of grain size, trace fossil assemblages and the relationship with facies 3B.

4A: Redistributed storm sands and silts.

Description.

Facies 4A nearly always overlies facies 3B with a gradational contact. It is comprised of numerous small (<1.0m) fining-up lithosomes and marks the transition from facies 3B to facies 4B.

Grain sizes are dominantly fine sands and coarse silts with subordinate muds and medium sands. Bedding varies from 1 - 10cm in thickness. Thin beds of normally graded silts are common. Bedding contacts near the base of the facies are planar with no primary current lineation. Upwards, the contacts may be undulating and occasionally irregular and are always rippled. Flasered and lenticular bedding is common and form sets are composed of asymmetrical current ripples which, in the beds just above facies 3A (Fig.37) display a 90° bimodality. Subordinate symmetrical wave ripples occur towards the top of some units. Current directions are surprisingly uniform with most ripples indicating easterly flow. The only exceptions are rare current ripples with northerly dipping laminae.

The ichnofauna is restricted and composed of Skolithos showing escape structures, a few Teichichnus and occasional Daedalus (Fig. 37). Rare Cruziana rugosa are found as casts on the base of some of the thicker sandstones. Bioturbation is slight and only occurs in the upper parts of the facies units.

Interpretation.

The suite of primary sedimentary structures suggests decreasing current power, possibly representing a general change from upper (parallel lamination) to lower (ripples) flow regime.

The transporting and depositional processes would appear to be genetically related to sub-facies 3B and is interpreted as the along-lagoon redistribution of storm sediments. A similar process has been described by Kraft (1971) as operating on the seaward margins of Rehoboth and Indian River Bays in the coastal lagoon system of Delaware. Here, storm and aeolian sands from thin inside barrier beaches are winnowed out by overtopping storm waves and carried over into the lagoon and mixed with lagoonal muds and silts by normal inter-lagoon, tidal circulation.

The ichnofauna would conform to the Skolithos facies of Seilacher (1964, 1967) and is supposedly very shallow marine. The escape structures (Hallam and Swett, 1966; Goldring, 1962, 1971) exhibited by some Skolithos indicate a response to variable rates of sedimentation and indicates the stage of recolonisation after storm input.

4B: Protected lagoon.

Description.

Sub-facies 4B usually grades up from sub-facies 4A and is often overlain by the erosive base of sub-facies 3B. On the limited section available for study only four examples of 4B grading laterally into 4A were seen.

The grain size varies from coarse and medium silt to mud and forms flasered and linsened complexes up to 4.0m thick. Individual beds of coarse silt up to 5cm thick are laterally continuous with gradational upper and lower contacts. Graded beds of coarse to medium silt are common and most beds are rippled. Interference and north/south trending symmetrical oscillation ripples are characteristic of this facies, whereas asymmetrical forms are almost entirely absent. The few current ripples that are present suggest an easterly flow direction.

Mud cracks of both desiccation and syneresis origin are present but difficult to differentiate from biogenic traces (Baldwin, 1974). Occasional ripples in coarse silt have sculptured surfaces which may either be incipient load casts or wrinkling (Goldring, 1971). Sand mounds, similar to those described by Bradshaw (1966) from the south of the Crozon Peninsular are present where sub-facies 4B directly overlies examples of sub-facies 3B, without the intervention of 4A. Phosphatic (Lingula ?) debris is concentrated around the complex micro-topography of the mounds.

Soft sediment deformation structures are common and include a range of forms from incipient bulges through to complete isolation structures of foundered silt in mud.

Bioturbation is fairly common but does not include complete destratification or intense mottling. The trace fossil spectrum is more diverse than in 4A and includes furrowing and winding horizontal traces as well as occasional vertical burrows. Genera include Cruziana, Planolites, Cochlichnus and Teichichnus.

Interpretation.

Sub-facies 4B represents the lowest energy end member of a series of sedimentary events preserved as sub-facies 3B, 4A through to 4B and indicates stable low energy conditions of a largely protected environment. Flaser and linsen bedding are typical of sub-tidal, intertidal, fluviatile, deltaic and lagoonal environments (Reineck, 1960; Reineck and Wunderlich, 1969; Terwindt, 1971; Terwindt and Breusers, 1972). A lagoonal interpretation would appear most acceptable for the origin of facies 4B, particularly when the relationship with adjacent facies 3 is considered. The presence of mud cracks indicates periodic exposure, possibly related to very low tide periods (Evans, 1965) and suggests an intertidal lagoon. This conclusion is supported by wrinkling structures on ripples which may correspond to antiripples (Goldring, 1971) and are considered to form subaerially (van Straaten, 1953). Further, the sand mounds similar to those described by Bradshaw (1966) may indicate a high or supratidal position at some periods.

This facies is comparable in many ways with the Lingula facies of Goldring (1971). The main difference is in the strong intertidal influence and lack of carbonate. A similar style of paleogeography would appear to fit but the modern analogues considered by Goldring (ibid, p. 32) seem too open and insufficiently affected by tidal action. The mud/sand 'Misch' flats of Jade Bay, North Sea described by Reineck (1967) are comparable although channels and longitudinal oblique beds (Reineck, 1958) appear to be absent from this part of the Grès Armoricain. The Higher Mud Flats of the Wash (Evans, 1965) have similar small scale structures and a lower incidence of downcutting channels.

Facies 5: Tidal sand flat.

Description.

Facies 5 is composed of medium sands with subordinate silts and thin shales in the lower part of the main unit. This facies follows on without perceptible break from the top of facies 3C but is interrupted by a five metre unit of facies 6; the bulk of facies 5 occuring above facies 6 (Fig . 37).

The lowest part of the facies which is transitional with facies 3 contains small scale tabular cross-beds with easterly dipping foresets. Extensive surfaces of arcuate fronted ripples (Pl. 2A) which pass laterally eastwards into linguoid ripples are exposed. The current ripples appear to radiate from almost a point source but no morphological feature forms a locus for the circumfrential patterns. These ripples may be situated at the front of a low, simple dune on top of which long crested linguoid and and sinuous current ripples are superimposed (Pl. 2 A). The slip face of the dune also carries straight crested ripples at right angles to the dune axis. An almost identical set of structures (excluding the arcuate ripples) has been figured by Klein (1970b, Fig. 14F) from a sand bar in the Minas Basin of Nova Scotia.

The linguoid ripples, which are the eastern equivalents of the arcuate ripples, have extremely extended lobate fronts (Pl. 2B), some appearing to overthrust the stoss side of the next downcurrent ripple.

This suggests slumping, either down slope or due to current drag of the ripples after construction. Ladder ripples (Hayes et al, 1969) are present above the surface with arcuate ripples (Pl. 3A). The first formed set trends north-west/south-east with flow from the north-east and the second superimposed symmetrical set is normal to the first.

The top of the lower unit is composed of fill to a broad shallow channel of unknown trend, the filling beds being thick, planar cross-beds with planar, interference rippled upper bounding surfaces.

The upper unit is composed of the same medium, well sorted sands, which are characteristic of the lower unit but is formed into smaller scale north-east/south-west trending channel forms and includes evidence of more active local erosion. Most of the units of this part of the facies are lenticular (Pl. 3B) with the sands forming draped fills to the erosive features. Mud pebbles and pellets are present in many of the sands and are concentrated in the lower parts of the channels. However, they do not form lag concentrade layers on the channel floor but are incorporated with the basal part of the fill (Pl. 4A).

Channel fill cross-bedding passes up into low angle (5 - 15^{o}) northerly dipping cross-bedding (Pl. 4A) which sometimes has weak primary current lineation on the foresets. Erosion surfaces, similar to Bradshaw's sand mounds are present and are draped with laminated silts and thin sands containing mud pellets (Pl.4 B). Desiccation cracks occur 15 - 20m to the south of the channels. These cracked surfaces may have provided the mud pellets present in the channels and other fill.

Diplichnites, Arenicolites and Skolithos are present in the beds with arcuate rippled surfaces. Cruziana goldfussi and Arthrophycus are abundant on the soles of some of the thicker sandstones near the base of the upper unit and Sabellarifex is present in the thinner bedded heterolithic parts of the facies.

Interpretation.

Facies 5 indicates increasing complexity of current flow patterns in comparison with the conditions of the underlying facies 3C. A process of ridge building by low dunes migrating both northwards and eastwards appears to have been followed by welding of the dunes on to a shore face producing a broad, gently shoreward (north) dipping berm which was periodically built over by low dunes.

Davis *et al* (1972) describes, from the northern Massachusetts coast, the welding of intertidal sand ridges onto the back beach to form a broad convex-up wave washed berm which dips gently landwards. In this structure both landward dipping berm cross laminae and seaward dipping laminae of the foreshore slope are noted. In the Gres Armoricain, only the berm crest laminae are preserved, the primary current lineated foresets possibly reflecting upper flow regime conditions produced by shallow sheet flow as waves passed over the berm crest (Davis *et al*, 1972). McKee and Sterrett (1961), in experimental work and in reports of bars off North Bimini Island, record landward dipping sets (9° - 20°) and conclude they were constructed under conditions of shallow water with an offshore sand supply.

Low dunes periodically built across the berm surface and the resultant water flow patterns appear to have been complex. The dune fronts on two extensive rippled surfaces are oriented north-north-east/south-south-west with transport towards the east and south-east. A general sequence of ripple types, comparable with schematic depth related sequence described by Allen (1967, Fig. 4.61, p. 93), is present. The suite of ripples on the upper dune surface includes sinuous crested and transitional symmetrical linguoid forms. After passage over the dune crest, arcuate asymmetrical ripples pass into large symmetric and asymmetric linguoid forms. Such a series is characteristic of down current increase in depth. The origin of the arcuate ripples is a problem. Allen (1967, p. 84) has described 'concentric loops' of ripples which he called *Ripplefans*. Those figured all seem to be related to other major ripple forms, mostly of the lunate type. Ripplefans appear to have a distinct morphology in that the up current centre of the fan is the deepest point of a scooped, flute mark form. The examples in facies 5 are much flatter, rising only very slightly in the down current direction. These structures may have formed as a result of flow over the bar crest which had a straight swept geometry (Allen, 1967, p. 65) relative to the current. Allen (ibid, Fig. 4.40a, c) indicates no scale for the cell dimension, cell corresponding in this case to a single arcuate or ripplefan set. It may be that with straight crest lines to the major dunes, ripplefans will be widely spaced so that as in the facies 5 examples, only individual cells are formed without bounding seams of other fans impinging.

Paleocurrents in the lower part of the facies appear to have been controlled by the local geometry of bar and berm structures. Ladder ripples have been described from runnels in both Lake Michigan and the coast of northern Massachusetts (Davis *et al*, 1972).

The upper channelled part of facies 5, which follows the barrier and berm group, is characterised by both erosive and constructional events which are separated in time. The shallow, channel shaped scours are filled with sigmoidal cross-beds which contain abundant mud pellets concentrated in the toe sets. This scouring may be storm produced as the fill is quite discrete from the channel wall material and lacks the inclined relationships of lateral accretion deposits. Formation by channel migration seems unlikely. Evans (1965) mentions shallow scour and fill structures and the presence of associated mud pellets in the *Arenicola* Sand Flats of the Wash. Bioturbation is much lower in facies 5 than in Evans' *Arenicola* Flat but the sand mounds, interbedded fine sands and muds and mud cracks closely resemble the mixed *Arenicola* facies. The analogy is reinforced by the presence of extensive surfaces with *Arenicolites* and *Skolithos*.

Facies 6: Mixed tidal flat.

Description.

Facies 6 is composed of lenticular, laterally discontinuous flasered and linsened silts and muds with intermittent more continuous stringers of medium and fine sand. Bedding contacts of the sands are sharp but not deeply erosive. Interference ripples and small scale, low angle trough cross-bedding with mud flakes are present. Weak, wavy and irregular lamination is present in the thicker sandstones.

Bioturbation is not intense except in occasional beds of fine sand which are heavily burrowed and contain *Sabellarifex*, *Skolithos* and *Cruziana*.

Interpretation.

This facies perhaps represents an intertidal mud dominated equivalent of the higher parts of facies 5. Channels and lateral accretion deposits are again lacking so that a Wash type of Lower Mud Flat (Evans, 1965, p. 223) rather than the Jade Bay, Misch flat (Reineck, 1967) seems likely. The small scale irregularity of the surface suggests periodic wave scouring (Banks, 1973). Evans (op. cit) attributes the infilled scour structures to both wave action and the filling of ephemeral rills.

The thicker, more continuous sands may be strong tidal or storm products.

Facies 7: Low mud flat.

Description.

The facies is composed of laminated and thin bedded silts and muds with thin fine and medium sandstone stringers. All the sandstones have interference and wave rippled surfaces and many display desiccation cracks, superimposed over the ripples . Bases are planar and usually weakly erosive. Wavy bedding and lamination and limited flaser bedding are the most common stratification types, bundles of laminae pinching out over a distance of a few metres. Thin, graded coarse silt beds and rippled sands are both laterally continuous, although they pinch and swell throughout their length.

Bioturbation is highly variable. Groups of beds up to 35cm thick are completely destratified, whereas in other parts of the facies stratification remains almost entirely intact. Phycodes circinatum and P. palmatum are common at the base of the facies (Fig.37) and persist throughout. Cruziana furcifera occurs in limited numbers where occasional thicker silts appear in the top half of the facies.

Small scale planar cross-lamination in coarse silts at the top of the facies indicate westerly flow directions.

Interpretation.

This facies has many of the properties of facies 6 but the increased lateral continuity of the sands and silts and even of some of the laminated bundles suggests a less complex local topography and probably deeper water environment.

The association of desiccation cracks with thicker rippled sands may be due to periodic tidal exposure during very low spring tide-like events.

The thin graded silts indicate sedimentation from suspension, possibly a result of storm residue deposition or storm reworking of sediment transported by waves or currents (Hobday and Reading, 1972). These silts suggest nearshore, possibly just intertidal, deposition, whereas the subordinate flasered and wavy bedding are indicative of tidal effects. A nearshore environment, fluctuating but progressively increasing in water depth, appears likely.

Horizontal feeding burrows dominate the ichnospectrum for the first time, possible reflecting reduced rates of sedimentation so that organic matter was dissipated throughout many of the beds of fine silt and mud.

Weak westerly currents may indicate the final breakdown of the influence of nearshore barriers and their associated rip induced easterly flow patterns of the lower facies.

Facies 8: Marine shelf muds.

Description.

Thin, graded, medium and fine silt laminae are the only stratification types seen in facies 8. Otherwise the facies is composed of blue-grey pyritic muds with fairly common phosphatic concretionary horizons. Body fossils occur dispersed and also concentrated in bioclastic lenticles (Bishop et al, 1969). Enrolled trilobites, cystoids, ostracods, bivalves, gastropods, brachiopods and graptolites are all present (Bishop et al, op. cit.). Chondrites, in places completely permeating the rock, is the only distinguishable trace fossil. The base of the facies is entirely gradational with the top of facies 7.

Interpretation.

The facies is composed of normal marine shales and the phosphatic horizons are related to concentrations of chitino-phosphatic body fossils.

4. DISCUSSION

The fining-up sequence of the Crozon Formation is similar to a number of transgressive barrier systems described from the Atlantic and Gulf Coasts of the U. S. A.

The Oligocene Frio Sand Complex of the Texas Gulf Coast (Boyd and Dyer, 1964; Shelton, 1973), though thicker than the Crozon Formation, has features in common. It is interpreted as a linear barrier island with, to landward, brackish water lagoonal deposits, while to seaward, offshore marine depositis are present. Shelton (op. cit.) has recognized features within the sequence which indicate the operation of transgressive-regressive couplets during deposition. As a result, the interdigitation of lagoonal and marine barrier sands reflects oscillations within the general transgression (cf. Fig.38).

On a more comparable scale, many of the features of the barrier system of the Delaware coast described by Kraft (1971) and Kraft et al (1973) assist in interpretation of the Crozon Formation. Most of the schematic cross sections given by Kraft et al (Figures 9 & 10) match the sequence of facies in that part of the Crozon Formation which lie above the base of the lagoonal facies (facies 4, Fig.39).

The transgressive mechanism of superimposition of laterally equivalent facies through time (Walthers Law) proposed for the Delaware and other barrier systems (Boyd and Dyer, 1964; Shepard and Moore, 1955; Corbeille, 1962; Fischer, 1961; Shelton, 1973; Kraft, 1971; Kraft et al, 1973; Davis and Fox, 1972; Davis et al, 1972; Sonu, 1973) would seem applicable to this part of the Crozon Formation. However the relationship of the obviously transgressive facies 1/2 and sub-facies 3A with the overlying lagoonal facies is a departure from the classical transgressive sequence.

The control of facies deposition by largely local depositional topography may provide the answer to the problem of the relationship of all the facies. The acceptance of the lagoonal origin for facies 4 excludes a process of two separate transgressive phases and possibly even the

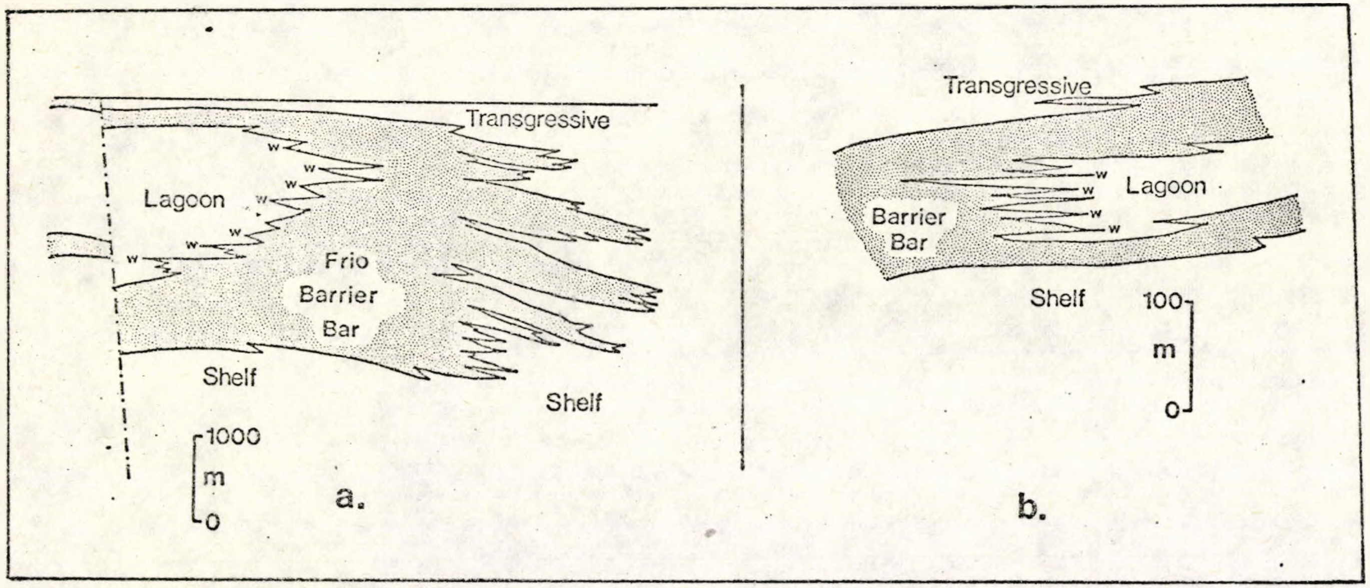

Figure 38

Comparison of the cross-sectional form of (a) the Oligocene Frio Sand Complex (after Boyd & Dyer, 1964) and (b) the Cambro-Ordovician Crozon Formation sequence. Note washover sands (w).

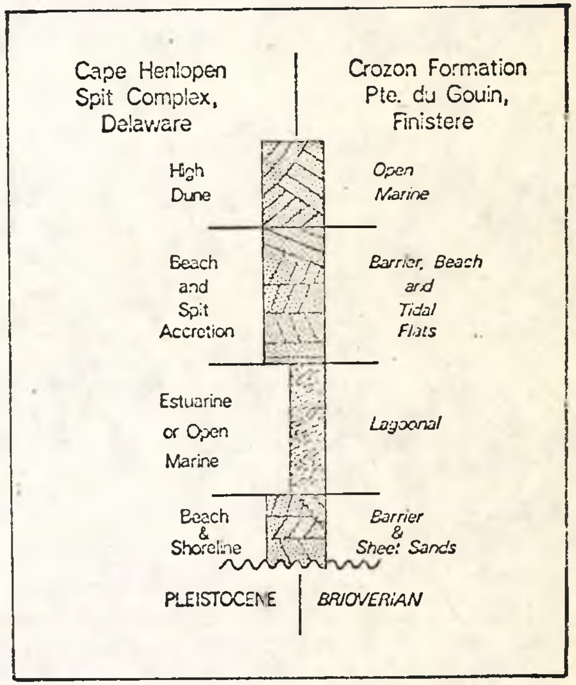

Figure 39

Facies and sequence comparison of Cape Henlopen Spit complex (after Kraft et al , 1973) and the Crozon Formation.

operation of transgressive-regressive couplets. Kraft et al (1973, Fig. 20) record a Holocene sedimentary lithosome from the migrating spit complex at Cape Henlopen, Delaware (Fig.39). As the spit advances in a longitudinal sense as well as by the same process involved in onshore barrier migration, a more complex sequence of facies follows. The Cape Henlopen sequence reflects the migration of the tip of the spit complex over shallow marine or estuarine sediments which had previously followed the underlying transgressive beach and shoreline deposits onshore during the initial stage of transgression.

In the Crozon Formation the lowest part of the transgressive sequence indicates progressive shoaling of shoreward migrating sand waves and are perhaps comparable with the basal shore facies of Cape Henlopen. These are followed by lagoonal facies, corresponding to the estuarine facies of Cape Henlopen spit model. It seems likely that the lagoonal facies was always developed landward of the barrier bar feature until its final removal during facies 5, and was not a lateral equivalent as is suggested for the Cape Henlopen sequence.

A further link with a spit complex origin may be gained from the uniform eastward along-lagoon secondary transport directions. Ebb flows appear to have been largely confined to easterly dipping paleoslopes and the maintenance of this discharge pattern throughout the period of deposition of the heterolithic facies may either have been due to a termination of the barrier system in some form of spit towards the east or to the existence of a stable rip or tidal channel through the barrier chain.

5. CONCLUSIONS

The Crozon Formation is a normal transgressive sedimentary sequence which effectively commenced with coarse breccio-conglomerates of the underlying Telgruc Formation. The basal conglomerate of the Crozon Formation is composed of reworked material from the top of the Telgruc Formation. A chain of barrier sand bars developed from the onshore migration of sub-tidal sand waves and provided protection for a lagoonal environment on the inshore side of the sand bars. Occasional storm activity fed sand and silt over the bars and these storm deposits

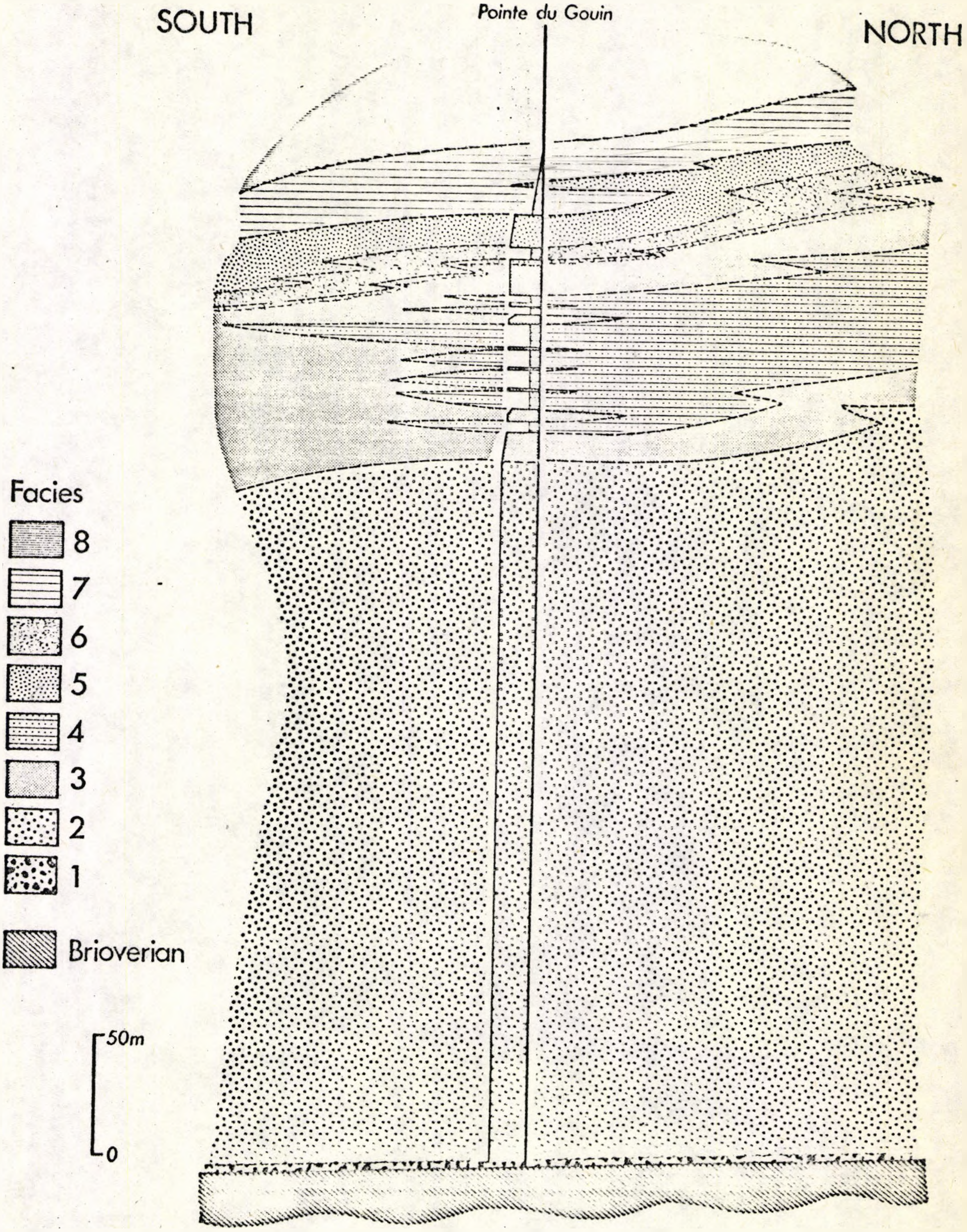

Figure 40
Facies model for the northward transgressive Crozon Formation.
Facies 1 is most proximal; Facies 8 is most distal.

were redistributed by ebb flows within the lagoon.

The protecting barriers were wiped out, possibly by storm action, and transgressed the lagoonal environment to become welded to the shore. Intertidal sand and mixed sand/mud flats were gradually transgressed until they were replaced by open marine shelf muds.

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Explanation of Plate 1

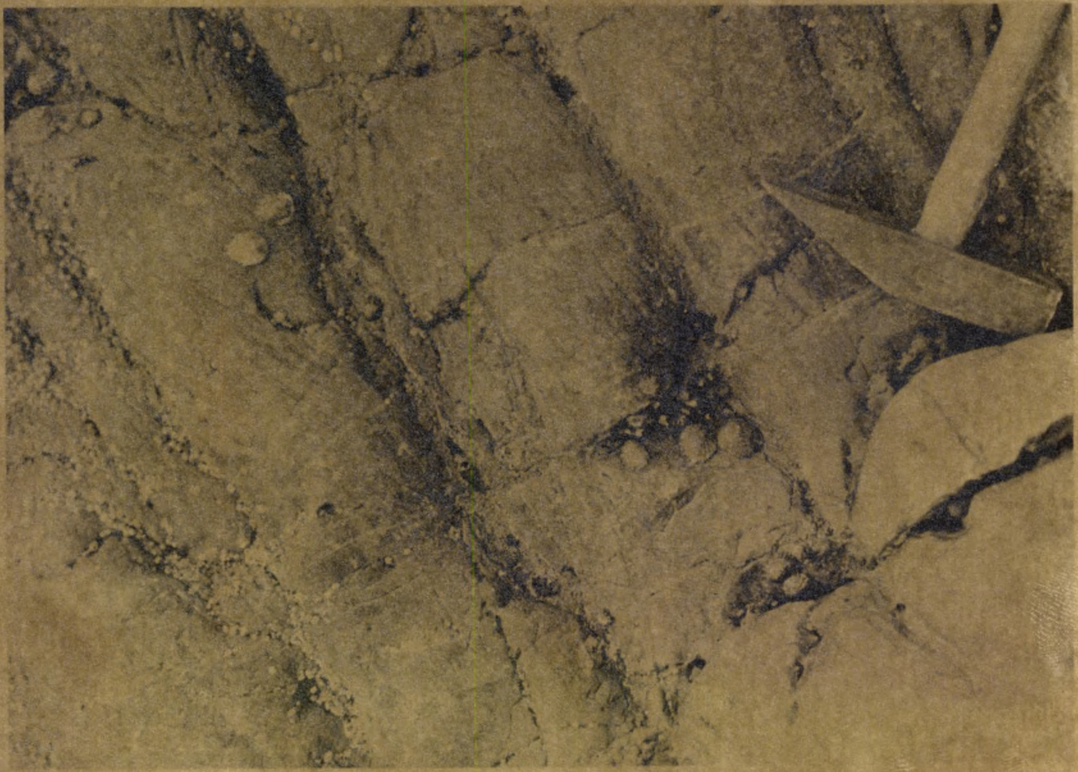
Figure

Facies 3A.

1A. Herring bone cross stratification defined by heavy mineral bands.

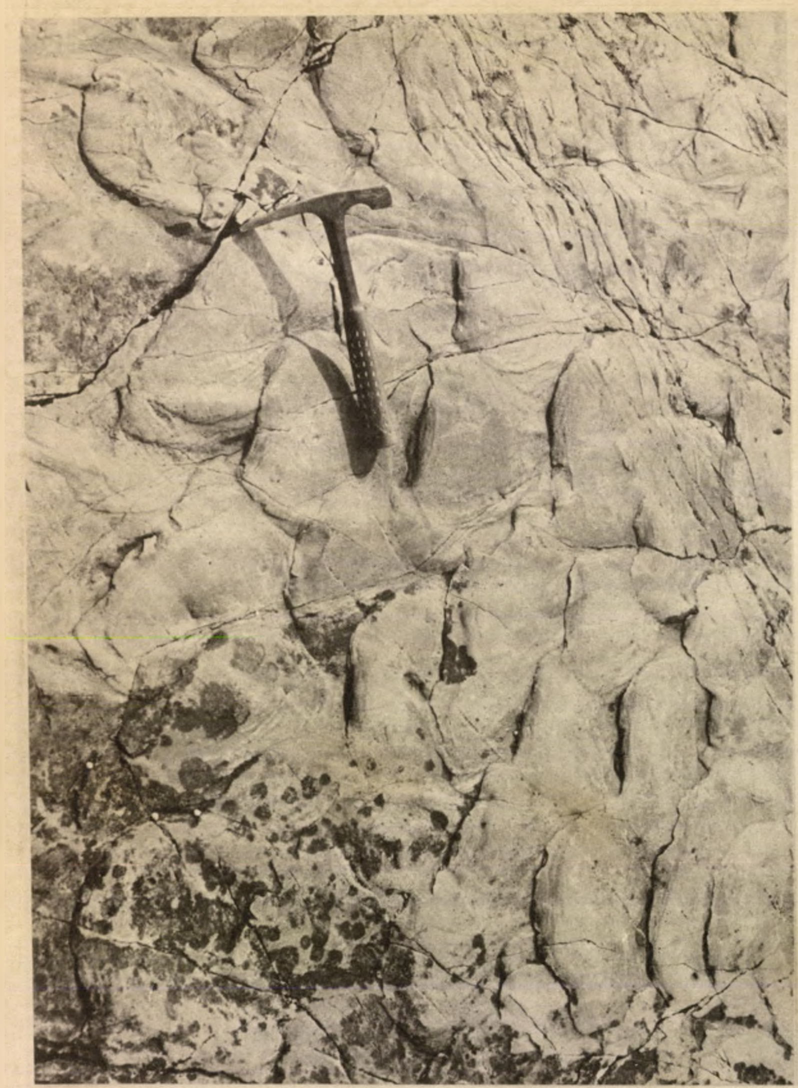
Facies 3B and 4A.

1B. Erosive amalgamation of laminated and rippled facies 3B. Facies 3B passes up by transition into laminated and flasered 4A.



Explanation of Plate 2

Figure	
	Facies 5.
2A.	Arcuate fronted current ripples (centre) in the lee of a low simple, straight crested dune. Straight crested current ripples superimposed at right angles to the slip face of the dune. Linguoid and sinuous crested ripples on dune surface (top). Arcuate ripples pass into linguoid ripples (bottom).
2B.	Slumped linguoid ripples. Lateral equivalent of arcuate ripples in Plate 2A.



Explanation of Plate 3

Figure

Facies 5.

3A. Ladder ripples associated with arcuate rippled surfaces. Symmetrical wave ripples superimposed over current ripples.

3B. Lenticular and channel bedded sands with thin mud interbeds.

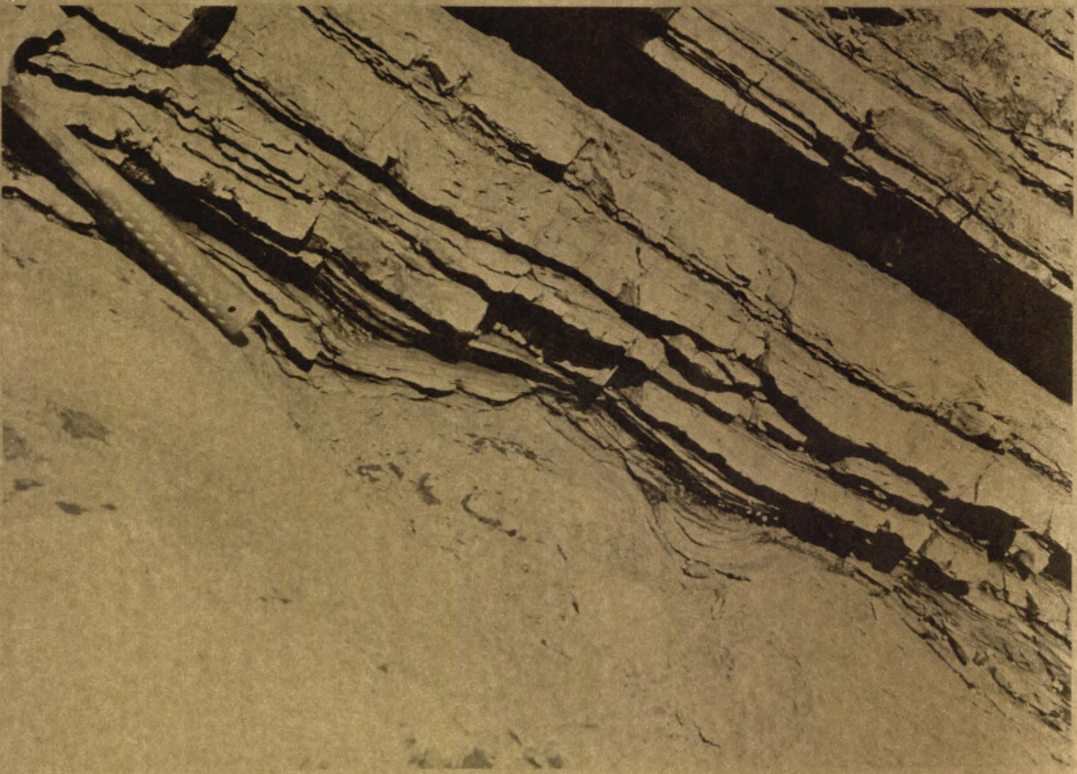
Explanation of Plate 4

Figure

Facies 5 .

4A. Concentration of mud pellets on foresets filling a shallow channel. Channel fill passes up into low angle beach cross-bedding.

4B. Sand mounds covered by draped laminated sands with mud pellets and silts.



CHAPTER 5

TRACE FOSSIL SYSTEMATIC DESCRIPTIONS

1. INTRODUCTION

The trace fossils described in this chapter were recorded from two main sections and seven additional localities on the Crozon Peninsula, western Brittany (Fig. 21). All specimens are restricted to the Crozon Formation (Bradshaw, 1963; see Chapter 4 herein) and their distribution in the Camaret section is shown in Fig. 37

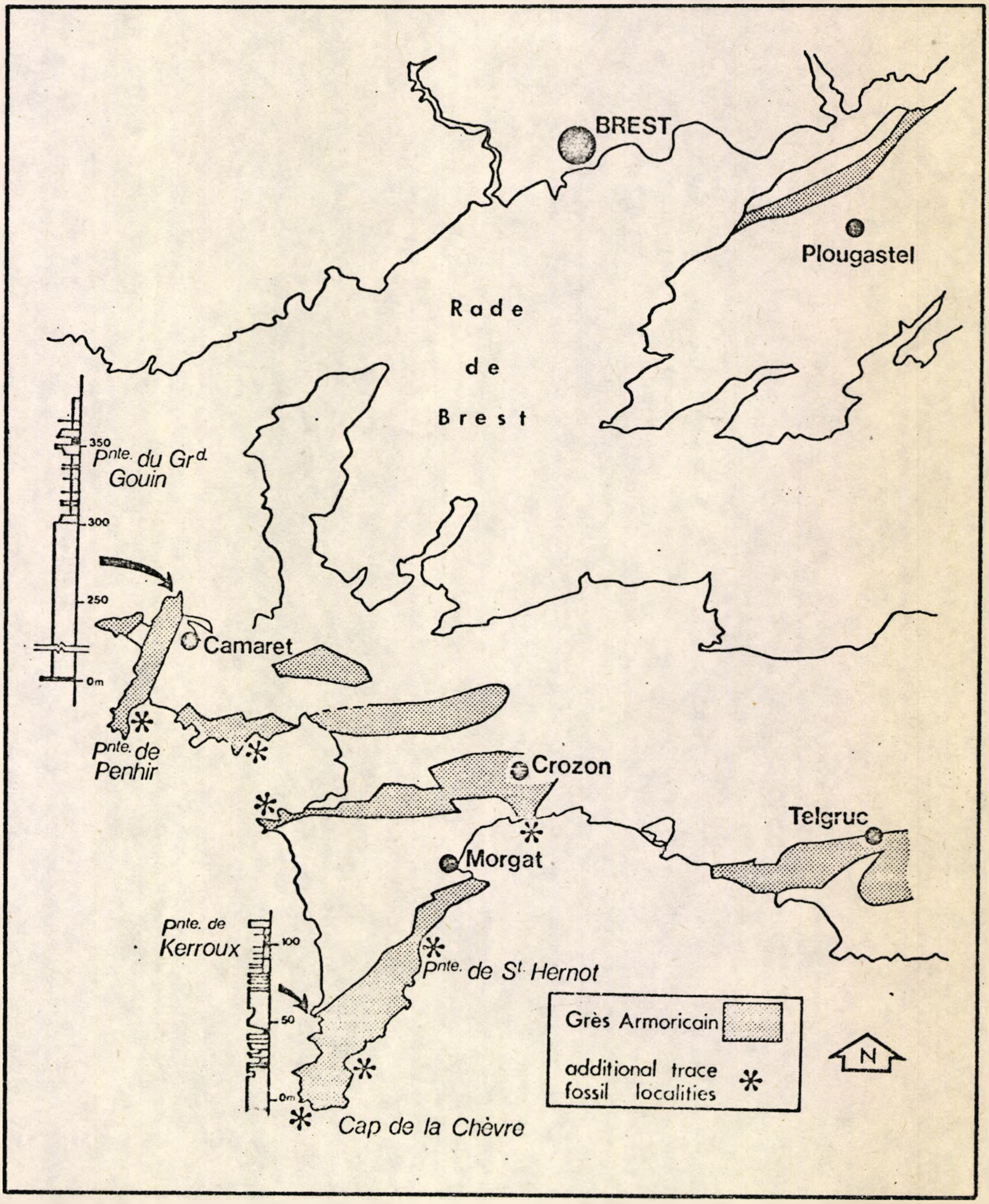


Figure 41
Trace Fossil Localities in the Crozon Region.

2. SYSTEMATICS OF TRACE FOSSILS: FRANCE

Ichnogenus CRUZIANA d'Orbigny 1842

Cruziana gouini sp. nov.

Plate 33

Species name.

After the Point du Grand Gouin, north of Camaret-sur-Mer, Presqu'ile de Crozon, Finistere from which all specimens were collected (Fig. 41).

Material.

Over 20 specimens of variable preservation (Specimen Nos. T901 - T921, British Museum) and at least 25 other specimens studied in situ from the Crozon Formation (Bishop et al, 1969). All are preserved as casts on the sole of a single cross-bedded, silt-pelleted quartzite, on which all are oriented along the current direction as indicated by the foresets of the casting bed (Baldwin, in press).

Syntypes.

Specimen Nos. T 903 and T904 .

Diagnosis.

Trilobite furrowing traces with steep or vertical margins, prominent genal welts and low relief to the lobes. Faint appendage V-impressions are preserved on some traces, and on the anterior and posterior terminations multi-digited claw impressions are preserved.

Description.

The widest specimen recorded is 41mm wide, but widths vary from 17mm with a mean of 26. 5mm. Depths of excavation of the whole band-like traces bears no relationship to the amplitude of the individual lobes, the lobes appearing to be superimposed on the bottom of the rectilinear trough-like excavations. A depth of over 15mm was recorded from a slightly load cast-deformed specimen which was approximately 22mm wide. Genal welts up to 1.5mm wide form the margin to all traces. (For additional description and discussion of the production and preservation see page 136).

On most specimens, appendage V-impressions are faint, but on those specimens on which the V's can be separated they are composed of shallow, multi-digited sets which in places have C. rugosa-like interruptions (Pl.33.1). These dig marks are more prominent on the steep anterior and posterior terminations of the traces (Pl.33.4). If, in these positions, the individual digits of the dig marks are not preserved, these parts of the traces have an appearance similar to C. imbricata; otherwise the multi-digited sets are similar to C. rugosa. On the flatter sections of the traces, the V-impressions are composed of simple, straight, multiple sets with V-angles of 30^o to 50^o.

The current orientation and alignment of all specimens of C. gouini is most pronounced and, where it is possible to determine the anterior end of the trace, this end is without exception directed into the palaeocurrent flow direction (Baldwin, in press). A process of surface excavation followed by filling at the surface has produced cross-bedded fills. The intersection of the inclined lamination produces a surface morphology, to abraded specimens, which appears as pronounced, imbricate lines cross-cutting the trace (Pl.33.1) and which may be confused with excavation morphology.

Discussion.

The current orientation of C. gouini and the presence of cross-bedded fills to the casts supports the surface excavation and casting origins for many Cruziana.

The detail of the individual dig marks preserved on many of these traces suggests that this species could well be associated with C. rugosa. Eight digits may be preserved on C. gouini, but preservation is not good enough to permit certain enumeration. The general form of the dig marks is, however, similar to that typical of C. rugosa. The flat bedding plane parallel sections of the trace are similar to some examples of C. goldfussi collected from the Cabos Series of Asturias, north-west Spain.

The pronounced wall-like and continuous band-form, and the presence of genal welts on all specimens differentiates this species from C. rugosa and C. goldfussi. The maximum width of 41mm further differentiates C. gouini from other members of the Rugosa Group which may range in width up to 200mm.

An Upper Tremadoc or Arenig is indicated by the presence of C. rugosa in laterally equivalent beds in the same section.

Cruziana rugosa d'Orbigny 1842

Plates
25, 26, 27, 28, 29, 34

Material.

22 specimens recovered from all three sections with the section at Pte. St. Hernot furnishing the bulk of the material. Additional specimens recorded in situ in the Kerroux and St. Hernot sections. All recovered specimens are preserved as casts on the soles of thick, medium and thinly bedded quartzitic sandstones. 2 specimens preserved as top surface moulds were recorded in situ.

Description.

Bilobate, trilobite furrows varying in width from 26 to 122mm, mean 84.7mm. Most specimens are deeply excavated but do not have planar, vertical lateral margins. Anterior and posterior margins are characteristically steeply sloping and it is in these two regions that the majority of the detailed morphology is preserved.

Appendage impressions are grouped in sets of 8 and V-angles are variable both between different individuals and along single specimens. V-angles vary from less than 15^o to 125^o with a mean of 60^o. Appendage impressions preserved on the anterior slopes of the Cruziana tend to be oriented almost parallel to the long axis of the trace. The regular ridge-like interruptions which cross-cut the appendage V-impressions impart the characteristic rugosa form of the species and may be raised up to 5mm above the adjacent grooved depressions.

Discussion.

In the United Kingdom C. rugosa is restricted to the Arenig (Crimes, 1970), and from world wide material Seilacher (1970) suggests a Tremadoc to Llandeilo age range for the Rugosa Group, but no specific limit is given for C. rugosa alone. In Asturias and the Cantabrian Mountains of north-west Spain, C. furcifera and C. goldfussi (the other members of the Rugosa Group) occur below C. rugosa and in higher beds in combination with C. rugosa.

Cruziana goldfussi (Rouault) 1883

Plates 30, 31

Material.

6 well preserved specimens from the Kerroux section. Preserved as casts in thin bedded medium and fine quartzitic sandstones which are interbedded with black mudstones.

Description.

Bilobate, trilobite furrows with pronounced and continuous genal welts along the lateral margins. Widths vary from 35 to 89mm, mean 59mm, and depth may be variable along individuals. Appendage V-impressions are, in most cases, nearly straight but are interrupted along their length. Sets are so aligned with each other that they appear to form larger sets which would be too long to have been produced by a relatively simple, single digging stroke. Digging impressions are formed in sets of up to 5 individuals, and the form suggests digits of approximately similar length and shape in each set. V-angles vary from less than 30^{o} to 65^{o}, mean 43.3^{o} and usually remain more or less constant along individuals.

Genal welts are closely connected and sometimes merge with the lateral margins of the two lobes. The individual raised welts may be up to 3mm broad and 2mm high and always mark the extreme width of the trace.

Discussion.

In the Kerroux section *C. goldfussi* is intimately associated with *C. rugosa* and an Arenig age appears probable.

Crimes (1970) indicates an Arenig age for *C. goldfussi* from the Lleyn Peninsula, north Wales, and a Tremadoc to Arenig range is suggested by Seilacher (1970). In north-west Spain, *C. goldfussi* occurs both together with *C. semiplicata* and *C. furcifera*, below the zone with *C. rugosa* as well as with *C. rugosa* at higher stratigraphic levels. An Upper Cambrian (Tremadoc) to Arenig age range is supported.

Cruziana furcifera d'Orbigny 1842

Plates 31, 32

Material.

8 well preserved specimens from all three localities. Preserved as casts on the soles of medium and thick bedded quartzites.

Description.

Bilobate, trilobite furrows without genal welts and without the pronounced irregular annulations of *C. rugosa*. Recovered specimens are characteristically of a rounded form with widths varying from 6mm to 70mm, mean 42.6mm. Appendage V-impressions are grouped in sets of up to a maximum of 8 individual digits. Digging strokes form siculate patterns with the distal and proximal portions being oriented at lower angles to the median axis of the whole *Cruziana* than the central section. V-angles vary from 10° to 67° with a mean of 38.5°. Variation along the length of a single specimen is common.

Most specimens are deeply excavated and on two examples, low, vertical surfaces form the lateral margins indicating furrowing below the depth at which the appendages could extend from the sediment surface.

Discussion.

C. furcifera has been recorded from the Arenig of the United

Kingdom, Newfoundland and Iberia (Seilacher and Crimes, 1969).

The presence of C. furcifera with C. semiplicata in north-west Spain suggests that the range of C. furcifera may include the Tremadoc. Species of Cruziana transitional between C. semiplicata and C. furcifera as well as species with strong affinities with C. furcifera have been recorded from the Tremadoc of Gloucestershire (Crimes, 1975).

Ichnogenus RUSOPHYCUS Hall 1852

Rusophycus didymus Salter 1853

Plate 33.4

Material.

Numerous specimens from a single bed in the Crozon Formation, Camaret section, preserved on the sole of a cross-bedded quartzite. Associated with species of Cruziana and Rusophycus which are one or two orders of magnitude greater in width than the R. didymus.

Description.

Small, bilobate traces less than 8mm long, varying in width from 3mm to 8mm and less than 3mm deep. No surface morphology preserved on any part of the lobes. Each lobe expands slightly towards one end and gapes slightly wider apart in the same direction. The long axes of these traces are more or less randomly oriented.

Discussion.

The production and preservation of these traces is discussed in Chapter 6 , page 153. The current assisted excavation hypothesis of Birkenmajer and Bruton (1971) seems inappropriate, and conventional active limb processes of excavation in weakly cohesive mud are proposed.

The shape factor (length:width ratio) of 1.25 is more typical of Upper Cambrian species of Rusophycus, but the presence of C. rugosa in equivalent beds nearby in the Crozon Formation indicates an Arenig age for these particular traces.

Rusophycus carleyi (James) 1885

Plates 34, 36

Material.

Three well preserved specimens plus seven other specimens recorded in situ in the Camaret section. Preserved as casts on the sole of a thick, cross-bedded quartzite. Associated on the same bedding surface with numerous C. gouini sp nov and R. didymus.

Description.

Bilobate trilobite resting impressions with the two lobes either joined medially or separate. In forms in which the lobes are distinctly separated two pairs of at least eight nodes and corresponding depressions are present along the inside edge of the two lobes. In most specimens the lobes are relatively smooth with no regular pattern of digging impressions preserved. Specimens in which digging strokes can be identified suggest a directly medially directed digging stroke rather than the medio-posterior stroke of most other Cruziana and Rusophycus.

Widths vary from 34 to 70mm, mean 65.8mm, and shape factors range from 1.6 (shallow, possibly incomplete form) to 2.2 with a mean of 2.0. The flat, medial zone between the two lobes may occupy up to a third of the total width of the trace.

The specimens showing the most morphological detail between the two lobes tend to be elliptical in shape, whereas the more deeply excavated forms, in which the lobes merge, taper more sharply at one end, presumably the posterior.

No genal welts appear to be present.

Discussion.

James (1855) interpreted R. carleyi from the Upper Ordovician of the Cincinnati area of the U.S.A. as the burrows of isotelid trilobites. Osgood (1970) confirmed James' proposal and suggested, on the grounds of conformity of size, that Isotelus was the trace maker.

The nodes present between the two lobes appear to correspond to the impressions of coxae or proximal podomeres and conform in number to those on C. carleyi from the Cincinnatian material (Osgood, op. cit., p. 306).

Bradshaw (1963) and Seilacher (1970) described R. carleyi from the Camaret section.

Rusophycus moustachei ichnosp. nov.

Plates 35.3, 35.5

Species name.

From the moustache-like appearance of the complete trace.

Material.

One recovered specimen and two other partially incomplete specimens recorded in situ in the Pte. St. Hernot section, Cap de la Chevre. All specimens are preserved as casts on the sole of a very thickly bedded white quartzite.

Holotype.

Specimen No. T1003, British Museum.

Diagnosis.

Trilobite resting traces, formed from two medially separated arcuate lobes which taper towards the lateral margins.

Description.

The holotype is 126mm wide, with a 6mm gap between the two lobes. At the median edge of the lobes (= the broadest part) they are 35mm wide and the right hand lobe tapers in a curve approximately 80mm long to less than 12mm in width. (The left lobe appears to be incomplete.) Indistinct scratch markings are preserved on one of the specimens recorded in situ. These run in a curve, rougly parallel to the long edge of one of the lobes, but unfortunately, due to poor preservation, it is impossible to determine whether these marks represent medially directed digging strokes or the terminal withdrawal portions of posteriorally directed movements.

The two specimens recorded in situ (Pl. 35.5) are positioned one behind the other and appear to have been produced by the same trilobite. Both are tightly curved and taper to a point at the lateral margins.

Discussion.

R. moustachei is associated with examples of C. rugosa which are of the same order of width as the Rusophycus (see page 112). The form of the curve of the two specimens recorded in situ is similar to that seen on the anterior, steep edges of most of the C. rugosa. It appears probable that the convex side of R. moustachei represents the anterior edge of the trace. The recovered specimen is not as tightly curved nor are the lateral margins posteriorally directed as on the other two specimens, but, while it still appears analogous to the anterior portions of C. rugosa, it lacks the 8 digit sets of appendage scratches. However, R. moustachei may correspond to an abbreviated form of C. rugosa, possibly excavated by a single pair of anterior appendages which produced little or no forward movement of the trace maker. The relatively abbreviated distance across the individual lobes of C. moustachei differentiates this species from C. cantabrica Seilacher (1970) which is composed of more complete and clearly impressed lobes.

Rusophycus morgati ichnosp.nov.

For details of R.morgati see Chapter 2, page 95.

Ichnogenus DIPLICHNITES Dawson 1873

Diplichnites sp.

Plate 35

Material.

Numerous tracks studied in situ in the Camaret section where they are preserved on the top surface of a linguoid rippled sand bar (see Chapter 4 , Facies 5).

Description.

Trilobite tracks up to 20mm wide, composed of two parallel sets of imprints each of which, in most cases, is gently curved and oriented more or less at right angles to the linear extension of the track (Pl.35.4). In two specimens the regular linear pattern is broken down and the imprints appear partially superimposed. Spacing of imprints is not regular along the length of individual tracks, but most tend to be spaced at approximately 2mm intervals.

All specimens are preserved superimposed on large scale linguoid ripples which in many cases have oversteepened and partially slumped lee surfaces. These ripples are themselves superimposed on larger scale sand wave features, so that considerable micro (ripples) and macro (sand wave) topography was present when the tracks were formed. The effects of this topography are reflected in the changes in morphology of the imprints of the Diplichnites which on the gently sloping stoss sides of the ripples are relatively simple: in the form of crescent or straight depressions approximately 3mm long. Where the trails encounter the steeper lee sides of the same ripples, the imprints become expanded in the direction of the track extension and pronounced ridges of sand (cf. withdrawal markings, Osgood, 1970, p. 351 & 354, Fig. 18). These ridges appear to have been formed by the pushing back of the sediment due to gravity and the exertion of climbing the steeper slopes. Similar modifications to Limulid tracks were reported by Caster (1944), and he suggested that beach slopes accounted for this type of variable morphology.

Discussion.

Osgood (1970) described tracks similar to this French material from the Cincinnatian (Middle Ordovician) of the U. S. A. Due to the apparent lack of precision of Dawson's original description and diagnosis of Diplichnites, Osgood chose to retain the parochial terminology already established for the wide range of associated tracks by Miller (1880). Consequently such tracks were named Petalichnus, and other more or less similar examples from which trace/trilobite correlations could be made were afforded separate generic designations. Osgood (op. cit., p. 362) acknowledged that these separated genera would effectively be in synonymy with Petalichnus and similarly that Petalichnus is probably synonymous with Diplichnites.

Seilacher (1955) discussed the variability and genetic relationships of Diplichnites and effectively restated and redefined Dawson's designation of the genus. Hantzschel (1962) followed Seilacher's amplification of Dawson's original work.

The Diplichnites recorded in the Camaret section represent fortuitous preservation as they are in what, sedimentologically, appears to have been a highly active environment with bed form migration. The tracks were obviously formed post this period of active sediment transport, but no indication is present to suggest that the tracks were formed below a mud or silt cover in the form of undertracks (cf. Osgood, op. cit., p. 354, Fig. 19).

Ichnogenus ARTHROPHYCUS Hall 1852

Arthrophycus sp.

Plate 37

Material.

Extensive material studied in situ in the Camaret section. Preserved as casts on the sole of a single 0.75m thick, poorly sorted quartzitic sandstone.

Description.

Individual and bunched wall-like and cylindrical traces up to 28mm in diameter with indistinct annulations. Only two specimens showed a distinct bilobate form and both these had pronounced annulations.

Bundled specimens tend to be relatively straight and are usually less than 200mm long. Most of this form is preserved higher in the bed than the individual forms. Ramification of the multiple sets is usually confined to one end of the set. Individual traces may be up to 0.4m long and wind, cross-cutting themselves and at all angles. Ring-like forms up to 0.25m in diameter may be produced by the spiralling of these individual Arthrophycus.

The bedding surface studied is composed of a mat of Arthrophycus which imparts a distinctly mottled texture to the top of the trace bearing layer. The bulk of the lower specimens (hence the specimens most carefully studied) appear to be uniformly greater in diameter than the higher, intermeshed specimens.

Discussion.

The specimens which could be studied in detail represent the most deeply excavated individuals and appear to be the largest in width and diameter. It thus appears that the largest trace makers were able to burrow the deepest into the mud layer. If these structures represent galleries of sediment feeders (Seilacher, 1955), most individuals were restricted to mining only a relatively small distance (c. 75mm - 120mm) into the mud layer. Exceptionally large burrowers were able to extend down beyond this depth and into a zone of reduced competition so that the grouped, ramifying burrow system was not required and food supply could be exploited by randomly winding burrow systems.

Ichnogenus DAEDALUS Rouault 1850

Daedalus desglandi (Rouault) 1850

Plate 39

Material.

5 well preserved specimens from the Kerroux section plus additional extensive material studied in situ. Specimens are preserved as full relief casts in ripple and wavy laminated fine sandstones and interbedded muds and fine silts.

Description.

Meandering and sinuous wall-like traces, the loops and spirals converging upwards to form truncated, crudely conical structures.

In bedding plane sections the traces appear as low, band-like, meandering and spiralling traces, the bands being up to 4mm wide. Diffuse, straight and slightly curved spreite cross-cut the bands at high angles. In sections normal to bedding it can be seen that the band-like traces continue into the bed, more or less at right angles to the bedding surface, so that conical and convergent ring-wall structures up to 60mm deep are preserved. The spreite seen in the bedding plane sections are preserved as regularly spaced but continuous annulations or ridges which extend to the full depth of the wall structures (Fig. 42a).

D. desglandi is confined to the laminated fine sand beds, the interbedded laminated fine silts and muds being only bioturbated and destratified. Interbeds of flasered and linsened sands, muds and silts are burrowed and heavily destratified by numerous discontinuous and chaotic D. desglandi.

Discussion.

Daedalus Rouault (1850), Vexillum Rouault (1850) and Humilis Rouault (1850) were proposed for various forms of the same trace (Rouault, 1883). The three genera represent (1) continuous wall-like traces (Daedalus), (2) spiral - conical and J-shaped traces (Vexillum) and (3) band-like meandering traces seen on bedding planes (Humilis) (Fig. 42a).

Vexillum Rouault is invalid on the grounds that this name was previously used by Bolten-Rodig for a gastropod (Bolten-Rodig, 1898), and as the daignosed genus in fact corresponded to a spiral form of Daedalus, Vexillum was additionally invalid on grounds of duplication (Lessertisseur, 1971). Sectioning of material demonstrates the continuity and equivalence of the three 'genera', so that only one generic name is required. Daedalus represents a complete trace and hence appears more pertinent than Humilis.

These French specimens of D. desglandi appear similar in form to Dictyodora Weiss, but differ in the greater width of the individual walls and in the degree of complexity of cross-cutting and meandering,

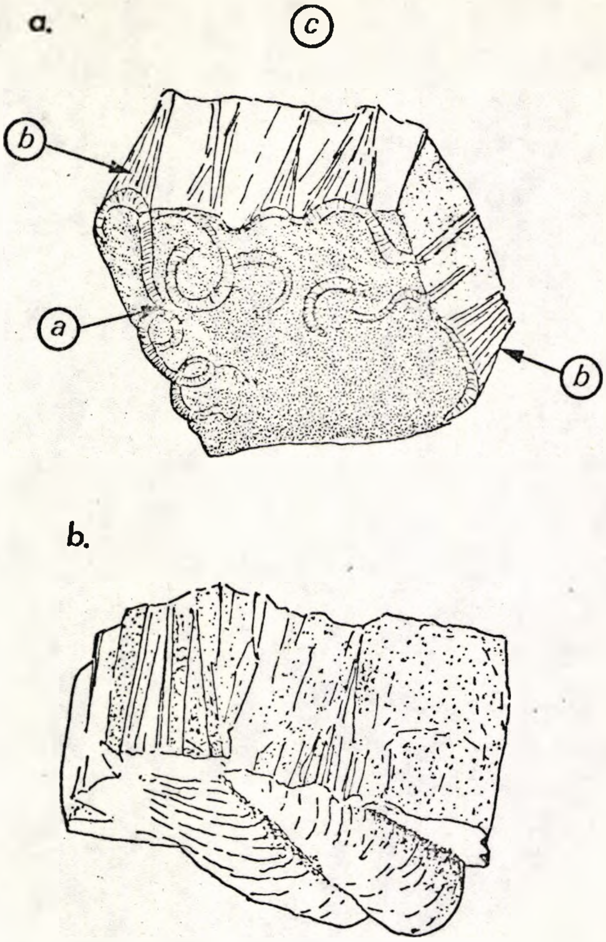


Figure 42

a. The relationship of the three ichnogenera: a) Humilis (nomen invalididium); b) Vexillum (nomen invalididium); c) Daedalus.

b. Orientation of Daedalus (tapers upwards) from a Cruziana on same bed (redrawn from Lessertisseur, 1955, Plate IX, Figure 9).

Dictyodora being extremely complicated. The spreite preserved on D. desglandi and their continuation up the wall of all the traces indicates a probable mode of formation similar to that suggested by Seilacher's reconstruction of Dictyodora (Seilacher, in Hantzschel, 1962, Fig. 119. 2, p. W194), whereby the conical, ring-wall structure is formed from the addition of a series of backfilled, overlapping tubes.

Daedalus labechi (Rouault) 1850

Plate 40

Material.

A single well preserved specimen from the Kerroux section and three other specimens studied in situ in the Camaret section. Preserved as full relief silty traces in thick bedded orthoquartzite.

Description.

Curved or partly spiralling, sheet-like traces composed of spreite which spread from a single point at or near a bedding surface and which diverge and curve downwards.

On bedding plane exposure the traces appear as low curved, or circular mounds with an irregular apical depression and pronounced, partially radiating, spreite disappearing into the underlying bed (Pl.40.2). The traces are formed as relatively sharp walled excavations with a silt and clay rich fill.

Discussion.

D. labechi is similar to the lamina forming the helical spirals of Spirophyton and Zoophycos (Simpson, 1970, p. 507), but in D. labechi the spreite tend to be more coarse and lack associated lamelae. Similarly the sheets of D. labechi are characteristically at high angles to the bedding surface with the strongly curved end of the spreite extending almost vertically below the apical point (Pl.40·2).

Ichnogenus RHIZOCORALLIUM Zenker 1836

Rhizocorallium sp.

Material.

2 specimens studied in situ in the Camaret section. Preserved as shallow full relief casts on the upper surface of rippled, thick bedded quartzite. Possible casts of desiccation cracks are present on the same surface suggesting the presence of a pre-existing mud layer, below which the Rhizocorallium were excavated.

Description.

Horizontal spreite filled U burrows over 200mm long by 25mm wide. Only the central portions of the burrows are preserved, the steeper sections having been removed during the stripping away of the superincumbent bed. The U tubes are less than 1. 5mm in diameter and the standard of preservation is insufficient to allow the determination of striae on the tubes.

The spreite portions between the main U tubes are formed from silty, ill-sorted sand which is friable and contrasts with the surrounding completely cemented host rock.

Discussion.

Hantzschel (1962, p. W210) suggests that Rhizocorallium is a combination of dwelling and feeding structures, the latter being the more or less horizontal part. The presence of desiccation crack casts fixed to the surface on which the Rhizocorallium are preserved suggest that the dwelling section may have been present in the, now removed, mud layer, while the feeding section was confined to the sand layer. Sorting, and possibly incorporation of dwelling burrow material fixed to the burrow walls, could have produced the textural difference between the spreite and the host rock.

Ichnogenus COROPHIOIDES Smith 1893

Corophioides (?)luniformis (Blanckenhorn) 1916

Plates 37, 38

Material.

Extensive well preserved material studied in situ in the Kerroux and Camaret sections. Preserved as full relief burrows in thick and thin bedded rippled quartzites. Studied material was restricted to bedding plane sections.

Description.

Vertical U tubes with protrusive spreite. Due to the available exposure, it is difficult to determine in detail the form of the U, but all specimens in which the apex of the U could be seen appear to lack any form of extension of the vertical sections of the tubes and seem to remain simply curved and unmodified. The U tubes, approximately 5mm in diameter, are quartx filled (? druzy), while the spreite bearing zones between the limbs of the U and a zone approximately 1. 5mm wide around the margins are formed from mud and silt grade sediment. The spreite is defined by pale coloured, medium silt laminae.

Discussion.

Smith (1893) supposed that Corophioides were constructed by animals similar to the Recent filter feeding amphipod, Corophium, and contended that the U in U form of the burrow (= spreite) reflected an extension of the burrow system in order to accomodate an increase in body size.

Osgood (1970) has discussed Upper Ordovician examples of Corophioides and reviewed the historical development of the genus. He (op. cit., Fig. 7, p. 321) in part supports Smith's (1893) contention that the U burrow system represents an accomodation of body size increase of the trace maker. Consequently the diagrammatic reconstruction of U tube morphology provided by Osgood (op. cit., Fig. 7C & 7D, 2 & 3) shows the zone of inter-U protrusive spreite to be narrower than the diameter of the U tube. This suggests that the spreite represents the period of burrowing when the burrower had a relatively small body size, and that the greater diameter of the U tube represents the final maximum body size prior to death or evacuation of the burrow.

In the French material studied, the spreite zone is always as great or greater in width than the diameter of the U tube. The spreite are still of the protrusive type so that the body size mechanism discussed by Osgood does not seem applicable. Possible Diplocraterion type of escape mechanisms, similar to those discussed by Goldring (1971) in which retrusive and protrusive spreite are produced respectively in response to deposition and erosion, may account for the protrusive spreite of Corophioides. Osgood (op. cit., p. 321) supports this response mechanism for this Cincinnatian species of C. aff. luniformis.

The sandstone zone surrounding two specimens of Corophioides does not seem to be simply related to the normal spreite producing processes. Diageneitc mechanisms seem improbable, but absence of cross-sectional exposure makes discussion difficult.

Ichnogenus ARENICOLITES Salter 1857

Arenicolites sp.

Plate 38

Material.

Numerous specimens studied in situ in the Camaret section and additional material in the same section studied in loose blocks. Preserved as full relief burrows in medium to thickly bedded sandstones and orthoquartzites.

Description.

Simple, vertical U tubes without intervening spreite, mostly studied in bedding plane sections where they appear as paired tubes which are not linked by any morphological feature. In most specimens the U tube is filled with sparry quartz, and is surrounded by a slightly silty, ill-sorted and concentrically laminated zone up to 8mm in diameter which tends to weather preferentially to shallow ring-like depressions (Pl.38.4). The U tubes rarely exceed 4mm in diameter.

The varied impressions seen on bedding surface exposure may be spaced up to 45mm apart, but examples in which the two impressions interfere with themselves and with another single impression (? Skolithos) are present on the same surface. There appears to be no preferred orientation to the burrows.

The single, isolated burrows present on the same slabs are identical in bedding plane morphology to the U burrows.

Discussion.

Arenicolites has been considered homologous with the feeding tubes of the Recent polchaete Arenicola marina (Lamarck), but, as has been pointed out by Osgood (1970) and others, the tubes of Arenicola tend to be J rather than U shaped and exhibit collapse structures at the feeding end (cf. Schafer, 1972, p. 302, Figs. 174 & 175). The open part of the tube (faecal tube, Schäfer, op. cit., p. 302) tends to be agglutinated so that it can remain open during the period of residence of the Arenicola. There appears to be no morphological differentiation of the two limbs of the U tubes in the French material studied so that a direct link with Arenicola seems unlikely. It is possible that the preserved bedding surfaces on which the Arenicolites were observed represent levels of erosion sufficiently low to intersect the two open limbs of the U, but, as no noticeable flaring or scouring around the tubes can be seen, this seems unlikely. Similarly, both parts of the tube are concentrically rimmed with finer sediment and this contrasts with the support only of the faecal section of the tube of Arenicola.

The similarity of the Skolithos and Arenicolites suggests that their production may have been carried out by the same organism. Possibly the Skolithos represent only partially excavated Arenicolites.

Ichnogenus SKOLITHOS Haldeman 1840

Skolithos linearis Haldeman 1840

Material.

Extensive material studied in situ in the Camaret section and also throughout much of the lower 250m of the Telgruc Formation. Preserved as full relief burrows in thick and medium bedded orthoquartzitic sandstones.

Description.

Simple unbranched vertical tubes, less than 7mm in diameter and extending for up to 0.45m and often completely through sandstone beds. In the lower part of the Telgruc Formation, bedding planes are often almost totally eradicated by extensive closely packed burrows, both above and below the pre-existing bedding plane. An often silty, chaotic, pipey textured zone marks most bedding surfaces. In the Camaret section less densely packed S. linearis are common in facies 2, 5 and 6. Central cores of drussy quartz fill indicate crystallisation into voids. Narrow depressed, slightly silty, rings, a few mm greater in diameter than the quartz cores, mark the margins of the burrows in bedding plane sections, and also parallel the full length of the burrows in sections normal to the bedding planes.

Discussion.

In the Telgruc Formation the density of burrows below bedding planes suggests periods of very slow or even non-deposition of sufficient duration for the almost complete colonisation of the surfaces by burrowing organisms. The similar density of burrows across and above such bedding planes possibly indicates an escape response (Schäfer, 1972; Hallam and Swett, 1966) of the burrowers following the ingress of sand. The decline of bioturbation away from the bedding planes may indicate that the ingress of sediment was relatively slow at first, permitting burrowing and bioturbation to keep pace with sedimentation. This was apparently followed by an acceleration of the rate of sediment ingress so that burrowing organisms were restricted to isolated escape burrows and their associated low bioturbation and destratification values.

Ichnogenus TIGILLITES Rouault 1850

Tigillites dufrenoyi Rouault 1850

Plate 40

Material.

3 well preserved specimens recovered from the Camaret section and other material studied in situ. Preserved in find sands and silts interlaminated with mud.

Description.

Simple unbranched, vertical tubes which expand to form funnel shaped openings at the intersection with the upper bedding plane. The tubes are less than 4mm in diameter and the funnels are up to 26mm in diameter at the surface, tapering down to the normal tube diameter over a distance of 20mm. All beds containing T. dufrenoyi are less than 100mm thick and most tubes extend to the full thickness. The funnels are composed of concentrically stacked inverted conical laminae which, in section (Pl.40.3), have the appearance of diffuse spreite. On the surface the traces appear as a number of concentric rings with a more prominent raised nipple-like feature at the centre of the rings. Most tubes are spaced at least 20mm apart.

Discussion.

Selley (1970) described identical trace fossils from the Palaeozoic sandstones of Jordon, but named them Sabellarifex dufrenoyi (Rouault). In the discussion of these traces Selley (op. cit.) acknowledged that some of his burrows fall into the ichnogenus Tigillites, but, apparently due to the presence of non-funnel top forms, the Sabellarifex designation was chosen.

Hallam and Swett (1966), in a discussion of similar structures from the Lower Cambrian Pipe Rock of north-west Scotland which they named *Monocraterion* (Torrel), chose to disregard the Treatise designation of *Monocraterion* as a junior synonym of *Tigillites* Rouault (Hantzschel, 1962). They argued that *Monocraterion* was more rigorously diagnosed than Rouault's description of *Tigillites*.

T. dufrenoyi differ slightly from the figured material of Hallam and Swett (*op. cit.*, Pl. 1, Figs. 4 - 6), in that the funnels of this French material are formed from laminae which are discrete from any of the adjacent primary sedimentary laminae, and in fact appear to cross-cut all sedimentary laminae (Pl. 40.3). In Hallam's and Swett's specimens, the funnels are formed from deflected and/or modified sedimentary laminae, and these differences suggest distinct ethological interpretations. The interpretation of *Monocraterion* given by Hallam and Swett (*op. cit.*, p. 104 -105) suggests that the funnels are formed from the peripheral collapse of sedimentary laminae into the vertical burrow during an escape response (i. e. rising in the burrow) resulting from burial of the burrower and burrow structure (cf. Schafer, 1962, p. 325 - 327). The association of *Skolithos* with *Monocraterion* in the Pipe Rock led Hallam and Swett to propose that these two traces could have been produced by the same organism, and that *Skolithos* represents the burrows created during periods of negligible sedimentation. From Hallam's and Swett's figured material the funnels of their *Monocraterion* appear more closely related to the collapse feeding cones of *Arenicola marina* figured by Schafer (1971, p. 302, Figs. 174 & 175).

The funnels of *T. dufrenoyi* do not appear to be passive fill structures, so that the ethological interpretation of *Monocraterion* would seem inappropriate. The genetic association of *Tigillites* and *Skolithos* is possible, but in this case *Skolithos* would represent truncated (i. e. eroded) *Tigillites*. The laminae present in the funnels may correspond to the fixed wall structures of *Skolithos linearis*, and may in fact reflect a stabilisation of the sediment *around* the burrow orifice so that sediment could be prevented from washing in.

Ichnogenus PLANOLITES Nicholson 1873

Planolites cf. vulgaris Nicholson & Ethridge 1875

Plate 36

Material.

1 specimen recovered from the Kerroux section plus additional material studied in situ in all sections. Preserved as full relief burrows composed of ill-sorted and often pyritic silt and fine sandstone.

Description.

Simple, usually horizontal, unbranched cylindrical burrows which differ slightly in lithology and texture from the surrounding host sediment. They vary in diameter from approximately 3mm to just over 12mm.

The recovered specimen (No. 153) extended parallel to bedding for over 150mm, but at one end turned at right angles to penetrate the bedding plane. Faint irregular annulations are present on the inside of the right angle bend. Elsewhere the cylindrical burrow is unornamented.

Specimens of Planolites continuous for a distance in excess of 0.2m could be traced in the Kerroux and Camaret sections. Both straight and winding forms are present, many crossing and recrossing themselves and other individuals.

Discussion.

P. cf. vulgaris has a cosmopolitan distribution in all three sections. The single specimen, which includes a short vertical section, suggests the penetration of the sediment feeding organism (? annelid), possibly to the level of a food containing 'seam' which was then exploited by horizontal burrowing.

Ichnogenus TAPHRHELMINTHOPSIS Sacco 1888

Taphrhelminthopsis cf. recta Sacco 1888

Plate 36

Material.

Numerous specimens studied in situ in the Camaret section and preserved on the upper, linguoid rippled surface of a sand bar. Associated on the same bedding surface with Diplichnites.

Description.

Continuous bilobate trails, approximately 10mm wide, which wind and cross-cut themselves and other individuals. The trails stand up to 3mm above the local bedding surface, and in most specimens the two lobes are separated medially by a flat or gently concave-up area up to 2mm wide. The lobes may extend fully to the lateral margins of the trail or stand in from the margin by up to 1.5mm, in which case the lateral margins slope steeply away from the outside edge of the rounded lobes (Pl.36 4). No annulations or striae are present either on the lobes or in the medial depression.

Discussion.

The general form of the trails studied is similar to Scolicia de Quarterfages, but the distinct and diagnostic ribbing of Scolicia is absent. The preservation of extremely fine detail on adjacent Diplichnites suggests that the absence of such ribbing may be related to production and not to preservation.

Trails similar to the Camaret material are figured and described by Ksiazkiewicz (1970, p. 290 - 293, Pl. 2) from the late Mesozoic and Cenozoic flysh of the Polish Carpatian Mountains. Most of this material is preserved as sole casts, but similar forms are found on the top surface of sand beds (Ksiazkiewicz, op. cit., p. 292).

An apparently similar form of trail was described by Cowie and Spencer (1970, p. 94 & 97, Pl. 2C) from the Lower Cambrian Bastion Formation of Ella Island, East Greenland. There is ambiguity as to the way-up of the figured specimen, but it probably represents a sole cast. Glaessner (1969, Figs. 9B & 9C) illustrates similar traces and interprets them as the result of activity of a 'mollusc-like organism', but again the material is preserved as sole casts.

Ichnogenus PHYCODES Richter 1850

Phycodes palmatum (Hall) 1852

Plates 34, 35

Material.

Numerous specimens studied in situ high in the Camaret section and a single specimen recovered from the Kerroux section. Preserved as full relief, fine sand filled burrows, usually in medium and fine sandstones interbedded with muds and fine silts.

Description.

Branched, broom-like traces composed of up to 5 wall-like limbs diverging from an indistinct master shaft. The limbs contain retrusive spreite, but the main apical shaft lacks any internal structure. Overall lengths vary from 35mm to approximately over 90mm, and widths of individual limbs from 3mm to approximately 10mm with a depth of up to 12mm.

The limbs of P. palmatum curve in the vertical plane, curving down into the sand bed, but returning almost to the same level at their distal termination. Little divergence of limbs is present, most remaining closely bunched throughout their length.

Discussion.

P. palmatum is confined to the off-shore mud facies in the Camaret section and is so rare in the Kerroux section that no generalisation as to facies specificity is possible. The French specimens lack the size, complexity and number of terminal tubes present on the Lower Cambrian specimens described by Seilacher (1955) from the Salt Range of Pakistan, but the form is comparable with a single unit of the material figured by Seilacher (op.cit.).

PART 3

TRACE FOSSIL PRODUCTION AND PRESERVATION

CHAPTER 6

TRACE PRODUCTION AND PRESERVATION: A GENERAL DISCUSSION USING THE RUGOSA GROUP

The following chapter includes a paper accepted for publication in Palaeo^3.

1. INTRODUCTION.

The genetic connection between trilobites and the large numbers of tracks and trails (Cruziana, Monomorphichnus, Rusophycus, Dimorphichnus and Diplichnites) typical of palaeozoic shallow marine sediments has been the subject of a considerable literature. Most of these works are included in the bibliographies of papers on trilobite ichnoceoses read at the International Conference held in Liverpool in 1970 (see Crimes and Harper, 1970). More recently Osgood (1970) and Bergström (1973) have reviewed this literature. Many of the papers cited are concerned only with the stratigraphic uses of traces, in some cases naming them only as heiroglyphs so that they are discussed as purely passive markers with no concern for their mode of origin, ethological value or value as indicators of environmental conditions. While the intrinsic value and stratigraphic index utility of these traces is accepted, more detailed analysis of their genesis and preservations seems worthwhile.

It is only in more recent works that the methods of production and subsequent preservation have been dealt with (e.g. Seilacher, 1955, 1962, 1970; Crimes, 1969, 1970a & b, 1975; Bergström, 1969, 1972, 1973; Osgood, 1970 and Birkenmajer and Bruton, 1971). However, even now there are still some difficulties, inconsistencies and opposing ideas.

In order to contribute to this discussion, large collections of trilobite trace fossils of Cambro-Ordovician age from Brittany, the Cantabrians and Asturias, north-west Spain and from the Welsh Borderlands of the United Kingdom have been made. Further material has been studied at the University of Brest and at the Museum of Natural History in Nantes, France.

Over 700 individual traces associated with, or of, the Rugosa group (Seilacher, 1970) have been studied. For detailed analysis, particularly of the kinematics of excavation, this particular group has a number of advantages over other groups which show less will differentiated or individualised claw patterns and groupings. A number of general concepts of trilobite activity can be determined from C. rugosa in particular, and can be traced in C. goldfussi and C. furcifera. Thus some points pertinent to most cruzianaform and rusophyciform traces can be outlined.

During this research it became apparent that a range of component parts of Cruziana and Rusophycus could be meaningfully separated and would in themselves serve as useful stratigraphic and ethological indicators. This 'component' aspect has been clarified by a series of traces which provide information particularly relevant to those with 'rugosa'-like morphology.

Dig marks.

A number of separate specimens from a variety of localities in Spain and the UK (e.g.: (i) Barrios Formation (approximately Upper Arenig to Lower or Middle Llandeilo, Compte, 1959), north-west of La Majua, Leon Province, Cantabrian Mountains, Spain; (ii) Barrios Formation (as above), La Vid section, Leon Province, Cantabrian Mountains, Spain; (iii) Ferreiro Schichten, Upper Clastic Series of Cabos Series (probably equivalent to Amoricain Quartzite = Arenigian, Farber and Jaritz, 1964), east of Luarca, Asturias, Spain; (iv) Upper Cwn Rhiwath siltstones (Lower Longvillian = Caradoc), Galt-yr-Ancr, Meifod, Montgomeryshire, Wales) match with features present on some Cruziana and Rusophycus recovered from the same and other ichnocoenoses. All specimens occur as casts on the soles of medium and fine sandstones or coarse silt beds and are often associated in groups (Pl.14). Individual markings may be elongate, quite strongly impressed boat shaped ridges (Pl.14.4), tapering shallow lobes (Pl.15.2), curved inclined wedges (Pl.9.3) or steep sided rounded mounds (Pl.15.1). All have in common distinct parallel claw impressions which may vary in number from one to multi-grooved individuals produced by a comb-like appendage (Pl.14.4). Grooves may cross cut the long or short axis, either obliquely or normal to the general outlines of the margin of the trace, and may vary in width and strength of impression along their length.

Discussion.

If trilobite tracks are to have utility as detailed stratigraphic indicators, analysis must proceed from the general forms of individuals to detailed use of minor taxonomic variations reflecting actual changes in the morphology of the trace maker. Behavioural variants are not stable so that 'mutant' forms controlled by factors external to the trace maker such as substrate variability or the dynamics of the sediment/water system may give erroneous stratigraphic information.

Claw impressions do seem to satisfy this 'stable' requirement, but up to the present time have only been mentioned en passant in descriptions of Cruziana (Seilacher, 1962, 1970; Crimes, 1970b), Dimorphichnus (Seilacher, 1955), Monomorphichnus (Crimes, 1970a) and at greater length in Diplichnites-type traces from the Cincinnatian (Osgood, 1970).

Osgood (op.cit.) has suggested the informal term 'imprint' for 'a single leg record of any sort, deformed or undeformed'. This term he suggests forms a convenient synonym for Seilacher's (1955) 'Trittsiegel'. The term 'Grabsiegel' is also used by Seilacher as a class heading for Text Figure 2 and as part of the discussion of Plate 25, Figure 4 in the same paper (Seilacher, op.cit.). Although these informal terms refer to individual limb impressions they suggest a passive walking, stepping or raking process and are always used in descriptions of series of individuals comprising double or less often single 'trails' (sensu Osgood, 1970). In the traces to be discussed below a pronounced digging action is indicated and the term DIG MARK is proposed. The dig mark will therefore constitute the fundamental component of trilobite produced trace fossils and should therefore be included in systematic diagnoses.

Examples of Cambro-Ordovician dig marks.

A number of slabs with multi-digit (= 8) produced dig marks were recovered from an asaphid/asaphacean coenosis (Baldwin, in press (d)) in the Cantabrian Mountains, north-west Spain.

All specimens occur as casts on the soles of ripple cross laminated, flaggy fine to medium sandstones. One large slab (Pl.14.2) occurs with ten in-line individuals plus other more weakly impressed individuals which do not form a distinct series. A similar, although incomplete, series occurs on a large slab adjacent to a shallow, uni-lobed Cruziana (probably new species = C. barriosi (see page 84) (Pl.13.1). Strongly oblique forms are present on the same slab and are considered transitional with Monomorphichnus (Crimes, 1970a).

The association of these traces with a Cruziana (Pl.13.1) on the same slab suggests that the trace is the product of a short, disconnected excavation stroke by an eight digited appendage, digging approximately parallel to the axis of the trace maker. Individual members of a series of dig marks may show remarkable accuracy of positioning relative to each other such that spaced individual claw impressions on each trace fall on a straight line (Pl.14.2).

No similar individualised traces have been described although components of C. rugosa appear similar (see below for further discussion). Seilacher (1962) figures an example of C. rugosa with clearly separable elements from the Armoricain Ora Quartzite of northern Iraq (Seilacher, 1962, Plate 25, Figure 4). In the description of this plate it is suggested that ten ridges are present, although from study of the photograph a maximum of only eight appear to be present in each set.

Cruziana material collected from Brittany along with contemporaneous very well preserved material in the Department of Geology, University of Brest and the Museum of Natural History, Nantes shows elements of their morphology identical with the eight ridged dig marks described above (Pls. 13 ,14). In all the material from Nantes (the collection of Lebesconte) specimens are labelled 'Cruziana prevosti'. Delgado (1886), in a discussion of the separation of C. prevosti from C. rugosa, describes at length the oblique and longitudinal scratches which '...are greater in number and more regular in direction...' in C. prevosti than in C. rugosa. It can be seen from the plates in Delgado's monograph (Pls. X , XI) that these 'regular sets of grooves' correspond to the dig marks discussed above. Lebesconte (in Delgado, op.cit.), referring to C. rugosa and C. prevosti, suggested that 'the rings of Bilobites have been formed successively, for they cover each other or are imbricate'. The rings in this description are again considered to be morphologically identical to the isolated dig marks from the Cantabrians. This imbricate form gives a valuable clue to trace excavation and trilobite ethology and is discussed more fully below.

The component parts of C. rugosa do suggest an imbricate form to their positioning in such a way that the anterior extensions of the units

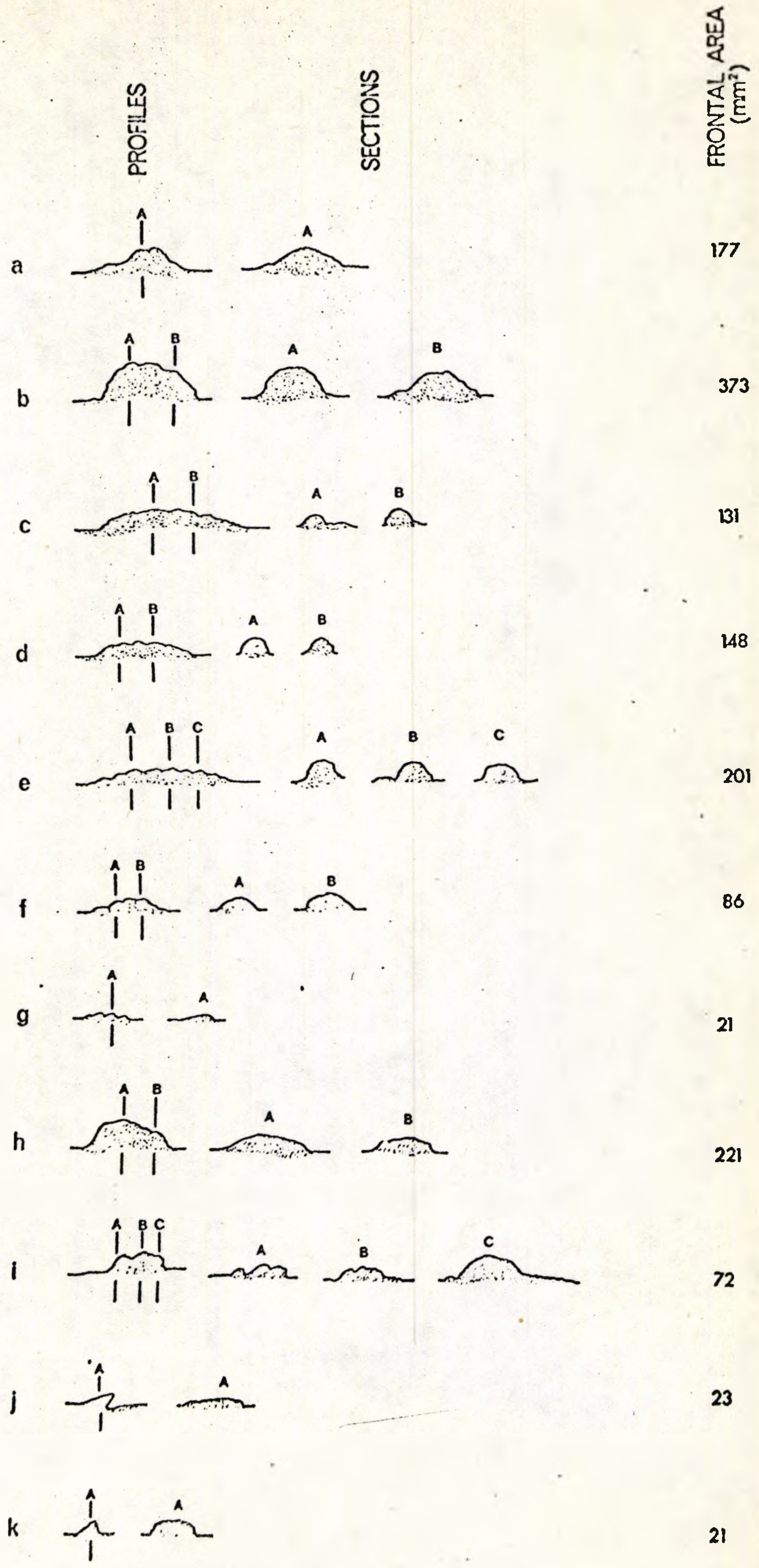


Figure 43
Profiles and sections through various Cambro-Ordovician and Middle Ordovician trilobite dig marks.

(i.e., dig marks), although narrower and more weakly impressed, are partially obscured by succeeding individuals which cross-cut. Only the terminal withdrawal portion of the complete appendage stroke is preserved. Because of this, the kinematics of *Cruziana* excavation can be more readily identified.

Dig mark profile analysis.

Some of the individualised dig marks discussed above provide morphological as well as ethological/stratigraphic information. Analysis of a variety of dig marks in terms of cross-sectional area (Fig.43) on sections normal to the plane of appendage movement (see Section 2 below for further discussion) provides information on the sediment shifting-capabilities of the trilobite trace makers. Such information may contribute, albeit indirectly, to a greater understanding of trilobite musculature and limb insertion.

The form of some dig marks indicate that the appendage which produced the trace was pulled through the sediment along an arc, in such a way that the distal edge of the appendage follows a cylindrical path. Such a form and movement is comparable with a single vane of typical vane test apparatus (Fig. 44) used to determine the shear strength of engineering soils. In such instruments the *force* required to rotate the vane through a given sediment is converted to the shear resistance and hence indicates the *in situ* shear strength of the soil. Values of shear strength and/or cohesion of marine shelf sediments are available (e.g., Richards, 1962; Hirst, *et al*, 1972; Kelman & Terry, 1972; Hirst, 1973; Perlow & Richards, 1973; Richards & Dzwilewski, 1974; Richards & Parks, 1974) and quoted figures range from a low of $0.2 kN/m^2$ to a high of $4.2 kN/m^2$ with a mean of $1.8 kN/m^2$. The semi-circular cross sectional form of analysed dig marks indicates the rotation of the digging appendage passed through π radians. The surface area of the appendage may be measured from the cross sectional area of the preserved trace. From these three sets of information the order of magnitude of the force required to move the given appendage through an average shelf sediment may be calculated from the following formula:

$$\text{Force} = c.\pi.a \qquad \text{....Eqn. 1}$$

where c = shear strength or cohension and a = surface area of appendage.

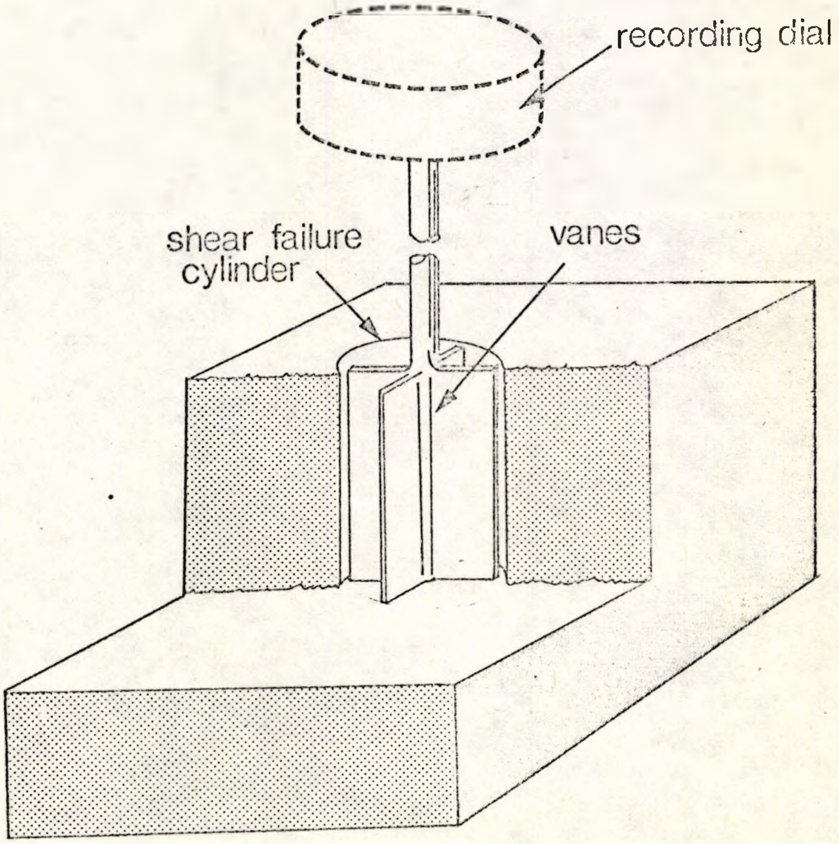


Figure 44
Schematic diagram of a typical shear strength vane testing apparatus.

Results indicate digging forces varying from approximately 0.1N to just over 2.0N, with a mean of 0.7N. While these data are superficially quantitative, just what they mean is difficult to determine. Quantitative data of this type is not available for extant Arthropods and what quantitative work has been done (e.g., Myers, 1973) is quoted in the form of ergs and dynes and is thus time dependent, a parameter which is impossible to determine from fossil material. The best hope is that the dig mark data can be used in a qualitative manner. Thus, a force in excess of 2.0N applied at the distal end of an appendage would seem intuitively, at least, to be quite large. One is, therefore, obliged to consider the ramifications of this vis a vis trilobite skeletal morphology. Manton (1969, page R33), in a general discussion of Arthropod locomotion, mentions the following morphological points. First, that from ethological information concerning running in myriapods it is possible to predict limb and joint morphology and the relative proportions of extrinsic and intrinsic muscles. Second, 'in strongly burrowing centipedes four pleurites encircle the coxa and support the strong slow leg movements, ...'. Thus, it may be possible, given appropriate morphological, ethological and para-quantitative data, to assist in some detailed aspects of trilobite appendage morphology. The morphology of isolated dig marks may therefore form a useful area of information beyond that of ethology and taxonomy.

2. EXCAVATION OF TRILOBITE TRACKS

(a) Physical excavation.

Seilacher (1955, 1959 and 1962) and Crimes (1970b) have outlined the general patterns of limb movements involved in the production of trilobite excavations. Both conclude that the distal end of the excavating limbs describe a curved or an arc shaped path, the arc centered on the relatively fixed coxae, so that the digging stroke commences at the lateral margin of the subsequently preserved trace. Seilacher (1955), working from tracks with individualised and separate imprints (Tritt-Siegel), was able to suggest a forward progressing wave of limb activity on the grounds of relative spacing of imprints at the margin of the trace. This conclusion is strongly supported by Manton's (1950, 1952, 1953, 1958, 1961, 1968) extremely detailed anatomical studies of extant arthropods. Crimes (1970b), working on Cruziana semiplicata, suggested that variation in the V-angle produced by the conjoining of the two sets of locomotory scratchings along the axis of Cruziana is related to variations in rates of forward movement of the trace maker. This idea is supported by Birkenmajer and Bruton (1970). A similar interpretation of the V-impressions was given by Seilacher (1959), but an opposite view is in part supported by mechanisms of Rusophycus excavation postulated by Birkenmajer and Bruton (1970, Fig. 8). (See below for further discussion.)

In all cases so far described this general pattern of limb movement on oppositely directed arcs at some angle to the central axis of the trace has been suggested. However, in numerous well preserved examples of C. rugosa collected both in Asturias and Brittany, and in further material studied in Nantes Museum, the pattern of limb movement remains that of an arc but the locus of movement lies more or less parallel to the axis of the trace. Due to forward progression of the trace maker, the fixed or central point for the digging stroke (viz. coxa) itself moves forward. Therefore, the impressions of each active limb only partially obscures the preceding one. Thus the Cruziana is composed of a fairly simple set of apparently imbricate excavations, such that the terminal part of each imbricate portion reflects accurately the morphology of the excavating appendage. The separation of individual limb impressions is further emphasized by the final tightly curved portion at the end of the imprint, indicating that the limb was withdrawn rapidly from the excavated surface at the end of the stroke. Due to changes in orientation of the limb about its own axis or the whole limb's relationship with the central line of the trace maker, often a trace comparable with Monomorphichnus is preserved.

This type of straight back style of excavation of furrows by trilobites is often preserved on the rusophyciform ends of Cruziana. Some specimens of Cruziana from Brittany are over 1cm deep with nearly vertical margins. Little or no detail is present along the length of the traces, but on the fairly steep terminations a number of structures similar to distinct dig marks are preserved stacked one above the other.

The preserved dig mark forms on C. rugosa provide a detailed record of the kinematics of excavation of this type of trace. The digging appendages extended, in some cases right forward so that the broad, multi-digited end of the of the appendage encountered the sediment surface quite close to the mid-line of the trace. In some cases the broad appendage commenced the digging stroke more towards the outer margin and in this position is often twisted obliquely to the centre line. As the limb is pulled back it twists about its own axis, presumably by a combined movement of the coxo-sternite articulation point and the dicondylic pivot joint between the coxa and the pre-femur (cf. Manton, 1969, p. R16, Fig. 1). From this slightly oblique position the appendage finishes the stroke at the centre line of the trace with the front face of the limb approximately normal to the axis of the trace. Such a limb motion appears ergonomically efficient: while the limb is extended furthest forward and presumably held fairly straight, it is thus in a mechanically weak position and so to compensate, a reduced frontal area is presented during the initial phase of the excavation stroke. As the distal portion of the limb is pulled further back towards a position adjacent (i. e. below) the coxa, progressive increase in the frontal area takes place. Not only is such a style of digging mechanically efficient, but in forward progression of the trace maker and in depth of excavation such a process has advantages over the oblique style more typical of members of most other Cruziana species, including C. furcifera and C. goldfussi. This same twisting motion of the distal portion of the excavating limb can be seen in other members of the Rugosa group. In some specimens of C. goldfussi a three digited appendage is indicated as the excavating tool, moving on the usual oblique path. However, at the lateral margins of the trace, the individual dig marks appear either as fairly deep unified ridges or as a main deep ridge with a more weakly impressed single or paired subordinate ridge which lies very close to the flank of the main ridge (Fig.28). As the excavation stroke is traced towards the centre of the trace, the weaker member of the pair gradually diverges from the main and becomes more strongly impressed (Fig28b). In many cases it is joined by a second subordinate digit on the other side of the strong central ridge and this gradually diverges and increases in strength of impression (Fig.28c)in the same way. Again, only when the distal end of the appendage is in a relatively advantageous position is the full frontal profile involved in the excavation.

The two types of limb movement described above involving straight back and oblique digging strokes leads to the separation of two basic forms of Cruziana or Rusophycus. Due to the constraints of limb movement, those traces which are formed from essentially longitudinal digging strokes usually have steep or vertical lateral margins. The bulk of these traces are short and discontinuous though they rarely have the proportions of true Rusophycus, some component of forward movement nearly always being involved. The heavily impressed dig marks in many examples of this type of trace are equally impressed along the length (Pls.25,29). In other examples, particularly in those from the Grès Armoricain of Brittany, the dig marks are most strongly developed on the anterior steep end of the traces (Pls.33.1,33.4). The dig marks of the main part of these traces are diffuse and indistinct so that the individual digit impressions cannot be easily separated and only the curved lobes of these individual excavations can be distinguished.

The distinct separation of the component dig marks of many C.rugosa suggests that a minimum number of individual appendages are involved in the digging process. There is no way of being certain, but the length of the anterior parts of some of the dig marks, and the nature of the overlap of each individual, may well indicate that in fact only one pair of large anterior appendages were involved. Bergström (1973) suggests this possibility on grounds of 'the regular morphology of the trail' which may be more precisely interpreted as, in fact, the regular form of the component parts (i.e. the dig marks). The accuracy of placing of individual appendages relative to themselves and others is often such that the digit ridges merge completely (Pl.29.5)and this seems to further support the idea of the utilisation of only one limb per side. This high degree of in-line accuracy of appendage placement on the substrate can be seen in a series of isolated dig marks from the Cantabrians (Pl.14.2). If more than a single pair of appendages were in active use during the excavation process, it is probable that the angular relationship of the dig marks to the centre line of the trace would vary in a manner suggested for C. furcifera by Birkenmajer and Bruton (1971, Fig. 10b). This is not the case, and the overlap is simply the result of forward movement of the complete trilobite (Pl.13) and partly due also to rotation of the individual appendage about its own axis, a feature also noted by Bergström (op.cit.) and used to account for minor divergences of 'tracks within a set' (= dig mark).

Seilacher (1970) has suggested two important forms of body attitude employed by furrowing trilobites. In the procline or head down position, limb movement almost normal to the median line of the trace is suggested by Seilacher (op. cit., Fig. 4, p.453). This interpretation is correct if the lines drawn on the lobes of the traces represent individualised claw impressions and not the terminations of imbricate dig marks as described above. Crimes (1970a) suggested a similar pattern of limb movement in order to account for no genal welt in some examples of C. semiplicata. Although the material figured by Seilacher are forms of C. semiplicata, the inference seems to be that details evinced apply to most trilobite furrows. Crimes (pers. comm.) has observed similar medially directed impressions from specimens of Cruziana of Lower Cambrian age. In such traces it is difficult to see how trilobites could progress forward if the limb movement was directly towards the median line, particularly if only an anterior pair or perhaps in other cases pairs of appendages were employed. No component of forward translation can be derived from such a pattern of appendage movement: only an excavation in a vertical sense may be achieved. Thus it would appear for Seilacher's proposed procline mechanism, as reflected in the preserved casts of C. semiplicata, to work either other appendages or pivoting on other appendages must have produced the component of forward push. Why then, if as argued only a limited number of anterior appendages were involved in strong digging, but weak or neutral forward moving strokes, are the impressions of posterior pushing appendages (posterior relative only to the anterior appendages discussed) not superimposed on the excavation strokes? With the arrangement described, sediment is excavated from the anterior end; thus, the anterior cephalic margin is not forced into the sediment as a wedge or plough blade but advances into a largely excavated zone. The force required to move the trilobite forward is quite small as it moves into a partial void and consequently the impressions left by the pushing limbs may be extremely small and could be obscured by later filling, slumping or diagenetic effects and may merge with the main excavation strokes.

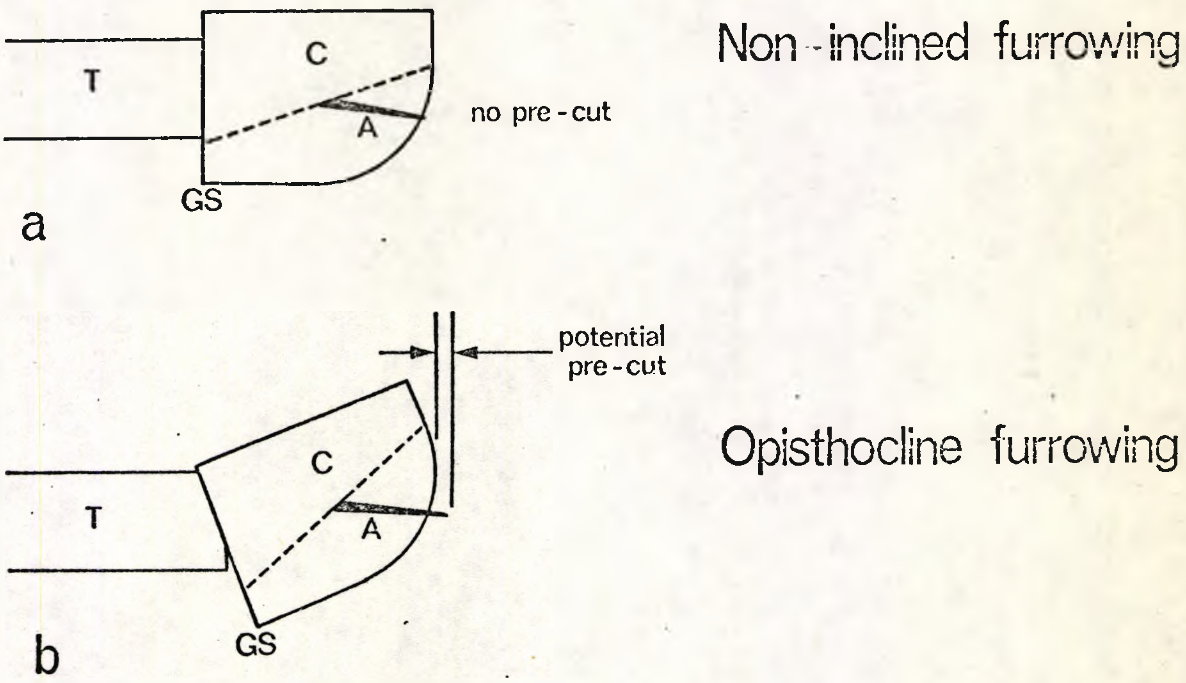


Figure 45
The effects of cephalon attitude on furrowing. In (a) the absence of any pre-cut would require anterior cephalic margin to 'bulldoze' through sediment. Pre-cut in (b) permits excavation of sediment in advance of cephalon. T - thorax; C - cephalon; GS - genal spine; A - anterior appendage.

The other important body attitude of furrowing trilobites is opisthocline or tail down posture. In this attitude Seilacher (1970, Fig. 4) suggests that the appendage marks preserved are the products of the activity of the posterior, relatively small apendages. This cannot of course mean that only those appendages were active during the furrowing process. Were this so the anterior ventral surface of the trilobite would be pushed passively forward through the sediment as a blunt flat wedge and this, on the grounds of efficiency, seems unlikely in all but the least coherent and uncompacted sediment. The preserved scratches therefore are likely to have been superimposed over fairly weak neutral digging impressions.

Seilacher (1970) has suggested that Illaenus could be the trace maker of Cruziana rugosa. This has been questioned by Bergström (1973) on the grounds that the anterior cephalic margin of the trilobite extends below the level of the ventral surface, presenting a 'large flattened wall' which would require powerful pushing mechanisms to bulldoze into the sediment. This further prevents efficient burrowing or furrowing by limiting the forward extension of the anterior appendages (Fig.45a).

It is argued by Bergström (op. cit., p. 58) that in order for the trilobite to reach the sediment surface of the steep anterior wall of the excavation the 'cephalon must probably be raised along its anterior margin.' The inference is that this must be a morphological feature of the trilobite and therefore excludes Illaenus on straight morphological grounds. However, Seilacher (1970) (and also quoted by Bergström, op. cit.) suggests an opisthocline position of the trace maker (Fig.45b). It is possible in this position that the axis of the trilobite might lie at an angle to the general sediment surface, anterior end raised (Fig.46a). In this position the anterior cephalic margin would be raised although in this case ethologically and not morphologically. The efficiency of this arrangement could be increased by 'breaking' the otherwise straight trilobite axis as described above at the occipital ring by raising the cephalon still further. This would further raise the anterior cephalic margin and give a clear sweep for the anterior appendages (Fig.46). In the position suggested, the cephalic shield is not bulldozed into the sediment but simply follows on passively behind the active appendages. This attitude is indicated in part by Seilacher's (1970, Fig. 5c) in which proverse excavation impressions are preserved on the steep anterior wall of C. dispar.

Genal spines must be present on the maker of C. rugosa if the connection with C. goldfussi is accepted. In the latter species the presence of genal welts is diagnostic and their rarity in C. rugosa must be accounted for. If the genal spines are short they will rarely impinge on the base of the excavation, particularly if in general the trilobite retains the opisthocline orientation, so raising the anterior portion. Thus a double opisthocline attitude is envisaged.

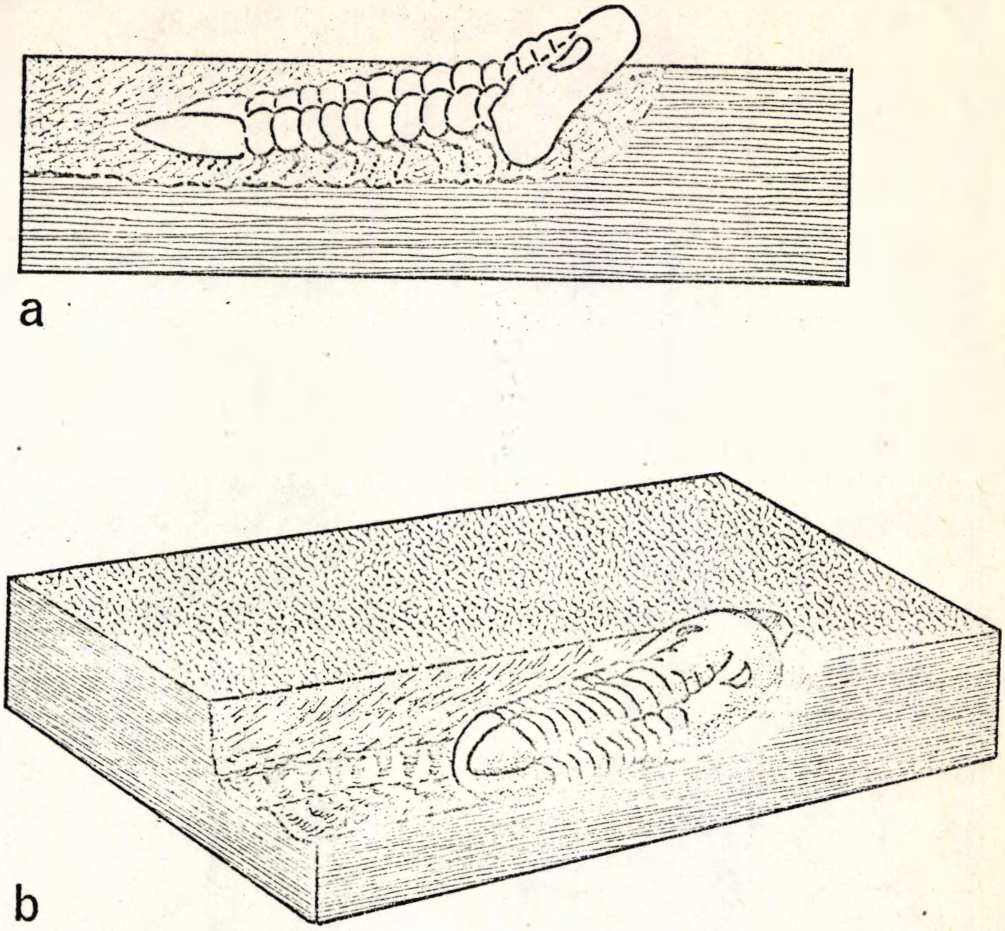


Figure 46
Postulated opisthocline furrowing attitude which could account for the isolation of distinct dig marks on *C. rugosa*.

(a) Note slightly inclined attitude of thorax and pygidium which, when combined with raised cephalon, would keep genal margin clear of sediment surface.

(b) Isometric block diagram showing dig marks along base of furrow and oblique scratches on side wall.

The appearance of genal welts preserved on wall-like *Cruziana* obtained from the top of the Grès Armoricain Quartzite of the Crozon Peninsula, France also needs to be explained. A well preserved specimen of a short *Cruziana* stands with nearly vertical lateral margins in places above the general bedding plane. A distinctly rusophyciform portion bears three short and discontinuous welts which are slightly imbricate (Pl.) and which if continued forward would intersect the median line of the whole trace, but would V in the opposite direction to that suggested for the limb impressions.

In order to produce discontinuous structures of this form, some positive action by the trace maker must be involved. Passive digging of any structural component must produce continuous ribbon like features and certainly excludes overlaps or imbrication in the resultant trace. Two possibilites may be considered for generation of the trace described. If, during the digging stroke, the mud substrate is very cohesive and resistant to the excavation action, the body of the trilobite will be lifted slightly, rather than the digging appendages extending far into the sediment. This seems a possible situation for this environment. Crimes (1975) has outlined the geotechnical parameters involved in Cruziana excavation and preservation which in general may be summarised as a need for cohesion of the excavated material in order that the sculptured surfaces may stand. A high degree of cohesion is suggested for this environment as most of the tracks exhibit perfectly vertical margins. Thus a possible lifting of the whole trilobite so that it moved forward in series of short lurches is in part consistent both with some features of track morphology and possible environmental characteristics. However, no indication of a change in the rate of forward movement is indicated in the main part of the trace. The appendage V-impressions though distinct do not appear to change in angle, a feature which would be expected if the rate of forward movement altered (cf. Crimes, 1970, Birkenmajer and Bruton, 1971).

An alternative method of producing the trace is for the rate of forward movement of the trace maker to remain constant or change only gradually so that no marked irregularities appear in the appendage V-impressions. If during this period of even forward movement the attitude of the cephalon is altered, perhaps by rocking at the occipital ring so that the double opisthocline attitude described above alternates with the normal opisthocline or procline attitude, the genal spines, which would normally remain clear of the sediment, may momentarily touch the sediment surface. Consequently, due to the tapering of the ventral cephalic margin anteriorally away from the genal spines, the overlapping pattern could be produced.

Seilacher (1970) indicates a similar style of cephalic movement in the production of some deep trilobite 'nests'. The anterior scratches of _C. jenningsi_ are interpreted by Seilacher (_op. cit_) as the product of shoveling by the head shield.

(b) Current assisted excavation.

Birkenmajer and Bruton (1971) discussed at length mechanisms of partial hydraulic excavation of smooth Rusophycus. The bulk of their argument rests on the preferred orientation of five individual Rusophycus, the long axes of which lie parallel to a primary current lineation on a slab from Tremadoc of Östergötland first figured by Holm (1887) and discussed by Westergård (1920), Henningsmoen (1957) and Seilacher (1955).

The details of the mechanism suggested by Birkenmajer and Bruton cannot be faulted on physical or morphological grounds and appears plausible for the limited sample considered. However, the general applicability of this mechanism to all smooth Rusophycus is more questionable. Crimes (1970a, 1974b) has recorded variable orientations of long axes of a number of smooth Rusophycus on a single bedding plane from the Upper Cambrian of north Wales. A uniform current direction is indicated for this slab and any secular variation of this direction would seem unlikely as all adjacent beds show a high degree of uniformity. Thus the requirement of funneling of a head-on current below the body appears questionable. The shadow of sand grains is neither evidence for or against the supposed mechanism, but simply gives an indication of actual flow direction. Any sediment transporting currents when flowing over an uneven bed will develop turbulence, and perturbations in stream competence will follow, so that material will be preferentially eroded or deposited at different points along the flow. Divergent tails to flute marks on the soles of turbidites exhibit the same fan-like pattern in the lee of completely inorganic structures, and the structures reported by Birkenmajer and Bruton could conceivably be the product of post-biogenic current scour.

The orientation of forty-one Cruziana and Rusophycus have been measured from the sole of a thick, cross-bedded quartzite from Pointe du Grand Gouin, Brittany, France. A total range of only 10^{o} covers the trends of all these traces, the longest of which is over 70cm. The trend of the traces is almost identical to the current trend deduced from foresets within the bed on the lower bedding plane of which the traces were measured. Thus the conformity of the current and trail trends suggest that the current operated during the period when the traces were being excavated. On twenty-four of the traces, orientation of the V-excavation impressions indicate a head towards current attitude of the trace maker while on the remainder no orientation can be determined. Although there are few deeply impressed or preserved digging impressions present along the main parts of these Cruziana, in many cases the trace may be oriented and in these and nearly all others genal welts are strongly impressed. Lateral margins are steep or nearly vertical and show no signs of abrasion or modification by current activity. On the anterior and posterior rusiphyciform terminations to the Cruziana, deeply impressed excavation structures (equals eight digit dig marks) are preserved so that a dimorphism of the appendages employed in digging and moving appears to be present. The furrow is advanced by digging strokes at the head wall by one or two pairs of eight digited appendages while at the same time a number of posterior appendages were active in pushing the trilobite forward. Therefore, while the tracks are certainly current oriented, the current appears to have played no part in the excavation process. Rusophycus similar to those described by Bradshaw (1963) with coxal impressions have diffuse lateral zones, while the central portions retain a high degree of detail. These occur on exactly the same bedding plane as that described above, but the type of excavation does not seem to indicate any high degree of current assistance.

On the same slabs as these Cruziana and large Rusophycus, very small bilobate impressions, similar in may respects to R. didymus, less than 4mm long, dot the general bedding surface. No particular preferred orientation is apparent so that a hydraulic excavation process would seem unlikely. Perhaps the position of the two groups of traces is the key to the different morphological characteristics. The Cruziana and Rusophycus with coxal and appendage impressions are all deeply impressed (most greater than 7.5mm), while those with no detail are less than 2mm deep.

Mud layers in shallow marine environments are often covered with a layer of liquid slurry, the cohesion of the mud increasing gradually downwards. The R. didymus may have been produced at a level of low cohesion in the mud layer, possibly only a few mm below the sediment/water interface, whereas the Cruziana were excavated at a level of greater cohesion. Consequently, these tracks excavated in nearly cohesionless sediment would only retain the gross morphology of the trace maker, the detailed irregularities and form which are preserved in cohesive material being obliterated by slumping and general stirring of the sediment by appendage activity. The degree of preserved morphological detail may therefore reflect not a direct variation in burrowing techniques, but simply variation in preservational capability of muds of varying moisture contents encountered at increasing depths from the water interface.

(c) Position of trilobite excavations relative to sediment/water interface.

This section is presented as a completed paper: in press, Palaeogeog., Palaeoclim., Palaeoecol.

INTERNAL STRUCTURES OF TRILOBITE TRACE FOSSILS INDICATIVE OF AN OPEN SURFACE FURROW ORIGIN

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ABSTRACT

X-radiography of sections cut from Cruziana and Rusophycus of Cambro-Ordovician age, show that they contain cross laminated, parallel laminated, pelleted and homogenous fills. The absence of bioturbation or mottling textures and the undisturbed nature of the primary sedimentary structures does not support a burrow origin for these trilobite produced trace fossils.

An open surface furrow origin is supported both by the presence of internal primary sedimentary structures and by the precise current orientation of many of these types of trace fossils.

INTRODUCTION

Cruziana and Rusophycus are usually recovered as sand casts of moulds previously excavated in mud layers. These trace fossils are now widely accepted as the products of various activities of trilobites (e.g. Crimes, 1970a; Häntzschell, 1975). The preservation of extremely fine morphological detail (e.g. individual claw marks, exite brush marks etc.) has led to some degree of controversy over the precise manner in which such traces were excavated and subsequently cast. There are effectively two major and one subordinate hypotheses dealing with trace production and preservation.

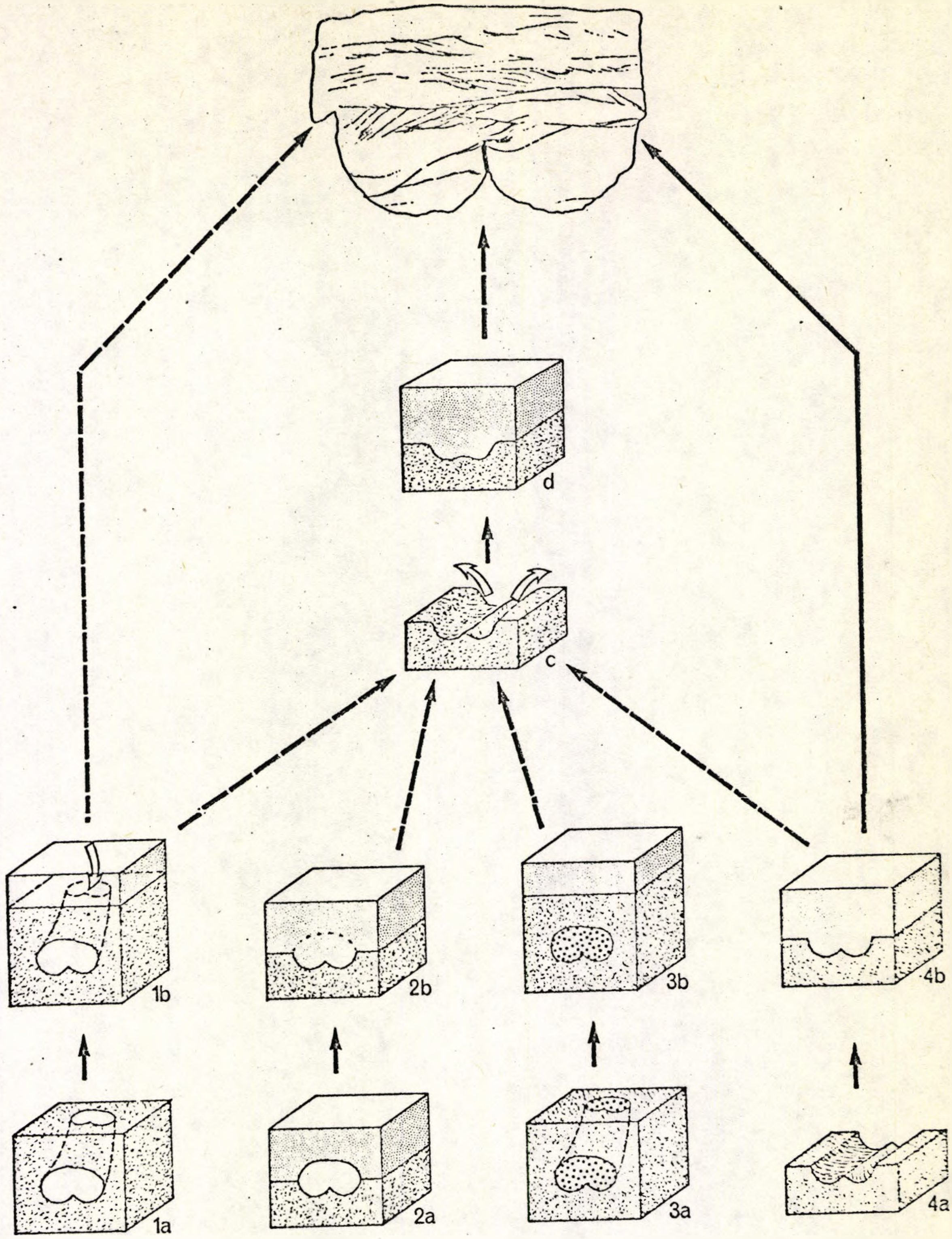

Figure 1

Possible modes of formation of a <u>Cruziana</u> (top) containing primary sedimentary structures.

(1) Passively filled burrows.
(2) Interface burrows - passive fill.
(3) Burrow - active fill.
(4) Open surface furrow.
  (a) Excavation.
  (b) Filling.
  (c) Exhumation.
  (d) Second filling.

Broken lines indicate possible modes. Unbroken line indicates more probable furrowed mode.

1. Surface furrows (Fig. 1.4a)

Numerous workers have proposed an open groove or furrow excavated at the sediment water interface (Lessertisseur, 1955; Radwanski and Roniewicz, 1963, 1970, 1972; Crimes, 1970a, 1970b, 1975; Orlowski, Radwanski and Roniewiecz, 1970, 1971; Seilacher, 1970; Cowie and Spencer, 1970; Osgood, 1970; Birkenmajer and Bruton, 1971; Bromley and Asgaard, 1972 (non-Cruziana sensu stricto).

2. Burrows

(a) Passively filled burrows in mud (Fig. 1.1a). Such burrows must have been open to the sediment surface in order to permit the ingress of casting sediment (Crimes, 1970a; Seilacher, 1970; Birkenmajerand Bruton, 1971; Frey, 1973; Baldwin, in prep).

In press

(b) Actively filled burrows in mud (Fig. 1.3a). In this case burrows are filled with fecal or backfill material (Frey, 1973).

(c) Interface burrows (Fig. 1.2a). Burrows are excavated at the interface of a sand layer over a mud layer. The immediate collapse of the sand roof fills the excavation (Seilacher, 1962, 1970; Birkenmajer and Bruton, 1971).

3. Exhumed traces (Fig. 1.c)

Traces by any of the preceding methods could be eroded so that the casting material was stripped away, thus exposing an exhumed furrow (Seilacher, 1962, 1964; Osgood, 1970).

Sedimentological approaches

Cruziana and Rusophycus are biogenic sedimentary structures and most discussions dealing with their genesis have been strongly biological and palaeontological in flavour. However, an approach from the sedimentological side may provide other equally informative data and lead to determination of their actual place of production.

(a) Internal structures . It has been demonstrated by Seilacher (1955) that digging strokes of trilobites pass from the lateral margin in towards the centre and it would therefore appear probable that excavated sediment would accumulate along the median axis of the trilobite excavation. In true burrows such sediment would be incorporated in the fill and would normally appear as a shale concentrate, or on eroded specimens as a deep and irregular median indentation. Fecal fills would on mineralogical and textural grounds be self evident. Back-filled traces might contain spreite-like laminae or be heavily mottled and destratified. Passively filled traces could exhibit primary sedimentary structures such as inclined or parallel lamination but such traces would rarely be recovered, as hypichnia (Martinssc 1970). Traces which were cast at the sediment/water interface, where the casting sediment is free to move appear to be the most likely positions for the production of fills containing primary sedimentary structures. Thus both open surface furrows of primary origin and exhumed traces might contain such structures.

(b) Orientation

If a trilobite burrowed below a sediment cover of any sort it would not be affected by any current shear and would consequently not be constrained to orient itself into any current-related position. For burrowed Cruziana, only the initial stage of excavation, away from the zone of influence of surface currents would be expected to indicate rheotaxis.

Trilobites furrowing along an open surface of a current washed mud layer would be in a position most likely to lead to oriented Cruziana and Rusophycus .

THE TRACE FOSSILS

As part of a much larger ichnostratigraphic study over 1000 individual specimens of trilobite trace fossils were collected from Cambro-Ordovician sections in the U.K., France and Spain. Material for this more specific ethological analysis was selected from five separate localities.

1. Cantabrian Mountains, Spain. Barrios Formation (Cambro-Ordovician), West of La Majua, Leon Province, Spain [43°00'N. 6°06'W]. Barrier beach and tidal facies (Geitelink,1973). Traces: Cruziana rugosa, C. furcifera, C. goldfussi (Plate 1a).

2. Asturian Coast, Spain. Cabos Series (Cambro-Ordovician) east side of Cabo Busto, Luarca, Asturias Province, Spain [43°34'N. 6°20'W]. Tidal flat and barrier bar facies. Part of the upper transgressive sequence (Baldwin, 1975).

Traces: Cruziana furcifera, C. goldfussi, C. rugosa (Plate 1b)

3. *Brittany, France*. Crozon Formation, Grès Armoricain, (Cambro-Ordovician) north of Pte de St. Herno, Cap de la Chevre, Finistere, France [48°12'N, 4°31'W] Transgressive barrier bar sequence (Baldwin (in prep). Traces: *Cruziana goldfussi*, *C.gouini*, *R.carleyi*, (Plate 1c).

4. *Cantabrian Mountains, Spain* . Transition Group (Arenig?) above Barrios Formation, Lancara de Luna, Leon Province, Spain [42°54'. 6°00'W] Delta slope, tidal non-channel and barrier beach facies (Geitelink, 1973). Trace: unusually deeply excavated *Cruziana rugosa* and *C. furcifera*. (Plate 2a).

5. *Welsh Borderlands, U.K.* Stiperstones Quartzite (Arenig) Nils Hill Quarry, 1 km south of Pontesbury, Shropshire, England. [52°39'N. 2°53'W] . Thin shales interbedded with wave rippled and flat bedded sandstones and granule conglomerates. The conglomerates form lag pavements on the upper surfaces of the flat bedded sandstones. No detailed facies interpretation is available but a transgressive near shore/tidal (*Skolithos* facies) environment appears likel
Traces: *Rusophycus* Form B (Crimes 1970b) (Plate 2b).

X-RADIOGRAPHY

Thirty specimens of *Cruziana* and *Rusophycus* have been sectioned and radiographed to study internal sedimentary structures. Parallel sided sections, 3 mm thick, were taken from each trace fossil and radiographed in the manner described by Hamblin (1962, 1965, 1967). A medical X-ray unit with Ilford Industrial X-ray film, Type G at 30 kv and 5 ma gave the best results. All plates are positive prints from X-ray negatives so that dark laminae correspond to the zones of maximum X-ray absorption.

Inclined lamination is the most common type of sedimentary fill, but flat laminated, massive and pelleted forms were also recorded. Cross- laminae may be angular (Pl. 1c) but tangential or concave-up forms (Pls. 1a & 1b) are more common, suggesting deposition of the fill from combined suspension and bed load tracting currents (Jopling, 1965). In one of the best preserved specimens (Pl. 1b), simple draped cross-laminae which represent the initial fill, pass up into current ripple lamination (bimodal?) without any noticeable sedimentary break. In practically all cases there exists no discontinuity between the cross-bedded fill of the trace and immediately overlying bed.

Two examples of casts with pellet fills differ in the types of pellets they contain. In the first (Pl. 2a), mud and silt pellets 'float' in a fine sand matrix, and are probably located along indistinct inclined bedding planes. The second Rusophycus (Pl. 2b) is filled with quartz sand, discoid shale clasts and quartz granules which are concentrated at the base of the cast. Associated with this specimen in the field are surfaces of lag conglomerate which cap thin sand beds. The mud interbeds are free from resistate granules.

Examples of traces filled with parallel laminated and massive sands and silts show no evidence of syndepositional bioturbation within the fills. Again, muds are not concentrated along the medial axes.

RHEOTAXIS

The orientation of forty one Cruziana and Rusophycus from the sole of a single cross-bedded quartzite in the Grès Armoricain of Brittany, France, show a dispersion of less than 10°. ient When the orientations of these traces are compared with palaeocurrents of the casting bed a marked conformity is apparent (Fig. 2).

DISCUSSION

The trace fossils studied during preparation of this paper vary in quality of preservation. In 27 specimens speciation is possible and of these, 18 are of a sufficiently high quality to permit determination of appendage and digit morphology.

The methods by which trilobite excavations could be cast, while still preserving detail has been much discussed. (Seilacher, 1953, 1970; Muller, 1962; Radwanski and Roniewicz, 1963; Martinsson, 1965, 1970; Osgood, 1970; Birkenmajer and Bruton, 1971; Bergström, 1973; Crimes, 1975). In many cases the preservation of extremely fine detail such as exite brush marks on Cruziana semiplicata has been considered incompatible with a sediment/water interface position. Usually the basic premise is that muds (i.e. the excavated medium) are relatively weak and the ingress of casting sand as a separate sedimentological event would scour all but the deepest morphological detail.

In order to explain the high quality of preservation various burrowing processes have been suggested.

True burrows, because of their isolated, near cylindrical form may be easily recognized. In their case simple burrow origins are acceptable. However, hypotheses which require sediment/sediment interface burrowing (Seilacher, 1962, 1970; Birkenmajer and Bruton, 1971) appear questionable. Traces produced by this latter process are the ones which might be confused with traces produced on the sediment surface.

Osgood (1970, p. 294) questioned the general applicability of the sediment/sediment interface burrow hypothesis on the grounds that (1) continuous wide spreads of sand over mud are uncommon in marine environments and (2) such processes cannot operate where light objects and passively dragged over the mud surface. This latter point would effectively exclude current assisted trilobite traces such as Monomorphichnus and Dimorphichnus.

Crimes (1975), by use of geotechnical parameters (viz. shear strength and bearing capacity), has demonstrated that strength is an intrinsic property of muds and that current velocities required to move the casting granular sediments are usually significantly lower than those required to entrain cohesive fine grained sediments which form the mould (cf. Hjulström, 1952; Kuenen, 1957; Postma, 1967; Osgood, 1970.) Such work shows that excavations in mud do not need the protection of a burrow system in order to retain extreme detail.

Seilacher (in discussion: International Trace Fossil Conference, Liverpool, 1970) proposed a new form of interface burrowing whereby a thin (few mm) sand layer, overlying mud, could be penetrated, allowing the trilobite to excavate the mud surface below. Casting by slumping and trickling in of a low sand wall, more or less contemporaneous with excavation, would it was presumed, preclude any scouring of the excavations. Here again the first point raised by Osgood (op. cit) in his criticism of interface burrows is relevant. Further, the slumping of sand walls only a few grains thick could fill only the narrowest of furrows; presumably those of Diplichnites and Dimorphichnus dimensions. It is with these latter tracks that Seilacher's (op. cit) preservation mechanism appears most acceptable. However, most Cambro-Ordovician Cruziana and Rusophycus are at least 2 cm wide and range to over 20 cm wide, and it is difficult to see how these could be filled by immediate post excavation slumping of such thin sand layers.

Cruziana and Rusophycus oriented parallel to the trends of palaeocurrents have been noted by Seilacher (1953), Crimes (1970), Birkenmajer and Bruton (1971) and Bromley and Asgaard (1972, non-Cruziana sensu stricto). These examples when linked with oriented examples of C. Gouini (sp nov) and R. carleyi (Fig. 2) from the Grès Armoricain of Brittany appears to cast further doubt on the infaunal positions of the trace makers. If the trilobite was burrowing below a sediment cover it would not be affected by any current shear and would consequently not be constrained to orientate itself into a current-related position. For burrowed Cruziana, only the initial stage of excavation away from the zone of influence of surface currents would be expected to indicate rheotaxis. In the examples from Brittany described above a number of Cruziana, over 0.5 m long are completely straight and consistently along the palaeocurrent trend.

CONCLUSION: THE SURFACE FURROW HYPOTHESIS SUPPORTED

Evidence of mechanisms of filling of trilobite excavations derived from X-ray photographs and consideration of rheotaxis displayed by some Cruziana and Rusophycus does not support wide applicability of the true burrow hypothesis. Fills composed of primary sedimentary structures appear to be most common whereas bioturbate and mottled fills are entirely absent from the sample discussed here. The most likely position for sedimentary structures to be produced and for the tactile stimulation of trilobites by flowing water is at the sediment/water interface and the absence of biogenic modification of these primary structures suggests that the whole process of excavation and casting was conducted on the exposed upper surface of a mud layer. The geotechnical data of Crimes (1975) and the conclusions of furrow origins derived from sectioned and polished material by Osgood (1970) and Cowie and Spencer (1970) further strengthens the argument that most Cambro-Ordovician trilobites were active at or very close to the sediment water interface.

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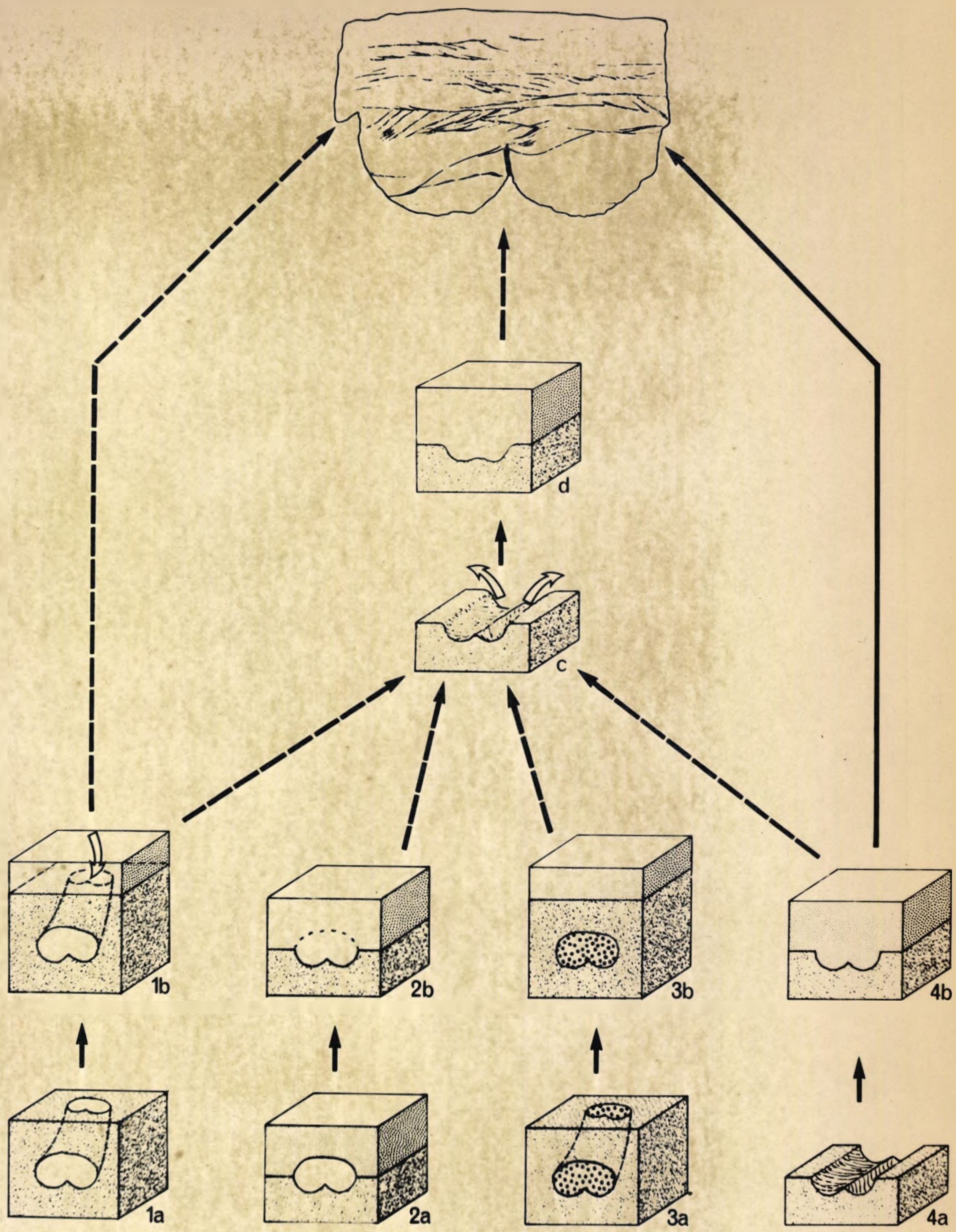


Figure 1.

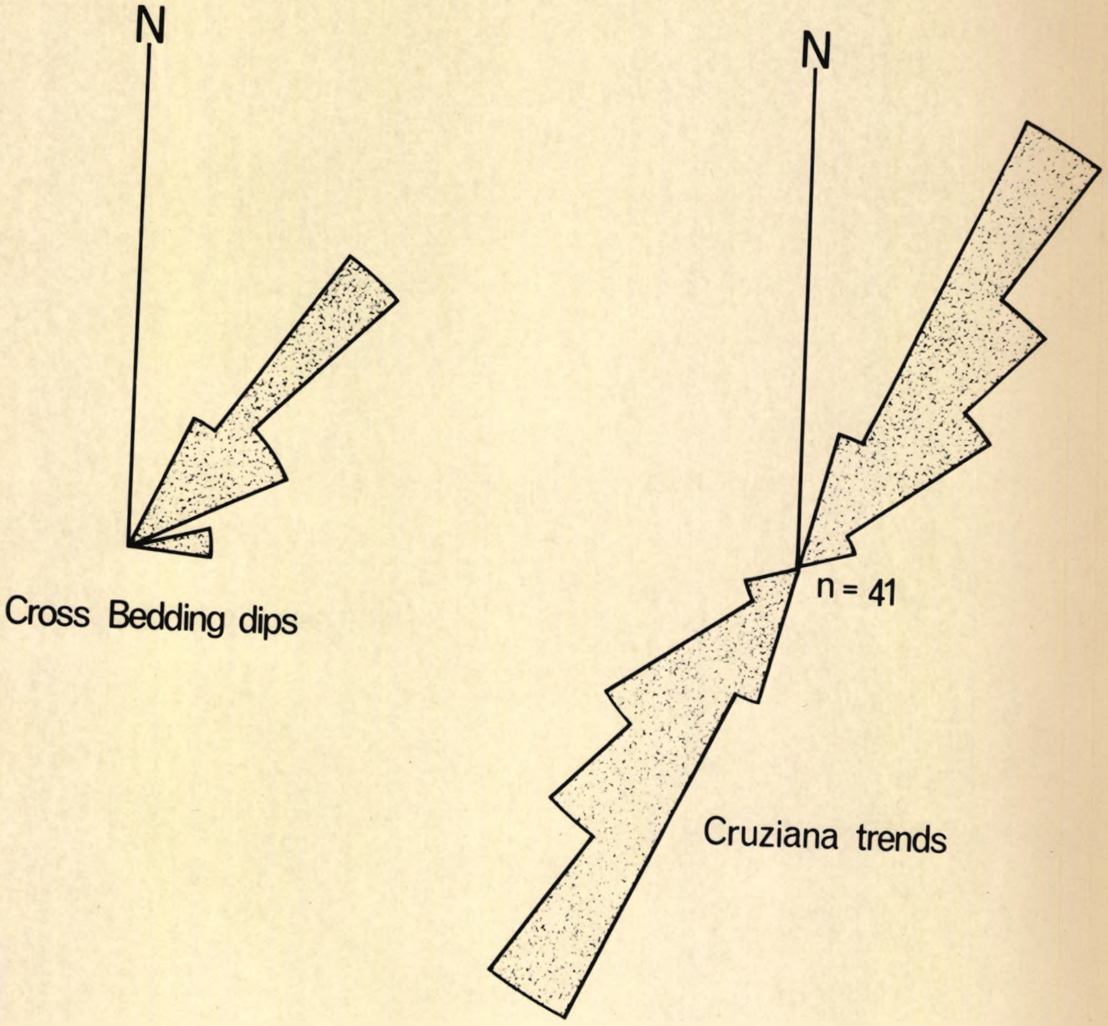


Figure 2.

PLATE 1

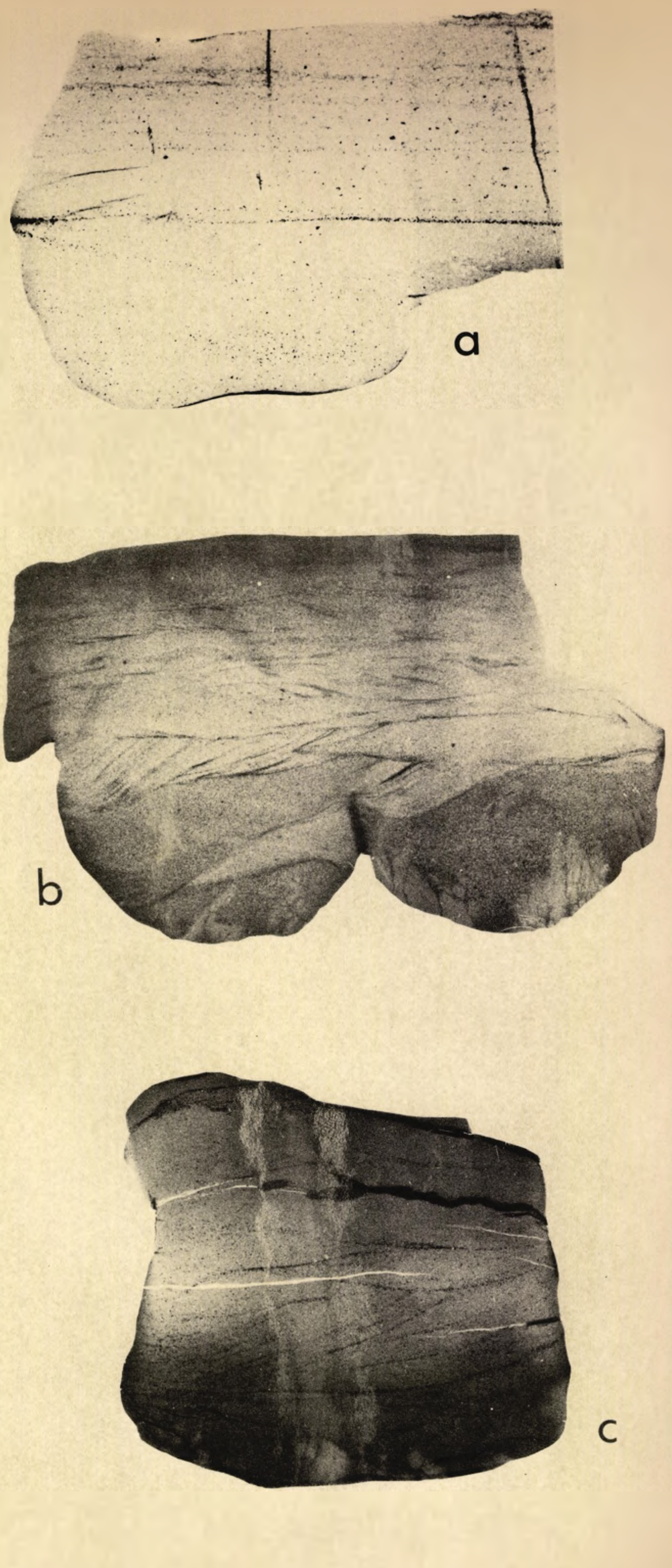
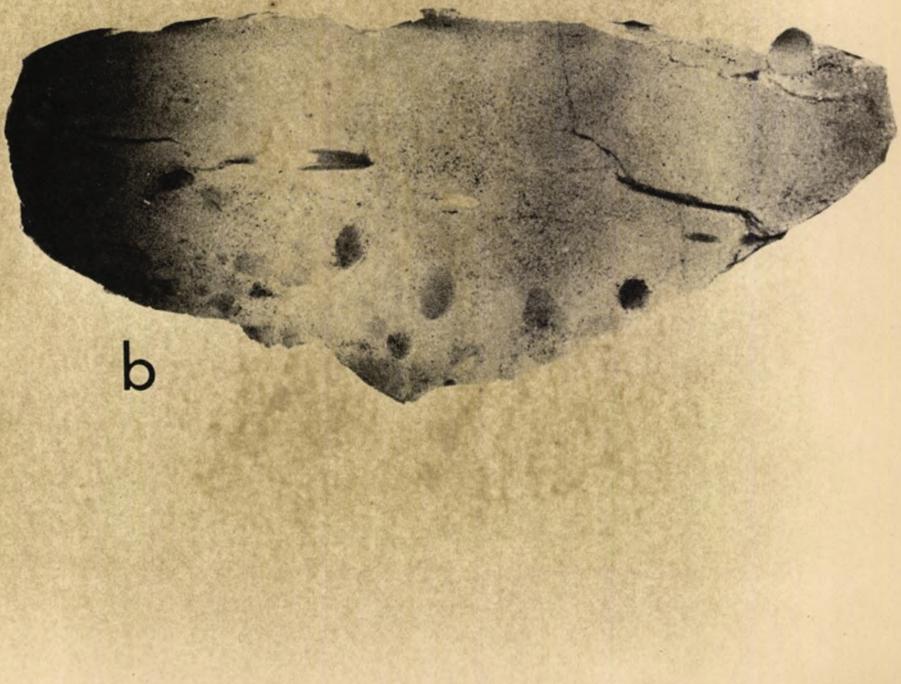


PLATE 2

a



b

FIGURE CAPTIONS

Figure 1

Possible modes of formation of a *Cruziana* (top) containing primary sedimentary structures

1. Passively filled burrows.
2. Interface burrows - passive fill.
3. Burrow - active fill.
4. Open surface furrow.
    - (a) Excavation
    - (b) Filling
    - (c) Exhumation
    - (d) Second filling

Broken lines indicate possible modes. Unbroken line indicates more probable furrow mode.

Figure 2

Relationship between the direction of inclination of foresets and the orientation of 41 specimens of *C. gouini* and *C. carleyi* found on the sole of the same bed. Vector means differ by less than 10°.

PLATE CAPTIONS

Plate 1

X-ray photographs of trilobite trace fossils.

(a) Cross-section of *C. furcifera* with cross-laminated fill. Barrios Formation, Cantabrian Mountains, Spain. XI.0.

(b) Cross-section of *C. furcifera* with complex ripple cross-laminated fill. Cabos Series, Asturias, N.W. Spain. XI.8.

(c) Cross-section of C. goldfussi with cross-laminated fill.

Crozon Formation, Finistere, France XI.0.

Plate 2

X-ray photographs of trilobite trace fossils.

(a) Cross-section of C. rugosa with mud pellet fill.

Barrios Formation, Lancara de Luna, Cantabrian Mountains, Spain. X0.5.

(b) Long-section of Rusophycus Form B with quartz granule and mud pellet fill. Stiperstones Quartzite, Habberly Quarry, Shropshire, England. X0.75.

3. SYNOPSIS OF PRESERVATION CRITERIA

(a) General.

The problems of understanding how fine detail may be preserved on shallow, surface excavations while allowing for a subsequent casting of these excavations has led to complexities of ethological interpretation, which appear either inadequate or not all-encompassing.

Delgado (1886) was one of the earliest to question the preservation potential of sedimentary structures of biogenic origin. He correctly interpreted the Cambro-Ordovician Cruziana bearing rocks of Portugal as representing a shallow marine environment, largely on the grounds of the presence of ripple marks. As a result, he concluded that such an environment would be characterised by high energy conditions which would lead to regular reworking of sedimentary deposits, thus almost certainly obliterating any shallow furrow or burrow structures. The general bias towards a fucoid origin for Cruziana was already well established (Saporta, 1879, 1881, 1884a, 1884b, 1886; Lebesconte, 1883; Schimper, 1869) so that the combination of this conceptual framework with an overemphasis of the psammitic preservation of trace fossils promoted a bias in interpretation towards body fossil preservation mechanisms.

Even when the relevance of the mud layer was recognised, the adherence to a fucoid and body fossil idea was maintained. This led Saporta and Marion (1881) to propose the theory of 'fossilisation en demi-relief' (Fig.47) in which a fucoid resting on a mud surface (Fig.47a) becomes pressed down into the mud due to the pressure of superincumbent sand (Fig.47b). By some process poorly defined by Saporta and Marion (op. cit.), the fucoid decays and presumably is removed by pore fluids, allowing the sand to fill the vacant void (Fig.47c). This results in a cast characteristic of Cruziana and Rusophycus.

Some support for both of these ideas may be derived from features of some specimens of Cruziana. A number of well preserved specimens

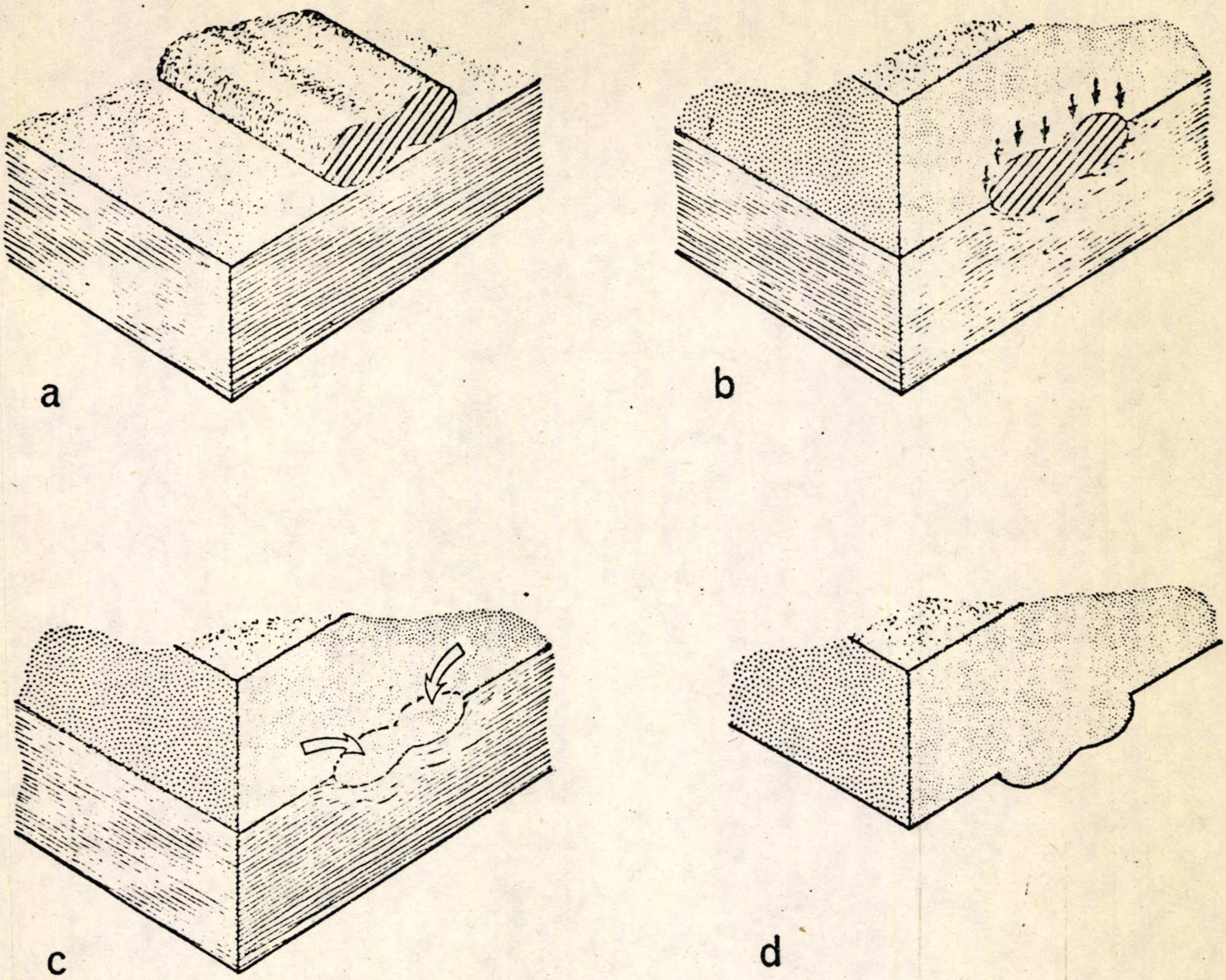


Figure 47
Late nineteenth century model of fucoide preservation 'endemi relief' (after Delgado, 1896).
a) Fucoide stem resting on mud surface.
b) Compaction due to overlying sand bed.
c) Fucoide disolved - void filled immediately by sand.
d) Resultant cast.

studied suggest, for at least part of their length, a crude symmetry which suggests that they occur as full relief forms rather than semi-relief

(= normal casts) (Pl.31.5). This form could perhaps be sufficiently misleading to suggest an original body fossil form similar to that described by Saporta and Marion (Fig.47a) and to some extent consistent with the algal (body fossil) stem ('stolon') of Delgado (1886). When these particular Cruziana are traced further along their length, they appear as normal casts and the tubular end figured (Pl.31.5)appears to be the product of syn-depositional or post-depositional deformation, local small scale slumping or actual breakage during extraction of the specimen. Other roughly tubular forms of Cruziana comparable with that figured by Delgado (1886, Pl. IV, Fig. 2) may stem from a true burrow origin, but these may be easily differentiated from surface excavations by considering their relationship with the enclosing sediment (see above, page). True burrows have totally cross-cutting margins and do not pass laterally into similar lithologies as do surface traces.

Due very largely to the work of Nathorst in the late nineteenth century and later by Richter's school in the 1920's, the 'fucoid' origins of Cruziana were discredited and a 'biogenic sedimentary structure' interpretation assigned to these forms. Consequently, largely sedimentological concepts had to be applied in discussions of preservation mechanisms, particularly for surface or near surface forms characteristic of fairly high energy environments.

(b) Problems of erosion.

With the redundancy of the underlying body fossil concept for the origin of Cruziana and Rusophycus, the biogenic sedimentary structure framework presented what appears to have been interpreted by some workers as a too ephemeral medium for the preservation of surface excavations. This partly seems to have stemmed from the misconception that mud is more easily eroded than coarser grained sediment: it is incorrectly argued that sand grains are heavy whereas mud or silt are lighter and thus require only relatively weak currents to entrain the finest of size classes. This is certainly not true, as has been repeatedly demonstrated (Hjulstrom, 1935; Shields, 1936; White, 1949; Sundborg, 1956; Postma, 1961, 1967;

Vanoni, 1964; Bagnold, 1966; Crimes, 1975).

As has been mentioned previously, Delgado (1886) used the above incorrect assumption in his defence of the fucoid origins of Cruziana, while at the same time criticizing Nathorst's (1881) biogenic surface excavation theory. Nathorst (1886) countered Delgado's (1886) criticism by erecting a slightly elaborate and complex sequence of events involving submarine excavation followed by sub-aerial exposure and desiccation in order to preserve the trace. Few Cruziana show features consistent with desiccation, but they have been recorded from braided alluvial channel systems characterised by periodic floods and dry spells by Selley (1970). Examples of C. rugosa from Brittany, France occur on beds which do carry possible desiccation (or alternatively hysteresis) cracks (Baldwin, 1974; Baldwin, in press(a)).

Osgood (1970), after reviewing Seilacher's (1964) various forms of preserved traces, discusses at some length the preservation of 'exogenous imprints', but comes to no final conclusion on the mechanism of abrasion protection.

Crimes (1975) has presented a qualitative discussion of trace production and initial preservation. His geotechnical treatment would appear to answer the non-surface protagonists, but the treatment falls short of discussion of the ultimate preservation of extremely fine detail so characteristic of trilobite tracks. The absence of abraded surfaces is not discussed.

(c) Physical properties of sediment excavated.

Most ichnologists appear to agree that some property of the mud layer is critical for the genesis and possibly preservation of surface traces. Radwanski and Roniewicz (1963) state that the consolidation is the key to the persistence of 'grooves burrowed by animals'. This general point is amplified by Osgood (1970) who recognises the 'cohesiveness of mud' as being the most important preservational factor. Dzulinski and Sanders (1962), in a study which largely deals with inorganic current marks, conclude that the 'uniqueness' of mud bottoms, which are able to give information on some of the mechanics of sediment transport, is dependent on the cohesion between grains 'which prevents total dispersal of this type of medium'. Hjulstrom (1935) has, perhaps more than anyone, presented the most widely known evidence for the special properties of fine grained sediment. However, this early work is largely concerned with the hydrodynamics of the situation, rather than the purely physical parameters. Postma (1967) has included these physical parameters in his discussion of critical erosion velocites, but has qualified his conclusions on the importance of cohesion by stressing the importance of turbulence and bottom roughness. This work is used by Rhoads (1970) and by Crimes (1975) in their discussions of fine grained sediment properties.

In Crimes' (1975) work physical equations are used to demonstrate the overriding importance of cohesion in the initial formation of trilobite surface excavations. To some extent, in demonstrating the validity of his arguments, Crimes tends to reduce the full potential strength by largely discounting the angle of internal friction (Ø). This may be justified in semi-theoretical treatments, but in practice Ø would appear to be important (cf. Crimes, op. cit., p.43). Terwindt and Breusers (1972) state that 'a higher sand content of muds gives a more rapid initial consolidation'. Mignot (1968) has suggested that a sand content of 40% leads to a greater strength than for pure mud and Grim (1962) that a mixture of sand, silt and clay grades has greater cohesion than any of these size classes alone. Holmes and Goodell (1964), in an empirical study of strength of near-shore sediments, recognize only three important variables which condition cohesion: (in decreasing order of importance) water content; sediment depth below sediment/water interface; characteristics of the clay mineral assemblage. In a breakdown of the factors influencing these three major parameters, Holmes and Goodell conclude that 'mean grain size is the most important parameter and accounts for 72.4% of the variation in water content' and hence bears directly on strength also. Thus, in practice, Crimes' (1975) arguments are amplified when positive values of Ø are included in the analysis. Further, from a purely environmental point of view, Crimes' use of 'ocean floor' muds might be questioned. Cruziana are almost entirely confined to shallow water and shelf or near-shore deposits, sediments which are typified by alternations of sands and muds. Terwindt and Breusers (1972) suggest that muds in natural near-shore (intertidal) waters may be assumed to have around 37% sand incorporated (Mud 1 of Terwindt and Breusers, 1972, p. 4) and an original volumetric water content of 80% soon after deposition. Terzaghi and Peck (1948) give a range from 20°-30° for values of ϕ for remoulded clays, $\phi = 0^\circ$ for completely saturated clay and $\phi = 30^\circ$ for fairly dry clays. The combination of even reduced values of ϕ for high water content clays with a component of positive ϕ from the sand fraction will certainly produce the cohesive conditions suitable for trace production and preservation.

Terwindt's and Breusers' (1972) consideration of the various forms of sand-clay bedding is extremely relevant to the discussion of the preservation of biogenic structures. As has been mentioned, the environmental framework is identical to that of Cruziana associated lithotopes, but perhaps as important is the time span they identify in which the system may work. Terwindt and Breusers suggest that consolidation is so rapid (initial consolidation) that part of the mud layer is not resuspended, but remains so that repetition leads to net accretion. Oertel (1973) and McCave (1970) suggest that mud may be deposited from bed load rather than simply from suspension (the process accepted by Terwindt and Breusers), thus allowing the addition of mud layers at times other than maximum tidal slack. These two alternative accretionary processes are not important in this discussion, but the accumulation of fairly thick mud layers and their compaction and consolidation history is. Thin mud layers have the faster initial consolidation rates, and this is intensified by the incorporated sand fraction. Thus those layers which are preserved over the maximum current velocity ebb and flood tide periods are retained because of their inherent strength in the first place. Consequently mud layers accumulate with consolidation values typically at the high end of the possible range. Therefore, any mud layer preserved in the intertidal or immediate sub-tidal environment may have a high cohesion value as a basic property.

A gradient of compaction and water content has been demonstrated by Rhoads (1970) for shelf sediments in Buzzards Bay, Massachusetts, U.S.A. A similar gradient is also recognized by Holmes and Goodell (1964) in St. Andrew Bay, Florida, U.S.A. The high near-surface water content shown by Rhoads (1970) stems from biogenic reworking of the surface and feacal pellitization, so producing sand sized aggregates and disproportionately large pore volumes for the actual component (= mud) grain sizes. Even without this reworking, strength and cohesion of mud layers appears to be directly related to depth (Holmes and Goodell, 1964) so that a liquid slurry gradually increasing in cohesion would be likely to cover any consolidated portion.

Terwindt and Breusers (1972) and Crimes (1975) have stressed the importance of bearing capacity, the former authors from the point of view of preservation of precise bedding plane separation between sands overlying muds and the latter in discussion of initial existence of trilobite excavations.

Crimes (1975, Fig. 6) infers that with bearing capacity failure no trace is preserved. However, it may be that a progressively downward increasing bearing capacity may serve to protect the extreme fine detail on Cruziana and Rusophycus. As the trilobite settles on the unstable mud surface it sinks to the level at which it is just supported by the inherent bearing capacity of that level (Fig.48). By limb activity (effectively sediment remoulding), the bearing capacity at that level is further reduced so that the trilobite attains a natural support level in the mud layer where, even with movement, the underlying mud is more or less stable, Thus, any digging activity is performed below a protective layer of remoulded sediment derived both from the material excavated and the thin layer of superincumbent mud present over the whole layer.

With increased current shear, perhaps during the period prior to the ingress of the casting sediment, only the remoulded sediment and the sediment of low cohesion will be resedimented, a finite gap existing in the values of bearing capacity and strength between the remoulded mud above the base of the excavation and the non-remoulded mud below. Therefore, the reworked mud filling the mould will be easily removed by a relatively weak current without scour of the walls of the mould and the general bedding plane will be reduced to a level at which current shear and the critical shear velocity of the sediment are in balance.

True open surface excavations are probably common in nature, but the arrangement outlined above may be equally or more important. It is difficult to imagine total high cohesion right to the upper surface

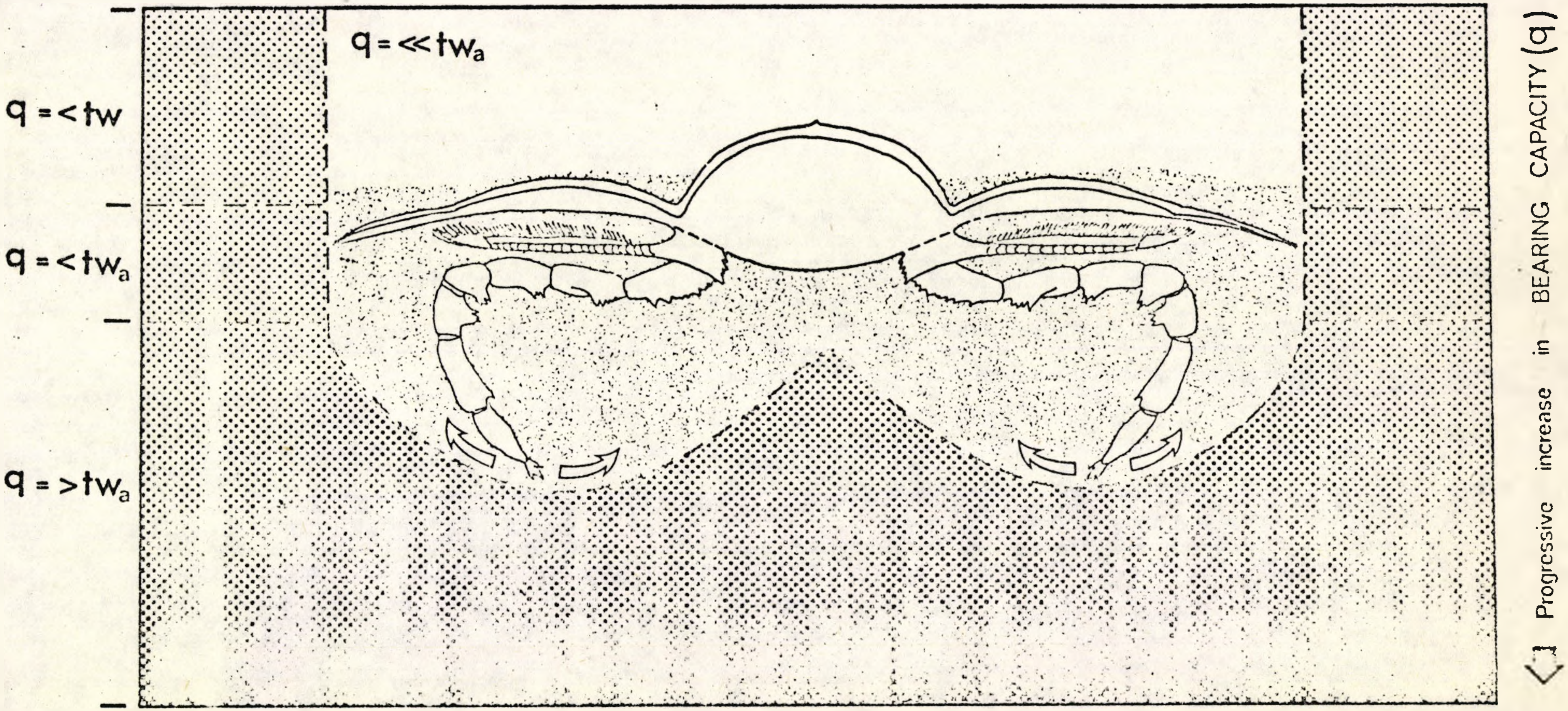


Figure 48
Changes in the relative values of Bearing Capacity (q) due to trilobite furrowing activity. tw – trilobite weight; tw_a – subscript 'a' indicates <u>active</u> trilobite and implies a remoulding ability. Trilobite will reach equilibrium level in sediment where $q = tw_a$. Note finite difference of (q) at base of furrow and within furrow.

of a complete mud layer. With either very slight wave or tidal movement of the water column above the sediment, the top few mm would be constantly disturbed and characterized by very high water contents and reduced cohesion. unless there is initial cementation.

(d) Hydrodynamics of the sediment/water system.

The production of a cast is obviously a two stage process. First, there is the excavation of the mould, the maintainence of which has been discussed above. This is followed by the second stage of casting by some different lithology in order that a distinct, but morphologically complex bedding plane may be developed (Radwanski and Roniewicz, 1963).

Most authors fail to discuss this later stage (Birkenmajer and Bruton, 1971; Radwanski and Roniewicz, 1963) or avoid it altogether by proposing alternative processes which do not involve this type of two stage process (Birkenmajer and Bruton, 1971; Seilacher, 1962, 1970; Osgood, 1970).

Crimes (1975) considers that overconsolidation may in part account for the preservation of extreme detail. However, the very wide occurrence of overconsolidated shallow marine seems doubtful and the example described by Almagor (1967) may well be fairly atypical (e.g. McClelland, 1956; Fisk and McClelland, 1959; Richards, 1961; Richards and Hamilton, 1967; Skempton, 1970). Crimes (op. cit.) suggests that in shallow marine sediments such overconsolidation is unlikely to form as a result of slow rates of sedimentation and submarine cementation - the process which appears fairly common in deep ocean muds. In order to achieve overconsolidation he suggests that drainage downwards into underlying sand layers may assist. Except for cases of extremely high sediment concentrations rarely occurring in nature, '... the drainage effect on the consolidation is not important under natural conditions in the estuary where thinner mud layers prevail ... ' (Terwindt and Breusers, 1972). The consolidation values given by Holmes and Goodell (1964), Richards (1961), Terwindt and Breusers (1972) and Mignot (1968) all suggest quite normal consolidation curves.

Even if over consolidation was the key to preservation, the problem of the retention of extreme detail similar to that found on the outer lobes of many C. semiplicata (e.g. Crimes, 1970a) is difficult to understand. Even with the transport of sand or fine silt, sufficient velocity seems likely to be involved for even weak sand blasting of trilobite tracks open to the surface. Mean velocities at a variety of distances above the sediment/water interface have been given for a number of shallow marine environments characterised by intermittent sand and mud deposition (Table 30). Terwindt and Breusers suggest a value of 20cm/sec as the critical shear velocity for the maintainence of mud layers. This value may well be higher in the natural environment and Postma's (1967) figures, when combined with the variations in water content indicated by Rhoads (1970, Pl. 1) just a few mm below the sediment/water interface, suggest that in fact critical current velocities of the order of 100-200cm/sec may in fact be required to completely strip mud layers. The ballistic transport of even slowly saltating grains when transported into an open excavation in an otherwise nearly flat surface would seem likely to be sufficient to slowly abrade the finest detail. This action would be intensified by the generation of eddies in and around the excavation. Maull and East (1963) have studied three dimensional flows in open cavities, the elements of which are similar to the gross form of Cruziana furrows. Their studies have demonstrated that quite extreme turbulence generated by trapped eddies within such troughs is likely to further increase the erosion capacity of the sand/water system and so reduce the 'Hjulstrom effect' in the manner outlined by Postma (1967) by increasing roughness and turbulence. Consequently either some arrangement whereby the mud surface is protected from abrasion or some characteristic of the sand transporting system must be invoked in order to maintain detail in open excavations.

Osgood (1970) pursues the final preservation problem further than most, particularly in the discussion of Dzulinski's and Sanders' (1962) work. One point is missed in Osgood's discussion of the traction carpet idea. In turbidity flows, even with a traction carpet, there is net erosion and removal of part of the mud surface prior to its blanketing by the graded material deposited by the back end of the same traction carpet. Tool marks (e.g. grain stria, etc.) characteristic of this type of grain transporting system suggest eroding tools and such transport would probably cause noticeable abrasion of surface furrows. The direct application of this type of flow to non-turbidity currents seems doubtful. Kuenen (1966) suggests that traction carpets form out of the turbulent part of the current and their movement is due to the drag by the turbidity current and by the input of kinetic energy from the momentum of added grains, again derived from the turbidity flow. It seems unlikely that sufficient power would be present in normal shallow marine tidal or current flows.

AUTHOR	HEIGHT ABOVE SEDIMENT/WATER INTERFACE	SHEAR VELOCITY cm/sec
Oertel 1973	+ 1.0m	< 40
Terwindt & Breusers 1972	+0.5m	> 60(springs) < 60(neaps)
Terwindt 1971	-	40-50
Postma 1961	-	25-80
Kranck 1972	-	13-52

Table 30

Mean velocities at a variety of distances above the sediment/water interface

4. SUMMARY

An understanding of the preservation potential as well as production and preservation processes are of considerable importance if sensible morphological data are to be derived from trilobite trace fossils. With the backing of such process-orientated information, one is able to identify stable morphological data and isolate that which is modified by or dependent upon preservation processes. In this way, the component parts of traces can be identified and the detailed kinematics of production outlined. Thus, an understanding of morphologically based features can lead to greater insight into behavioural factors.

Geotechnical and sedimentological parameters relating to production, temporary existence and ultimate preservation of trilobite furrows lead one to expect the preservation of fine detail on many Cruziana and Rusophycus. These features are of critical importance in taxonomic studies and, hence, eventually to the stratigrapher.

PART 4

PALAEOGEOGRAPHY OF WESTERN EUROPE DURING THE CAMBRO-ORDOVICIAN

CHAPTER 7

PALAEOGEOGRAPHICAL SYNTHESIS

1. INTRODUCTION

Sedimentological and environmental models for the Grès Armoricain and its equivalents have been discussed in previous chapters. Trace fossil data has allowed refinement of the stratigraphic subdivision of these sequences so that the temporal evolution of all depositional environments has been facilitated.

In order to establish the spatial relationships (and possible contiguity) of the geographically separate areas throughout Cambro-Ordovician time, it is necessary to accept the operation of Plate tectonic processes during the early Palaeozoic. A brief review of extant but conflicting palaeontological and geophysical based Palaeozoic plate distribution models will establish a range of possible configurations. From this, a plate paradigm may be developed around which a palaeogeographical synthesis may be discussed.

2. PLATE DISTRIBUTION DURING THE LOWER PALAEOZOIC

(a) Faunal models.

(i) Basic assumptions.

In two publications (Hughes, 1973 and Middlemiss et al. 1971) the concepts of faunal based interpretations of lithospheric plate distributions have been reviewed. The concept of faunal contiguity indicating environmental (plate ?) contiguity (e.g., Wilson, 1966) is of course extended so that indirect information in the form of climatic zonation (Spjeldnaes, 1961; Valentine and Moores, 1970; Whittington, 1973) and oceanic circulation (Williams, 1969; Dewey et al. 1974) can supplement the spatial data.

(ii) Cambro-Ordovician examples.

Brachiopods: From cluster analysis of Arenig brachiopod faunas, Williams (1973) determined distinctive American and European Realms; the latter being composed of the Baltic, Celtic and Anglo-French Provinces. This Anglo-French Province (Williams, op.cit., Text Figure 9) encompasses the three areas of the present study. Williams (op.cit., page 259) concludes that early Ordovician European faunas were 'fragmented' into three provinces with 'fairly stable boundaries'. The nature of these early

Ordovician boundaries is not discussed by Williams, but it can perhaps be inferred from a later discussion of Caradocian faunas (*op.cit.*, page 261) that lithological/climate association may have had a major influence.

Thus, a spatial model derived from brachiopod information indicates that the UK, Brittany and Iberia formed parts of a contiguous faunal province at the beginning of the Ordovician and that these areas either constituted parts of a single plate or, if on separate plates, were adjacent to each other.

Trilobites: Lower Ordovician trilobite faunal provinces are described by Whittington and Hughes (1972, 1973). These authors conclude that their Selenopeltis and Asaphopsis faunas inhabited 'shallow seas around the margins of Palaeozoic Gondwanaland'. The Selenopeltis fauna was limited to Ireland, *Britain* (south of the Southern Uplands), *Brittany*, Czechoslovakia, *southern France*, *Spain*, *Portugal*, Turkey and possibly southern Florida. Whittington and Hughes (1972, Figure 3) indicate the faunal contiguity of the UK, Brittany and Spain, a pattern further refined in their later work (Whittington and Hughes, 1962, Figure 2) in which Britain is more closely linked with the main mass of the 'southern European plate'.

Cruziana: For the Lower Ordovician Seilacher and Crimes (1969, Figure 2) indicate ichnofaunal links between, amongst others, Wales, Brittany and Spain, and conclude that *Cruziana* define an ichnofaunal province which resembles the European body fossil provinces.

(b) *Geophysical models*.

(i) Basic assumptions.

Reconstructions of Palaeozoic lithospheric plate distributions can be attempted by two geophysical methods. In the first, palaeopole positions are computed from remnant magnetism and the resultant mean pole is fitted (within the constraints of spherical geometry) to the geographical pole. As this orientation is unique and as latitudes are defined, the palaeolatitude is similarly fixed in space. Not so longitude, which is based on an arbitrary datum and which, therefore, provides potentially ambiguous spatial data.

In the second, an understanding, or at least partial reconstruction, of the kinematics of plate movement towards an identified point is required.

The identified point is represented by orogenic belts which are taken to indicate plate to plate contacts or collisions. Again within the confines of spherical geometry, plate movements are modelled so that a logical sequence of collisions follows the observed and dated sequence of orogenic events. Structural, igneous and stratigraphic evidence serves to refine these models.

(ii) Cambro-Ordovician examples.

Smith, Briden and Drewry (1973) provided a paradigmatic study which formed the basis of discussion at a symposium entitled 'Organisms and Continents through time' (Hughes, 1973). Both forms of geophysical data were utilised and composite palaeogeographical maps were presented as mercator and stereographic projections (Smith et al. op.cit., Figs. 13 and 21A). On these maps Iberia is shown adjacent to the margins of Gondwanaland, with the UK and France forming the western margin of a European plate which is remote from Gondwanaland. A slightly modified configuration is presented by Briden, Drewry and Smith (1974), but a latitudinal separation of Iberia and France of 25° and a longitudinal separation of 70° is still maintained.

Bard, Capdevila, Matte and Ribeiro (1973) reviewed the geotectonic history of the Iberian Variscan Orogen and concluded that its late Pre-Cambrian and Palaeozoic development was more or less identical with that of the West European Variscides (Bard et al. op.cit., p. 52). Further, they indicate a nearly uniform Sialic basement for the whole of the northern and eastern Iberian Variscides, and presumably, therefore, their extension or continuation on the northern side of the Bay of Biscay.

Riding (1974) proposed a model for the development of the Hercynian foldbelt and by extension defined some aspects of Lower Palaeozoic plate distributions. Riding's (op.cit., Fig. 2) main thesis is that the Cantabrians, Pyrenees and Montagne Noire (south-east France) areas constituted a micro-plate which was located within a bifurcating metamorphic zone: the latter indicating the pre-existing positions of front-plate and back-plate suture zones. In this way Riding implies the spatial separation of Iberia and Brittany.

3. DISCUSSION

The contiguity of England and Wales with Brittany and possibly other areas of southern France (e.g. Montagne Noire) appears to be accepted on both palaeontological and geophysical evidence (e.g. Seilacher and Crimes, 1969; Whittington and Hughes, 1973; Williams, 1973; Smith et al, 1973; Bard et al, 1973). The isolation of Iberia from the European plate (European plate sensu Whittington and Hughes, 1973) presents a major problem. Evidence of the 'orogenic' type taken from the Pyreneean fold zone is complex, and, almost certainly represents, long term polyphase deformation involving both distensional and compressional phases (Le Pichon and Sibuet, 1971). The kinematic history of this area provides practically no information for Lower Palaeozoic reconstruction (Riding, 1974, p. 128). The central-northern areas of Iberia which were not affected by Mesozoic and Tertiary orogeny provide more useful information. The data of Bard et al (1973) suggests an in-plate position for northern Iberia with a possible plate margin with a northward dippling benioff zone in Southern Portugal (cf. Bird and Dewey, 1970). Then, with the accepted pre-Tertiary closed geometry of the Bay of Biscay (Carey, 1958; Bullard, Everett and Smith, 1965; Mattouer, 1969; Le Pichon, Bohin and Sibuet, 1970; Le Pichon and Sibuet, 1971; Sylvester-Bradley, 1974), a continuous, albeit locally irregular, Sialic basement would link Iberia with Brittany and the rest of the European plate.

The extension of Riding's (1974) model from the late-Carboniferous to the lower Palaeozoic is possibly unwise, particularly as that author acknowledges the 'relatively poor documentation of the Palaeozoic geology of relevant areas of Spain (and north Africa)'. The fragmented expression of the southern margin of the Franco-Iberian Hercenides can perhaps be explained by a geometry other than that of a 'north-Spain micro-plate'. Basement control which is important in other discussions of Iberian geology (e.g. Bard, 1971; Bard et al, 1973) may have influenced the pattern. However, Riding (op.cit.) acknowledges similar tectonic stratigraphies in Iberia and southern France: areas which are considered to have formed parts of a lower Palaeozoic faunal province which was contiguous with Brittany and the UK (Williams, 1973; Whittington and Hughes, 1973).

In this context Williams (1973, p. 241) considers 'palaeontological evidence ... at least as trustworthy as geophysical (evidence)'. Similarly Vine (pers.comm., 1975) considers palaeontological data to be of more use than geophysical data in any lower Palaeozoic reconstructions.

Thus, on faunal grounds Iberia, Brittany and the southern UK appear to have formed during the lower Palaeozoic a more or less continuous western margin to a European lithospheric plate. Northern England and Southern Eire formed part of the margin of the Proto Atlantic (Wilson, 1966), while Brittany and Iberia occupied a more intra-plate position with eastern Newfoundland separating these two areas from the true plate margin.

Palaeogeographical Models.

(a) Recapitulation.

Sedimentological and trace fossil information shows that the Cambro-Ordovician sediments of north Spain, Brittany and the UK were deposited in marine shelf environments. Those slightly deeper water facies (for example in Wales, Asturias and Brittany) appear to represent off-shore open marine environments. Nowhere are deep water, off-shelf conditions indicated. In all cases sedimentological models incorporate deltaic, near-shore, barrier bar, lagoon and tidal flat development. Analogue models have been developed from the North Sea, the Eastern Seaboard and Gulf Coast of the USA.

(b) Local Palaeogeographies.

(i) Iberia.

The contrast in thickness of sediments in the Cantabrian and Asturian-Leonese Zones defines a major positive element in the Cambro-Ordovician geography of this area. The Cantabrians are characterised by paralic and near-shore environments with accumulation near to source on a more or less rigid basement. Relatively little sediment was able to accumulate in this zone, but eventually did so, transgressing(?) the Narcea anticlinorium to the more actively subsiding Asturian-Leonese Zone to the west, south and south-east. In central northern Asturias the Cambro-Ordovician laps on the Narcea anticlinorium (Julivert et al, 1973), and this structure may, therefore, have had some topographic expression during sedimentation. It could not have, however, formed a major barrier as the Asturian sediments are derived from the Cantabrian Zone and the geanticlinal interpretation with attendant facies separation proposed by Parga (1970) and supported by Van den Bosch (1969) and Wagner and Martinez-Garcia (1974) seems unlikely. All the Asturian sediments exhibit evidence of extensive reworking and complex long-shore redistribution. Deltaic environments are missing from this zone and are replaced by near-shore and shelf facies.

To the west of the Asturian-Leonese Zone is the Galician orogenic belt. Sediment supply from this area, eastwards into the Asturian-Leonese Zone, appears to have been negligable (Jaritz and Walter, 1970). The metamorphic terrain of Galicia does, however, define an abrupt westerly margin of the Asturian-Leonese Zone and, with the thinning of the lower Palaeozoics on to it, almost certainly formed a topographic high during Cambro-Ordovician deposition.

Further to the south-west in northern Portugal Cambro-Ordovician shallow marine facies similar to those in Asturias crop out. These rocks are at present under investigation, but preliminary results (Diggens, pers. comm., 1972) suggest that close to the southern margin of the Galician Zone palaeocurrent directions indicate transport dominantly along and towards that margin. Again, as in Asturias, Galicia appears to have provided only minor quantities of detritus.

Thus, the Cantabrian Zone appears to have existed as an eroding land area, with, to the west and south, more or less rigid, gently undulating flanking zones. These stable flanks gave way along an imprecise hinge line to a wider and potentially more actively subsiding shallow trough. Only after Arenig time did this trough depart from the condition of near isostatic equilibrium which appears to have permitted the accumulation of over 6km of shallow marine sediments. The isostatic balance of the Asturian-Leonese arcuate basin provided an extensive low relief marine area upon which spreads of shelf and near-shore sediments were distributed. Alternations of off-shore bar and tidal flat facies indicate a complex backward and forward migration of lithotopes. Such sequences are predicted for low relief, gently inclined topographies, and carbonate analogues of Cambro-Ordovician age are present in Scandinavia.

(ii) Brittany.

The spatially and temporally complex pattern of phases of transgression in western Brittany proposed by Pruvost (1949) has been rejected and modified by Bishop et al (1969) into a simpler and more extensively uniform pattern. The latter authors proposed (Bishop et al, op.cit., Fig. 6c) a source area, south of the Brittany peninsula, which supplied clastic material for the northward transgression across southern and central west Brittany and on to a line north of Brest. Chauval and Le Corre (1971) correlated a number of Grès Armoricain sequences both in western and eastern Brittany and concluded that sedimentation was essentially similar in all areas: deposition taking place across an extensive but irregular peneplain. These irregularities were first filled with red sands and conglomerates which Chauval and Le Corre (op.cit.) consider represented post-Cadomian mollase. Deeper erosion provided iron deficient quartz sands which spread over this near flat topography. Bishop et al (op.cit.) indicate a topography more complex than that inferred by Chauval and Le Corre (op.cit.), and suggest that Cadomian structures 'influenced the pattern of Ordovician sedimentation'. During the early Ordovician, therefore, in western Brittany was a low relief, but locally irregular, peneplain with a structurally imparted grain producing low amplitude east/west trending swells and lows. The first stages of transgression filled the irregularities with iron-stained conglomerates and sands. The later phases, involving cleaner polycylic super-mature sands, presumably reflects a more remote southern source area. The low amplitude topography of the area determined facies changes and provided temporary barriers to northward transgression. Thick shelf sands blanketed the terrain and provided a nearly flat surface for the development of northward transgressive barrier bar, lagoonal and tidal flat facies. Continued transgression coupled with a possible termination of supply of coarse detritus led to pelitic shelf deposition during Llanvirn times.

(iii) Southern United Kingdom.

Crimes (1970) demonstrates that during Arenig times sub-littoral depositional environments were present over the whole of Wales. Similar facies (*Cruziana* facies) existed during the Arenig times in the Welsh Borderlands (Crimes, 1970a) and earlier in the Tremadoc in Gloucestershire (Crimes, 1975). The presence of a fault bounded land mass in the position of the present Irish Sea is demonstrated by Crimes (1970b) and this narrow positive, fault bounded feature exhibits a dual role. It firstly delimited a boundary between two sections of crust which behave in different ways. To the west was an area of rapid subsidence, while to the east was a quasi-stable, but topographically complex shelf. Crimes (1970b) shows that in this Welsh shelf area local variations in subsidence and hence local facies variations were related to faulting and volcanic topographies.

The second role of the Irish Sea land mass was to supply considerable thicknesses of sediments both to the east and west.

4. EUROPEAN PALAEOGEOGRAPHY: SUMMARY

In Spain and Brittany similar palaeogeographical settings are apparent. In both areas pre-existing and perhaps coeval crustal warping controlled the general pattern of facies. Minor irregularities within this type of tectonic frame, in conjunction with possible eustatic changes, determined detailed facies evolution. The most important single factor was the presence of essentially stable or only slowly subsiding Sialic basement which permitted the maintenance of shallow marine facies from Cambrian to Llanvirn times.

The United Kingdom differs from Spain and Brittany in only one respect: the presence of important syn-depositional volcanic and volcaniclastic components. Otherwise the depositonal environments of all three areas are similar.

In a palaeogeographical sense it appears probable that northern Iberia and western Brittany were both deriving sediments from a Cantabrian/Pyreneean source area. If this were the case, then it is possible that the main expression of Cadomian tectogenesis was limited to the northern side of this land mass where more typical mollase types of sediments were deposited. A further expression of enhanced relief in this northern area of Brittany may be seen in the main transgressive phase as late as Arenig rather than Cambrian in Iberia.

As the main direction of transgression was northwards in Brittany, it is apparent that some positive area separated Brittany from southern UK. In south Wales Arenig sediments may possibly lap southwards on to Pre-Cambrian Pebidian and Dimentian rocks. Northward palaeocurrents in the Upper Cambrian (Ffestiniog Stage) of Pembrokeshire (Crimes, 1970c) suggest the presence of some form of positive and possibly exposed area in the south.

In terms of plate tectonics it may have been that Iberia/Brittany and the UK differed slightly. The Iberia/Brittany setting was one of long duration stability. Barrier bar sequences were the dominant sedimentation response. Inman and Nordstrom (1971) in a plate tectonically based classification of coasts show that present day coasts analogous to Cambro-Ordovician examples are found on 'Amero trailing edges'. Such coasts are situated on the trailing edges of plates with collision coasts on the leading edge. A possible incipient subduction zone was present in the extreme south-west of Spain and Portugal during early Ordovician (Bard et al. 1973), but it seems unlikely that any associated relief in that area would have contributed sediment to the northern areas of Spain and Brittany.

The key morphological factor to barrier bar and associated features appears to be the existence of an extensive shelf permitting sediment reworking and wave build-up conditions (Swift, 1975). Such conditions appear to have existed in Spain and Brittany. A conservative plate margin or intra-plate setting may have influenced or determined these conditions.

The UK was an area of more vigorous volcanic and tectonic activity, and Crimes (1970b) indicates that Wales was separated from deep basinal developments by the narrow 'Irish Sea Landmass'. Extensive shelf development was restricted so that reworking and associated barrier build-ups were limited. Facies patterns are more complex than areas to the south.

The setting of the western margin of the Cambro-Ordovician 'west European plate' was of an inland 'Mediterranean type' of sea margining the western, southern and northern flanks of a Cantabrian land area. This 'sea', on thin continental crust, was isolated from the true western margin of the plate by another positive area (Eastern Newfoundland) which may have been continuous with the northern true plate margin west of Wales.

CONCLUSIONS

8. CONCLUSIONS

Concluding remarks are incorporated at the end of most of the preceding discursive chapters. The more important general conclusions are listed below.

1. Cruziana stratigraphy.

The Cambro-Ordovician *Cruziana* stratigraphy developed by Crimes (1970a & b, 1975) and Seilacher (1970) from geographically isolated sections in the UK and elsewhere is confirmed by similar distributions of trilobite trace fossils in the Cabos Series Reference Section between Cadavedo and Luarca, Asturias, N.W. Spain. Its general applicability is indicated by similar trace distributions in Cambro-Ordovician rocks of southern, central and northern Spain and in Western Brittany.

2. Cambro-Ordovician Palaeoenvironments.

Shelf, barrier bar and near-shore environments characterise the Cambro-Ordovician rocks of the Cantabrians, Asturias and Brittany. The vertical persistance of barrier bar sequences attests to long term environmental stability and suggests either a trailing edge or mediterranean plate tectonic setting.

The Cambro-Ordovician Cabos Series of the west Asturian-Leonese Zone is at least 4380m thick, whereas the contemporaneous sequence in the Cantabrian Zone is less than 1000m thick. Correlations based on trilobite trace fossils indicate that at least the upper 250m of the Cantabrian sequence is condensed equivalent to that recorded in Asturias.

The contrast in geosynclinal facies proposed by Wagner and Martinez-Garcia (1974) for the Cantabrian Zone (miogeosynclinal) and west Asturian-Leonese Zone (eugeosynclinal) is untenable for Cambro-Ordovician time.

3. Trilobite trace production and preservation.

(a) Dig marks.

Component parts (dig marks) can be identified on many traces. These units form taxonomically stable elements of trilobite traces and should be described in detail in systematic work.

(b) Surface furrow origin of most Cruziana.

Internal primary sedimentary structures and evidence of trophic responses indicate that the majority of Cambro-Ordovician Cruziana and Rusophycus were produced at the sediment/water interface.

(c) Influence of geotechnical factors during production and preservation.

The critical importance during production of a vertical gradient in bearing capacity is demonstrated. Sediment remoulding by active trilobites is sufficient to produce well preserved detail on deeply excavated furrows. The same model predicts the preservation of reduced detail on smaller and more shallowly excavated furrows.

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