ENVIRONMENTS OF DEPOSITION OF MIDDLE JURASSIC SANDSTONES IN THE GREAT ESTUARINE GROUP, N. W. SCOTLAND.

by

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THESIS ABSTRACT

The lithostratigraphy of the Great Estuarine Group is revised by reference to defined type sections of the eight formations (joint publication with J.D. Hudson). Within this framework a series of lagoonal delta and lagoon shoreline depositional models are proposed for the two sandstone dominated formations (Elgol and Valtos). Sedimentation was controlled by brackish, widely fluctuating and locally marine salinities in two elongate basins (Inner Hebrides and Sea of the Hebrides) separated by a slowly subsiding ridge termed the mid-Skye palaeohigh. Low sinuosity rivers of rapidly fluctuating discharge supplied the deltas with sand sourced from the Moinian and Dalradian (probably via the ORS) of the Scottish landmass to the east and from the Lewisian of the Outer Hebrides landmass to the west.

The Elgol Formation represents a fluvial-wave-tide interaction delta in the north of the Sea of the Hebrides Basin where salinities were marine and shows a southwards transition to a fluvial dominated delta with buoyant mouth bar dynamics. In the Inner Hebrides Basin it represents a fluvially dominated lobate delta system with fresh-brackish salinities controlling friction dominated mouth bar hydrodynamics.

The Valtos Formation in the Sea of the Hebrides Basin represents 8 phases of fluvial-wave interaction delta progradation separated by transgressive shell debris beds. The deltas pass laterally into interdeltaic lagoon shorelines and part of the formation represents offshore shell debris sheets and shoals. In the smaller Inner Hebrides Basin the formation represents 6 fluvially dominated lobate delta progradation phases with only minor wave reworking.

The identification of genetic relationships between facies allows correlation and the prediction of sand body geometry while the recognition of the overall control of contemporary subsidence rates allows palaeogeographic reconstruction.

CONTENTS

INTRODUCTION

Hudson (1962,1966) has presented a general interpretation of the sandstones of the Great Estuarine Group as small scale deltas prograding into restricted lagoons. The objectives of this thesis are:

i) to evaluate and extend this interpretation by producing a series of more specific depositional models for the Elgol and Valtos Formations based on modern and ancient analogues.

ii) to produce a palaeogeographic scheme to account for and define the distribution of the Elgol and Valtos Formation sandbodies in the Hebridean Basins.

Previous work on the rocks of the Great Estauarine Group has concentrated on stratigraphy (Hudson 1962), in petrography (Hudson 1964), palaeoecology (Hudson 1962,1963a&b,1980) and stable isotope geochemistry (Tan and Hudson 1974). These papers provide essential background information defining controls and constraints on the interpretation of the Elgol and Valtos Sandstone Formations presented in chapters 2,3 and 4 of this thesis. Each chapter in this thesis is presented in the form of manuscripts prepared for publication as separate papers and therefore involve some repetition of basic information. Subsidiary information on heavy mineral analysis and descriptions of outcrops and access to them are presented in appendices.

Chapter 1 is a revision of the lithostratigraphy of the Great Estuarine Group published as a joint paper (Harris and Hudson 1980). This paper defines the stratigraphic framework used for the interpretation of the Elgol and Valtos Formations. The subsections of this paper dealing with Cullaidh, Elgol, Valtos and Skudiburgh Formations were written by the present author. The subsections concerning the Lealt, Duntulm and Kilmaluag Formations were written by John Hudson. The introductory and concluding sections were written jointly. All the figures were constructed by the present author from the field notes and logs of both authors.

Chapters 2,3 and 4 deal with the facies analysis interpretation and palaeogeography of the Elgol and Valtos Formations. They are based on graphic field logs of the main outcrop sections. These logs, palaeocurrent data and outcrop maps are presented as text figures. The concluding sections of these chapters include palaeogeographic maps assounting for sandbody distribution in the Sea of the Hebrides and Inner Hebrides Basins.

Some preliminary sedimentological interpretations are presented in a published joint paper (Hudson and Harris 1979) included at the back of the thesis.

CHAPTER 1

LITHOSTRATIGRAPHY OF THE GREAT ESTUARINE GROUP (MIDDLE JURASSIC), INNER HEBRIDES

SYNOPSIS

Revised lithostratigraphical terminology for the Great Estuarine Group in Skye, Raasay, Eigg and Muck is proposed. The group comprises the Cullaidh Shale Formation, Elgol Sandstone Formation with Kildonnan Member and Lonfearn Member, Valtos Sandstone Formation, Duntulm Formation, Kilmaluag Formation and Skudiburgh Formation. The type sections of these formations are defined, new measured sections of 5 of them are illustrated and their lateral variations described. The Group is predominantly Bathonian in age, having its base in the Garantiana Zone (Upper Bajocian) and its top in the Macrocephalus Zone (Lower Callovian). The mainly argillaceous formations show wide lateral continuity indicating that a single depositional basin must have occupied the Inner Hebrides-Minch area during the Bathonian.*

INTRODUCTION

The great Estuarine Group (formerly Series) crops out in the islands of the Inner Hebrides (Fig.1) and represents a sequence of paralic environments of variable, generally brackish salinity (Hudson 1963; Hudson and Harris 1979). The Group is intercalated conformably within

* Recent work on thickness and facies variations in the sandy formations indicate that the basin was divided by a slowly subsiding 'high' controlled by the Camasunary Fault. (See Chapters 2,3 and 4)

the marine Jurassic section occupying the Minch Basin off North Western Scotland. Between the base of the Group (Garantiana Zone) and its top (Macrocephalus Zone) there are no fully marine fossils and no good zonal faunas.

However, the group includes a distinctive sequence of diverse lithologies which may be defined as mappable formations in any one area, and which can be recognized as lithostratigraphical correlatives throughout the region. Recent work has emphasized this by proving the continuity of the Mytilus Shales (=Kildonnan Member of Lealt Formation) from Eigg and Strathaird, where they were first recognized, into Trotternish. Individual marker beds, notably the algal limestone at the top of the Kildonnan Member (Hudson 1970), can be recognized throughout the Inner Hebrides, and maintain their relationship to formational boundaries. Thus, although strict biostratigraphic correlation is at present impossible within the Great Estuarine Group, lithostratigraphy is rather precise, and the constant sequence of facies throughout the area make it likely that diachronism is not extreme. It therefore seems appropriate to present a revision of the stratigraphy to include new and more precise information, and at the same time to define type sections and revise the nomenclature according to the guidelines of Holland at al. (1978).

A revision of the existing stratigraphical nomenclature (Anderson 1948; Anderson 1963; Hudson 1962) is also appropriate because it includes a number of indistinctive names and stratigraphical inconsistencies (Fig. 2). The White Sandstone varies from white to dark brown while maintaining other more important characteristics.

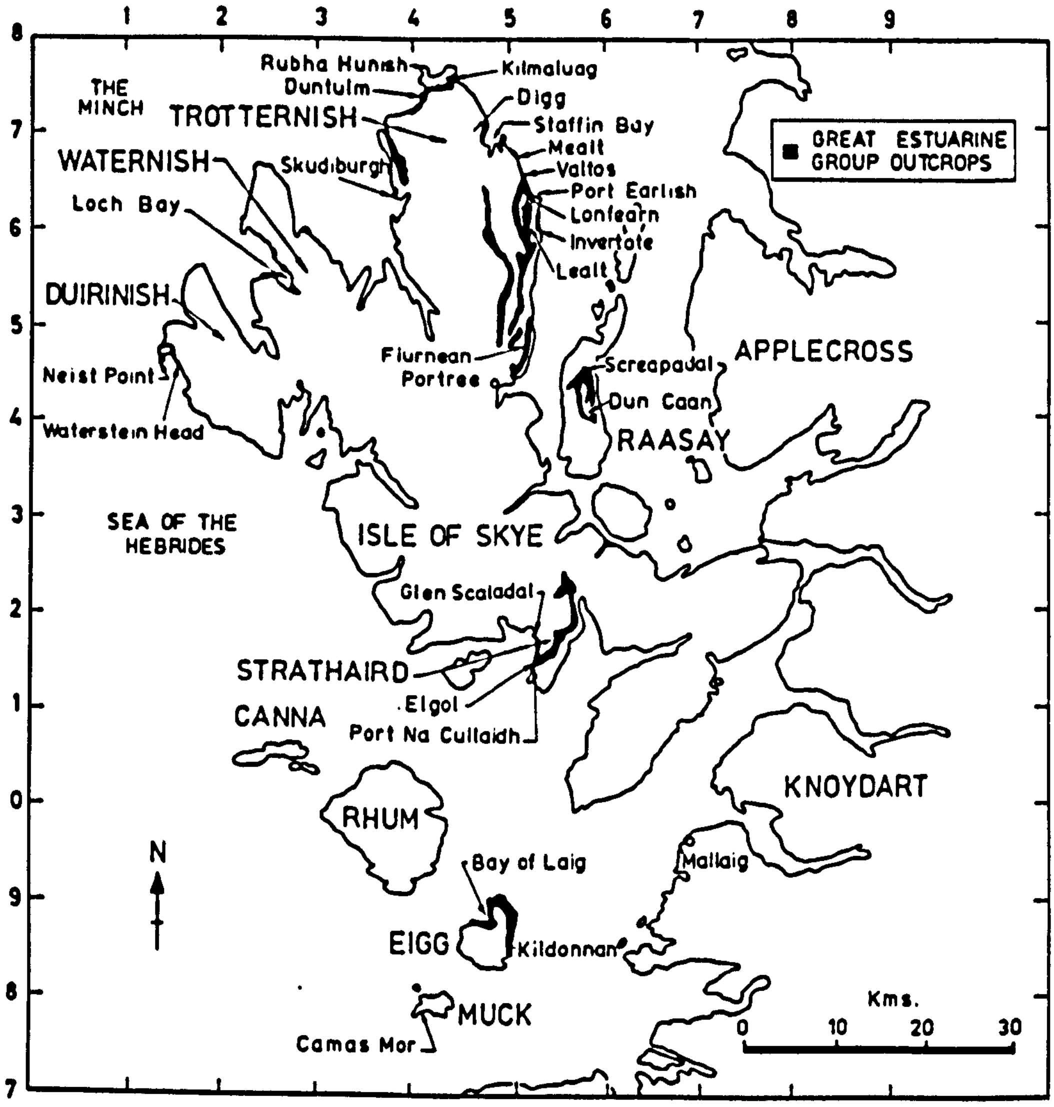


FIG. 1. Location Map, Great Estuarine Group outcrop in black.

Stage		EXISTING TERMINOLOGY MAINLY ANDERSON 1963 - HUDSON 1962	REVISED TERMINOLOGY		TYPE SECTIONS		NATIONAL GRID REFS.
CALLOVIAN-?	STAFFIN BAY FM Macrocephalus zone						
BATHONIAN	GREAT ESTUARINE GROUP	MOTTLED CLAYS (M C)	SKUDIBURGH Fm.		Coast at Skudiburgh & Foreshore below Digg, Trotternish. (Composite) (16M Digg)		NG 374 649 & NG 472 708
		OSTRACOD LIMESTONES (O L)	KILMALUAG Fm.		Kilmaluag Bay, Trotternish & N Shore, Glen Scaladal, Strathaird (Strathaird 25M)		NG 437 748 & NG 164 531
		LOWER OSTREA BEDS (L O B)	DUNTULM Fm.		Cairidh Ghlumaig & Lon Ostation Duntulm, Trotternish. (Composite) 54M		NG 411 739 & NG 406 728
		CONGRETIONARY SANDSTONES (C S S)	VALTOS SANDSTONE Fm		Cliffs between Valtos & Mealt Falls, Trotternish. 120M		NG 517 638 to NG 509 653
		ESTHERIA SHALES (E S)	LONFEARN MEMBER	LEALT SHALE Fm.	Lealt River & Cliffs North of River Mouth Trotternish (Composite) 45M	S of Port Earlish, Trotternish (Composite) 30M	NG 520 605 to NG 521 627 515 604
		MYTILUS SHALES (M S)	KILDONNAN MEMBER			Coast 1.5km N of Kildonnan, Isle of Eigg. 23M	NM 495870
		WHITE SANDSTONE (W S)	ELGOL SANDSTONE Fm.		Coast N Side Port Na Cullaidh, Elgol, Strathaird 22M		NG 517 138
		BASAL OIL SHALE (B O S)	CULLAIDH SHALE Fm		Foreshore Port Na Cullaidh, Elgol, Strathaird. 6M		NG 517 137
?-BAJOCIAN	Garantiana zone						
	BEARRERAIG SANDSTONE FORMATION						

FIG. 2. Table to show new and old terminology with details of the type sections.

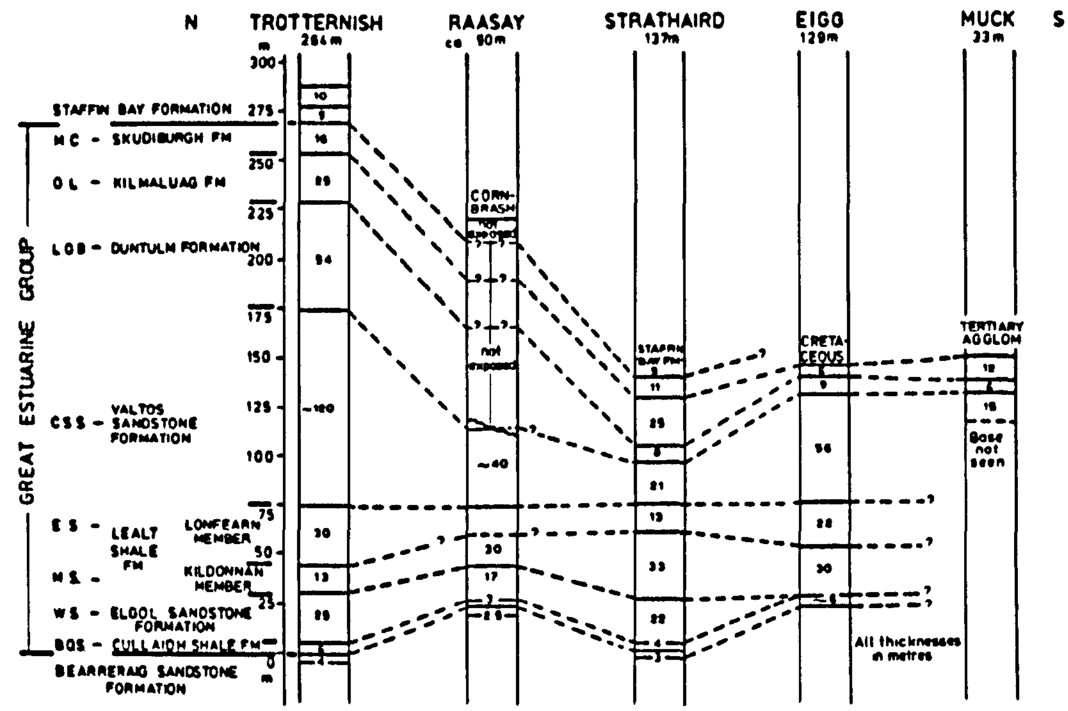


FIG. 3. Generalized sections from the principal outcrop areas showing thickness variation over the 90 km from North Trotternish to Muck.

The term 'Series' in Concretionary Sandstone Series as originally defined by Anderson (1948) is inappropriate as it forms a part of the Great Estuarine Series; also the name 'Concretionary' is not distinctive because concretions occur in most of the Jurassic sandstones in the Hebrides. The Lower Ostrea Beds are now inappropriately named because their counterpart the Upper Ostrea Beds have been placed in the Lower Callovian Staffin Bay Formation (Sykes, 1975b). The Ostracod Limestones of the previous nomenclature are not distinctively named, and include very few limestones. An outline of our proposals is shown in Figures 2 and 3.

CULLAIDH SHALE FORMATION

Basal Oil Shale, B.O.S., of previous nomenclature and the base of the Great Estuarine Group.

At the top of the fully marine Bearreraig Sandstone Formation (Bajocian) in southern Trotternish, Raasay and Strathaird is the Garantiana Clay, G. garantiana Zone (Morton 1965; 1976). This grey or brown clay passes upwards gradationally into the Cullaidh Shale Formation. The base of this formation is defined by the first occurrence of fissile carbonaceous shales, with fish scales, above the paler blocky clays, with ammonites, of the Garantiana Clay. This horizon therefore also defines the base of the Great Estuarine Group (Lee 1920; Anderson 1961; Hudson 1962). Unfortunately, continuous exposures are infrequent; one is in the cliff section in south Trotternish [NG 513 476]. The top of the formation is the first occurrence of bioturbated siltstones at the gradational base of the

Elgol Sandstone Formation.

Type Section. Exposure in Port na Cullaidh, Strathaird (Fig. 1) is variable, occurring between mobile boulders of the storm beach north of the river mouth [NG 517 317]. At this locality the Garantiana Clay and its transition to the Cullaidh Formation is intruded by thick sills; a baked and contorted raft of Garantiana Clay occurs 150 m south of the river mouth [NG 525 135]. Further exposures of Cullaidh Formation in Strathaird occur in roadside quarries between Elgol and Keppoch, 6 km to the northwest; these give a composite section of 4-6 m, transitional at the top to the Elgol Sandstone Formation (base of Fig. 5).

Apart from a loss of fissility through slight thermal metamorphism the Callaidh Formation of Strathaird is very similar to its south Trotternish and Raasay development. It is a black bituminous shale, occasionally a true oil shale in the lower 2 m (Lee 1920; Anderson 1961; Hudson 1962) with numerous fish scales, abundant Quenstedtia (?), occasional articulated fish and rare, regular echinoids Diademopsis cf woodwardi (identification by R.P.S.Jeffries).

Lateral Variations. Northwards both the Garantiana Clay and Cullaidh Shale Formation show marked lateral variation in facies such that it is not possible to differentiate them. The interval between the top sandstone of the Bearreraig Sandstone Formation and the Elgol Sandstone Formation at Rigg [NG 517 564] consists of 4.5 m of shaly sands and silts with a distinctive red mottled limestone at the base, taken as marking the top of the Bearreraig Sandsonte Formation. At

Invertote [NG 520 605], it comprises 95 cm of shales, shaly calcareous sandstones and thin (5 cm) allochthonous lignite lenses, with a fully marine fauna of Nerinella cf expansa (Hudleston), Cucullea or Grammatodon spp., Isocyprina ?sp., Pleuromya uniformis (J.Sowerby) and Globularia sp. (Hudson and Morton 1969). Southwards the formation is difficult to define, the overlying Elgol Sandstone Formation being laterally discontinuous. On Eigg dark silty shales succeed the sands of the Bearreraig Sandstone Formation and may represent the lateral equivalents of the Cullaidh Shale Formation or the Garantiana Clay.

ELGOL SANDSTONE FORMATION

White Sandstone, W.S., of previous nomenclature.

The Elgol Formation is a classic deltaic coarsening upwards sequence 9 to 25 m thick (Hudson and Harris 1979; Chapter 2). The formation is gradational at its base to the Cullaidh formation. It has a laterally persistent coarse, often pebbly, top and is succeeded by the Lealt Shale Formation. Apart from plant remains, some rootlets and trace fossils, the formation is unfossiliferous.

Type Section. Murchison (1828) gives a measured section including a 'great white sandstone' from the cliffs north of Portree, south Trotternish, and Anderson (1963) defined the type section for the White Sandstone in this area. However, the best and most easily accessible sections are in Strathaird, where the rocks are hardened by slight thermal metamorphism. The cliffs on the north side of Port na Cullaidh, Elgol [NG 517 138] provide a superbly exposed section 22 m thick (Pl. 1a), here adopted as the type section for the formation.

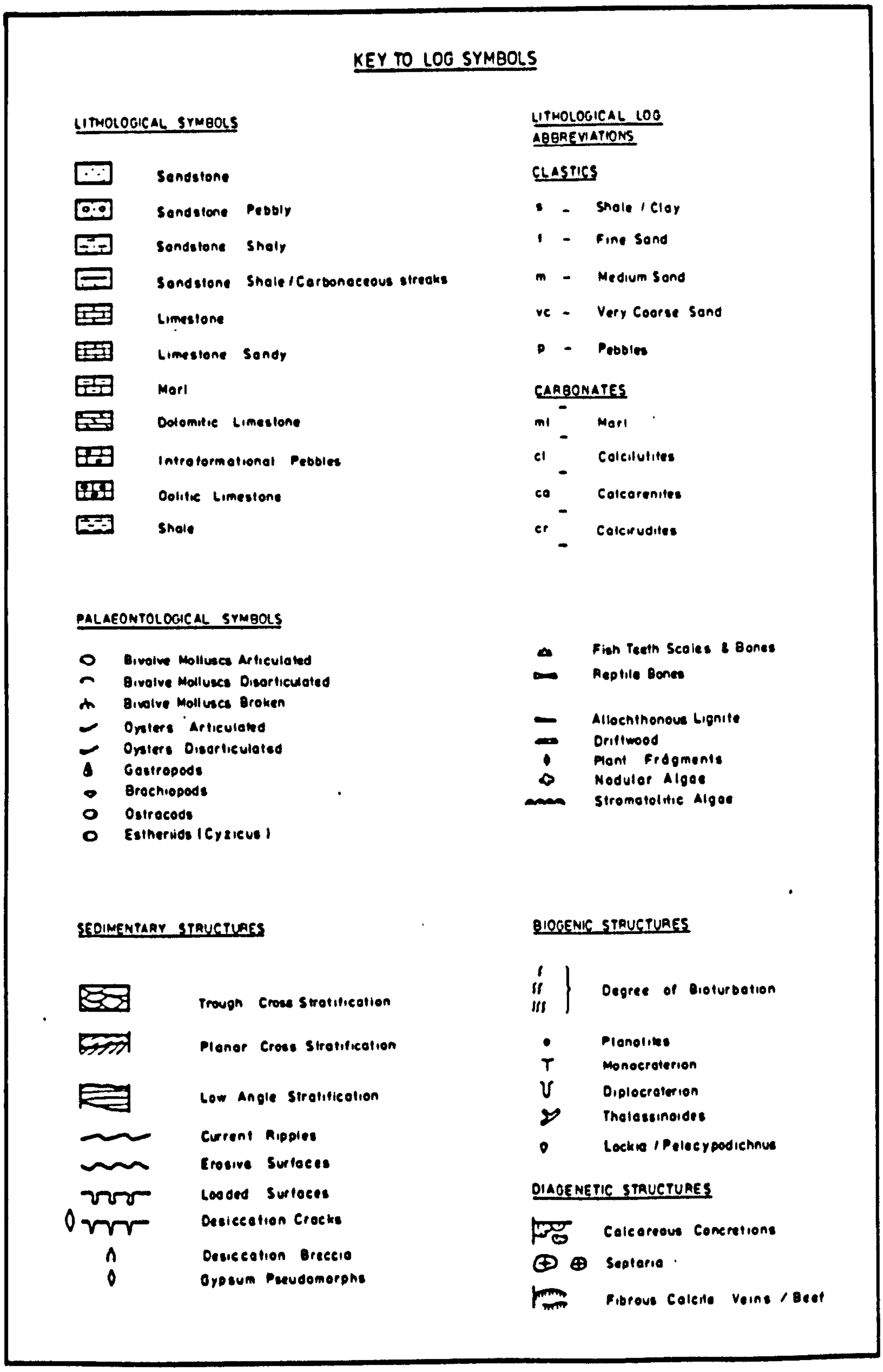


Fig. 4. Legend for Figs. 5–9.

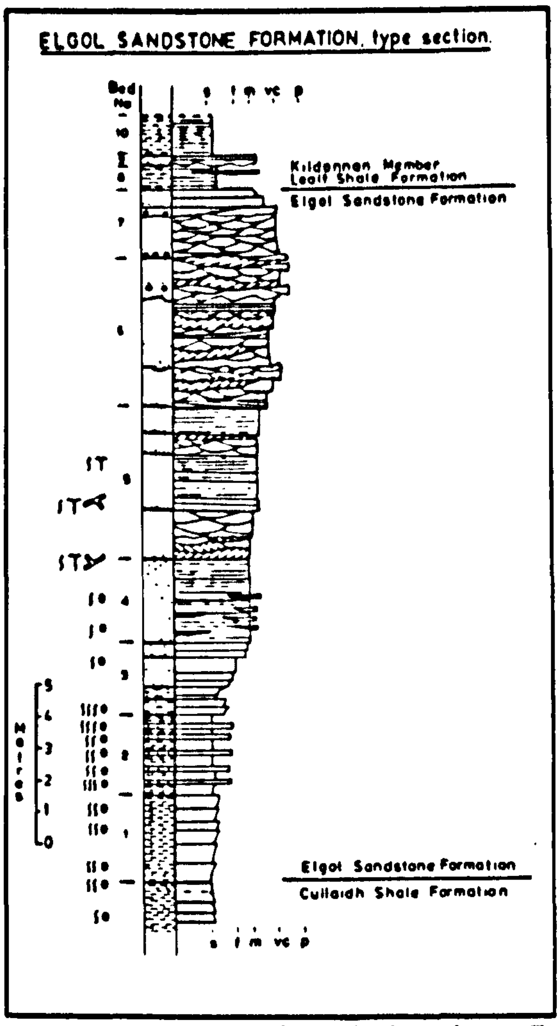


Fig. 5. Type section of the Elgol Sandstone Formation, White Sandstone of previous nomenclature.

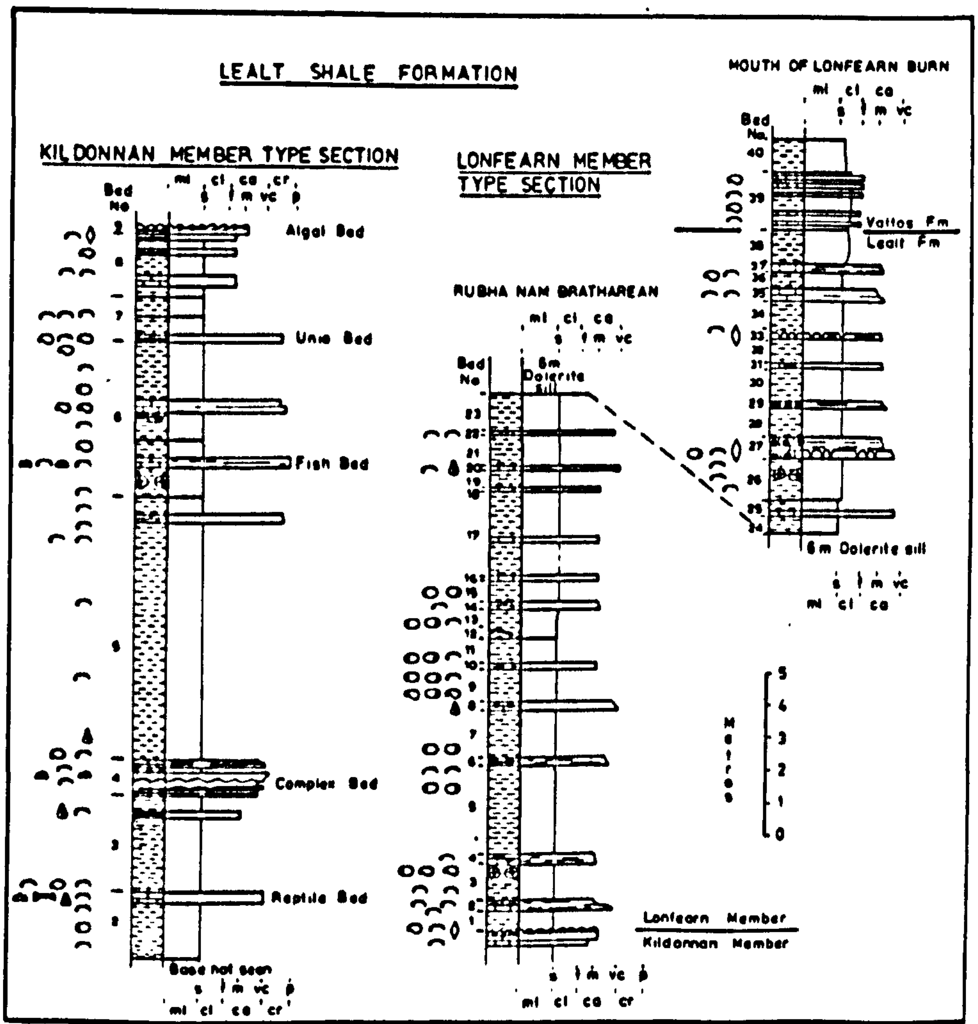


Fig. 6. Type sections of the Lealt Shale Formation members; Estheria Shales and Mytilus Shales of previous nomenclature.

At the base of the formation at Elgol (Fig. 5) are prodeltaic bioturbated shaly sands intercalated with dark silty shales transitional to the Cullaidh Shale Formation. Above these are white delta-front sands, fine to medium grained, with very well developed honeycomb weathering. These are succeeded by medium grained sands with large scale, low angle cross stratification representing the delta front. The formation is capped by a trough and planar cross stratified, very coarse sand with granules and pebbly lenses. It represents the laterally persistent wave and current reworked delta shoreline. The Elgol Formation forms a distinct scarp traceable with some lateral variation in facies for 7 km to the northwest. Interdistributary bay, crevasse splay and distributary channel facies are identified.

Lateral Variations. Northwards from the type area the formation shows considerable facies variation. In south Trotternish, below Fiurnean [NG 515 477 to 515 495] (Anderson's type section, in Donovan and Hemingway 1963) and in Raasay north of Dun Caan [NG 581 420] the Elgol Formation is between 17 and 25 m thick, fine to medium grained and greenish white. At the top is a fining-upwards distributary channel sequence with a pebbly granule conglomerate at the base. At Rigg in north Trotternish [NG 517 564] the sequence is only 9 m thick and, apart from some well developed Thalassinoides borrows, is very similar to that in south Trotternish. The most northerly exposure is near Invertote 750 m north of the river mouth [NG 523 612]. Here and at Invertote [NG 520 605] the very coarse top facies persists but the rest of the sequence is more complex including, in the lower half, a 3m fining-upwards distributary channel sequence with a pebbly base and laterally persistent bioturbated top. Above this the normal coarsening-upwards distributary mouth bar sequence is seen. The Elgol Formation here is buff to chocolate brown and a minimum of 12 m thick.

The formation is laterally discontinuous to the south (Fig. 3); dark silty shales occur at this horizon on Eigg in a poorly exposed section between the sands of the Bearreraig Sandstone Formation and the type section of the Kildonnan Member of the Lealt Shale Formation.

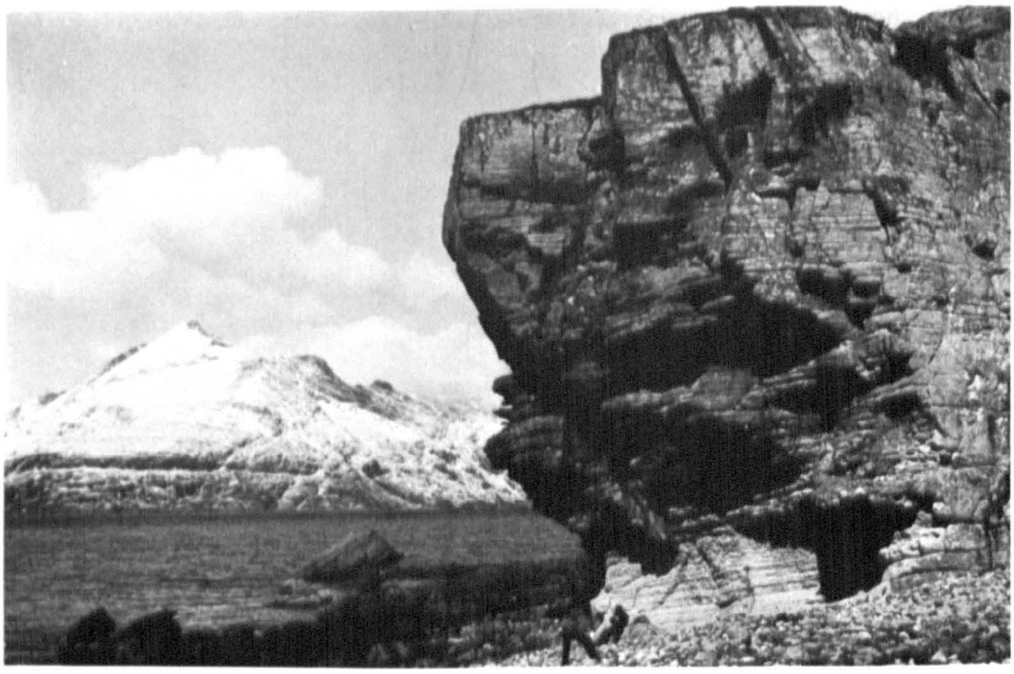
LEALT SHALE FORMATION

Estheria Shales, E.S., including Mytilus Shale, M.S., of previous nomenclature.

A shale formation separates the predominantly sandy Elgol and Valtos Formations in Skye, and underlies the Valtos Formation on Eigg, where the Elgol Formation is absent. It was named the Estheria Shale(s) by Anderson (1948), working mainly in Trotternish. His type section is given as the Lealt River (Anderson, p. 124 in Donovan and Hemingway 1963) which is now proposed as the name of the Lealt Shale Formation. The base of the formation is defined where silty of bituminous shales abruptly overlie the coarse top of the Elgol Sandstone Formation (top of Fig. 5). Its top is gradational to the base of the Valtos Sandstone Formation; it is marked lithologically by a transition from true shales to silty shales with siltstone intercalations, and faunally by the dying-out of Cyzicus and the occurrence of valves of Neomiodon in monotypic shell-beds. Subsequently Hudson (1962; 1966) recognized from exposures on Eigg that the lower part of the formation contained a distinctive fauna dominated by a mytilid bivalve, and

Plate 1

a



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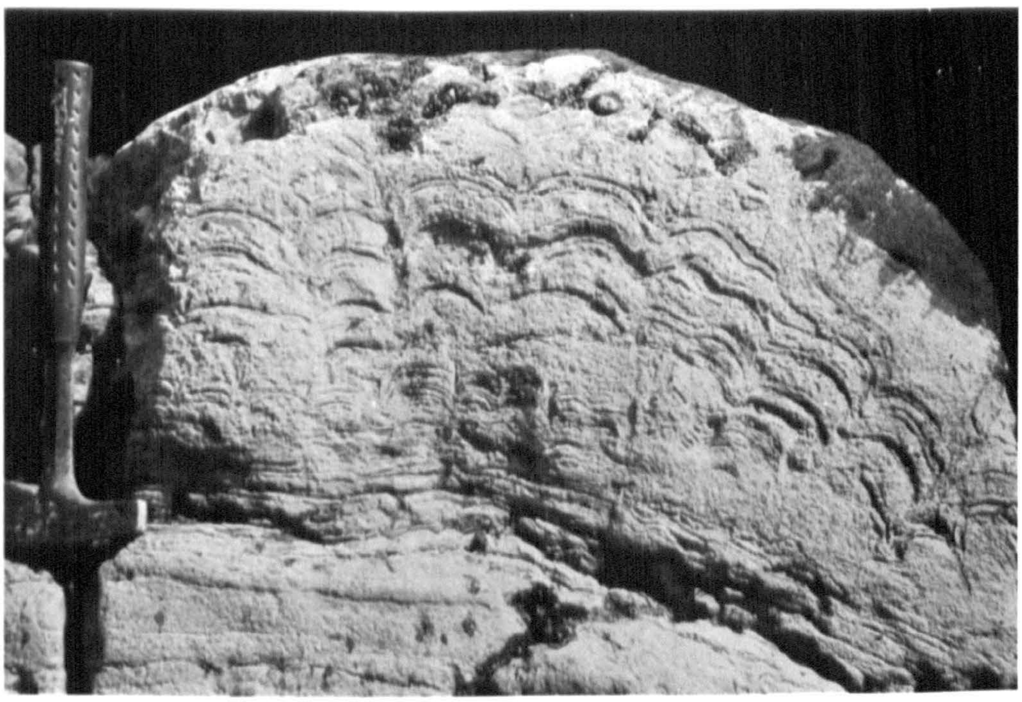


Plate 1a

The Elgol Formation, cliff section at Elgol, Strathaird.

Plate 1b

Stromatolitic algal limestone. Top of Kildonnan Member, Lealt Formation, North shore, Isle of Eigg. This bed can be traced from Eigg to Trotternish.

called this division the Mytilus Shales. It was known also to occur in Strathaird, but not at that time in Trotternish. Subsequently, the algal bed that caps the Mytilus Shales has been found in Trotternish, and it is now feasible to divide the Lealt Shale Formation into two members throughout its outcrop (Hudson and Harris 1979). The names proposed are Kildonan Member (=Mytilus Shales) and Lonfearn Member (=Estheria Shales less Mytilus Shales).

Type Section. The Lealt River in Trotternish displays a conveniently accessible exposure of the typical lithology of the formation, especially of its upper member, just above the road bridge [NG 515 604]. (This exposure has been partly obliterated during construction of a new bridge in September 1979. Others occur, but less accessibly, elsewhere in the Lealt River). Shales, with bedding planes covered with Cyzicus (Estheria) carapaces, are interbedded with thin oolitic limestones (oobiosparites) in which the oolites are composed of ferroan dolomite. Unfortunately, parts of the total section are intruded by thick dolerite sills, and parts are not easily accessible. The beds immediately above the coarse top of the Elgol Formation [NG 520 605] are not well exposed in the Lealt River, but are seen to be thin-bedded 'paper shales' at several outcrops along the coast to the north. The top of the Lealt Shale Formation is not actually exposed in the river section, but may be inferred between the exposures near the roadbridge, mentioned above, and the lowest exposure of the Valtos Formation upstream. The gradational contact between the formations can be seen near Lonfearn (see below)

The exposures in this part of Skye can fairly readily be correlated lithostratigraphically by the use of marker beds, and a composite section 48 m thick drawn up (Hudson and Harris 1979).

Kildonnan Member. The Mytilus Shales of the previous nomenclature are very well developed, and highly fossiliferous, at their type locality (Hudson, 1966) 2.5 km north of Kildonnan, Isle of Eigg [NM 495 870] (Fig. 6). The dominant lithology is grey silty shale, with monotypic shell-beds of *Praemytilus strathairdensis* (Anderson and Cox 1948), but thin limestones and one coarse sandstone bed occur, and two bone-beds. Although shales with Cyzicus occur in the Kildonnan Member, they are not as dominant as in the Lonfearn Member and the total sequence of lithologies and fossils is quite different.

The base of the Member is easily defined in Skye above the coarse top of the Elgol Sandstone Formation, but on Eigg that formation is absent and the beds between the base of this type section and the top of the Bearreraig Sandstone, exposed to the north at [NM 496 896], are poorly exposed. The top of the member is clearly defined by a stromatolitic algal limestone (Hudson 1970) which occurs throughout the outcrop: it is now less well exposed at the type section, however, than in North Eigg (Pl. 1b) and several localities in Skye.

Lateral Variations. The algal bed is well exposed (and was first recognized by Anderson 1948) in the Elgol shore section, Strathaird, but the beds below it are poorly exposed there. Scattered inland exposures yield the characteristic fossils, however, and one of them is the type locality of *Praemytilus strathairdensis.*

The key to recognizing the Kildonnan Member in Trotternish, where it is thinner than farther south, is again the algal bed at its top. In the Lealt-Lonfearn district the member is 18 m thick. The lower part, approximately 13 m, is sparsely fossiliferous 'paper' shales, lithologically similar to the Cullaidh Formation. Only one bed, 0.25 m above this, contains abundant Praemytilus. The remaining 4.5 m of section beneath the algal bed is mainly shale with Cyzicus, in which two layers of septarian concretions are developed. The Algal Bed shows all the features described by Hudson (1970) from the southern outcrops. It is readily recognized in the field at several outcrops between [NG 526 625] and [NG 521 627]. The Kildonnan Member is poorly exposed in Raasay but both Praemytilus and the algal bed occur there.

Lonfearn Member. The Estheria Shales of the old nomenclature are typically developed in the Lealt River district of north Trotternish, and are exposed at sea level farther north near Lonfearn. The typical lithology is dark grey or olive-brown shales (black, when metamorphosed by intrusions, as they usually are in this region), with Cyzicus, ostracods and small gastropods. The base is defined by the top of the Kildonnan Member, the top is the base of the Valtos Sandstone Formation. The total thickness of about 30 m (Fig. 6) must be pieced together from scattered sections. The best are between the coast south of Rudha nam Braithairean [NG 526 625[, where the base is well exposed, and the mouth of the Lonfearn Burn [NG 521 627]. Similar exposures occur as far south as near Rigg [NG 517 551]. A limestone with Isognomon consistently occurs 0.6 m above the base of the Member, and a conspicuous layer of septaria nearly 2 m above the base. Above this are shales and oolitic biosparites, including those in the Lealt River itself. At the mouth of the Lonfearn Burn shales with desiccation cracks and _Cyzicus_ pass gradationally into the siltstones with Neomiodon of the basal Valtos Sandstone Formation. The shales with _Cyzicus_ thus mark the top of the Lonfearn Member and of the Lealt Shale Formation.

Lateral Variation. The Lonfearn Member maintains its characteristic lithology, and its thickness, more faithfully than any other part of the Great Estuarine Group. It is well exposed, and instantly recognizable, in Strathaird and Eigg; also, though less well exposed, in the Fiurnean cliffs of South Trotternish, Raasay, and at Neist Point, west Skye.

VALTOS SANDSTONE FORMATION

Concretionary Sandstone Series of previous nomenclature.
This formation is dominated by medium to coarse-grained sandstones, several metres thick, with conspicuous calcite concretions. These are usually capped by very coarse, sandy, _Neomiodon_ biosparites, while silty bioturbated shales and _Neomiodon_ limestones intervene between the sandstone units. The base is defined by the lowest occurrence of silty shales with monotypic _Neomiodon_ beds, and the top by the lowest occurrence of _Praeexogyra hebridica_, above the thick sandstones (Fig. 7). The formation was deposited as a series of lagoonal delta and lagoon shoreline sequences, associated with a major fluvial source of coarse clastic sediment and plant debris (Chapter 3 and 4).

Neomiodon is the only common body-fossil, forming the 'Cyrena

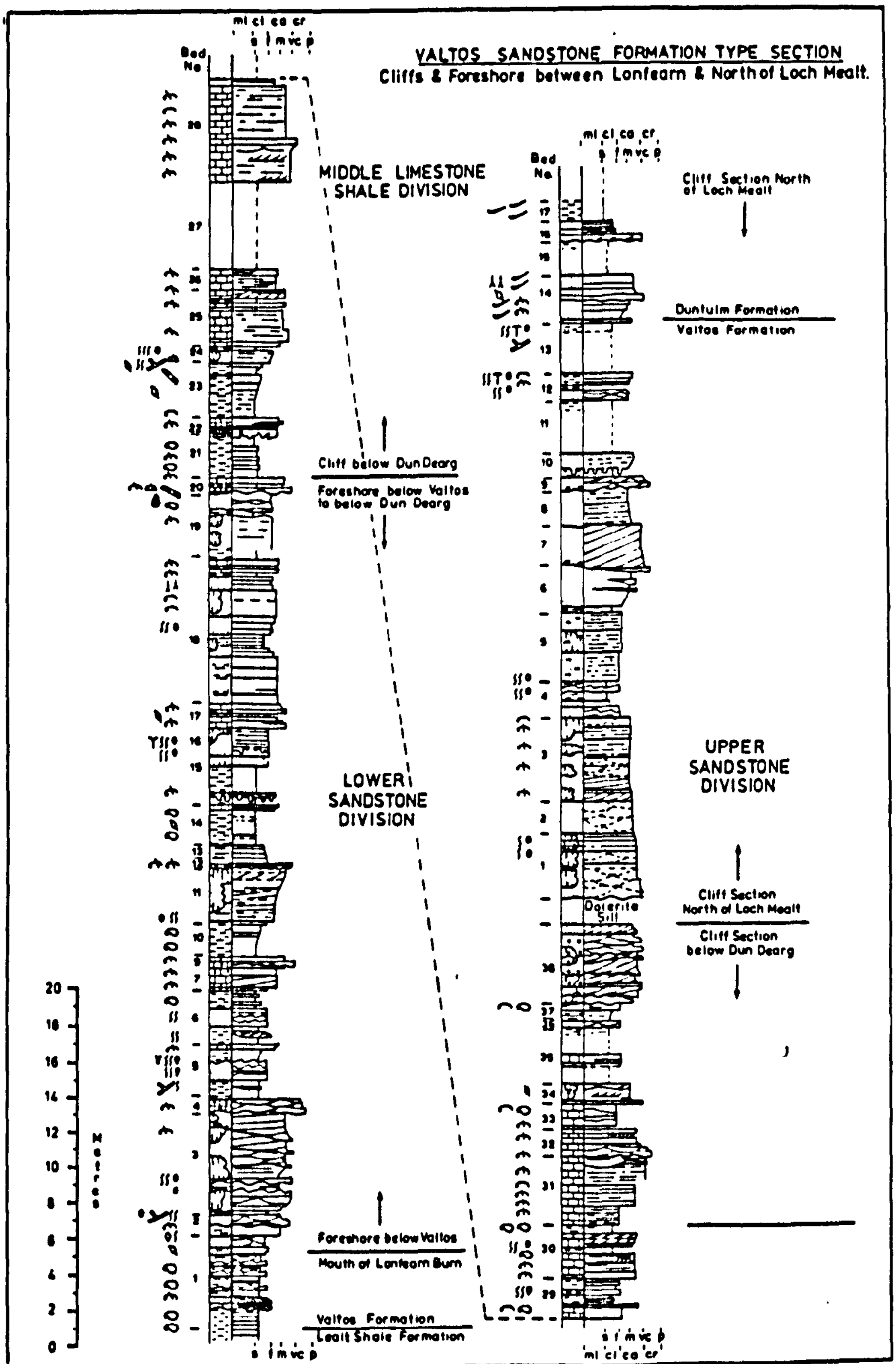


Fig. 7. Type section of the Valtos Sandstone Formation, Concretionary Sandstone Series of previous nomenclature.

Limestones' of Lee (1920). A few beds contain Viviparus, and at two horizons shark teeth and fin-spines, and fish scales, are common. Fragments of coniferous driftwood occur sporadically and some fine sandstones are quite carbonaceous.

The Valtos Formation in Trotternish can be divided into 3 parts, an upper 46 m and a lower 48 m unit dominated by cross-bedded coarsening-upwards sandstones with intervening silty shales, and a 27 m thick middle unit of fine sands, silty shales and coarse Neomiodon sparites.

Type Section. Anderson (in Donovan and Hemingway 1963) gave Rudha Garbhaig, 2 km south of Staffin Bay, as the type section for his Concretionary Sandstone Series; however, here only the upper 25 m of the formation is exposed. A more complete section including all but the base and 20-30 m of the upper sandstone-dominated division occurs in the sea cliffs below Valtos, here adopted as the type locality for the formation (Fig. 7).

The base is exposed 1 km south of Valtos at a small waterfall 25 m upstream from the mouth of the Lonfearn Burn [NG 521 627]. Below this point are black silty shales with Cyzicus and Globularia of the Lealt Shale Formation and above, below the first thick sandstone unit, are c.5 m of silty shales and fine rippled sands with ubiquitous Neomiodon.

The lower predominantly sandstone section (48 m) is virtually continuously exposed in the cliffs between Valtos and Mealt Falls [NG

517 638 to NG 509 653]. The top of this lower unit is marked by a reddish limestone with small intraformational limestone pebbles and numerous fish scales and teeth, representing a delta abandonment facies. In the higher cliffs at the northern end of the section the middle unit, 27 m of fine sands, silty shales and grey Neomiodon limestones is intruded by numerous transgressive sills. Exposure is intermittent giving an almost complete composite section. Below the thick sill of the Kilt Rock at this locality is the lower part of the upper sandstone-dominated unit, the rest of which, a minimum of 46 m, with the transition to oyster bearing Duntulm Formation, is exposed in cliff section 1.5 km to the north [NG 504 673]. Part of this unit, medium to very coarse trough and planar cross stratified sandstones, with Neomiodon preserved in superb subspherical and botryoidal concretions, is very well exposed in a roadside quarry at Dun Dearg [NG 514 644].*

Lateral Variation. The Valtos Formation shows marked lateral facies variation; however, on Raasay the only good continuous exposure south-west of Screapadal [NG 578 424] is similar to the middle and upper part of the lower unit in Trotternish.

In Strathaird the Valtos Formation outcrops at two localities on the shore north of Elgol [NG 516 144 and NG 521 161]. Limestones, which are only occasionally sandy, predominate. The base has desiccation cracks developed at three horizons and the upper sandy limestone-shale intercalation has prominent load casts.

Excellent exposures in the cliffs on the east side of Laig Bay, Eigg,

*This outcrop has been obliterated during widening of the A855 Portree-Staffin Road, Spring 1983.

from the base [NM 468 905] to close to the top [NM 473 885], demonstrate very rapid lateral facies variation in a minimum 63 m thick section of the Valtos Formation (Hudson and Harris 1979). The style of sedimentation is similar to the upper and lower sandstone-dominated units in Trotternish. It comprises a series of 5 coarsening upwards sandstone sequences.

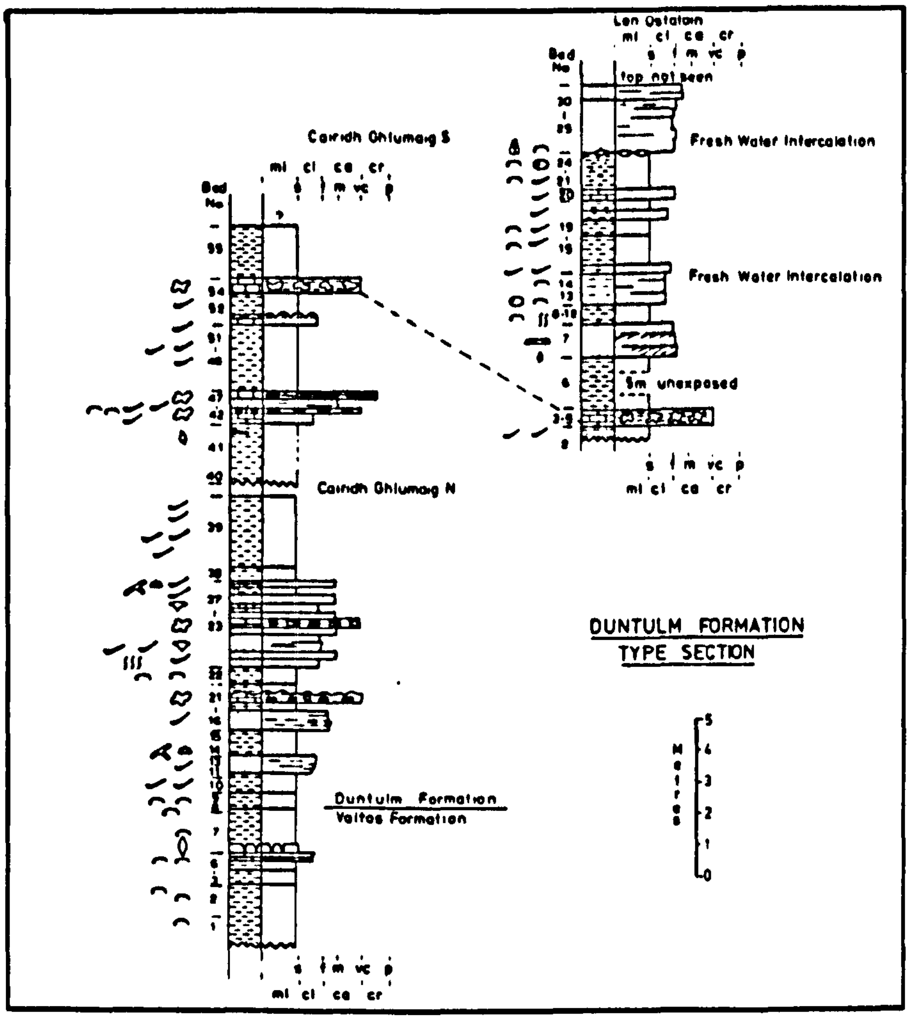
The upper 15 m of Valtos Formation with the transition to the Duntulm Formation is very well exposed on the fore-shore in Camas Mor, Muck [NM 406 793]. Just above low water is an 8 m thick coarsening upwards sandstone unit capped by a very coarse sand with granules and Neomiodon. Above this is a 7 m thick intercalation of sandy limestones and shales with some spectacular load casts before the occurrence of the first oyster bed defining the base of the Duntulm Formation.

In north-west Skye the Valtos Formation is exposed at 3 localities. At the head of Loch Bay, Waternish [NG 265 542] a series of exposures gives a discontinuous section of 16 m close to the top of the formation. The section comprises 6 m of shales and limestones with desiccation cracks, similar to those in Strathaird, 5 m of fine sands and silts and at the top 5 m of medium-grained sandstone. At Waterstein, Duirinish, there are two main Valtos Formation exposures, In a thick sill complex below Waterstein Head [NG 144 468], rafts of medium and coarse, cross-bedded sandstone are associated with a raft of the Duntulm Formation and represent lithologies close to the top of the formation. Lithologies close to the base are exposed in Camas nan Sidhean [NG 141 477]. The cliffs here give a discontinuous section through c.50 m of pale mudstones, silty limestones with Neomiodon, occasional silty sands and at the top, 2 m of silty shale and marl with Viviparus.

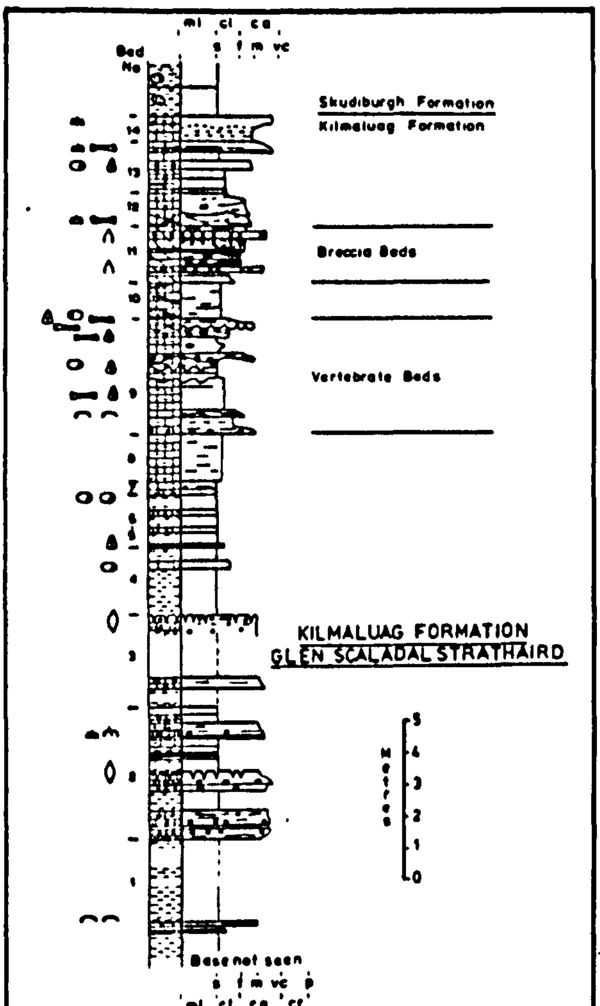
DUNTULM FORMATION

Lower Ostrea Beds, L.O.B., of previous nomenclature.
The Duntulm Formation is characterized by beds largely composed of oyster shells: Praeexogyra hebridica (Forbes); see Hudson and Palmer (1976). The oyster beds have either a shale or a limestone matrix, and range from mere shell layers to a thickness of 2 m. They are interbedded with siltstones, shales, and fine sandstone which bear a more varied fauna of marine bivalves, gastropods and rhynchonellids. In northern Skye there are, additionally, beds with non-marine Neomiodon-Unio faunas in the formation. Further south these are lacking, as are the sandstones, and the whole formation is reduced in thickness (Fig. 3). Nodular and stromatolitic algal beds (Hudson 1970) occur throughout the area.

P. hebridica occurs in such rock-forming abundance that the Duntulm Formation can almost be defined by its range within the Great Estuarine Group. Earlier records of it from the Lealt Formation are apparently erroneous. It does, however, reappear in the Staffin Bay Formation. Thus, there is little ambiguity in defining the base of the formation by the first appearance of P. hebridica above the freshwater-brackish faunas of the Valtos Formation (top of Fig. 7), and its top where the oysters die out into the ostracod-bearing marls and calcilutites of the Kilmaluag Formation. The only problem occurs



Fɪɢ. 8. Type section of the Duntulm Formation, Lower Ostrea Beds of previous nomenclature.



Fɪɢ. 9. Kilmaluag Formation, Ostracod Limestones of previous nomenclature. Glen Scaladal section.

where, as at Duntulm, the associated marine fossils occur in beds below those that yield the first oyster. It seems sensible to include such beds (never more than a metre or so thick) in the Duntulm Formation.

Type Section. Duntulm, on the north-west corner of Trotternish, is chosen to give its name to the Formation as the most fossiliferous, lithologically varied and accessible sections are displayed there. Anderson (1948) gives An Corran, south of Staffin Bay, as the type section of his Lower Ostrea Beds, but the exposures are poor.

The main exposures at Duntulm are in the bay, Cairdh Ghlumaig [NG 411 739], and 600 m south in the stream, Lon Ostatoin [NG 406 728] (map and sections in Hudson and Morton 1969,pp. D33-35). They are separated by non-exposed ground and by a fault that displaces the picrite-dolerite sill above them. The correlation advocated by Hudson and Morton (1969) is illustrated by Hudson and Harris (1979, Fig. 6). Further consideration of the structural evidence leads us now to correlate the two thickest algal limestones, Bed 54 of Cairidh Ghlumaig and Bed 5 of Lon Ostatoin, as shown on Fig. 8. On this correlation, Beds 1-7 of Cairidh Ghlumaig are the lowest exposed in the area; they contain Neomiodon, Unio and large desiccation cracks, but no oysters. They can be referred to the top of the Valtos Formation, Bed 7 marking the base of the Duntulm Formation. (The Valtos Formation tentatively identified at the mouth of Lon Ostatoin (Hudson and Morton 1969) was based on a temporary exposure of unfossiliferous sandstone, and is now discounted). The remainder of the Cairidh Ghlumaig section displays predominantly marine-brackish strata with oyster and algal beds. In Lon Ostatoin a freshwater intercalation with Unio and Neomiodon is well exposed (Hudson and Morton 1969; Hudson 1970; Tan and Hudson 1974). The top of the formation in Lon Ostatoin must occur within the unexposed interval of 25 m before exposures of the Kilmaluag Formation are reached. This gives a maximum thickness for the Duntulm Formation of 35 m. The exposed thickness is about 30 m, and mapping evidence gives a likely minimum of 40 m. (The smaller thickness of 60 ft (18 m) recorded by Anderson and Dunham (1966,pp. 18,32-3) is based on the identification of Kilmaluag Formation (Ostracod Limestones) in sections south-east of Rudha Garbhaig; this was accepted by Hudson (1963). It is equally likely that the strata concerned are a freshwater intercalation within the Duntulm Formation). The exposures in Kilmaluag Bay (see below) show that the typical lithologies of the Duntulm formation, including oyster beds and nodular algal limestones, occur only c.4 m below the local base of the Kilmaluag Formation.

Lateral Variation. Exposures of the Duntulm Formation are widespread in north Trotternish. They also occur in the Loch Bay inlier, Waternish [NG 264 539], and below Waterstein Head, Duirinish, where exposures south of the headland at [NG 156 468] display a particularly fine development of the algal horizon that has not previously been recognized. In Strathaird, Eigg and Muck the formation is much thinner than in Trotternish. The exposures in Camas Mor, Muck [NM 405 794] are particularly good (Hudson 1963).

KILMALUAG FORMATION

Ostracod Limestones, O.L., of previous nomenclature.

The Kilmaluag Formation is characterized by alternations of calcareous mudstones and argillaceous calcilutites (marlstones) that are frequently nodular. Some of the calcilutites are dolomitic. Deep and wide desiccation cracks are frequent. Many beds contain abundant ostracods (particularly *Theriosynoecum*) and *Cyzicus*. This combination of lithologies contrasts markedly with the alternations of laminated shales or silts with biosparites that is typical of the lower formations of the Great Estuarine Group. *Viviparus* is the commonest macrofossil in the Kilmaluag Formation, and *Unio* occurs frequently, but neither occurs in rock-forming abundance. In Trotternish, thin, generally fine-grained sandstones are intercalated in the formation, but as with the underlying Duntulm formation it is practically sand-free in the south.

The base of the formation is defined by the loss of the oyster biosparites of the Duntulm formation, and the incoming of ostracod-bearing calcilutites as the most calcareous beds in shale (or marl)-limestone alternations. Its top is taken where calcareous beds with ostracods die out, and red, as well as grey or greenish, mudstones appear, defining the base of the Skudiburgh Formation.

Type Section. Anderson (1963) gives the Stenscholl River, Staffin, as the type section of his Ostracod Limestones, but the sections there are very discontinuous. The best exposures in Trotternish are those in Kilmaluag Bay [NG 437 748]. Although also discontinuous, they are accessible (at low tide) and highly fossiliferous. The base of the formation can be defined to within about 3 m, although its top is not seen (and is apparently nowhere exposed in Trotternish). Accordingly, Kilmaluag is chosen as the name locality. It has the additional advantage of being close to Duntulm, the type locality of the underlying formation. By far the best and most continuous sections of the formation are in Strathaird, particularly that at Glan Scaladal [NG 164 531]. The name Scaladal, which we might otherwise have used, is pre-occupied for a Member in the Oxfordian Staffin Shale Formation (Sykes 1975b,p.68).

Kilmaluag Sections. The sections at Kilmaluag are described in Hudson and Morton (1969),pp. D36-8); Figure D12 of that paper needs modification as do details of the sections, but the general description will still suffice. Since then, loose blocks of limestone with Viviparus (and Unio and Neomiodon) similar to the material described by Yen (1948), have been found just NE of the boatslip. Assuming they are nearly in situ, they would occur low in the Kilmaluag Formation, in the 'gap' of 3-5 m between exposed Duntulm and Kilmaluag Formations. The exposed thickness of the Kilmaluag Formation is about 16 m; the actual thickness beneath the Cnoc a Chlachain sill is at least 21 m, with an unknown thickness above.

Lateral variation; North Skye. There are many small exposures of the Kilmaluag Formation in north-west Trotternish. A notable one is that at Rubha Hunish [NG 414 762], which yields Unio and Viviparus. It comprises 7 m of fine carbonaceous sands and two trough and planar cross-stratified coarse sands one of which contains large clay galls. It is mapped on I.G.S. Sheet 90 as Concretionary Sandstones. There is also a small exposure in the Loch Bay inlier, Waternish.

Strathaird, Eigg and Muck. The section in the cliffs on the north side of Glen Scaladal [NG 164 531] is the best and most accessible in the formation. It is described by Hudson and Morton (1969,pp. D21-2) and illustrated here (Fig.9). It lacks the sandstones of the Trotternish sections, but shows all the other characteristics of the formation, including dolomitic breccias. Other similar sections occur in the Elgol shore section to the south (Hudson 1962,p.149).

The only exposures on Eigg are at Laig Gorge [NM 482 875], but there are excellent exposures in Camas Mor, Muck [NM 404 793] with dolomites briefly described by Tan and Hudson (1971,p.759).

SKUDIBURGH FORMATION AND THE TOP OF THE GREAT ESTUARINE GROUP

The Skudiburgh Formation (Mottled Clay, M.C., of previous nomenclature) comprises a series of mottled silty mudstones, with thin channel sands only developed in the Trotternish sections. Outcrops are poor and the only fossils are Unio, fish teeth and plant fragments testifying to the freshwater origin of the formation.

The base is defined by the lowest occurrence of red and grey-green mudstones, overlying the ostracod-bearing marls of the Kilmaluag Formation. The top also defines the top of the Great Estuarine Group (Hudson 1962; Sykes 1975b) and is marked by the marine transgression of the overlying Staffin Bay Formation (Sykes 1975a,b; Hudson and Harris 1979). In Trotternish, red mudstones and dark clays of the Skudiburgh Formation are abruptly overlain, in several Staffin Bay exposures, by dark shales with shell-beds of the Upper Ostrea Member; a thin basal shell-bed contains abundant Isognomon (Hudson and Morton 1969; Sykes 1975b). In Strathaird, the Skudiburgh Formation mudstones are truncated by a sharp erosion surface with burrows beneath it, marking the base of the Carn Mor Sandstone Member of the Staffin Bay Formation (Sykes 1975b). On Eigg the Skudiburgh Formation does not occur; the Kilmaluag Formation is overlain disconformably by the Upper Cretaceous, Laig Gorge Beds (Hudson 1960). On Raasay the formation is not exposed.

Type Section. Anderson (in Donovan and Hemingway 1963) gives Staffin Bay, north Trotternish, as the type section for the Mottled Clay; however, at Skudiburgh on the west coast of the Trotternish peninsula exposure is very much better although the exposed section is shorter.

In the cliffs on the north side of Dun Skudiburgh, 2 km north-west of Uig, Trotternish [NG 374 648] is a very good section through 3.5 m of the Skudiburgh Formation. Here the formation consists of an intercalation of buff-red, occasionally green, mottled silty shales with small calcareous concretions resembling caliche nodules (Steel 1973) and lenticular channel sands up to 60 cm thick, with Unio.

Mottled mudstones are intermittently exposed between tide marks in the bay to the north, and more accessibly though somewhat metamorphosed, beneath the transgressive sill at Geodha Dubh [NG 375 655].

Lateral Variation. Outcrops elsewhere in Trotternish, at Duntulm [NG 412 743] and below Digg [NG 472 709], where there is a more complete but very poorly exposed section, show a similar series of rock types but without the caliche nodules. At Digg a laterally impersistant clay with numerous plant fragments occurs at the top of the formation. The Skudiburgh Formation also occurs in a similar facies on the shore north of Elgol, Strathaird [NG 517 149], but is slightly metamorphosed.

CONCLUDING REMARKS

Perhaps the most remarkable feature of the stratigraphy of the Great Estuarine Group is the lateral continuity of its formations, particularly the mainly argillaceous ones. The Lealt, Duntulm and Kilmaluag Formations are instantly recognizable throughout the region. The Elgol and Valtos Sandstone Formations are more discontinuous in their development. However, the facies association of the Valtos Formation are reproduced in Trotternish and Eigg, 90 km apart, despite the aberrant development in Strathaird halfway between. This contrasts with the extreme lithostratigraphical heterogeneity shown by some shallow-water marine formations: the Lincolnshire Limestone for example, or even the shallow marine Bearreraig Sandstone immediately beneath the Great Estuarine Group.

A partial explanation is that the present main outcrop is parallel to the depositional strike, with a shore or hinge line near the present west coast of the Scottish mainland (Hudson 1964). Nevertheless, the outcrops do not define a NNE-SSW line: Waterstein Head is 50 km east of Raasay and the facies, while not identical, are recognizable across this distance. Nor are depositional strikes normally straight lines. If the Group as a whole is correctly interpreted in terms of partially-protected lagoons (Hudson 1963; Hudson and Harris 1979), the facies belts within them must have been km or tens of km across, except where and when the sandy lagoonal deltas of the Elgol and Valtos Formations were being built or destroyed.

A consequence is that the Minch Basin (in the wide sense) must have been one continuous basin of deposition during the deposition of the Great Estuarine Group. Although it is crossed by important faults (notably the Camasunary Fault), there is no direct evidence that these were moving during the Jurassic. The Great Estuarine Group crosses them unbroken. (It is perhaps most likely that bounding faults to the basin, such as the Minch Fault, were active during the Jurassic, as were many known faults in the North Sea).* The anomalously thin section of the Valtos Formation in Strathaird is close to the Camasunary Fault, but it is on the downthrown side of it (see discussion in Chapter 3). The first break-up of the basin appears to be post-Kimmeridgian and pre-Upper Cretaceous, with further fault movements associated with and post-dating the early Tertiary igneous activity (Binns et al. 1975).

* More recent work on differences in thickness and facies of sandstone formations across and close to the Camasunary Fault (see Chapters 2,3 and 4) lead us now to conclude that faults within the Minch Basin separated rapidly, from slowly subsiding areas, such that they controlled the configuration of the Sea of the Hebrides and Inner Hebrides Basins.

From the economic point of view, the occurrence of alternating organic-rich shales and lenticular sands of high porosity is of obvious interest. While the immediate area of outcrop is not likely to be oil-prospective (because of shallow burial and igneous intrusions), the Group undoubtedly affords well-exposed and relatively accessible sections to serve as analogies for interpreting the North Sea and continental shelf basins.

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CHAPTER 2 THE SEDIMENTOLOGY OF A MIDDLE JURASSIC, LAGOONAL DELTA SYSTEM: ELGOL FORMATION, (GREAT ESTUARINE GROUP), INNER HEBRIDES BASIN AND SEA OF THE HEBRIDES BASIN.

ABSTRACT

Within a previously defined framework of fresh-brackish and marine salinities and a sub-tropical seasonal climate the Elgol Formation is interpreted as a copiously supplied, north-south prograding lagoonal delta system. Sections in north Trotternish, south Trotternish - Raasay and Strathaird represent 3 different styles of lagoonal delta sedimentation corresponding with different salinities and basinal energy regimes. In north Trotternish marine macro-faunas and micro-floras occur in a fluvial-wave-tide interaction delta system in which tidal currents controlled distributary and mouth bar hydrodynamics and high wave energies generated beach ridge sediments at the delta shoreline. In south Trotternish and Raasay probable brackish-marine salinities and a deeper basin with lower wave energies are reflected in bouyant mouth bar hydrodynamics and a low sinuosity delta distributary system. Further south in Strathaird (Inner Hebrides Basin) probable fresh-brackish salinities correspond with a fluvial dominated delta recording friction dominated mouth bar hydrodynamics. This lobate delta is characterised by low angle offshore inclined bar front sands. In the Inner Hebrides Basin the Elgol Formation delta reaches a depositional limit between Strathaird and Eigg. The north-south transition from marine to fresh-brackish salinities records the gradual establishment of a non marine depositional system (which is maintained throughout the rest of the Great Estuarine Group) during progradation of the Elgol Formation. Delta progradation directions mirror the Triassic palaeogeography (Steel 1976) and the modern structure (Binns et al 1974) and demonstrate the existence in the Mid-Jurassic of a slowly subsiding ridge (mid-Skye palaeohigh) separating the Sea of the Hebrides Basin from the Inner Hebrides Basin.

CHAPTER 2

CHAPTER 2

INTRODUCTION

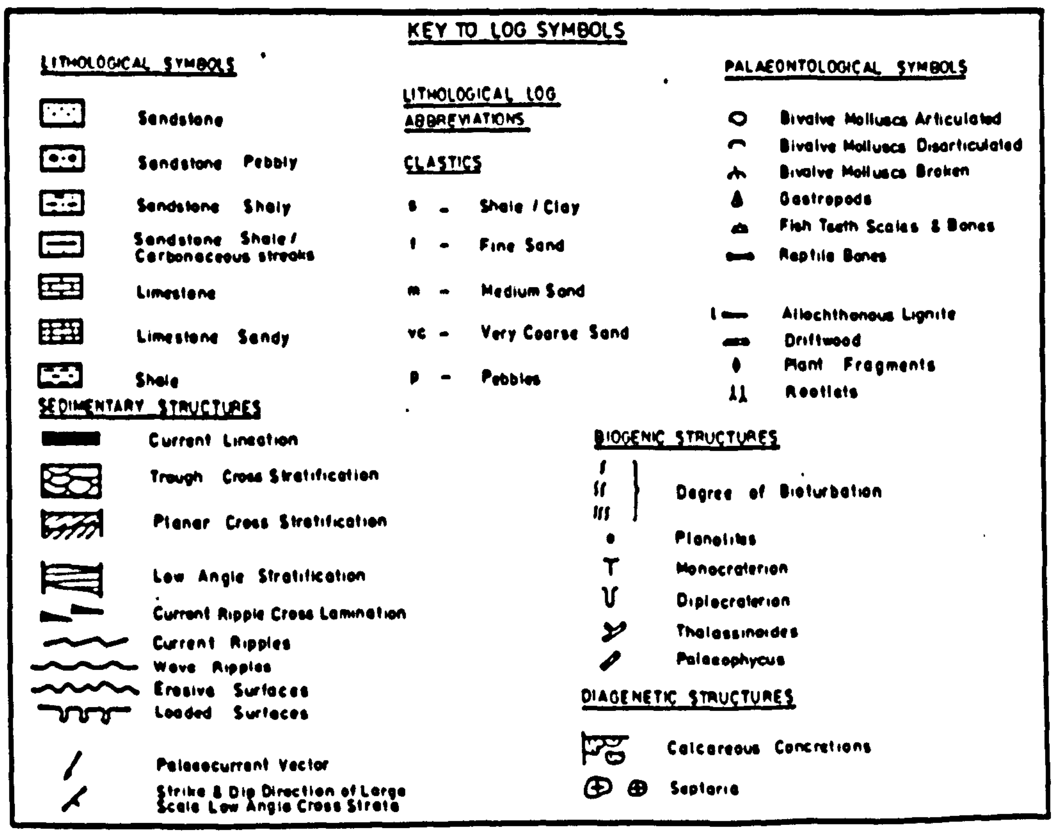
The Elgol Sandstone Formation is a coarsening upwards sheet sand between 11 and 27m thick. Petrographically the sands are moderately to very well sorted with a maximum of 10% feldspar. The Formation occurs close to the base of the Great Estuarine Group (Upper Bajocian to Upper Bathonian), above the laterally variable Cullaidh Shale Formation and below the Lealt Shale Formation (Harris and Hudson 1980). The Lithostratigraphical terminology of the Great Estuarine Group has recently been reorganised (see Table 1).

The Elgol Formation crops out in 4 main areas of the Inner Hebrides. Strathaird (maximum 25m thick) in the Inner Hebrides basin and South Trotternish (27m), Raasay (15.5m) and North Trotternish (12m) in the Sea of the Hebrides basin. The outcrops are aligned roughly N-S; (Fig.1) sub-parallel to the inferred eastern margins of these basins (Hudson 1966: Hudson and Harris 1979). The Formation is laterally discontinuous to the south; dark silty shales occur at this horizon on Eigg, 26 Km south of Elgol.

In Strathaird, Tertiary thermal metamorphism has resulted in quartz cements in the sandstones, giving rise to harder rocks that form a prominent scarp traceable for 7 Km inland from Elgol shore. Elsewhere, although cut by numerous Tertiary dykes, the rocks of the Elgol Formation are only lightly cemented and therefore form less persistent outcrops. The extent of these exposures varies from sea

		EXISTING TERMINOLOGY MAINLY ANDERSON 1963 - HUDSON 1962	REVISED TERMINOLOGY	
BATHONIAN	GREAT ESTUARINE GROUP LOWER PART			
		ESTHERIA SHALES (E.S)	LONFEARN MEMBER	LEALT SHALE Fm.
		MYTILUS SHALES (M.S.)	KILDONNAN MEMBER	
		WHITE SANDSTONE (W.S)	ELGOL SANDSTONE Fm.	
?		BASAL OIL SHALE (B.O.S)	CULLAIDH SHALE Fm.	
BAJOCIAN	Garantiana zone			
	BEARRERAIG SANDSTONE FORMATION			

Table 1 Table to show the stratigraphy of the lower part of the Great Estuarine Group, with the pre-existing and the revised terminology of Harris and Hudson (1980).



cliffs exposing complete sequences including both the top and bottom of the Formation (Elgol shore, Strathaird and Invertote, North Trotternish) to inland scarp face exposures where the contact with the shales of the underlying Cullaidh Formation and overlying Lealt Formation is only rarely exposed (inland Strathaird, and South Trotternish). Stream sections expose reasonably complete sequences (Raasay and Rigg, North Trotternish).

Hudson (1962, 1966) and Hudson and Morton (1969) interpret the Elgol Formation as representing deltas prograding into lagoons. The present paper elaborates on this interpretation by identifying genetically related facies and proposing a depositional history of delta progradation and abandonment based on modern analogues. Vertical sequences were recorded graphically and are here used for environmental reconstruction in the manner proposed by Visher (1965).

The main problems with this approach are the apparent differences between the Elgol Formation and most well documented, modern delta systems. Work on modern deltas has concentrated on very large systems, principally the Mississippi, Niger and Rhone which are generally fine grained, and comprise numerous progradational and abandonment phases. The Elgol Formation delta was small (maximum 27m thick), comprises only 2 progradational and abandonment phases and is generally coarse grained. Bar crest and distributary channel deposits usually include granule conglomerates and are often pebbly. In spite of these differences most of the sub-environments identified have direct modern analogies which are drawn in this paper from descriptions of the Mississippi, (Fisk, 1955. 1961: Fisk et al 1954;

Scruton 1960; Coleman and Gagliano, 1964, Coleman et al, 1964; Frazier, 1967; Fisher et al, 1969; Arndorfer, 1973; Coleman and Wright, 1975) the Rhone delta, (Kraft, 1955; Oomkens, 1967, 1970), the Niger delta, (Allen, 1965a; Weber, 1971; Oomkens, 1974), the Colorado delta, Texas, (Kanes, 1970), the Guadalupe delta, Texas, (Donaldson et al, 1970, Gum Hollow fan delta (McGowan 1970) and the Ebro delta, (Maldonado, 1975).

The graphic logs (Figs. 2-4 and 8-9) illustrate complex coarsening upwards sequences which are here interpreted as representing the two phase progradational and abandonment history of deltaic deposition outlined by Scruton (1960). The logs also bear a superficial resemblance to shore face, barrier island sequences (e.g. Davies et al, 1971; Kraft 1971; Davis, 1978) and linear offshore bar sequences, (e.g. Hobday and Reading, 1972; Brenner and Davis, 1973 and 1974; Berg, 1975). The application of these models to the Elgol Formation can be rejected on the following grounds. Barrier island and shoreface sequence are dependent on a basinal energy regime which is sufficient to generate a beach face with low-angle seaward dipping lamination and thereby maintain a marine - non-marine polarity across the sand body. Neither of these characteristics occurs in the Elgol Formation except in the north of the area, (fig. 9-10, Invertote) where a probable barrier sand body composed of reworked mouth bar sands is identified (see discussion below). Progradation of the Elgol Formation sand body at all localities south of North Trotternish took place into a lagoon with a non-marine fauna (Hudson, 1962; Hudson and Harris, 1979) and a low energy regime (see discussion below). There is therefore no marine - non-marine polarity in the facies above and below the Formation in these areas.

All documented occurrences of linear offshore bar systems occur in high energy open marine systems. The sand bodies produced are elongate in form and do not include the plant fragments and lignite lenses commonly found in the Elgol Formation (Johnson, 1978, Table 9.40, p.246). The sheet geometry of the Elgol Formation, progradation into a restricted non-marine basin and ubiquitous terrestrial plant fragments (together with rootlet horizons in Strathaird) therefore precludes its interpretation as an offshore bar).

CONTROLS ON THE FORM AND INTERNAL CONFIGURATION OF THE ELGOL FORMATION DELTA

The critical variables affecting a delta system are hinterland and receiving basin characteristics (Fisher 1969; Fisher et al, 1969; Wright and Coleman, 1973; Wright et al, 1974; Coleman and Wright, 1975; Galloway, 1975; Elliott, 1977, 1978). Previous work on the rocks of the Great Estuarine Group has provided a detailed framework for the interpretation of the Elgol Formation delta in terms of the nature and climate of the hinterland and the salinity and climate of the receiving basin.

Palaeogeography and Characteristics of the Hinterland

The palaeogeographical framework proposed by Hudson (1964) is supported by subsequent work on the lithology of pebbles and heavy assemblages (Appendix 1). Hudson (1964) has a Scottish landmass of variable relief in the east with a thick regolith derived from Old Red Sandstone sediments capping Moine and Dalradian rocks and a less well defined Outer Hebrides land area in the west composed largely of Lewisian Gneiss. Deposition of Middle Jurassic rocks took place in a 'Minch Basin' between these two positive areas almost exactly corresponding to the present day, Minch - Sea of the Hebrides - Inner Hebrides area. Subsequent work on the structure of the area (Binns et al 1975) and on Triassic palaeogeography (Steel et al 1975; Steel 1976) supports this palaeogeographical scheme but suggests that, in the Skye area, the basin is divided into two NNE/SSW trending troughs; the Sea of the Hebrides Basin in the west and the Inner Hebrides Basin in the east. These two basins are separated by a fault bounded palaeohigh also trending NNE/SSW, (see palaeogeographical map fig. 11). Differential subsidence or tilting involving a progressive increase in the rate of subsidence south westwards is thought to have controlled the distribution of deltaic sediments in these basins (see discussion below).

Water temperatures in the basin based on oxygen isotopic ratios (Tan et al, 1970; Tan and Hudson, 1974) were warm, averaging 17°-22°C, depending on assumptions about the isotopic composition of the Jurassic oceans (cf Hudson, 1978, p.351). The climate was humid with marked seasonality. These conditions led to rapid periodic run off from a hilly hinterland thereby supplying large amounts of coarse clastic sediment to the basin, via short energetic rivers.

Characteristics of the Receiving Basin

The Elgol Formation is gradational at its base to the shales of the Cullaidh Formation, which therefore represents the prodeltaic and basin environments of the actively prograding delta.

In Strathaird (Inner Hebrides Basin), black bituminous shales represent an enclosed lagoon of reduced but variable salinity. Bottom conditions were probably anoxic with the depositional surface below wave base (10-15m on the Atlantic shelf therefore less than 10m in an enclosed basin). The fauna is dominated by fish scales with occasional articulated specimens (Hudson, 1962, 1963; Hudson and Morton, 1969; Hudson and Harris, 1979). Northwards in south Trotternish (Sea of the Hebrides Basin) these conditions prevail with the deposition of an oil shale, but on Raasay in some sections this interval includes a bed with a marine fauna d minated by crinoid debris (Forsyth, 1960). In north Trotternish at Rigg and Invertote these lagoonal sediments show a marked facies change. They include thin limestones, carbonaceous sandy limestones, shales with a marine fauna and thin allochthonous lignites (Hudson and Morton, 1969). This change from enclosed, fresh to brackish, anoxic, lagoonal sediments in the south to marine salinities, though still probably lagoonal sediments, in the north is reflected in lateral facies variations in the Elgol Formation delta.

Because of this facies variation the sections are described and interpreted in order of increasing influence of basin processes (wave and tide induced currents). Fluvial-dominated sequences in Strathaird are described first, followed by South Trotternish and Raasay dealing finally with the fluvial-wave-tide interaction sequences in North Trotternish.

Each section or group of sections is described and then interpreted so that the field evidence for a particular model is outlined before any interpretation is made.

STRATHAIRD - DESCRIPTION AND INTERPRETATION

In Strathaird the Elgol Formation consists of hard quartz cemented sandstones (caused by Tertiary thermal metamorphism) with a very coarse, often pebbly, top. The Formation is exposed as a distinct scarp traceable from the type section of the Formation at Elgol shore (Plate 1) to north of Keppoch 7½ km to the north west (Figs. 1 and 5).

9 measured sections from along this scarp (Figs. 2-4 and 6) represent 3 distinct phases of deltaic sedimentation. A lower sequence (comprising the lower half of logs 4 and 6 exposed at north Elgol and Drinan road respectively) represents the initial phase of progradation and abandonment (Figs. 3,5 and 6). A laterally persistent upper sequence seen in all sections except log 9 (Fig. 4 and 5) represents a distinct second phase of progradation and abandonment initiated in the same area but after subsidence of the first progradational phase. The sequence north of Keppoch (log. 9 figs. 4 and 6) is interpreted as a distinct third phase consisting of

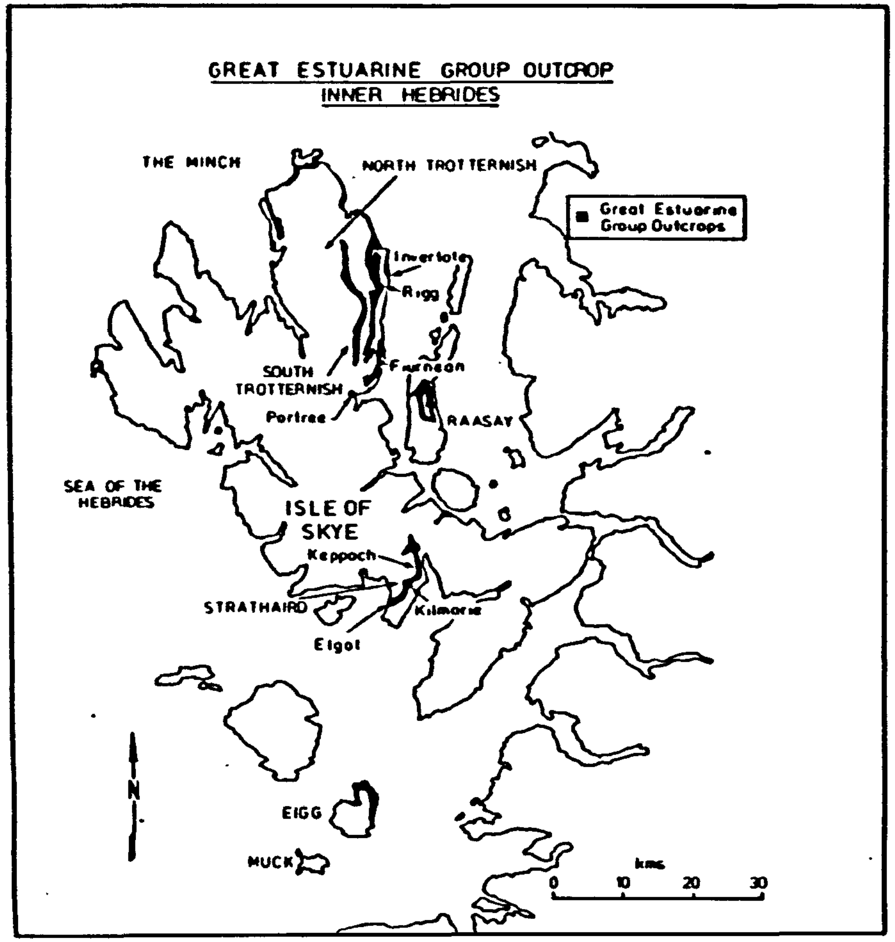


FIGURE 1 Sketch map to show the distribution fo Great Estuarine Group outcrops and the localities mentioned in the text.

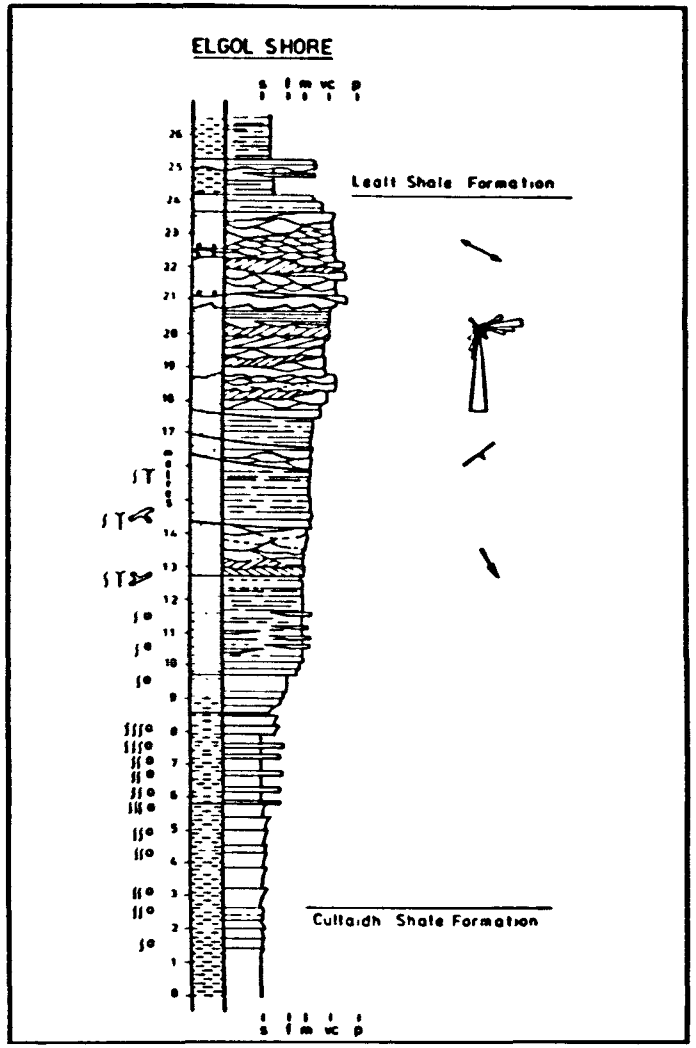


FIGURE 2 Log 1, type section of the Elgol Formation, Elgol shore; sea cliff and foreshore exposures, Stathaird.

channel incision and the deposition of a composite channel fill. These deposits postdate progradation of the second phase but formed before the subsidence of this pre-existing delta lobe.

The sequences are described and interpreted in the order of their deposition.

FIRST PROGRADATINAL AND ABANDONMENT PHASE: DESCRIPTION: (logs 4 and 6, figs, 3 and 6).

At north Elgol (log 4, fig. 3 and 6) fine-medium sands close to the base of the Formation coarsen upwards and ca 5.5m above the base show the development of rootlets and thin lenticular lignites. (The basal transition to shales of the Cullaidh Formation is poorly exposed at this locality). Also developed at this rootlet horizon are erosively based fining upwards sands (10-50cm thick) with parting lineation (9.5-10.5m Log 4, fig. 3 and 6). Wave ripples and small-scale planar tabular sets of cross strata developed in the top of some of these units are penetrated by rootlets (Plate 2), or succeeded by a fine sediment drape. Palaeocurrents are bimodal with S and W flow directions. Above this level, thin bedded sands with rootlets are succeeded by an erosively based, very coarse, planar laminated unit (11.5m - 16m Log 4) with scour and fill structures (10-15cm thick) indicating southerly flowing palaeocurrents. This unit fines upwards and is penetrated by rootlets at the top. The top of the deposits of this first progradational phase consist of shaly carbonaceous sands with coarse sand lenses 1-8cm thick (16-19.8m log 4) (Plate 3). This part of the sequence is intensively bioturbated (probably in part by

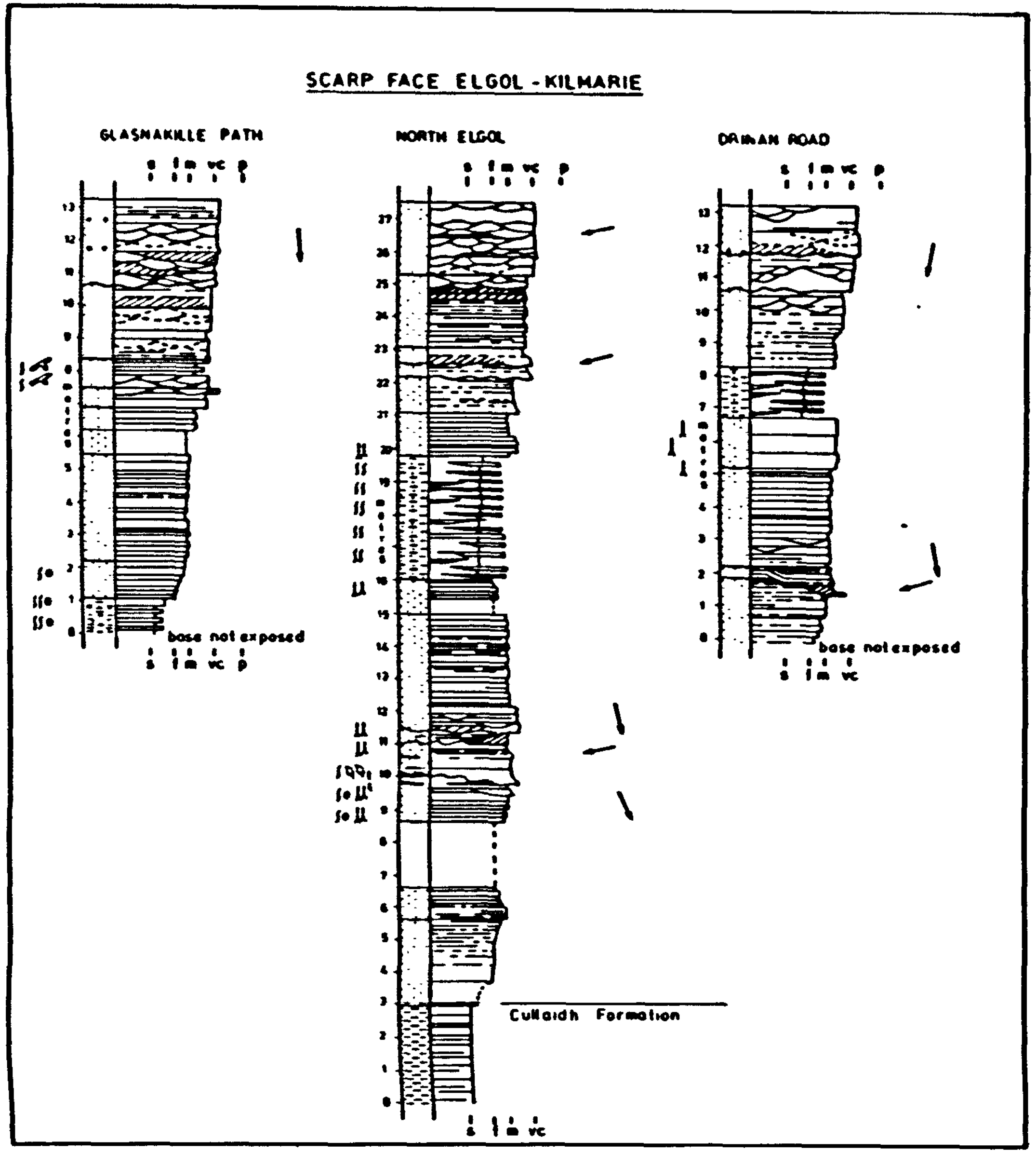


FIGURE 3 Logs 2, 4 & 6, scarp face sequences between Elgol shore and Kilmarie, Strathaird.

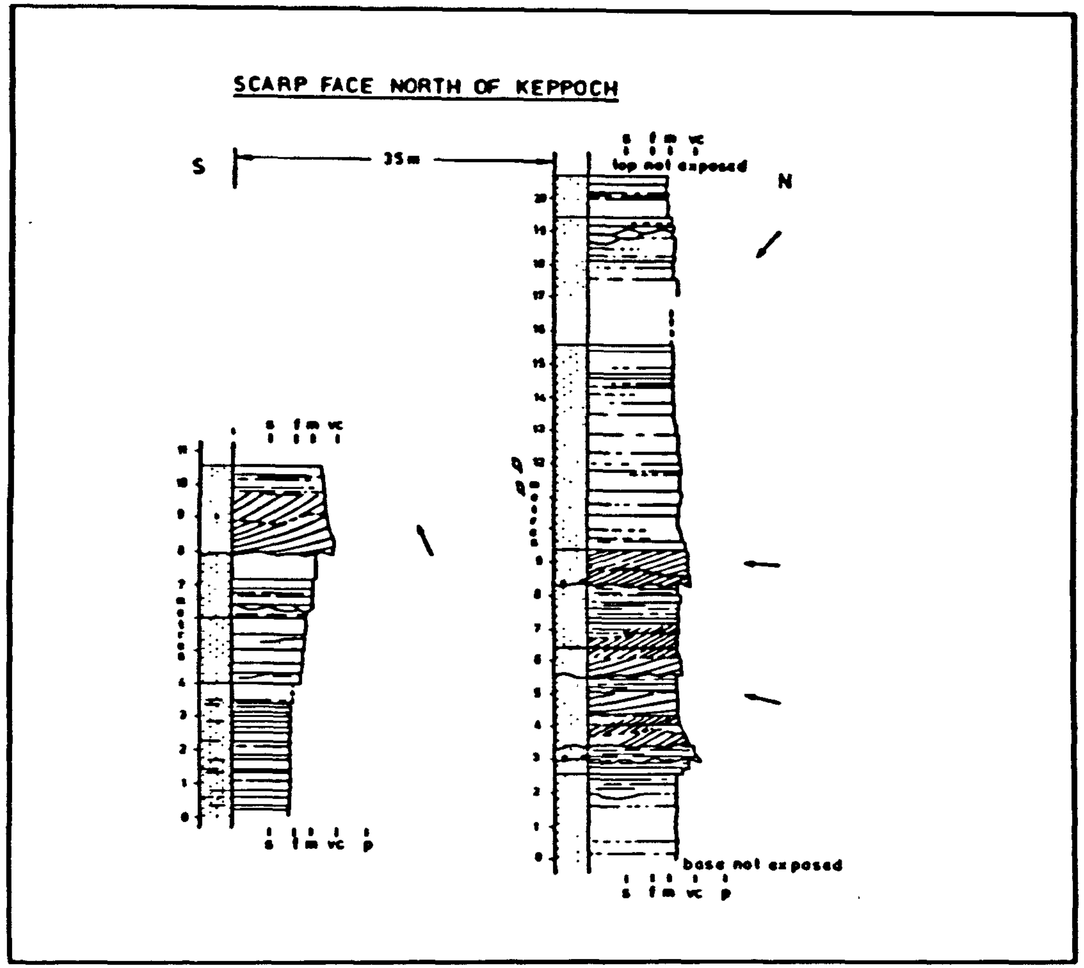


FIGURE 4 Log 9, scarp face north of Keppoch, Strathaird.

rootlet penetration).

At Drinan Road (log 6, figs. 3 and 6) the sequence is similar to that at North Elgol. The prominent erosion surface close to the base, (1.5m Log 6, fig 3) downcuts by a minimum of 70cm into flat bedded, medium sands and is succeeded by a fining upwards sequence with structures which drape or are parallel with the basal scour surface (Plate 4). Although it is not possible to observe the three dimensional form of these structures they probably resemble the epsilon cross stratification of Allen (1965b). Above this is a sequence with scour and fill structures, rootlets and at the top shaly, carbonaceous sands identical to those seen at North Elgol.

Both sequences are laterally discontinuous (Fig. 6). Intermittent exposures can be traced along the scarp for a maximum of 400m in each case before the sequences thin and are replaced in the scarp by the coarsening upwards sequence of the second progradational phase. Both these sequences are therefore lenticular and probably represent parts of two elongate lobes. The scarp in this area runs roughly NE-SW so that the elongate lobes must have their long axes orientated between E and S. Palaeocurrent evidence indicates a long axis orientation towards the SSE (Figs. 5 and 7).

FIRST PROGRADATIONAL PHASE: INTERPRETATION

At North Elgol the base of the sequence represents a progressive upwards increase in current velocity, replacing deposition from suspension with fluctuating, low to relatively high velocity currents. 6.5m above the base these deposits are cut by small channels with S and E palaeocurrents at North Elgol and by a larger scale channel with probable lateral accretion surfaces (epsilon cross stratification), at Drinan Road. At both localities the sequence is capped by shaly carbonaceous sand with medium-coarse sand lenses, representing deposition from suspension with periodic influxes of coarse sand coupled with wave reworking to give the lenticular lamination. The very intensive bioturbation probably represents prolific plant growth. Rootlets also occur below this level demonstrating that at times the deposits were emergent, or nearly so.

The deposits of this progradational phase can therefore be divided into a lower coarsening upwards sequence probably representing minor delta, distributary mouth bar progradation and an upper, fining upwards sequence with rootlets representing distributary channel and interdistributary bay deposits of the delta plain.
This succession represents a small version of the modern elongate delta sequences described from the Mississippi (Fisk, 1961; Fisher et al, 1969; Coleman and Wright, 1975). The closest modern analogy on this scale is the Holocene Guadalupe delta, San Antonio Bay, Texas, described by Donaldson et al (1970). The elongate configuration of these deposits and the lack of intensive wave or current reworking places the deposits in the high, constructive, elongate category of Fisher (1969) and the fluvial-dominated category of Elliott (1978).

The receiving basin (using Klein's (1974) model for determining palaeo water depth) was shallow (less than 5.5m): rootlets occur 5.5m above the base, defining the top of the distributary mouth bar.

Deltaic deposits on this scale are also described from modern interdistributary bay and levee sequences. In this system sub-aerial levees built by sheet flooding are cut by crevasse channels which deposit a sub-delta, comprising the minor mouth bar, crevasse channel couplet of Elliott (1974). Modern examples are described by Kruit (1955), Coleman and Gagliano (1964); Arndorfer (1973). The North Elgol and Drinan Road sections possibly therefore represent elongate, crevasse sub-deltas, which could represent an interdistributary bay sequence.

The channel fill sequences at North Elgol (Log 4,9.4-10m) are small and were occasionally submerged so that the tops of some of them are reworked by wave ripples. Subsequent rootlets penetration indicates re-emergence, (Plate 2). The period of high discharge initiating minor channel formation could possibly also be responsible for the subsequent inundation and reworking. Rapid fluctuations in discharge which would be expected in a crevasse system are also indicated by fine sediment drapes succeeding many of the channel deposits.

Above these small channels at North Elgol (log 4) rootlet penetrated sands are cut by a planar erosion surface (11.5m log 4) and succeeded by a fining upwards sequence which is capped by intensively bioturbated carbonaceous shaly sands. This sequence is very similar to the sheet, crevasse splay lobes, described by Elliott, (1974, sequence C.p.614; 1975 p.508). The larger scale channel at Drinan Road (Plate 4) is very similar to Elliott's lenticular crevasse splay channel (sequence D p.614. 1974).

The intensively bioturbated carbonaceous shaly sands with coarse sand lenses (16m-19.75m log 4, 6.75m-8.25m log 6) represent ponded sedimentation. The unit is very similar to recent interdistributary bay deposits described by Coleman and Gagliano (1964) and Coleman et al. (1964). This sequence of sub environments is characteristic of interdistributary bay fill sequences (Elliott, 1974, p.613).

If these sequences are crevasse sub-deltas they represent substantial breaches in the levees of a major distributary channel. A channel of this type could occur in the area to the north around Kilmarine (fig. 5) where, because of a thick till sheet, the Elgol Formation is unexposed or only very poorly exposed for over 2.5km. Alternatively, the sequences could represent small scale southerly, prograding, elongate, fluvial-dominated deltas which are not associated with a major distributary.

It is difficult to decide between these two interpretations because the delta lobes were deposited in a receiving basin with a very low energy regime (resembling a large shallow interdistributary bay) and were supplied by rivers with rapidly fluctuating discharge which therefore resemble crevasse channels (that are only supplied at bank full discharge periods).

The three dimensional form of part of these two lobes and the distal part of a hypothetical third lobe at Glasnakille path (log 2, figs. 3 and 5) is tentatively reconstructed in fig. 7.

SECOND PROGRADATIONAL AND ABANDONMENT PHASE: DESCRIPTION

(logs 1-8 figs. 2-4 and 6).

The type section for the Elgol Formation (Harris and Hudson 1980) is exposed in the cliffs and foreshore below Elgol, where there is a complete sequence including the top and bottom of the Formation (Plate 1). The detailed sequence is described by reference to this section (log 1, fig. 2 and 6). Lateral variations are described by reference to logs 2-8 (fig. 3,4 and 6) from along the scarp to the north (fig. 5).

On Elgol shore dark shales of the Cullaidh Formation have an oscillatory transition to well sorted fine sands, at the base of the Elgol Formation. Black micaceous shales are intercalated with successively thicker, fine shaly sands. These sand units become progressively more intensively bioturbated upwards, culminating in the lower part of the Formation, in massive shaly sands with pyritic concretions (8m fig.2). Planolites and occasional branched horizontal and oblique burrows represent a restricted assemblage of burrowing organisms.

The fine basal sands coarsen upwards to well sorted medium sands with thin lenticular coarse sand units (9.75m - 12.75m fig 2). This material exhibits superb honeycomb weathering under the overhang on Elgol shore (Plate 5). Above this are well-sorted medium-coarse sands with large scale, low angle, asymptotic cross stratification, (set at height up to 5m) (14m-17.75m log 3, Plate 6) dipping at between 4° and 11° SE, (corrected for tectonic dip to the NW of 11°).

These large scale foresets commonly have weak basal scours and contain secondary low amplitude (less than 10cm) trough and tabular, planar cross stratification. Palaeocurrent flow directions are complex at this horizon with SW and SE modes. Monocraterion and indistinct ?Thalassinoides burrows occur intermittently (fig.2).

This part of the Formation can be traced along the scarp for 7½km (apart from a 2½ km gap in the exposures around Kilmarie; fig. 5), before it is truncated by the deposits of the third depositional phase, north of Keppoch (figs. 5 and 6). Fig. 6 shows how the deposits of this phase thin markedly with the elimination of the low angle, large scale cross stratification, wherever the elongate delta lobes of the initial progradational phase are present. These two groups of strata have a mutually exclusive relationship everywhere, except at Glasnakille Path (log 2, fig. 3 and 6). Here however the basal deposits are very poorly exposed and could either be part of the basal transition to Cullaidh Formation shales or the fine grained deposits at the top of a third elongate lobe of the first progradational phase. Fig. 7 shows a hypothetical, elongate lobe in this position.

The depositional dip direction of the large scale, low angle cross stratification can be mapped at many localities along the scarp fce to the north of Elgol. The orientation of these surfaces swings round progressively from SE (142° -152°) at Elgol shore to SW (234°) at north Elgol back to SSE (172°) at Dinan Road and W (260°) at Keppoch (Figs. 5 and 6).

Coarse and very coarse sands with granules and pebbly lenses make up the top of the coarsening upwards sequence. At Elgol this upper facies comprises a thick lower unit, gradational at the base and an upper unit (above 21.75m log 1), comprising a single planar, tabular set and two laterally discontinuous trough cross stratified cosets. Medium and medium-coarse grained sands at the top of the sequence contain the moulds of large bivalves in life position (probably Unio; J. D. Hudson pers. comm) and their escape burrows (Plate 7). The lower unit (18-21.75m log 1) is dominated by scours, forming the bounding surfaces of trough and tabular cross stratified cosets (max set height 30cm). Parting lineation is developed at two horizons. Palaeocurrents are bimodal in the lower unit and unimodal in the upper unit, but both give vector means which are sub-parallel to the dip direction of the underlying large-scale cross strata.

This distinction of an upper and lower unit at this level is possible virtually all aong the scarp with only a small amount of lateral variation. In some places, as at north Elgol there are no pebbly laminations, while at others such as Keppoch the Formation contains thin conglomeratic units. Palaeocurrents are sub-parallel to the dip of the underlying large scale surfaces, as at Elgol shore.

At the top (base of the Lealt Formation) are 50cm of structureless silty shales capped by 10-20cm of coarse erosively based sand with pyritic concretions. Above this there are black silty bituminous shales similar to those of the Cullaidh Formation.

SECOND PROGRADATION AND ABANDONMENT PHASE: INTERPRETATION

The lower part of the sequence, with gradual upward coarsening, thin coarse lenses and a vertical increase in degree of bioturbation, represents an upward increase in current velocity. This replaces deposition from suspension (black bituminous shales probably representing anoxic bottom conditions) with low and eventually relatively high velocity fluctuating currents. Current velocities were high enough to initiate saltation of medium sand with occasional incursions of coarse sand. Current velocities show a further increase upwards with the deposition of large scale low angle cross strata (12.75-18m log 1) representing the SE progradation of a subaqueous bar, at times greater than 5m high. Progradation was episodic, allowing the development of large Monocraterion and Thalassinoides? burrows in the bar front sands. The weak basal scours and internal cross stratification of some of these large scale, low angle inclined beds demonstrates that progradation took place by deposition from traction currents flowing SE (at Elgol shore), down the low angle bar front.

The upper part of the sequence (18-20.75m fig. 2) represents very high current velocities producing numerous scour surfaces which were subsequently blanketed by small scale dune and bar bedforms migrating S & E under decelerating flow conditions. The top of the Formation at Elgol, (above 20.75m fig.2) comprises trough cross stratified cosets, succeeded by finer grained sands. These also represent high current velocities but involve a more consistent flow regime with a

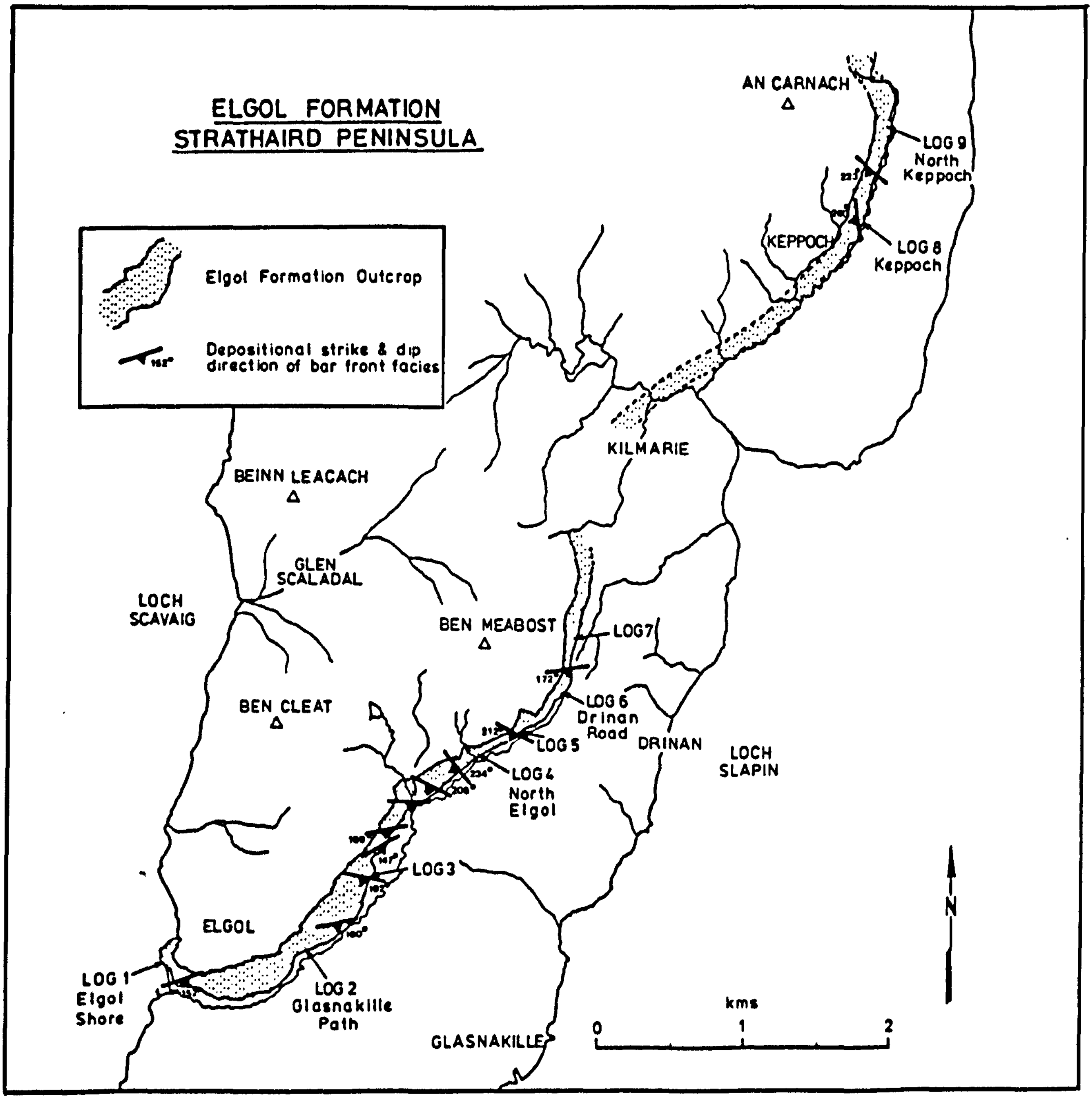


FIGURE 5 Sketch map showing distribution of the Elgol Formation outcrop in Strathaird, distribution of log localities and the depositional dip direction of units in the inclined bar front facies.

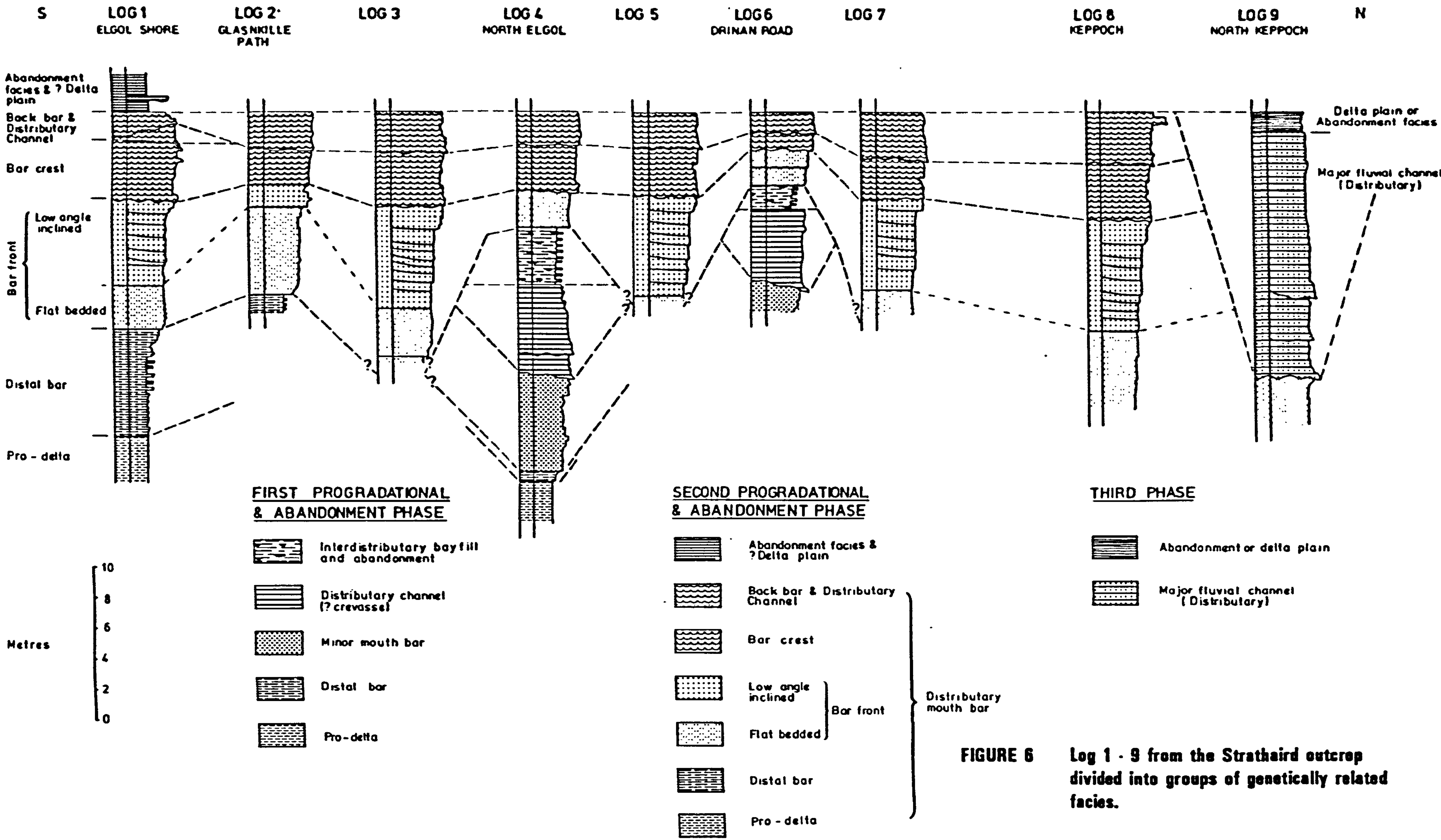


FIGURE 6 **Log 1 - 9 from the Strathaird outcrop divided into groups of genetically related facies.**

continued upward deceleration in flow. This part of the sequence is attributable to deposition in a shallow braided distributary channel. Finer grained planar laminated sands with large bivalve escape burrows (?Unio) at the top of the Formation are interpreted as a beach face sequence formed by minor wave reworking at the delta shoreline.

The sequence in the base of the Lealt Formation, (above 24.25m fig.2) represents deposition from suspension with the coarse sands (at around 25m fig 2) representing discrete high flow velocity systems. The structureless silty shales below these sand intercalations reflect intense bioturbation which could possibly represent rootlet penetration. The shales above this sand intercalation (above 25.25m fig. 2) however represent probably anoxic bottom conditions similar to that described for the Cullaidh Shale Formation.

The sequence of current velocities and flow directions within the Elgol Formation (up to 24.25m fig. 2) is in general similar to the hydrodynamic profile observed in recent delta distributary mouth areas; e.g. the Mississippi Delta, Wright and Coleman (1974) and the Po Delta, Nelson (1970) although the Elgol Formation differs considerably from these modern deltas. Coarsening upwards sequences with some similarities to the Elgol Formation occur from fluvial-dominated delta distributary mouth bars (see Elliott 1978); Frazier (1967); Kanes (1970); Coleman and Wright (1975); Wright (1977). The top of the sequence also has features in common with the Gum Hollow fan delta (Mcgowan 1970). Adopting the terminology for distributary mouth bars of Wright and Coleman (1974), prodeltaic, distal bar, bar front and bar crest, sub-environments are recognised. Together with distributary channel and abandonment facies these make up a classic deltaic coarsening upwards sequence. As described above, the Cullaidh Formation shales are prodeltaic. The lower part of the Formation up to 9.75m (fig. 2) represents the distal bar in which periodic influxes of silt to fine sand replaced anoxic lagoonal conditions allowing burrowing organisms to colonize the area and eventually thrive, before being engulfed by more rapid but also episodic deposition in the bar front. (9.75-18m fig. 2). The large scale, low angle (5°-11°) asymptotic sets at this level are interpreted as representing the offshore directed depositional surfaces of this bar front. It is important to differentiate these structures from large scale high angle (greater than 20°) asymptotic sets which in the past have been interpreted as deltaic, e.g. Collinson (1968) but represent the deposits of large scale, in channel, transverse bars similar to those described by Coleman (1969) from the Brahmaputra River. The Elgol Formation structures are more closely analogous to the delta foresets of modern and Pleistocene Gilbert type deltas (Gilbert 1885; Gustavson et al 1975). They are however inclined at a lower angle (5°-11°) than true Gilbert type foresets which are deposited at the angle of rest of the sediment (20°-30°) and therefore represent different hydrodynamic conditions (see discussion below). The high current velocity deposits above this level (18-20.75m fig.2) represent the bar crest. Prominent scour surfaces demonstrate episodic flow velocities in the shallow channelised area just offshore from the distributary mouth.

The coarse pebbly sands at the top of the Formation above 20.75m truncate the bar crest sands and are interpreted as representing deposition in a shallow braided distributary. This part of the sequence is generally similar to a non-fining upward sequence described by Harms and Fahenstock (1965) from a modern fluvial system, characterized by rapidly fluctuating discharge. It is also similar to the braided stream and sheet flood dominated delta (fan) plain facies of the Gum Hollow fan delta (McGowan 1970). In this system the delta plain is composed of shallow braided channels containing transverse and longitudinal bars. Trough cross stratification formed by the migration of longitudinal bars is probably the dominant sedimentary structure and occurs with occasional planar tabular sets, (McGowan 1970 p.46). The trough cross stratified cosets and isolated tabular planar sets at the top of the Elgol Formation possibly therefore represent the migration of longitudinal and transverse bars in a braided distributary system. In addition the Gum Hollow delta plain is virtually devoid of vegetation therefore providing a close parallel with the non-rootlet penetrated sandstones in this part of the Elgol Formation.

The sands with probable unionids at the top of the sequence represent the cessation of active channel migration and probably records the wave reworking of sediment to form a minor beach face deposited before the abandonment of the delta lobe. This sequence of events is also similar to that described by McGowan (1970) from the Gum Hollow fan delta.

The basal Lealt Formation represents abandonment of the delta lobe, followed by subsidence and a resumption of anoxic lagoonal sedimentation, in a system similar to that described for the Cullaidh Formation. The base however possibly represents vertical accretion deposits of the delta plain (see discussion below).

Distributary Mouth Bar Deposits - Hydrodynamic Controls

In the distributary mouth area density contrasts between the effluent and ambient water are critical in controlling the configuration and internal form of the mouth bar deposits (Fisher et al, 1969; Wright and Coleman 1974). The receiving basin for the Elgol Formation delta in Strathaird has been shown to be of low salinity, often almost fresh (see above). Effluent dynamics would therefore be dominated by non-stratified or non-buoyant outflow. Consequently, friction between the effluent and the bar crest would cause very high turbulence. In modern systems these conditions lead to the formation of very shallow, funnel-shaped distributary mouths with non-parallel subaqueous levees (Wright and Coleman, 1974). Episodic flow conditions of this type are illustrated in the bar crest and back bar deposits of the Elgol Formation, by pebble-lined scours succeeded by high energy structures and with a complex palaeocurrent pattern with a wide (90°) spread of palaeocurrent modes.

This configuration (although smaller in scale) compares with the middle ground mouth bars, described by Coleman and Wright, (1975 p.107, fig. 6) from the modern Mississippi, in which very shallow distributary channels bifurcate around a mid channel island. A problem with this interpretation is the importance which Coleman and

Wright (1975) place on periods of buoyant effluent at normal stage in the formation of this type of mouth bar. It is possible however that frictional processes operating at flood stage are the most important factor controlling mouth bar configuration. (Wright and Coleman 1974).

The lack of a density contrast between ambient and effluent water is the principal factor causing three dimensional mixing at the distributary mouth which initiates very rapid deposition and therefore the formation of Gilbert type foresets (Bates 1953; Wright 1977). However, the Elgol Formation bar front differs significantly from true Gilbert type foresets and therefore records different hydrodynamic conditions. It most probably represents the density controlled underflow of sediment laden effluent and its subsequent rapid deceleration. The process accounts for both the inclined bar front bedding units and their weak basal scour surfaces which are occasionally succeeded by trough cross stratification.

The continuous series of exposures along the scarp to the north of Elgol demonstrates the lateral merging of distributary mouth bars identified at Elgol shore to form a coalescent sheet sandstone capped by closely spaced, braided distributary channel sands representing a delta plain dominated by stream flood and sheet flood processes. The depositional dip directions in the bar front swing round progressively from SE at Elgol in the south to SW at North Elgol, SSE at Drinan Road and W at Keppoch in the north, demonstrating that the delta was broadly lobate in form (Figs. 5 and 7), but comprises a series of coalescent sub lobes.

Coalescent mouth bars of this type in recent delta systems are attributed to three main controlling conditions. i. depth of the receiving basin, ii. high levels of effluent discharge and sediment load, iii. lateral reworking by storm and tide generated currents (basin processes).

The sheet sands of the pre-modern shoal water deltas of the Mississippi, (Fisk 1955; Frazier, 1967) are attributed to progradation in a shallow receiving basin, less than 20 feet (6m) deep. Depth of the receiving basin has also been postulated for coalescent mouth bar development in the Guadalupe Delta, (Donaldson et al, 1970).

In the post-1930 Colorado River Delta, Texas, (Kanes, 1970) the occurrence of abnormally high levels of effluent discharge and sediment load (initiated by the clearing of log jams in the drainage basin) resulted in the formation of numerous closely spaced distributaries and a lobate coalescent mouth bar sand body. A similar situation occurred through the initiation of a crevasse channel in a recent Mississippi crevasse sub-delta described by Coleman et al. (1964 p.248).

Where the basin energy regime is high, wave reworking and lateral transport of mouth bar sand produces a similar geometry e.g. the Rhone Delta (Oomkens 1967; 1970) and the Ebro Delta, (Maldonado, 1975).

Some evidence of lateral reworking occurs on the bar front of the Elgol Formation delta, but is absent from the bar crest deposits. Depth of the receiving basin together with high effluent discharge and sediment load are therefore the most important factors controlling the geometry of these distributary mouth bar deposits.

Using Klein's (1974) model for estimating palaeo water depth (the Elgol Formation is well suited to this technique as it lacks any soft sediment deformation structures and was a rapidly prograding system), the receiving basin was shallow, occurring in, or below, Klein's category for stable, cratonic deltas. Depths were a maximum of 17.6m (13.8m at Elgol shore) estimated from sections with thick bar front deposits with depositional dips, and 4.4 - 3.2m in sequences with thin mouth bar sequences (north Elgol and Drinan Road respectively.)

The thin parts of the sequence probably therefore represent progradation into shallow water, where elevated areas of the basin floor were formed by the elongate delta lobes of the first progradational phase. This, therefore, demonstrates the depth/current velocity dependancy of the inclined bar front facies.

It is therefore probable, given high rapidly fluctuating levels of effluent discharge, copious coarse sediment supply (and therefore numerous rapidly shifting shallow braided distributaries) together with a shallow receiving basin, that numerous distributary mouth bars could prograde rapidly, across the basin forming a coalescent mouth bar sand body.

These conditions of mouth bar progradation (and by inference steeply sloping channel profiles) are the principal controls on a braided rather than meandering channel pattern (Walker and Cant, 1979). Numerous closely spaced braided distributary channels would therefore be expected in the Elgol Formation delta.

Abandonment Facies

Vertical accretion deposits of the delta plain are very poorly represented in the Elgol Formation delta. 50cm of possibly rootlet penetrated silty shale capped by a coarse sandstone at the base of the Lealt Formation (24-25.25m) are the only possible vertical accretion deposits. An explanation for this is that braided systems characteristically lack a significant thickness of flood plain deposits (Walker and Cant, 1979). The basal Lealt Formation could therefore represent thin vertical accretion deposits of the delta plain with small scale channels or crevasse sheet splays accounting for thin coarse sand intercalations.

Alternatively, because the bituminous shales above this sand intercalation (above 25.25m) represent subsidence after the stabilization of the top surface of the sand body (indicated by the insitu casts of Unionids) and its subsequent abandonment, the basal Lealt Formation must represent an abandonment facies (possibly involving a short period of vertical accretion on the delta plain). This part of the sequence was deposited before the re-establishment of an anoxic lagoon - similar to that described for the Cullaidh Shale Formation.

The coarse sand intercalations could then represent wave reworked mouth bar and distributary channel sands, moved landwards as the area of the delta lobe subsided and was transgressed. Modern examples of this type of sequence are limited to lobate deltas, of the same general configuration as the Elgol Formation, (Scruton, 1960; Coleman and Gagliano, 1964; Frazier, 1967).

Modern and Ancient Analogues

Among the modern analogues for the Elgol Formation which are referred to above, the best are probably the post-1930 Colorado River delta, Texas (Kanes 1970) and the Gum Hollow fan delta (McGowan 1970). However, although both these systems share common characteristics with the Elgol Formation they are both smaller, thinner and finer grained. They also have only a relatively short history of progradation (40-50 years largely controlled by the activities of man) so that the eventual form of the deposits is unknown. The term fan delta, defined by Holmes (1965) as the progradation of an alluvial fan into a body of water from an adjacent highland, is probably inappropriate for the Elgol Formation because it is supplied by a low sinuosity or braided fluvial system rather than an alluvial fan. The Elgol Formation environment is probably more accurately defined as lobate fluvial dominated, lagoonal delta in which the delta plain is dominated by braided fluvial channels.

The Gilbert type deltas of the Eocene, Green River Formation, Wyoming (Stanley and Surdam 1978), in many respects represent a similar

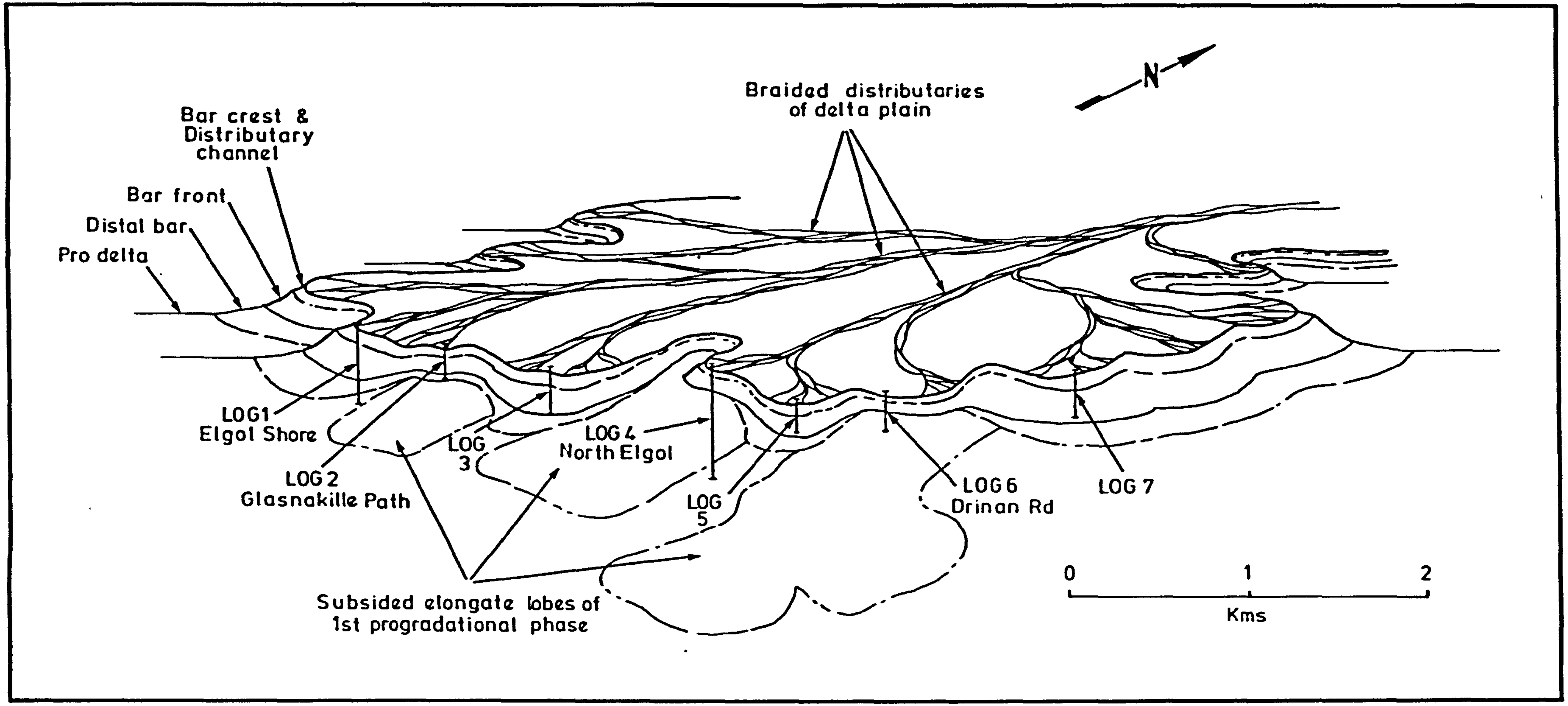


FIGURE 7 **Enviromental reconstruction of the Elgol Formation delta in Strathaird, a lobate high constructive/fluvial dominated system.**

depositional system and are associated with a very similar sequence of facies and faunas to those occurring in the Great Estuarine Group. This system is however much finer grained than the Elgol Formation and includes true Gilbert type deltas which the Elgol Formation system did not.

THIRD DEPOSITIONAL PHASE - DESCRIPTION. Log 9, Figs. 4 & 6.

At Keppoch in the north of the Strathaird outcrop, the southern part of the scarp face exposes a distributary mouth bar sequence of the same type as that described above (Fig. 6).

At the northern end of the section, two thick lenticular fining upwards sequences down-cut into these mouth bar deposits by a minimum of 7m. At the centre of this lens (Fig. 4 & 6) both units have a basal scour succeeded by pebbly sands which fine upwards, to coarse-medium sands.

Planar lamination and tabular cross stratification (up to 70cm) with one example of a reactivation surface (Collinson (1970) give unimodal W - WNW palaeocurrents (8.5m fig. 4). At the margins of the lens larger scale cross stratification (170cm), probably the epsilon type of Allen (1963) has depositional dips orientated towards the N.W. (338°).

The top of this lenticular sand body consists of medium and medium-coarse sandstones with small scale (less than 10 cm) trough cross stratification giving S.W. palaeocurrents. Above this is a medium grained highly carbonaceous, black sandstone with indistinct planar lamination. The contact of this facies and the underlying fining upwards sequence is not exposed.

THIRD DEPOSITIONAL PHASE - INTERPRETATION

The fining upwards sequences represent a channel incised into the lobate delta deposits of the second progradational phase. In the central part, the channel fill comprises large and small scale downstream-migrating bar bedforms. The two erosional surfaces, succeeded by fining upwards sequences, with unimodal palaeocurrents, record deposition from waning flow to give a composite channel fill with similarities to those described by Allen (1965b). The reactivation surfaces represent fluctuation in flow with modification of the bedforms at low or falling stage (Collinson 1970). Given the lagoonal character of the receiving basin it is most probable that river stage rather than tidal fluctuations are responsible. At the margin of the channel (Fig. 4) large scale probable epsilon cross stratification (Allen 1963) has depositional dips orientated obliquely to the inferred down channel palaeocurrents and probably represent lateral accretion surfaces. These deposits compare with distributary channel sequences from the recent Mississippi Delta (Fisk et al, 1954; Fisk 1955) and are very similar to the non-tidal distributary channels of the Niger Delta (Oomkens 1974, p.203).

The top of the sequence may represent the channel fill deposited during abandonment, or alternatively a levee sequence succeeded by highly carbonaceous, probably rootlet-disturbed, delta plain deposits. Palaeocurrents orientated approximately normal to the channel may represent overbank sheet flooding and therefore support the latter hypothesis.

STRATHAIRD: SUMMARY OF DEPOSITIONAL HISTORY

The sections exhibit two distinct phases of delta progradation and abandonment and a third phase of channel incision and subsequent deposition.

i) First Progradational and Abandonment Phase:

Small scale elongate delta lobes (possibly associated with a large unexposed distributary) deposited sequences closely resembling crevasse sub-deltas and splay lobes of an interdistributary bay fill sequence. Abandonment is recorded by finer grained intensively bioturbated material at the top of the sequence.

ii) Second Progradational and Abandonment Phase:

Subsidence and a marked increase in effluent discharge together with clastic supply, initiated coalescent mouth bar progradation fed by numerous braided distributaries. This formed a lobate, fluvial-dominated delta. Abandonment and rapid subsidence of the lobe is recorded in the basal Lealt Formation. Bar front and distributary channel sands indicate that the net progradation direction of the delta was SSW; sub-parallel to the Triassic basin margin and Triassic palaeoflow directions presented by Steel et al (1974) and Steel (1976) for the Strathaird-Central Skye area. (See discussion below).

iii) Third Depositional Phase:

Before subsidence of the lobate delta, avulsion and incision into these deposits was followed by deposition of a composite fluvial channel fill. Abandonment of the channel is marked by carbonaceous sands at the top of the sequence. The sequence as a whole records two distinct changes in the style of deposition in the Strathaird area. The switch from elongate delta progradation of the first phase, to lobate delta progradation of the second phase, has a modern analogy in the Colorado delta, Texas (Kanes, 1970). In this system the rapid increase in clastic supply and effluent discharge, responsible for the change in depositional style, occurred because of the artificial clearing of log jams in the hinterland. In the Elgol Formation tectonism resulting in rapid uplift of the hinterland would have the same effect.

SOUTH TROTTERNISH: DESCRIPTION (fig. 8a section 1.2.3)

The Elgol Formation attains its greatest exposed thickness in south Trotternish (consistently greater than 27m) and although it is not metamorphosed it forms a conspicuous series of outcrops over a distance of 3½ km in the cliffs below Fiurnean north of Portree (plate 8). However the contact with the overlying Lealt Shale Formation is not exposed.

The underlying Cullaidh Formation rests gradationally on the marine Carantiana Clay and is generally similar to its Strathaird development. In addition it contains rare regular echinoids,

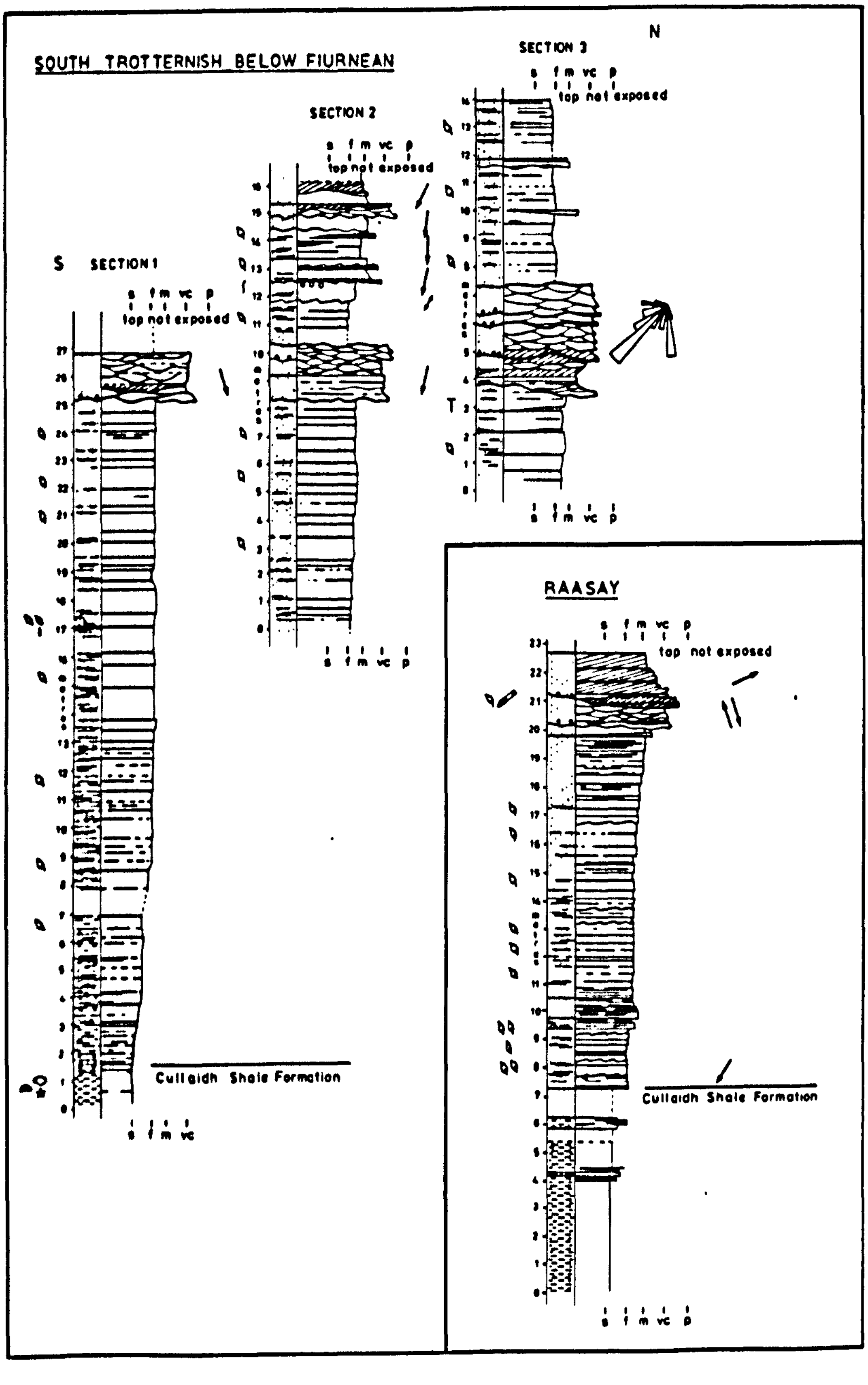


FIGURE 8 . (8a) Logs, of section 1 - 3, S - N from the cliffs below the Fiurnean south Troternish.
(8b) Log from a stream section 2.5km north of Dun Caan, Raasay.

Diademposis cf. *woodwardi*. It has a gradual upwards transition to seemingly massive, fine grained, moderately well sorted sands at the base of the Elgol Formation. The lower 24.5m of the Elgol Formation is a gradual coarsening upwards sequence with shaly partings, plant fragments and a thin allochthonous lignite lens (17m section 1 fig. 8a). The sands appear structureless but inclined carbonaceous mud drapes indicate the presence of low amplitude bedforms. Shaly lenses and small *Planolites* burrows occur in the medium grained sands at the top of this facies in section 3 (Fig. 8a).

The upper facies of the coarsening upwards sequence has a prominent basal erosion surface (25.25m section 1 fig. 8a). Trough (maximum amplitude 10 cm) and tabular cross stratified (amplitude 15-25 cm) very coarse and medium-coarse sands with granules and shale drapes are succeeded by a unit comprising trough cross stratified cosets with basal pebble accumulations. Both units have palaeocurrents orientated between S and W with the main mode SW. This facies thins from 3.5m in section 3 to 1.75m in section 1,2½ km due south.

The top of the Formation in sections 2 & 3 (fig. 7) is a second coarsening upwards sequence. Fine to medium sands are succeeded by medium sands with thin, rippled and tabular cross stratified (5-10 cm) coarse sand intercalations. Wave ripples and small load casts occur occasionally. A fining upwards sequence (14.8m Section 2) with a pebbly trough cross stratified base can be correlated over 600m from section 2 to section 3 (fig. 7a). The upper part of this fining upwards sequence comprises planar laminated and planar cross stratified (15-30 cm) medium to coarse sands with southerly palaeocurrents. Plant fragments occur throughout the Formation but no rootlets have been observed.

SOUTH TROTTERNISH: INTERPRETATION

As in Strathaird the Elgol Formation overlies lagoonal (pro-deltaic) shales of the Cullaidh Formation. Intermittent exposure over 2½ km shows only minimal lateral facies variation. The lower coarsening upwards sequence, as in the second progradational phase in Strathaird, represents the distal bar and bar front of a coalescent distributary mouth bar. The silty lenses and shaly, carbonaceous partings record fluctuating flow velocities. This facies differs from its equivalent in Strathaird in that it is finer grained and lacks apparent large scale, low angle cross stratification in the bar front. Using Klein's (1974) model, the receiving basin was consistently 25m deep. This contrasts with the rapid lateral depth variations postulated in Strathaird.

The very coarse top of this sequence differs from that in Strathaird, in that it never shows a gradation at the base to the bar front deposits. It does not therefore record bar crest development but represents a series of shallow, laterally coalescent distributary channels with SW flow directions. As postulated for braided distributary channels in Strathaird, these weakly fining-upwards sequences are similar to deposits controlled by rapidly fluctuating discharge in the modern Rio Grande (Harms and Fahenstock 1965). These deposits compare closely with coarse distributary channel sheet sands described by Oomkens, (1974 p. 204), the anastomosing distributary channels figured by Kanes (1970, p.86) from the Colorado River delta, Texas, and the sheet flood and stream flood dominated delta plain deposits described by McGowan (1970) from the Gum Hollow fan delta, Texas. The suite of sedimentary structures described above represents a distinct sequence of bedforms. At the base is a pebbly lag followed by trough and planar tabular sets representing shallow channel incision and the development of a compound in-channel, bar bedform. The complex palaeocurrent pattern at this level includes planar sets with foresets at 90° to the inferred (SW) down channel direction (indicated by trough cross stratified cosets). This sequence probably represents the development of a cross channel bar similar to that described by Cant and Walker (1978) from a braided fluvial system. The trough cross stratified cosets above this probably represent renewed channel aggradation comprising stacked sinuous crested dunes. The occurrence of shale drapes in the lower part of the sequence indicates rapid fluctuations in discharge similar to those documented by McGowan (1970) from the Gum Hollow fan delta. A lack of finer grained sands with planar lamination and/or ripples at the top of this sequence means that the broad sand flats (bar top) described by Cant and Walker (1976; 1978) were never developed.

The upper parts of the Formation, above the distributary channel deposits (above 10.25m, section 2, 7.25m, section 3 fig. 8a), have two possible interpretations: 1) vertical accretion deposits of the delta plain with small scale anastomosing distributaries and sheet floods represented by the coarse, cross stratified sand intercalations. A laterally persistent coarse, cross stratified sandstone (15m section 2, 11.75m section 3, fig. 8a) fines upwards and represents a second braided distributary channel; ii) a second smaller scale delta progradational phase, initiated after subsidence of the first delta lobe. The thin coarse sand intercalations then represent bar crest deposits, overlying a thin bar front. The laterally persistent fining upwards sequence also represents a distributary channel deposit in this interpretation. There is no abandonment facies above the main distributary channel sands (8.25-10.25m, section 2, fig 8a). Subsidence must therefore have been very rapid if alternative ii) is to be a possibility.

The delta in south Trotternish therefore represents a similar lobate fluvial dominated deltaic system to that described in Strathaird (second progradational phase). The main difference in the bar front and bar crest deposits probably reflect differences in sediment load and effluent dynamics.

The occurrence of an echinoid in the prodeltaic shales means that the receiving basin (Sea of the Hebrides Basin) must have had marine connection and would have been at least brackish (salinity here could however have been identical to that in Strathaird) thereby initiating buoyant outflow at the distributary mouths (hypopycnal flow of Fisher (1969); (Wright and Coleman, 1974). This, together with a finer grained sediment load than the equivalent in Strathaird would cause deposition over a wider area offshore from the distributary mouth, thereby precluding the development of measurable depositional dips in the bar front. A salinity induced difference in distributary channel hydrodynamics together with finer, more easily eroded mouth bar deposits, probably accounts for the lack of bar crest deposits below the major braided distributary channel, sand sheet.

RAASAY, DESCRIPTION: (fig. 8b).

The only good outcrop of the Formation on the Island occurs 2½ km north of Dun Caan; the Elgol Formation here is slightly different from the deposits in south Trotternish. These differences are outlined below. The pre-deltaic bituminous shales of the Cullaidh Formation in some sections contain a bed with a marine fauna of crinoid debris (Forsyth 1960) but are otherwise very similar to the deposits in south Trotternish. The distributary mouth bar deposits have occasional current ripples and are overlain by coarse, low amplitude trough cross stratified sands (20m, fig. 8b) with driftwood and NNW palaeocurrents. The distributary channel sands (above 20.75m, Plate 9) have a prominent basal scour with a lenticular, tabular and trough cross stratified fill which is transitional upwards to low angle planar laminated sands inclined towards ENE. These distributary channel deposits have a complex palaeocurrent pattern with SSE and NNW flow directions.

RAASAY INTERPRETATION:

The sequence represents similar depositional conditions to those in south Trotternish with buoyant effluent dynamics and a generally fine sediment load producing a broad bar front depositional area. The distributary channel sandstones on Raasay contain low angle planar laminated sands at the top of the sequence. The ca 90° divergence in the direction of inclination of these bedding units away from the inferred SSE down channel direction is based on a small sample but represents a very similar degree of angular discordance to that described by McGowan (1970) from the sand flats of the Gum Hollow fan delta plain. Coarse sands at the top of the bar front with NNW palaeocurrents probably represent bar crest deposits reworked by storm and possibly tide generated currents.

Receiving basin processes are therefore more important here than in south Trotternish and Strathaird. This probably reflects a different basin geometry and energy regime and correlates with the occurrence of a bed with a marine fauna in the prodeltaic shales.

NORTH TROTTERNISH:

Between Fiurnean in south Trotternish and Rigg, 7 km to the north, in north Trotternish, the Elgol Formation is not exposed. Considerable lateral variation occurs in this unexposed area, so that these two areas of Trotternish are treated separately. The two sections in north Trotternish, Rigg Burn (fig. 9a) which is an inland stream section and Invertote (fig. 9b) on the coast to the north, are 4 km apart. The Elgol Formation at both these localities is thinner (12m) than at any of the sections described to the south.

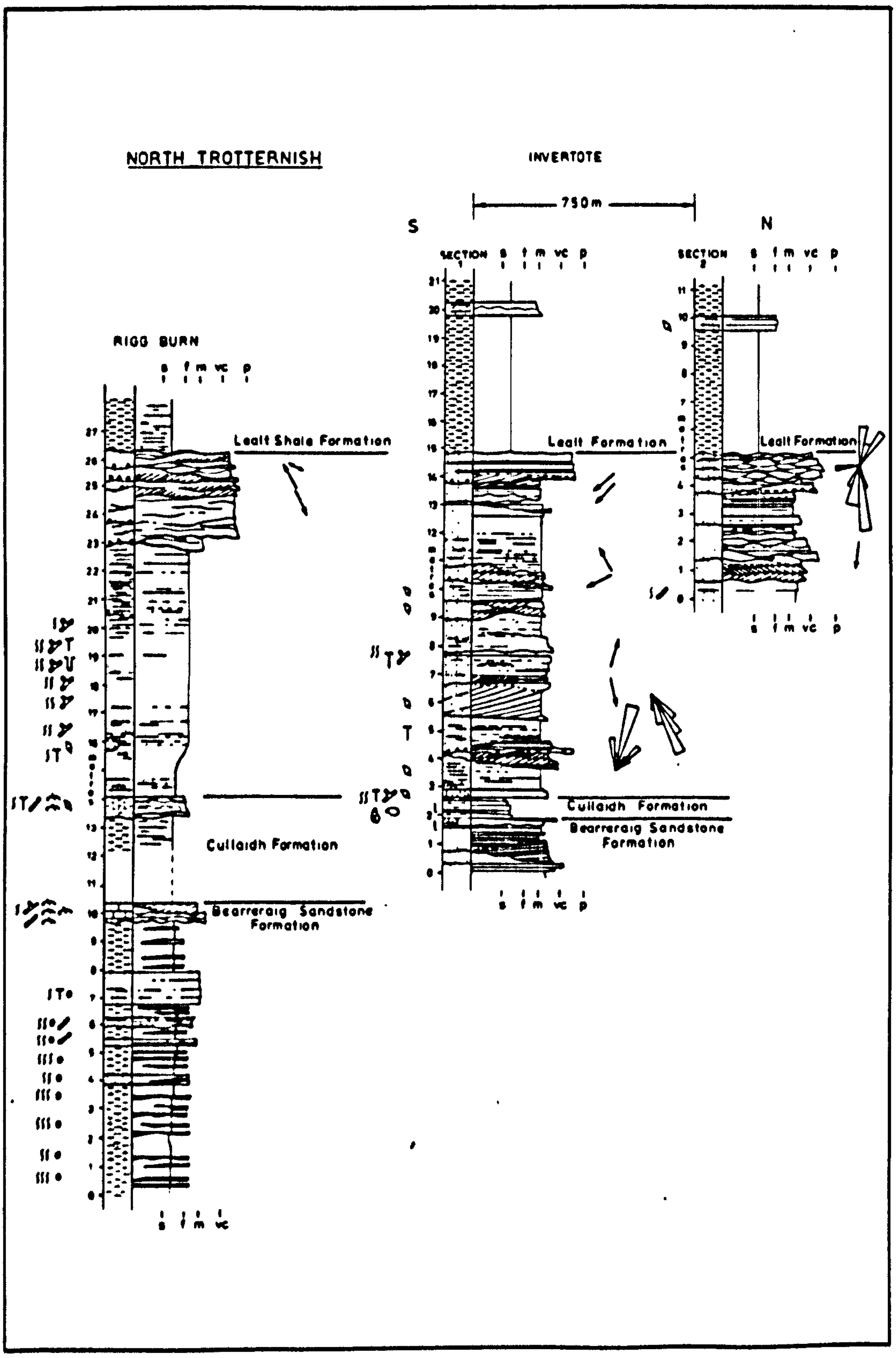


FIGURE 9 (9a) Log from the Rigg Burn, north Trotternish.
(9b) Logs from near Invertote; sections 1 sea cliffs close to the mouth of the Lealt River; section 2 from the foreshore 750m to the N.

RIGG BURN, DESCRIPTION: (fig 9b)

The Cullaidh Formation (10.3 - 14m fig. 9a) consists of carbonaceous silty shales overlying a distinctive, red mottled limestone with a marine fauna, marking the top of the Bearreraig Sandstone Formation. Bioturbation structures in this sequence increase in diversity upwards; Planolites is the only trace fossil in the lower part of the sequence (up to 7m fig. 9) while occasional Monocraterion and Palaeophycus occur in the top of the Bearreraig Sandstone Formation. (9.75 - 10.3m, fig. 9). The base of the Elgol formation is sharp and comprises a fine - medium grained current rippled bed. A diverse assemblage of trace fossils with Monocraterion, Diplocraterion (plate 10) and Thalassinoides occurs in the lower half of the Elgol Formation (14 - 20m, fig. 9). These trace fossils are picked out by fine carbonaceous laminations in the burrow walls (Plate 9).

Above these fine bioturbated sands are sands of similar grain size with wavy and bifurcating flasers (Reineck & Wunderlich, 1968). These are overlain erosively by very coarse sands with poorly defined cross stratifaction and shale drapes. They are similar to the distributary channel sands described from south Trotternish. The few palaeocurrent measurements made (5) give bipolar (NNE - SSW) palaeocurrents. The top of the Formation is overlain by silty carbonaceous shales at the base of the Lealt Formation.

RIGG BURN: INTERPRETATION:

Depositional conditions were similar to those described in Raasay. Receiving basin processes (tide, wave and storm generated currents) were probably responsible for the bipolar palaeocurrent pattern in the top of the sequence and for the flaser bedding structures in the fine sands below. These flasers themselves do not however imply tidal conditions in the basin: McCave (1970) has shown that slack water in a tidal cycle represents an inadequate time period for the deposition of a mud lamina. These structures probably indicate wave reworking of the bar crest sands prior to the incision of the braided distributary sheet sand (also partially reworked).

The marine fauna in the prodeltaic facies and the diverse trace fossil assemblage (probably indicating high, almost marine salinities) suggests that, as in Raasay, the receiving basin lagoon had a marine connection. The basin was probably larger than that existing during deposition of the south Trotternish sequence so that storm and tidally generated currents could operate.

The sequence is probably best accounted for by the reworking of mouth bar and distributary channel sands (similar to the sequence in south Trotternish) to form a shore face sequence capped by a coarse (possibly tidally reworked) distributary channel sand body. The suite of biogenic and physical sedimentary structures is similar to the Cretaceous and Recent shoreline sequences described by Howard (1972).

INVERTOTE DESCRIPTION: (Log. 1 & 2, fig. 9b)

At Invertote, cliffs close to the mouth of the Lealt River (section 1, fig. 9b) give a complete section through the Elgol Formation (Plate 11) while on the coast 750m to the north is the most northerly exposure of the Formation (section 2, fig 9b). This section however only exposes the upper 5m of the Formation.

The Cullaidh Shale Formation at Invertote is represented by only 95 cm of shales and shaly calcareous sands with allochthonous lignite lenses (1.8m - 2.75m, section 1, fig. 9). This unit contains a fully marine macro-fauna (Hudson and Morton 1969; Harris and Hudson 1980), and has a palynomorph assemblage dominated by vitrinitic plant debris but including gymnosperm spores and marine microplankton chiefly the dinocyst Sentusidinium sp. (J.P.G. Fenton pers. comm).

The Elgol Formation is more complex here than elsewhere; it is divided into two distinct units separated by a laterally persistent bioturbated shale (7.75m section 1). Medium grained sands, with shale partings at the base, are cut by a laterally discontinuous coarse, tabular cross stratified coset (10.40 cm) with NNE palaeocurrents (3.75m section 1). These are truncated by a prominent erosion surface lined with pebbles and succeeded by a composite fining upwards sequence of planar laminated and tabular cross stratified sands (5-10 cm) with shale partings and occasional Monocraterion burrows. Above this is a single large scale (up to 150 cm) low angle planar tabular set (depositional dip of foresets towards 160°) with occasional shale drapes on foreset surfaces. This is succeeded by medium-coarse sands with low amplitude planar cross strata (5-10 cm) and thin silty shale intercalations. Palaeocurrents are bimodal N & S at this level. The top of this lower unit is penetrated by large scale Monocraterion and Thalassinoides? burrows, (7.75m section 1) and succeeded by a thin shale 15-10 cm) which is laterally persistent over the extent of the outcrop (ca 500m).

The upper unit, at its base, consists of medium-coarse sands with indistinct planar lamination and shale partings. These sands include two fining upwards sequences with trough and tabular cross stratification (5-20 cm). The upper example has pebbles at the base and bimodal palaeocurrents with SW (Vector 249°) and NW (vector 338°) modes. The upper part of this unit (11.00 - 13.75m, section 1) is a dark-chocolate brown, medium sandstone with lenticular silty shales (max. 7 cm) and wave ripples. It is capped by low angle planar laminated sands, (4°-7° - S.W.) with low angle discordances between sets. The top of the formation here consists of a well sorted granule conglomerate with thin (2 cm) carbonaceous shale lenses, and at the base, low angle planar laminations also dipping towards the SW. Palynofacies samples from the carbonaceous shale intercalations include the same marine microplankton (Sentusidinium sp.) as samples from the Cullaidh shale Formation equivalent at Invertote. (J.P.G. Fenton pers. comm.).

The Lealt Formation here consists of black bituminous shales similar to the Cullaidh Formation further south. 5m above the base it includes a 30 cm thick, fine - very fine sandstone intercalation with shaly partings. Section 2, 750m to the north (Fig. 9b), at the base consists of bioturbated medium sands with isolated tabular cross stratified sets. These are cut by an erosively based, very coarse, trough cross stratified sand with southerly palaeocurrents which fines upwards to planar laminated and massive medium-coarse sands, (1.5 - 3.75m, section 2, fig. 9b). The top of the formation comprises three trough cross stratified cosets, bounded by shale drapes. These sands give complex bipolar palaeocurrents with a dominant southerly mode. The Lealt Formation here is identical to the section described above.

INVERTOTE, INTERPRETATION:

As at Rigg the prodeltaic facies is marine with the intercalation of shales, calcareous sands and allochthonous lignites, demonstrating widely fluctuating depositional conditions. The coarse tabular cross stratified coset close to the base of the Elgol Formation (3.74m section 1, fig 9b) represents powerful shoreward (NNE) directed palaeocurrents (orientation inferred from deposits above) actively eroding the deposits of an earlier lower flow velocity system. These deposits are truncated by a second higher energy system, represented by the conglomeratic base of a prominent fining upwards sequence with N (shoreward) and S (basinward) palaeocurrent modes (regressive shoreline orientation inferred from deposits above). This unit (4.25m - 7.75m section 1) records deposition under waning flow with downcurrent (SSE) migration of a large scale subaqueous bar to form a composite channel fill. Fluctuations in flow velocity are demonstrated by the scour surfaces, shale drapes and silty shale lenses which occur throughout the unit. Abandonment of this progradational phase is recorded by the laterally persistent bioturbated shale (7.75m section 1) at the top of the unit.

This sequence of grain sizes, structures and diametrically opposed palaeocurrent directions is comparable to the tidal channel and mouth bar deposits described from the recent Niger Delta (Allen, 1965a; Weber, 1971) and the Quaternary Niger and Recent Netherlands coast (Oomkens 1974). Scour surfaces, numerous clay laminae and shale drapes, are particularly characteristic of the tidal channel described by Oomkens (1974).

Diametrically opposed flow directions are also described from a modern Mississippi distributary mouth bar at flood stage (Wright and Coleman 1974, p. 770-772) and from the Po Delta by Nelson (1970). In these hydrodynamic systems, landward or return flow replaces basim water entrained in the lower layer of a buoyant effluent giving landward flow velocities just above the bottom, which are equal to those at the surface. It is unlikely however that this type of flow could operate in the distributary channel or bar crest region at flood stage because this period is characterized by the flushing of salt wedge (and therefore landward, return flow) beyond the bar crest (Wright and Coleman, 1974, fig. 12). This relationship effectively precludes this mechanism in the Elgol Formation because of the stratigraphic position of the deposit and the coarseness of the material involved.

It is therefore probable that the sequence represents shoreward (NNE) tidal currents, flowing in a tidal distributary channel with subsequent progradation of the channel mouth by deposition from dominant basinward (southerly directed) effluent currents. This sequence of events resulted in erosion of channel and mouth bar deposits and subsequent deposition of a fining upward sequence from fluctuating currents in a laterally migrating tidal distributary channel.

The upper sequence is best interpreted by first considering the more northerly section (fig. 9b), 750m north of the Lealt river mouth. The fining upwards sequence (1.3 - 3.75m), section 2, fig. 9) represents high flow velocities, eroding the underlying bioturbated sands with subsequent deposition under waning flow. These conditions are similar to those inferred for the distributary channel fill described above. Flow in this distributary channel was to the south. The trough cross stratified cosets at the top of the Formation (4 - 5.25m) record diametrically opposed palaeocurrents indicating wave and tidally induced flow reversals in the distributary channel. The dominant palaeocurrent mode however is southerly (basinward). This sequence, as with the deposits from the lower sequence, is similar to the tidal distributary and mouth bar sands described by Allen (1965), Weber (1971), and Oomkens (1974) from the Recent Niger Delta.

The upper sequence in section 1 (above 7.75m, section 1, fig. 9) has SW palaeocurrents with a suite of wave built sedimentary structures towards the top indicating that basinal processes were very important in the deposition of this part of the formation. This sequence of structures and grain sizes compares with the facies profile described from modern shorelines (Clifton et al, 1971; Davidson-Arnott and Greenwood, 1976, and Hill and Hunter, 1976).

The planar cross stratified fining upwards sequences developed towards the base (9.0 - 10.25m) (section 1, fig. 9b) represent high initial flow velocitites directed offshore (inferred from orientation of beach lamination above) and subsequent deposition under waning flow with oblique or longshore reworking to give the NW palaeocurrents. This sequence compares with the offshore directed, rip current channels, described from the shoreface facies of the New Brunswick coast (Davidson-Arnott and Greenwood, 1976). It is more probable however, that the sequence represents partial reworking on the shoreface of distributary channel and mouth bar sands after the lateral migration of the distributary mouth. The association of wave ripples and low angle planar laminae which are interpreted as swash cross stratification (Harms et al, 1975) dipping SW (220° - basinwards) represents the upper shoreface and foreshore (swash cross stratification) with silty lenses (13 & 13.75m, section 2) representing fluctuating depositional conditions. Possible wave built lamination also occurs in the well sorted granule conglomerates at the top of the Formation. These sediments include the marine palynomorphs discussed above and probably represent back shore beach ridges separated by runnels in which pools of standing water could accumulate. A generally similar sequence of storm-related deposits is described from the present-day Massachusetts coast (Davis et al 1972). The beach ridge and beach face sequence combine to produce a regressive barrier sand body similar to the delta front of the Niger Delta, examples described by Allen (1975, 1970), Weber (1971) and

Oomkens (1974).

The bituminous shales of the basal Lealt Formation represent lagoonal sedimentation on the subsiding delta plain. The fine grained sand intercalation (19.75m section 1 and 9.5m section 2) possibly represents a sheet splay deposit from an adjacent distributary. A similar barrier sand body, back barrier lagoon system, cut by tidal distributaries is described from the margins of the Niger Delta (Allen 1965). This facies association is reconstructed in fig. 10.

Section 2 (fig. 9b) therefore represents an active tidal distributary whereas section 1 represents the reworking on a regressive beach face of earlier deposited sands, in a similar system to that described by Allen (1965a). The shoreline orientation swings round from roughly E-W at the channel mouth to NW-SE in the lateral beach sequence (fig. 10), to give a cuspate or arcuate shoreline.

Modern deltas with similarities to this sequence occur in the Rhône (Oomkens 1967, 1970) and Ebro, Deltas (Maldonada 1975) both of which show extensive wave reworking and lateral transport of sand in the delta front. They occur in the fluvial-wave interaction category of Elliott (1978). However, the distributary channel and mouth bar sequences at Invertote were clearly deposited from both fluvial and tidal channels and so represent a system more closely allied to the Niger Delta distributaries. The delta here, therefore, occurs in the fluvial-wave-tide interaction category of Elliott (1978).

These sections therefore represent a greater degree of interaction

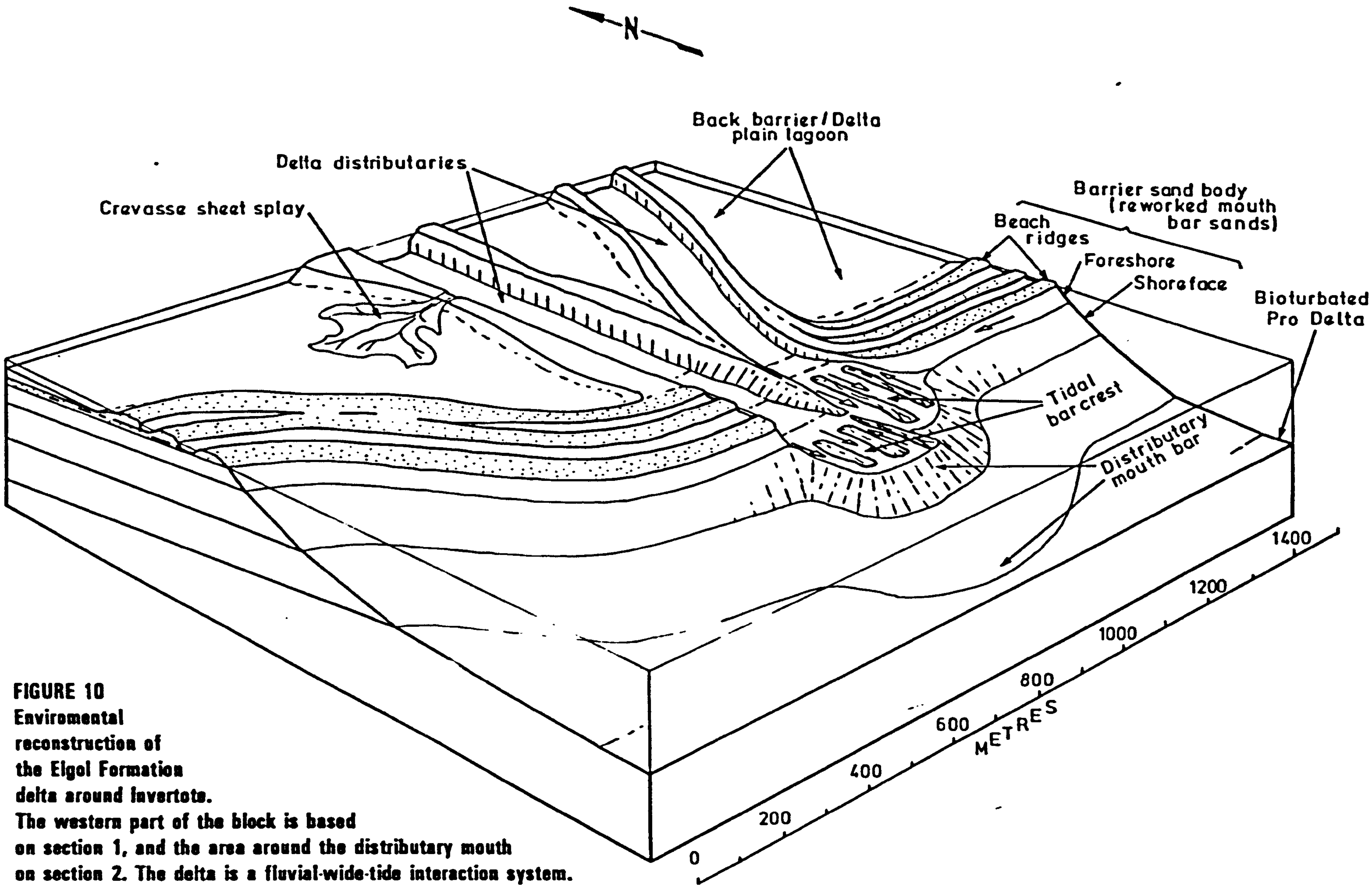


FIGURE 10
Enviromental reconstruction of the Elgol Formation delta around Invertote. The western part of the block is based on section 1, and the area around the distributary mouth on section 2. The delta is a fluvial-wide-tide interaction system.

between fluvial (effluent) and basinal (wave-tide) processes than any of the sections described to the south. This correlates with the occurrence at Invertote, of a fully marine macro fauna in the pro-deltaic Cullaidh Formation and marine microplankton (dinocysts) in both the Cullaidh Formation and the beach deposits of the Elgol Formation.

CONCLUSIONS AND PALAEOGEOGRAPHY

There is a northwards increase in the marine elements of the fauna in the pro-deltaic facies (Cullaidh Formation) of the Elgol Formation Delta. This is reflected in a continued northwards increase in the effects of basinal processes (waves and tides) on the configuration and internal form of the delta. In Strathaird (Inner Hebrides basin) the delta is a lobate, high constructive (cf. Fisher 1969) fluvial dominated (cf. Elliott 1978) system and probably indicates a low salinity receiving basin. The effects of a larger more saline receiving basin (Sea of Hebrides basin) are apparent in south Trotternish and Raasay where buoyant effluent dynamics are the probable control on a broad, fine grained bar front and are important in north Trotternish where the delta comprises a fluvial-wave-tide interaction system indicating a fully marine receiving basin. Because progradation took place from N or NE towards the S or SW the largely salinity controlled lateral variation in the form of the Elgol Formation probably records the relatively gradual initiation of non-marine salinities (variable but generally reduced, occasionally completely fresh) which persisted in the Sea of the Hebrides and Inner Hebrides basins from the basal Bathonian to the lower Callovian

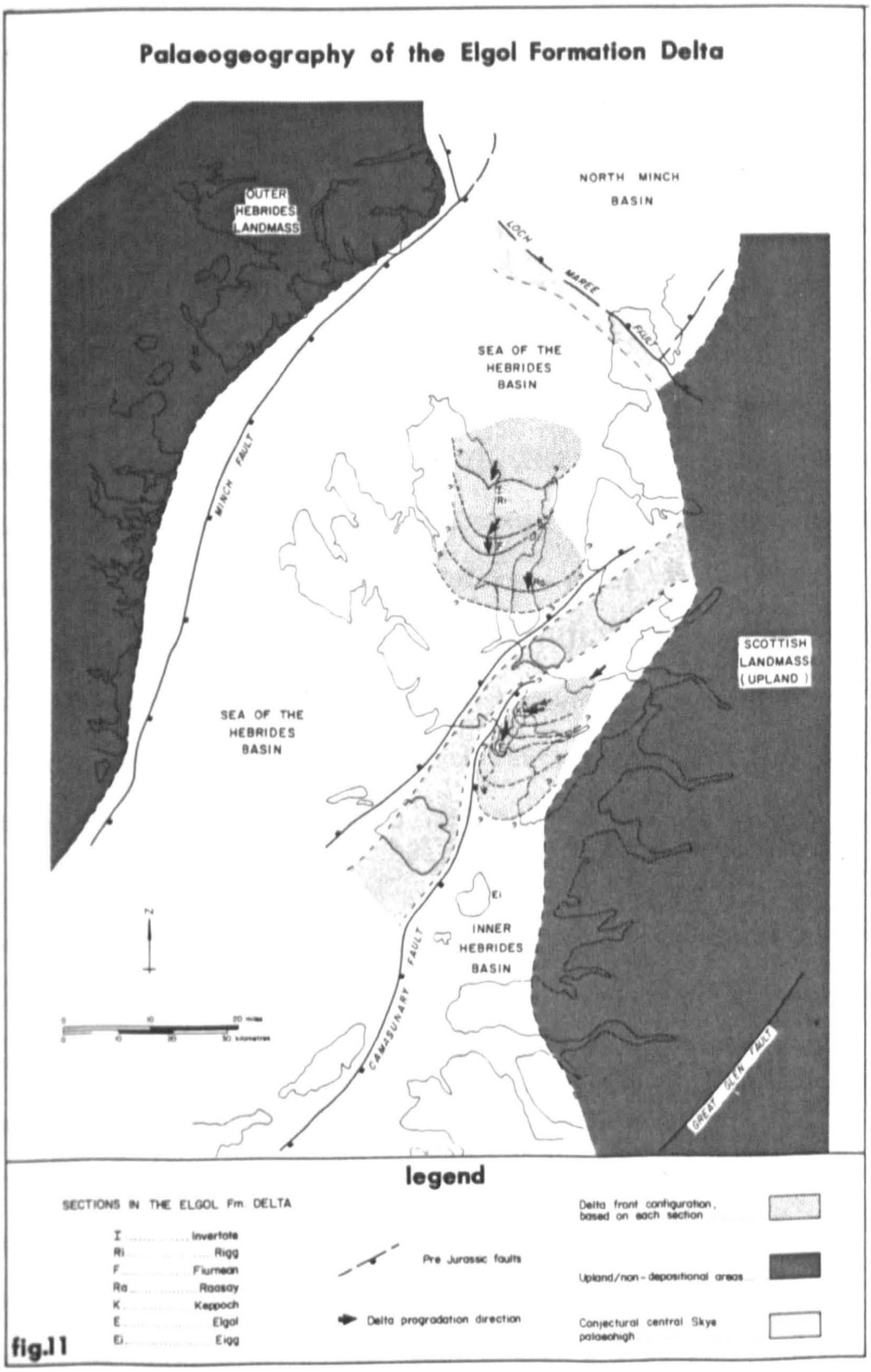


FIGURE 11 Palaeogeographical map of the Elgol Formation delta showing the major structural controls on sedimentation, the changing progradation direction of the delta and the configuration of the delta front. Basin configuration is based on the present day structural map of Binns et al (1975) and the Triassic palaeogeography of Steel (1976).

(Great Estuarine Group).

The Elgol Formation over most of the area represents the rapid progradation of a very coarse, fluvial dominated delta front fed by braided distributaries into a receiving basin of predominantly low but laterally variable salinity. This type of delta is not very well documented in the literature on modern delta systems. However, most of the sub-environments identified have direct modern analogues. This is in spite of being coarser grained and occurring in a much smaller delta system than the majority of well documented modern examples. The closet modern analogies for the Elgol Formation delta, in the south of the region (Strathaird, South Trotternish and Raasay) are probably the immediate post-1930 Colorado delta, Texas (Kanes, 1970) and the Gum Hollow fan delta (McGowan 1970). In the north of the region (north Trotternish) the delta is tidally influenced and although very much smaller is similar to parts of the modern Niger delta (Allen, 1965a, 1970); Oomkens, 1974).

Rapid progradation of this coarse grained delta system supports the palaeogeographical scheme proposed by Hudson (1964) and the receiving basin and hinterland characteristics described by Tan and Hudson (1974) and Hudson and Harris (1979). A hilly hinterland with a thick regolith and heavy seasonal rainfall is essential to the formation of this type of delta system. Evidence from these deltaic deposits indicates that the hinterland was uplifted initiating a relatively rapid influx of clastic material. This caused a copiously supplied delta front to prograde rapidly across the basin or basins.

The palaeogeographic scheme shown in fig. 11 is based on the present day structural map of Binns et al (1975) and the palaeogeographies of Hudson (1964); Steel et al (1975) and Steel (1976). The modern structure was not established until the late Jurassic or early Cretaceous (Binns et al 1974) but includes a number of major NNE/SSW trending faults (principally the Great Glen, Camasunary and Minch faults) which were in existence in the Triassic. The importance of these structures as controls on Triassic sedimentation has been demonstrated by Steel (1976) who proposes a system of elongate basins orientated NNE/SSW with shallow, slowly subsiding NE margins. In the Great Estuarine Group (Strathaird in particular) subsidence sensitive deposits of the Elgol Formation almost exactly mirror the pattern of sediment dispersal developed in the Triassic. It is therefore proposed that a system of differential subsidence or tilting and consequent basin fill by sediment transport (S-SW), sub-parallel to the basin margins, which was first established in the Triassic, also operated in the Middle Jurassic. The palaeogeographic map (fig. 11) includes a central Skye palaeohigh, controlled at its south eastern margin by the Camasunary Fault (downthrow to the SE) and at its north west margin by a major fault exposed near Applecross (downthrow to the NW). There is however no apparent evidence in the Elgol Formation for the existence in the Middle Jurassic of other major faults in the area. This particularly applies to the fault limiting the Mesozoic outcrop on Raasay and controlling the topographic depression of the Inner sound of Raasay. Although this has been proposed as a northwards extension of the Camasunary Fault (Anderson and Dunham 1966; Binns et al 1974).

The central Skye palaeohigh appears on the regional structural map of Binns et al (1974) and is a major element in Steel's (1976) Triassic palaeogeography. However, it was not included by Hudson (1964) and was dismissed as a mid-Jurassic feature by Harris and Hudson (1980) mainly because of the remarkable lateral continuity of facies within the Great Estuarine Group, the individual argillaceous Formations of which are identical to the north and south of the structure. It is unlikely therefore to have been anything except a very subdued feature during the Bathonian.

In this area of central Skye, marine siltstones of Liassic age overstep onto Durness Limestones and Torridonian Sandstone basement (Hallam 1959) and interdigitate with localy derived ortho and para conglomerates (Steel et al 1975 p.7 Nicholson 1978). There was therefore considerable local relief on the south eastern margin of the structure in the early Jurassic.

Middle Jurassic sediments in the area (Alt Strollamus) are difficult to interpret accurately because of poor exposure and severe Tertiary thermal metamorphism but probably include rocks of the Bearreraig Sandstone Formation and lower part of the Great Estuarine Group (Cullaidh Shale, Elgol Sandstone and Lealt Shale Formations). The structure was therefore blanketed by Mid Jurassic sediments at least at its south eastern margin. This provides additional evidence that it was not a major topographic feature in the Mid Jurassic. It is therefore possible that the Elgol Formation delta extended continuously from south Trotternish and Raasay into Strathaird.

However, there is considerable lateral variation across the structurein the thickness and facies of all the Middle and Upper Jurassic sandstones The Bajocian, Bearreraig Sandstone Formation (immediately below the Great Estuarine Group) is up to 500m thick in Strathaird while it is a maximum of 210m thick in Trotternish and Raasay north of the structure. Also the palaeoflow directions of tidally generated currents in the Bearreraig Sandstone Formation, parallel the Camasunary, Applecross and Screapadal faults (Morton 1983) demonstrating that they controlled the configuration of the Bajocian basins. Lateral variation in the facies of the Elgol Formation delta is described above. The Valtos Sandstone Formation (Great Estuarine Group) is anamolously thin (21m) in Strathaird, although this is on the downthrow side of the Camasunary Fault (Harris and Hudson 1980, discussion in Chapter 3). The Callovian-Oxfordian section (immediately above the Great Estuarine Group) is predominantly argillaceous at Staffin, north of the structure but consists almost entirely of coarse and medium grained sandstones in Strathaird (Sykes 1975b, fig. 7). It seems probable therefore (although there is no direct evidence) that Steel's (1976) Triassic palaeohigh was still present during the Jurassic and controlled rates of subidence in the basin and therefore the distribution and thickness of the Jurassic sandstones.

Steel's (1976) palaeogeography shows the Triassic basin margin (Inner Hebrides Basin) in north Strathaird swinging round from a SSW trend in the south to a WSW trend in the north (fig. 11). This is parallelled almost exactly by a change in the net progradaion direction of the Elgol Formation delta (fig. 5 & 11) from WSW in the

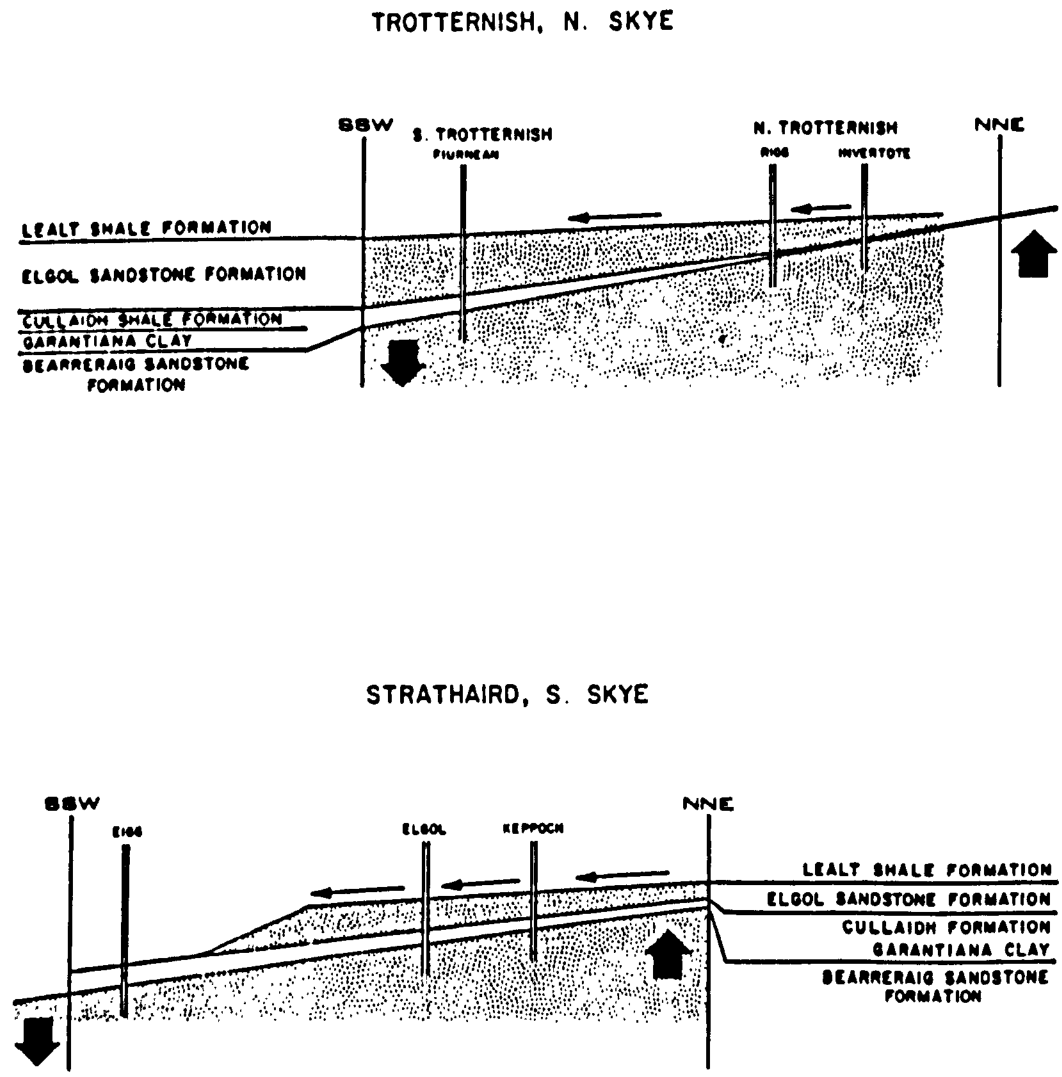


FIGURE 12 Tilting/differential subsidence and 'dip' source model for the Elgol Formation delta in the Sea of the Hebrides Basin and the Inner Hebrides Basin. A progressive SSW increase in the rate of subsidence causes a concomittant SW thickening of the deltaic clastic wedge and the underlying prodeltaic shales (based on Sykes 1975a, fig. 91 and 93).

north to S in southern Strathaird. This net progradation direction for the delta (controlled by basin configuration and style of subsidence) also matches the SW palaeoflow direction for the Triassic braided stream, flood plain phase for this part of the Inner Hebrides Basin (Steel et al 1975, p. 11).

Tilting or differential subsidence (a progressive increase in rate of subsidence south westwards) which controlled this pattern of sedimentation was probably therefore also responsible for the SW progradation direction and southerly depositional limit of the Elgol Formation delta in the Strathaird region (fig. 12).

A similar process is envisaged as the control on southerly delta progradation and southward thickening of the Cullaidh Shale and Garantiana Clay in Trotternish north of the structure (fig. 12). This model is based on the 'dip' source, tilting/differential subsidence model for sedimentation on tilted, subsiding fault blocks illustrated by Sykes (1975a, fig. 92 & 93). In this system deltaic progradation commences in the shallow end (NNE) of the basin (dip source) and is controlled in its direction by differential subsidence or tilting of the basement such that the clastic wedge and the underlying prodeltaic shales thicken towards the deep end of the basin (SSW). This occurs because deltaic deposits build up to a base level (sea level) and then prograde, in this case into a progressively deeper basin floored by a progressively thicker prodeltaic deposit. The rate of progradation during one progradational phase will therefore slow (given reasonably constant sediment supply) before either epeirogenetic (basin wide) subsidence or a decrease in sediment supply causes the lobe to be abandoned and transgressed.

The model represents a very similar system of longitudinal basin fill from the north to that proposed by Surlyk (1978) for a contemporaneous tectonic and sedimentological system in East Greenland.

PAGE

NUMBERING

AS ORIGINAL

Plate 1. Type section of the Elgol Formation, Elgol Shore, Strathaird. Cliff is 16m high.

Plate 2. North Elgol (log 4, ca.11m). Top of a minor channel fill penetrated by rootlets (arrow) and succeeded by a fine sediment drape.

Plate 3. North Elgol, (log 4, ca. 17m). Shaly carbonaceous sands with coarse sand lenses. Intensively bioturbated, wave influenced, delta plain muds and sands.


Plate 1

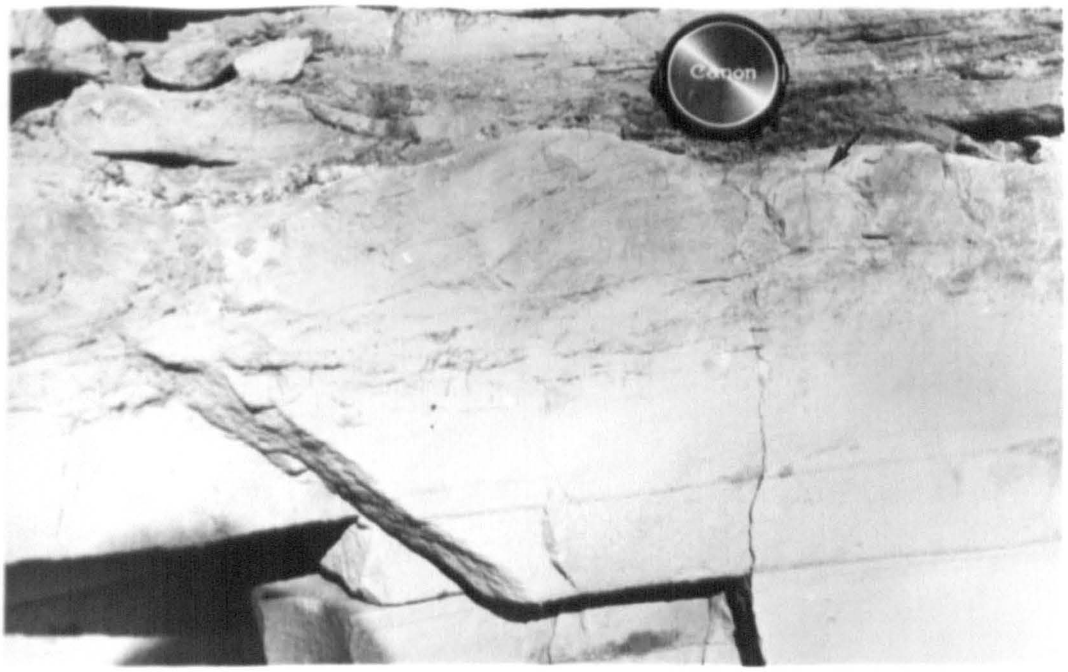


Plate 2

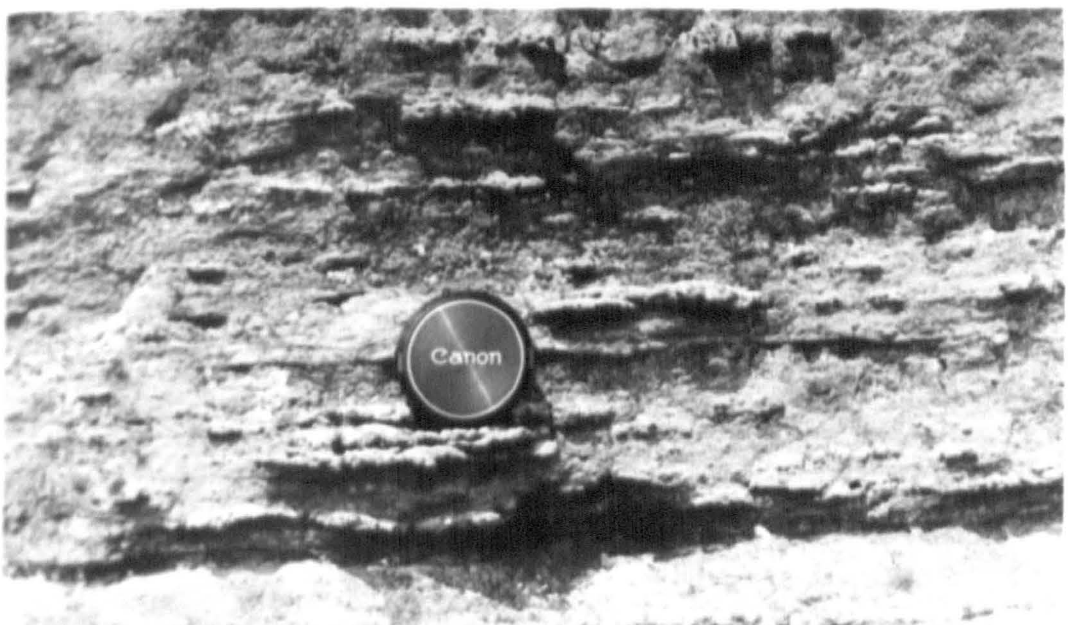
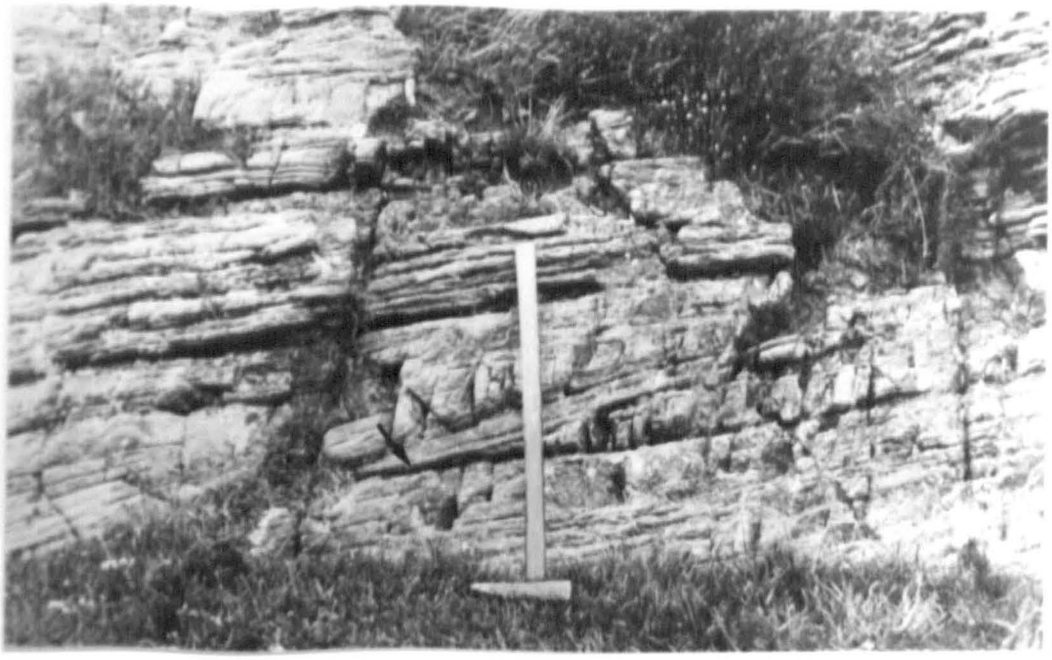


Plate 3

Plate 4. Drinan Road (log 6, ca. 1.5m). Lenticular channel fill with a prominent basal scour surface (arrowed) draped by channel fill sands. Hammer is 70cm in length.

Plate 5. Elgol shore (log 1, ca. 10.5m). Honey-comb weathering in lower bar front sands.

Plate 6. Elgol shore (close to log 1, 8-20m). Base of cliff is composed of lower bar front sands, gradational downwards to distal bar sands (arrow) dipping (tectonic) at 11 ° N.W. Upper part of cliff consists of inclined bar front sands (arrow) (depositional dip 4 -11 SE) capped by the lower part of the bar crest - distributary channel facies. Hammer for scale at base of cliff.



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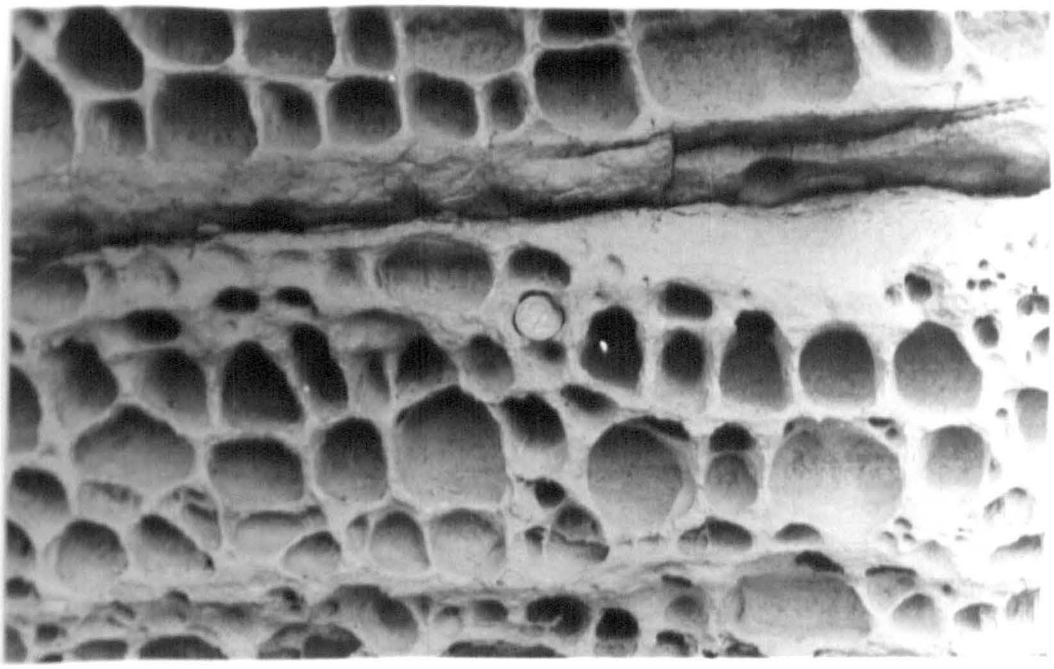

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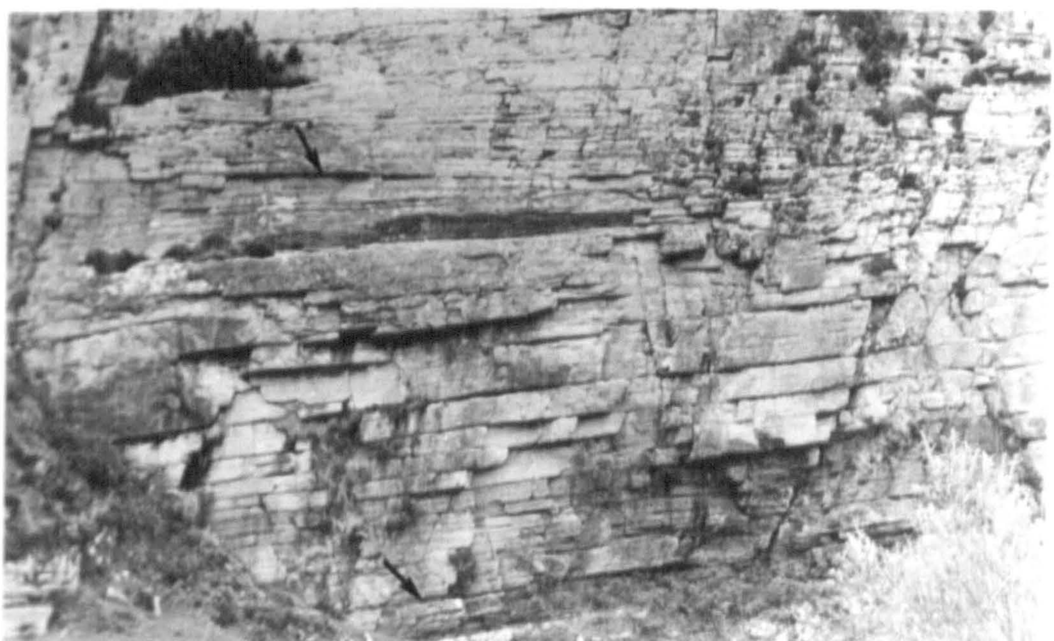
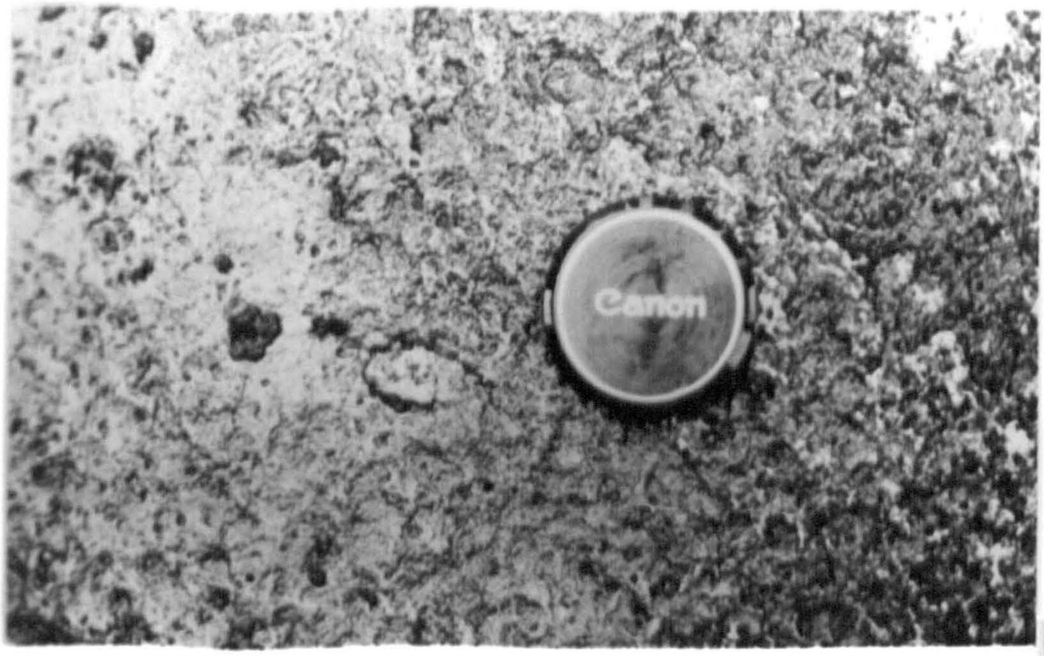


Plate 6

Plate 7. Medium grained sandstones at the top of the Elgol Formation containing the moulds of large burrowing bivalves, probably Unionids.

Plate 8. South Trotternish (close to section 1, fig 8a). Gradual coarsening upwards sequence in bar front sands, capped by coarse distributary channel sands (arrowed). Prodeltaic, Cullaidh Formation forms base of cliff. The cliff profile directly mirrors the grain size log. This part of the cliff face is ca 20m high.

Plate 9. Raasay (fig. 8b, ca. 20.25m). Low sinuosity distributary channel fining upwards sequence, comprising a coarse basal unit (arrow) with trough and planar cross and stratification transitional to medium grained planar laminated flaggy sands above.



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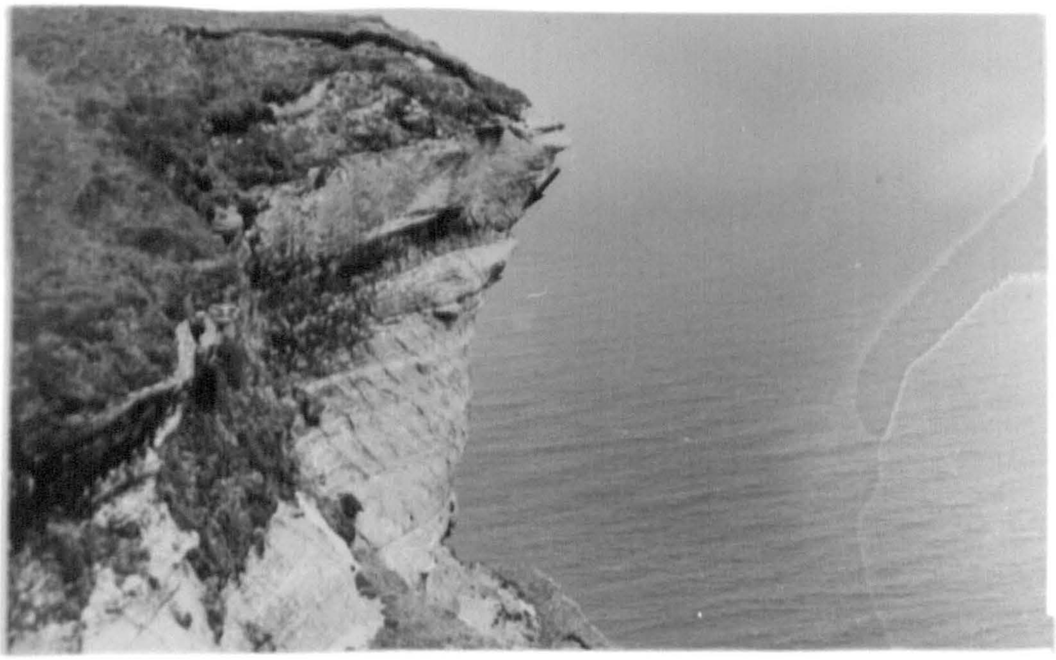

Plate 8

Plate 9

Plate 10. Rigg Burn, North Trotternish (fig. 9a, ca. 18m). Diplocraterion burrows picked out by carbonaceous laminae in the burrow walls. Lower shoreface facies.

Plate 11. Invertote, North Trotternish (close to section 1, fig. 9b). Sea cliffs exposing a complete sequence in the Elgol Formation. Line of grass tussocks (arrow 1) marks the laterally persistent shale at the top of the lower unit and arrow 2 marks the pebbly basal lag. Cullaidh Formation occupies the wave cut notch at the base of the cliff.

Plate 10

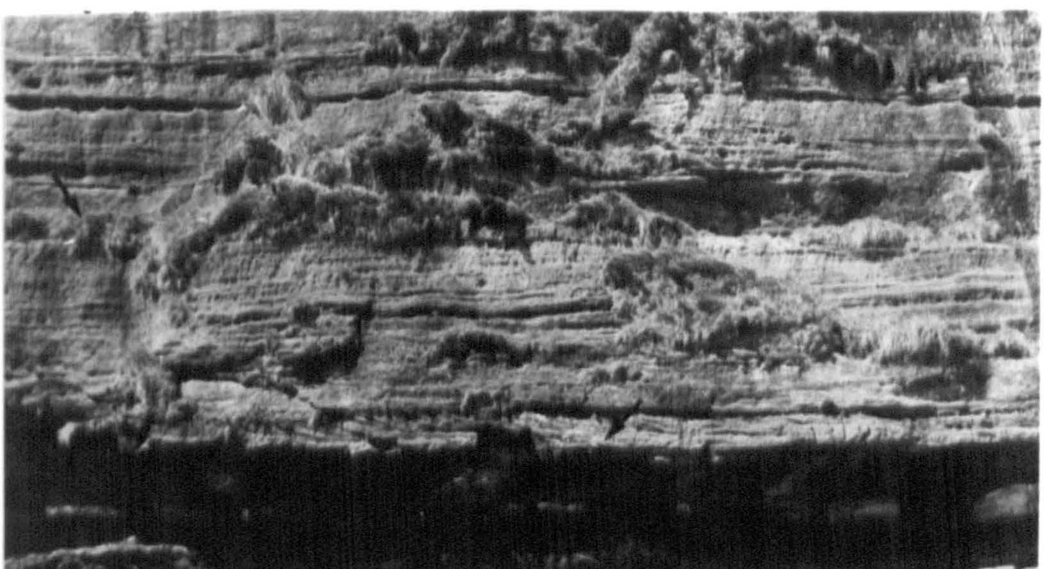

Plate 11

CHAPTER 2

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CHAPTER 3 THE MIDDLE JURASSIC VALTOS FORMATION OF THE INNER HEBRIDES BASIN (EIGG, MUCK, STRATHAIRD), A FLUVIAL DOMINATED, LOBATE, LAGOONAL DELTA SYSTEM.

ABSTRACT

The Middle Jurassic Valtos Formation in the Inner Hebrides Basin was probably derived from ORS sediments capping the Moines in the area of Wester Ross. It comprises a lagoonal delta facies group, a minor transgressive facies and a basin margin facies. Lagoonal delta progradation sequences overlie thin lagoonal muds - silts and include coarsening upward, low angle offshore inclined, delta front sands defining a lobate fluvially dominated configuration. Axial parts of delta sequences include pebbly low sinuosity distributary channel sands and demonstrate friction dominated processes at the distributary mouths. Minor wave redistribution of sediment has generated beach face sequences defining the delta shoreline. Sand flats of the delta plain were deposited from sheet floods. Transgressive facies comprise shell debris (Neomiodon) limestones overlying truncated progradational facies. The Neomiodon dominated fauna demonstrates fluctuating normal marine to fresh-brackish salinities probably controlled by rapidly fluctuating run off into a small basin with a marine connection to the SW. Facies distribution is controlled in part by the configuration of the elongate (NE-SW) basin and defines 6 SW prograding lagoonal delta phases separated by transgressive phases. An attenuated sand starved basin margin facies probably occupies intermittantly subsiding terrace structures controlled by the Camasunary Fault at the western basin margin.

CHAPTER 3

6) FACIES RELATIONSHIPS (3.38-3.46)

i) Delta Plain

ii) Delta Front

iii) Prodelta - Offshore Muds,

iv) Mud Flat & Lagoon

v) Transgressive Facies

7) PALAEOGEOGRAPHY AND FACIES DISTRIBUTION (3.46-3.49)

INTRODUCTION

The principal outcrops of the Valtos Sandstone Formation (Great Estuarine Group) in the Inner Hebrides Basin (fig 1) occur on the Island of Eigg. The upper part of the Formation is exposed on Muck and in Strathaird on Skye there is a thinner less sandy development of the Formation. Details of outcrop distribution are illustrated on the maps figs 2 and 3 and in Hudson (1962).

The Inner Hebrides Basin (Binns et al 1975) comprises the south eastern part of the Minch Basin invoked by Hudson (1964). It is a narrow, elongate, asymmetric basin (trough) controlled at its western margin by the NNE-SSW trending Camasunary - Skerryvore fault (downthrow to E) and is separated from the Sea of the Hebrides Basin (rest of Minch Basin) by a structural high termed the Central Skye palaeohigh (Steel et al 1975). The eastern margin of the basin is complex with numerous embayments (cf Steel 1976). It is bounded by a structural high controlled by the eastern margin of the Caledonian fold belt which roughly parallels the coastline of the Scottish mainland. The basin probably bifurcates around a minor structural high in the area of the Sleat Peninsula (see fig 1 based on Binns et al 1975). The sedimentary basins in the Hebrides were initiated in the Triassic (Steel 1976) but have been complicated by Tertiary plutonism and major Tertiary movements on pre-Mesozoic faults. The major structural controls on basin configuration are illustrated in figure 1.

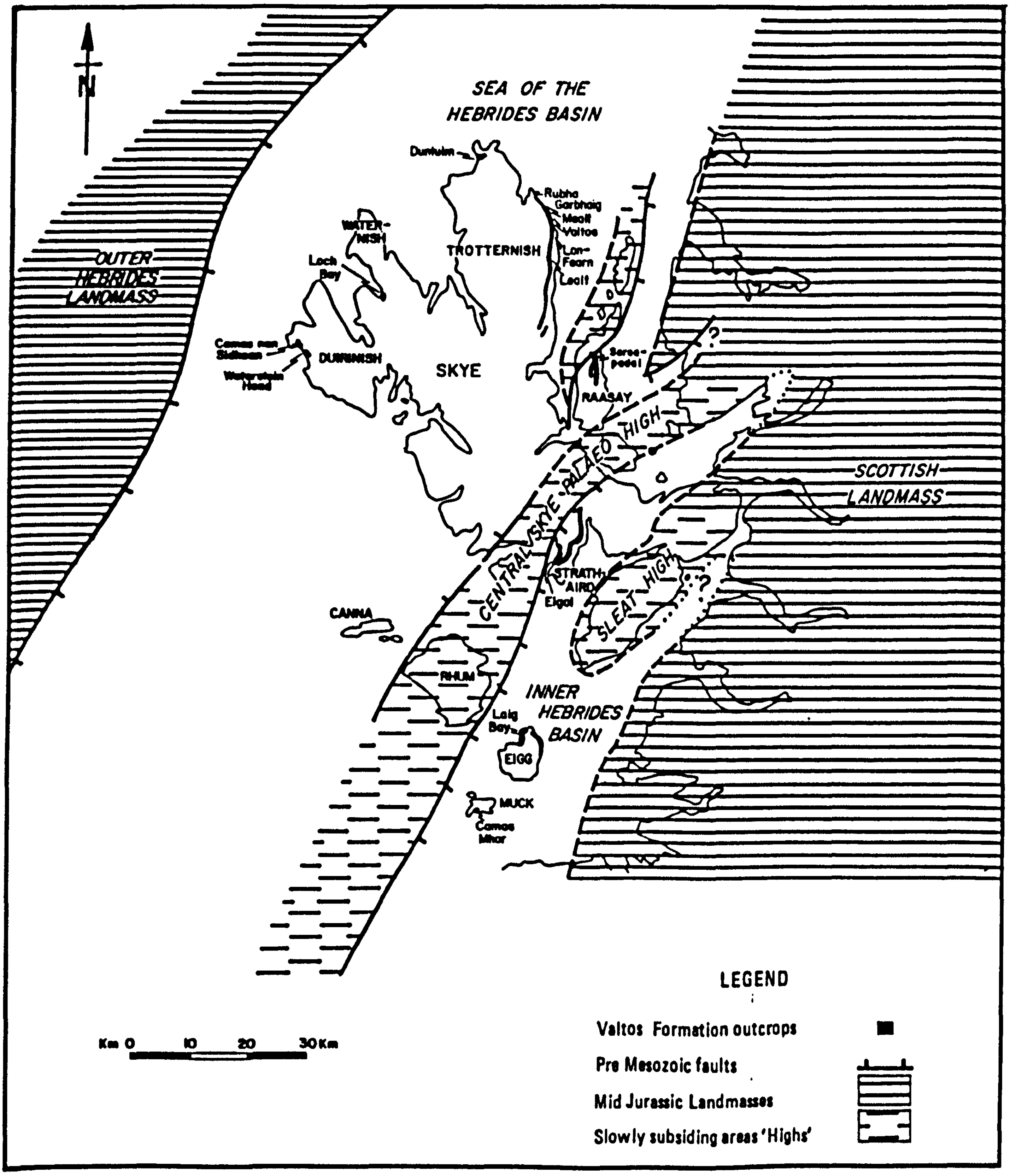


FIGURE 1 Major Mid-Jurassic structural controls on basin configuration (based on Binns et al., 1975; Steel 1976) and Valtos Formation outcrops

The Valtos Formation is a coarse sandy intercalation 63m thick between the limestones and shales of the Lealt and Duntulm Formations of the Great Estuarine Group (Harris and Hudson 1980). The Formation records a period of copious clastic supply to the basin and contrasts with the fresh-brackish and brackish-marine, lagoonal and shoreline facies of the underlying Lealt Shale Formation and the fresh water to marine-hypersaline, lagoonal shales and limestones of the overlying Duntulm Formation (Tan and Hudson 1974, Hudson and Harris 1979, Hudson 1980). The top and bottom of the Formation are marked by facies controlled faunal changes represented by the sudden occurrence of monotypic Neomiodon shell beds at the base and of Oyster bearing shales and limestones at the top (Harris and Hudson 1980). These faunal changes are probably directly associated with the onset and subsequent cessation of copious clastic supply to the basin.

The Valtos Formation records non-marine salinities and has a fauna dominated by the bivalve Neomiodon which was probably adapted to tolerate rapidly and widely fluctuating salinities (Hudson 1980).

Lithostratigraphy

In the main outcrop on Eigg Hudson (1962) has identified 4 sand bodies (divisions) and 2 units of shale and thin limestones and has erected a lithostratigraphic scheme comprising 6 divisions, termed A,B,C,D,E,F. I have adopted Hudsons lithostratigraphic terminology but in an attempt to identify genetic facies associations I have divided division A into Ai and Aii and have incorporated a laterally

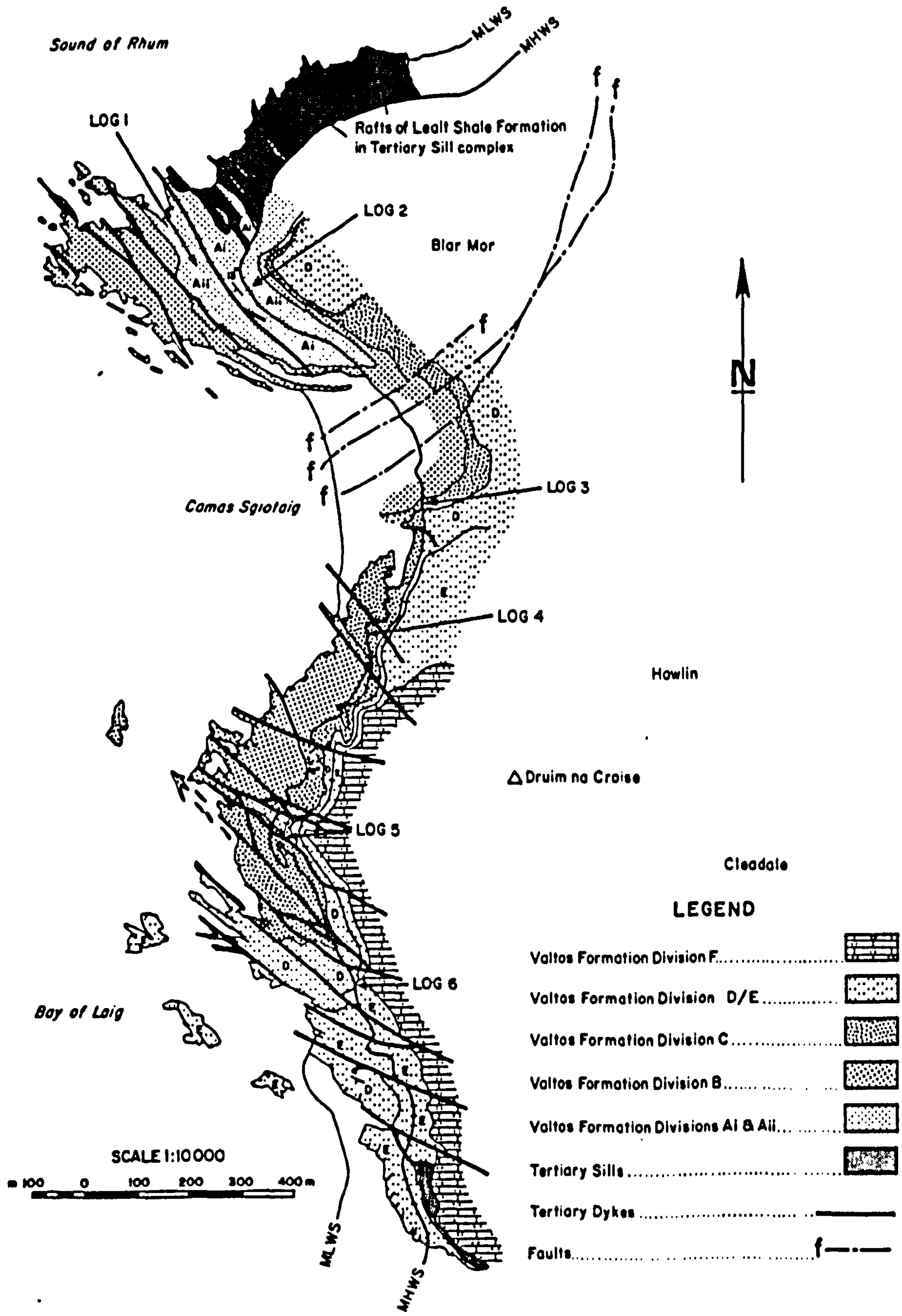
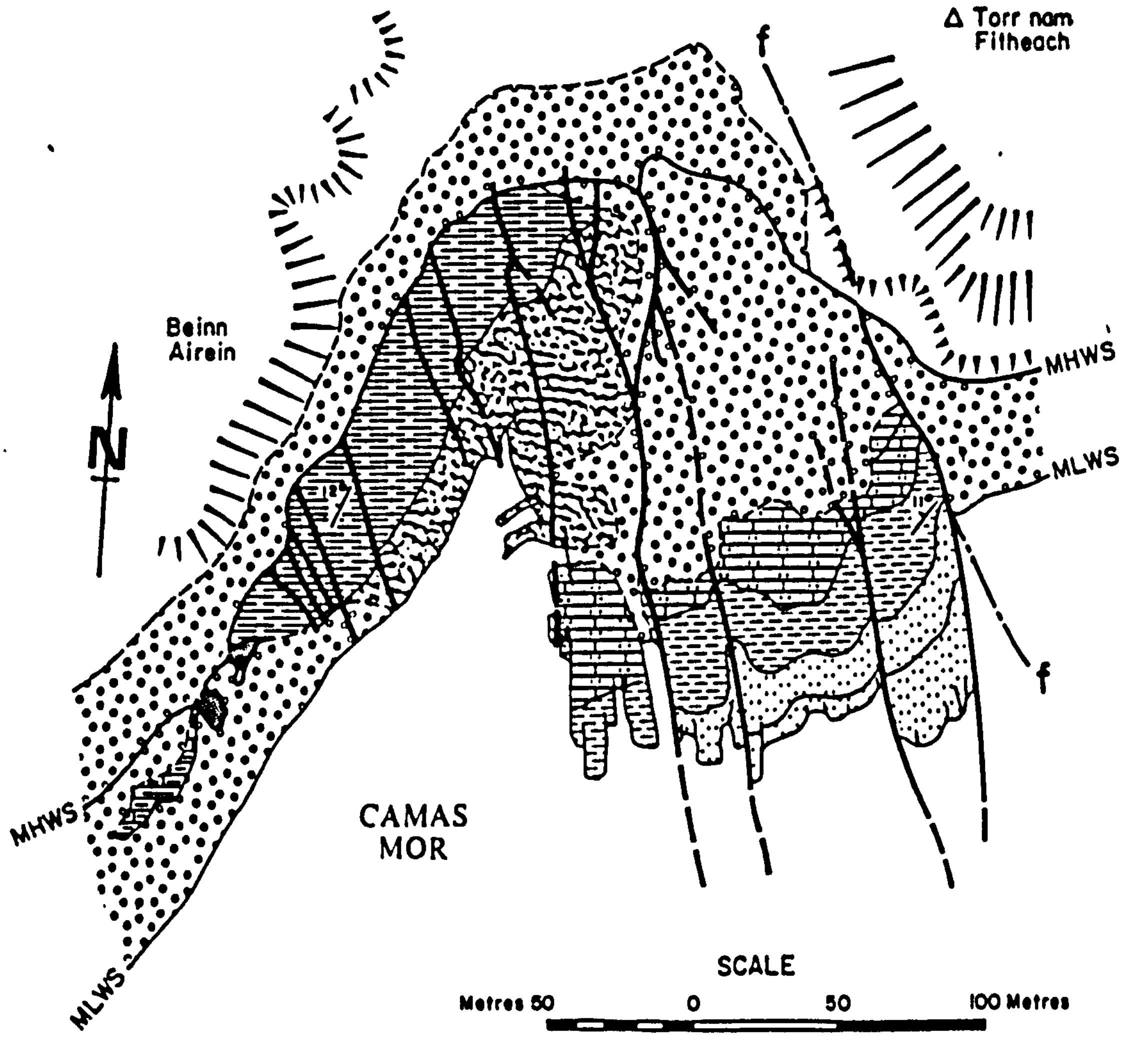


FIGURE 2 Outcrop map of the Valtos Formation in the Bay of Laig, Eigg.

FIGURE 3 Outcrop map of Camas Mor, Muck.



LEGEND

Kilmaluag Formation	Valtos Formation Div. F-4
Duntulm Formation	Valtos Formation Div. F-1&2
Valtos Formation Div. F-6	Valtos Formation Div. E
Tertiary dykes	Tertiary sills
Faults f	Boulders of storm beach

impersistent sandbody into division D (previously shale and thin limestones) to give 7 lithostratigraphic divisions (see figs 4, 5 & 6).

On Muck the outcrop is limited to the top of division E and division F with the transition to oyster bearing shales and limestones of the Duntulm Formation (fig 7).

In Strathaird the upper part of the Formation (above 5.5m fig 8) has similarities with division F on Muck but the major sand bodies of the lower parts of the Formation are missing. Instead there is an intercalation of burrowed and desiccation cracked limestones and shales (facies 7), giving a cumulative thickness for the Formation in this area of only ca 24m (fig 8).

Petrography and Provenance

Valtos Formation sandstones are generally well sorted locally only moderately - poorly sorted and have a wide range of modal grain size. Grain size illustrated on the graphic logs (figs 6,7 & 8) is based on a field estimation using a comparator and is checked against thin section measurements.

The mineralogy of the Great Estuarine Group sandstones has been fully described by Hudson (1964); my subsequent work on the Valtos Formation is in complete aggreement with his findings (see Appendix 1).

	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende
Inner Hebrides Basin (Eigg & Muck)	23	38	12	8	13	1	1	P		P	P
Sea of the Hebrides Basin (Trotternish & Raasay)	13	26	7	35	9	6	2	1	P	P	P

TABLE 1: AVERAGE HEAVY MINERAL COMPOSITION (%) OF SANDSTONES FROM THE INNER HEBRIDES BASIN AND SEA OF THE HEBRIDES BASIN. 1.5-3.0ϕ fraction, opaque grains omitted.

FIGURE 4 Ternary diagrams to illustrate the distribution of heavy mineral suites. Heavy mineral counts are included in appendix I.

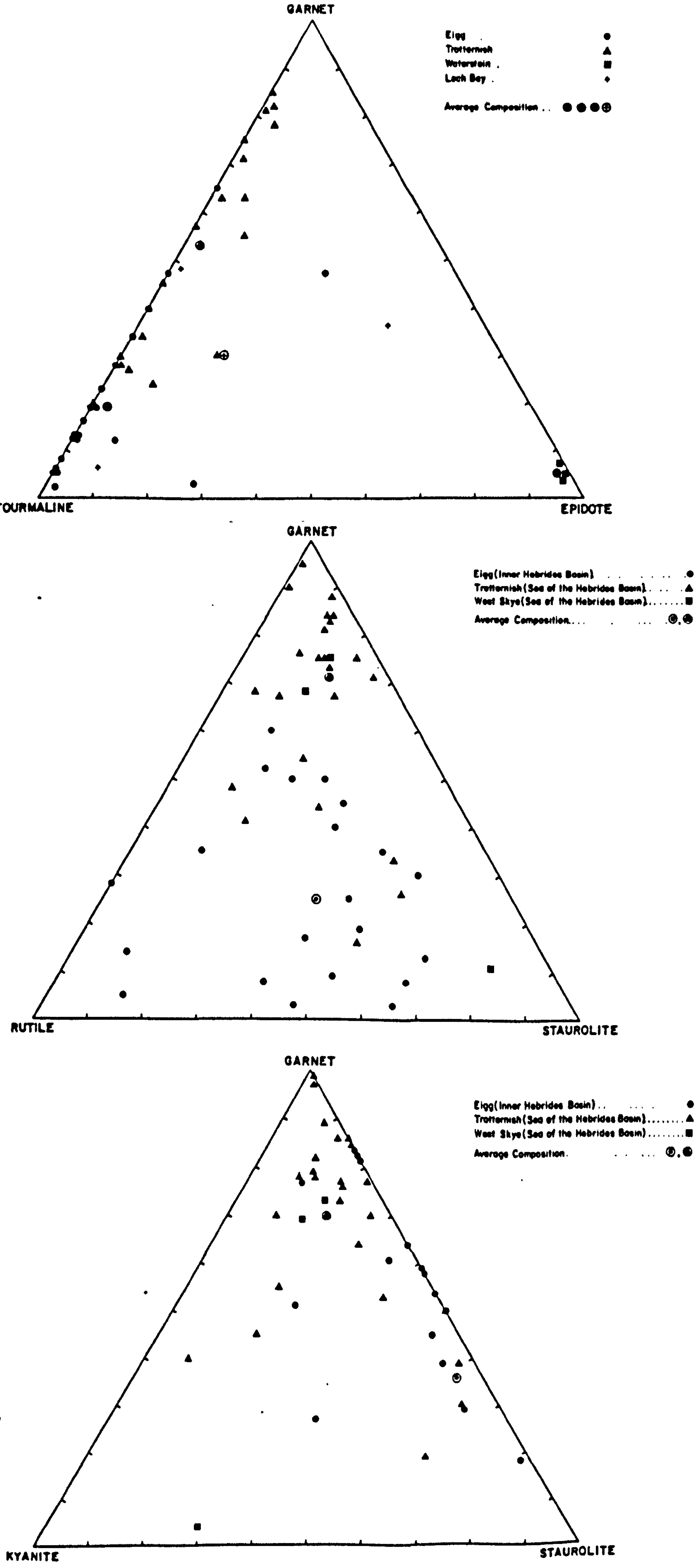

GARNET
Eigg
Trotternish
Waterstein
Loch Bay
Average Composition
TOURMALINE
EPIDOTE
GARNET
Eigg (Inner Hebrides Basin)
Trotternish (Sea of the Hebrides Basin)
West Skye (Sea of the Hebrides Basin)
Average Composition
RUTILE
STAUROLITE
GARNET
Eigg (Inner Hebrides Basin)
Trotternish (Sea of the Hebrides Basin)
West Skye (Sea of the Hebrides Basin)
Average Composition
KYANITE
STAUROLITE

FIGURE 4,

The Valtos Formation on Eigg comprises quartzose sandstones with less than 3.5% feldspars. These are distinctly different from the sub-feldspathic locally feldspathic sandstones (5-26% feldspar) of the same Formation in the Sea of the Hebrides Basin (Trotternish and Raasay).

Pebbles in Valtos Formation are particularly useful in identifying potential source rocks (Hudson 1964). They are predominantly vein quartz which could originate from any of the Scottish Metamorphic rocks but also include Moinian "Granulites", probable Basal Cambrian Quartzites from the north west Highlands, rare red jasper pebbles from the Torridonian and Cherts (Hudson 1964). These cherts are difficult to match with their most obvious source in the Durness Limestone, but include silicified algal limestones which are petrographically similar to Jurassic and Carboniferous algal pisolites.

Heavy mineral assemblages from the Valtos Formation are variations on the suite zircon - garnet - rutile - tourmaline - staurolite with less consistant kyanite, epidote, apatite and hornblende. In the Inner Hebrides basin (Eigg) staurolite and rutile occur more commonly than in the Sea of the Hebrides Basin (Trotternish and Raasay). Conversely garnet is much less abundant in the Inner Hebrides Basin and kyanite and epidote occur less consistantly (see table 1). Although the ternary diagrams (fig 4) exhibit a wide scatter of points, data from the two basins dominate different areas (fields) of the diagrams.

Both basins have very similar burial and diagenetic histories. The variations in light and heavy mineralogy must therefore be attributable to differences in the source rocks exposed in the hinterlands of the two basins.

Hudson (1964) concluded that quartzose, staurolite rich sands in Eigg record significant contribution of sediment from Dalradian quartzites while sub-feldspathic, garnet rich sands in the Sea of the Hebrides Basin reflect a much greater contribution of sediment from the Moinian. Moinian metamorphic rocks are therefore an important source in both basins but the Dalradian of the southern and eastern Highlands is probably the most important source for Valtos Formation sands in the Inner Hebrides Basin.

Major problems associated with deriving large quantities of sediment directly from the Dalradian were recognized by Hudson (1964). These problems are long distance transport from the southern and eastern Highlands and transport across the Great Glen. Although there are fault controlled Middle Old Red fanglomerates in the Great Glen (Stephenson 1972) it is considered most likely that the Valtos Formation was derived from the Old Red Sandstone (sourced from the Dalradian and Moinian) which previously extended much further west across the present day Moinian outcrop into the hinterlands of the Hebridean Basins.

Old Red Sandstones in the hinterland of the Inner Hebrides Basin probably therefore contained a greater proportion of sediment derived from the Dalradian than did the Old Red Sandstone in the hinterland of the Sea of the Hebrides Basin. In view of the presence of Carboniferous spores in Jurassic sediments in the Sea of the Hebrides Basin (Warrington 1974) together with Carboniferous glacial erratics in the Outer Hebrides (Jehu and Craig 1925) the possiblity exists that Carboniferous sediments were also present in the Valtos Formation Hinterland.

DESCRIPTION

Within the Valtos Formation in the Inner Hebrides Basin 6 facies types can be differentiated. These are based on distinct associations of lithology, grainsize profile, sedimentary structures, trace fossils and macrofossils. Figure 5 is a lithostratigraphic section (fence diagram) constructed to illustrate the distribution of 5 of these facies on Eigg. These facies comprise:

1) *Neomiodon* mudstone-siltstone facies, occurring at the base of each lithostratigraphic division.

2) Coarsening upward sandstone facies, represents a consistent stratigraphic element between facies 1 and 3a-b or 4.

3a) Coarse - pebbly sandstone facies, overlies facies 2 in divisions C and E.

3b) Thin bedded and trough cross bedded coarse sandstone facies, may pass gradationally into facies 3a.

4) Wave dominated sandstone facies, occurs close to the top of divisions B, D and E.

5) *Neomiodon* debris limestone facies, caps divisions B, D and E.

The Valtos Formation also includes 2 facies not represented in the Eigg section. These comprise:

6) Load cast facies, occurring at the top of the Formation on Muck and in Strathaird.

7) Crustacean burrow and desiccation crack facies, only occurring at the base of the Formation in Strathaird.

The characteristics and distribution of these facies are illustrated on the graphic logs (figs 6, 7 and 8).

FACIES 1 Neomiodon mudstone-siltstone facies.

Facies 1 occurs at the base of each lithostratigraphic division on Eigg and Muck. It comprises greenish-grey locally brown, variably silty and sandy mudstones. It varies from 10cm to 3m in thickness. The facies usually includes intact single valves and articulated Neomiodon but thin developments tend to be unfossiliferous. Neomiodon are locally concentrated in distinct shelly beds, and occasional white-buff micritic sandy limestones, also with intact and articulated Neomiodon, occur.

FACIES 2 Coarsening-upward sandstone facies.

Facies 2 represents a consistent lithostratigraphic unit overlying facies 1 at the base of each of the sandbodies. However, it shows considerable lithological variation which can be related to the character of the overlying facies (facies 3a-b).

In division Ai, Aii and B the facies is consistently between 7-7.5m thick and comprises 2-26cm thick, sharp based, occasionally lenticular sand beds with finely divided plant debris. These are intercalated with thin (<1cm), carbonaceous silty shales and thicker (<20cm), muddy sand beds with the wavy and lenticular flasers of Reineck and Wunderlich (1968). Planolites type burrows are common and some horizons are intensively bioturbated.

The thin, sharp based sand beds are usually structureless, but in places exhibit indistinct planar lamination and current ripple lamination giving SE palaeoflow directions.

The subdued coarsening upward profile in divisions Ai, Aii and B is mirrored by a general upward thickening of the sharp based sand beds (see bed thickness histograms and 5th bed moving average curves, fig 9). Distinct half cycles or rhythms are discernible (div. Ai and top of Aii and B) but the profiles are complicated by the presence of complete cycles with distinct waning (thickening upward) and waxing (thinning upward) phases.

In division D and E the lower part of the facies contains large subspherical calcite concretions which preserve Neomiodon shells and the muddy, bioturbated interbeds are absent.

The coarsening upward sequence in division E (6.5-8.5m thick) comprises sharp based sand beds, separated by mud partings associated with Planolites burrows. In the upper part of the facies these bedding surfaces dip at between 2-8° (Plate 1 and 7). These low angle inclined surfaces give depositional dip directions towards S and SE (see log 4, 5 and 6 fig 7). Towards the top the facies includes isolated scour and fill structures and occasional trough cross stratified cosets.

In division C, facies 2 sandstones are thinner and coarser grained, mud partings are rarer and trough and tabular cross stratification dominate the upper part of the facies. These structures give a dominant SSW palaeocurrent mode but also include subordinate NNE flow directions (see log 4 and 5 fig 7). The facies is locally capped by planar laminated sands and is truncated by a prominent erosion surface at the base of facies 3a.

FACIES 3a   Coarse - pebbly sandstone facies.

Coarse and medium-coarse grained sandstones occur at the top of all the Valtos Formation sandbodies. Of these the thick cross stratified frequently pebbly sands are placed in facies 3a. Thinner sandstones occassionally with mudstone intercalations, shale partings and isolated trough cross stratified cosets may pass gradationally into facies 3a and are placed in facies 3b. Those with wave generated sedimentary structures and Neomiodon are placed in facies 4.

In division C facies 3a comprises 2 laterally discontinuous units. These comprise a southward thinning wedge (logs 2, 3 and 4 fig 7) and a northward thinning wedge (logs 3, 4 and 5 fig 7).

Outcrop distribution and palaeocurrent evidence suggests that these complex lenticular sand bodies have ribbon geometries with long axes orientated towards the SSW. The coastline north of the bay of Laig runs almost exactly N - S so that the cliffs and forshore (figs 4 & 6) give an oblique section through the sand bodies.

The simplest development of the southward thinning wedge occurs north of Camas Sgiotaig (log 2) where it comprises a single 2-2.95m planar, tabular avalanche set with a pebbly erosive base and a SSW palaeocurrent vector. It is overlain by a trough cross stratified coset (max set height 12cm) and is capped by planar laminated fine - medium grained sandstones, defining a fining upward grain size profile.

South of Camas Sgiotaig (log 3) this southward thinning wedge has a prominent basal erosion surface which when seen at a distance is gently undulose. Lining this scour surface is a 20-30cm thick structureless very coarse sand with granules which is truncated by a second scour surface with a lag of quartz pebbles. Above this pebbly lag are a series of large scale (amplitude up to 150cm, average 85cm) planar, tabular avalanche sets with pebbly erosive bases. They are very similar to the single avalanche set described from log 2 but have a W palaeocurrent vector. Isolated trough cross sets and minor cosets which cap some of the avalanche sets give palaeocurrent flow directions to the S and SSW.

In log 4 250m to the south, this unit includes tabular sets of cross strata giving SW and SE palaeocurrent flow directions and has a similar composite fining upwards grain size profile to that in log 3 (fig 7). However the interval consists mainly of medium grained planar laminated sands with large scale recumbently folded slump structures.

The upper surface of this southward thinning wedge south of Camas Sgiotaig is truncated by a pebble lined scour surface at the base of the northward thinning wedge (log 3 & 4). North of Camas Sgiotaig however it is overlain by a thin highly carbonaceous shale marking the base of division D.

The northward thinning wedge is 1m thick in log 3 and 6.75m thick in log 5, 700m to the south. In the thin developments it comprises pebbly trough cross stratified cosets but in the thicker developments repeated pebble lined scour surfaces define a thinning upward sequence. Tabular and trough cross stratified sands (set height 5-30cm average 20cm) and trough cross stratified sands preserved between these scours give a simple unimodal SSW palaeocurrent distribution (see rose measured close to log 5 fig 7).

The top of this sandbody and its contact with the shales of facies 1 at the base of division D is never exposed. However the stratigraphically highest sandstones seen, are dark brown with indistinct sedimentary structures and in thin section contain up to 5% of finely divided organic material (probably humic).

Facies 3a sandstones in division E (log 4, 5 and 6) have a lenticular geometry and truncate sandstones with low angle inclined surfaces in the top of facies 2. Trough and tabular cross bed sets bounded by pebble lined scour surfaces give a complex palaeocurrent distribution with a dominant southerly component (see rose measured close to log 6 fig 5) sub-parallel to the depositional dip direction of the underlying beds.

FACIES 3b Thin bedded and trough cross bedded coarse sandstone facies.

In division Aii (log 1) facies 3b is gradational at the base to a subsidiary coarsening upward sequence developed in the top of facies 2. Planar laminated fine - medium sands with carbonaceous partings cap minor coarsening upward units in the base of the facies and are truncated by medium - coarse trough cross stratified cosets (max set height 25cm) with granule rich laminae. Palaeocurrent distribution is unimodal with a southerly vector of 172°. Pockets of wood debris are common and the sandstone contains numerous drifted coniferous logs with a southerly preferred long axis orientation. (mean 160°).

In division Ai (log 1) facies 3b comprises white, medium - coarse and very coarse grained sandstones with driftwood and thin carbonaceous shale intercalations. It has a sharp erosive base and is capped by a 1.4m thick fining upward sequence.

The lower part of the facies comprises 10-20cm thick sharp based, poorly sorted sandstones, the tops of which are commonly wave rippled (trend of ripple crests averages 256°) and capped by single grain laminae or pockets of granules and small pebbles. Occasional examples are current rippled and have interference ripples at their upper surfaces (Plate 2) together with current orientated driftwood. Driftwood long axes have a preferred orientation towards the SE (average 130°) with a small number of specimens orientated normal to this probably representing a rolling population.

The fining upward part of the facies comprises 2-10cm sharp based sandstones and thicker intensively bioturbated argillaceous sands.

FACIES 4 Wave dominated sandstone facies.

Sandstones of facies 4 overly facies 2 (divisions B and D) or facies 3 (division E). The facies is characterized by calcite concretions which preserve Neomiodon debris. Scour and fill strucures often with pebble accumulations (division E log 4, 5 and 6) or trough cross stratified cosets (division D log 2) occur in the base of the facies. The upper part in division E comprises granule rich sands with planar lamination and low angle planar cross lamination with low angle discordances between sets. These and similar structure in fine - medium grained sands with isolated coarse lenses in division D probably represent the swash cross stratification of Harms et al (1975). Division D also includes high angle planar, tabular cross stratification. Palaeocurrent distribution in both divisions are bipolar with NE and SW modes.

In division B (log 2) the facies has a coarsening upward grain size profile and primary current lineated sands with Pelecypodichnus burrows occur at the base (preserved on lower bedding surfaces). At the top is a muddy locally sandy limestone (marl) with intact and articulated Neomiodon.

FACIES 5 Neomiodon debris limestone facies.

Very coarse grained sandy locally pebbly Neomiodon debris limestones with sparitic cements cap the sandbodies of divisions D and E. The facies has a basal erosion surface and includes poorly defined trough cross stratification, undulose lamination and horizons of planar lamination (logs 2, 4, 5 and 6). In division B plane bedded pebbly limestones include abraded Neomiodon debris.

Thicker Neomiodon debris limestones truncate a thin facies 2 sandstone in division F on Eigg and on Muck. On Eigg (log 5 & 6) these limestones contain numerous low amplitude pebble lined scours and pass upwards into seemingly massive Neomiodon debris limestones with a fine - very fine grained sand matrix. Similar pebbly limestones on Muck drape a deeply scoured basal erosion surface. This basal part of the facies fines upwards and is overlain by a thin black shale with fibrous calcite veins (beef). It is capped by coarsening upward shell debris limestones with pebble concentrations at the top and indistinct undulo lamination.

In Strathaird, facies 5 forms a distinct coarsening upward sequence with thin black shale intercalations (log 8 fig 8). It is capped by coarsening upward pebbly limestones similar to those on Muck. It also includes an horizon of large scale "load like" slump structures (Plate 3) and poorly defined wave ripple lamination.

FACIES 6 Load cast facies

Facies 6 occurs on Muck and in Strathaird (log 7 and 8). It overlies thick pebbly limestones of facies 4 and includes the transition to oyster bearing limestones and shales of the overlying Duntulm Formation (top of the Valtos Formation).

The facies is sandier in Strathaird than in Muck. It comprises an intercalation of fine - very fine grained sandy limestones/calcareous sandstones (10-40cm thick) with Neomiodon, thin dark shales (5-25cm thick) and siltstones. In Strathaird the mudstone-siltstone intercalations at the base contain wavy and lenticular silt - very fine sand flasers and numerous Planolites burrows. Towards the base of the facies the sandy beds are disrupted by loading into the underlying shales and horizons of completely detached load balls, occur. These load structures are large scale features with amplitudes up to 30cm. At one horizon on Muck a series of large scale load structures are truncated at the base of a plane bedded sandy shelly bed (Plate 4).

FACIES 7 Crustacean burrow and desiccation crack facies.

Facies 7 only occurs in Strathaird at the base of the Valtos Formation (log 8 fig 8). Outcrops are complicated by numerous minor faults and Tertiary dykes but comprise an intercalation of sandy and micritic limestones (5-30cm thick) and thin dark shales. The facies also includes an intensively bioturbated, very fine grained, silty sandstone with common muddy interbeds towards the base.

KEY TO LOG SYMBOLS

LITHOLOGICAL SYMBOLS

- Sandstone
- Sandstone Pebbly
- Sandstone Shaly
- Sandstone Shale / Carbonaceous streaks
- Limestone
- Limestone Sandy
- Marl
- Dolomitic Limestone
- Intraformational Pebbles
- Oolitic Limestone
- Shale

LITHOLOGICAL LOG ABBREVIATIONS

CLASTICS

s - Shale / Clay
f - Fine Sand
m - Medium Sand
vc - Very Coarse Sand
p - Pebbles

CARBONATES

ml Marl
cl Calcilutites
ca Calcarenites
cr Calcirudites

PALAEONTOLOGICAL SYMBOLS

- Bivalve Molluscs Articulated
- Bivalve Molluscs Disarticulated
- Bivalve Molluscs Broken
- Oysters Articulated
- Oysters Disarticulated
- Gastropods
- Brachiopods
- Ostracods
- Estherids (Cyzicus)
- Fish Teeth Scales & Bones
- Reptile Bones
- Allochthonous Lignite
- Driftwood
- Plant Fragments
- Nodular Algae
- Stromatolitic Algae

SEDIMENTARY STRUCTURES

- Trough Cross Stratification
- Planar Cross Stratification
- Low Angle Stratification
- Current Ripples
- Erosive Surfaces
- Loaded Surfaces
- Desiccation Cracks
- Desiccation Breccia
- Gypsum Pseudomorphs

BIOGENIC STRUCTURES

/ // /// Degree of Bioturbation

- Planolites
- Monocraterion
- Diplocraterion
- Thalassinoides
- Lockia / Pelecypodichnus

DIAGENETIC STRUCTURES

- Calcareous Concretions
- Septaria
- Fibrous Calcite Veins / Beef

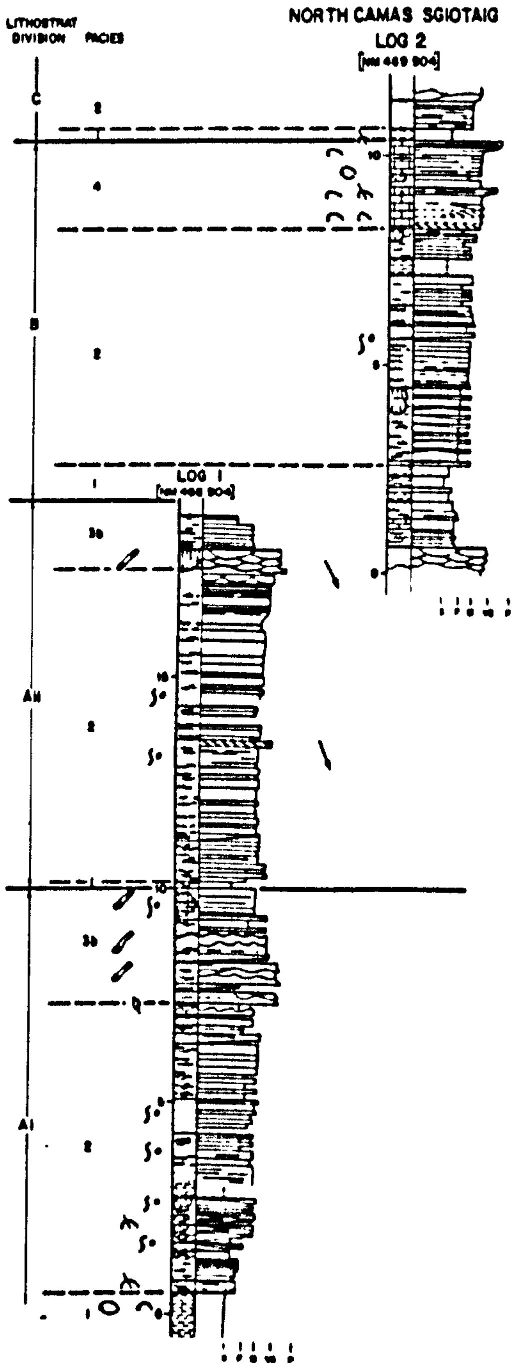


FIGURE 6 Graphic log of divisions Ai,Aii and B, Valtos Formation, North Camas, Sgiotaig, Eigg.

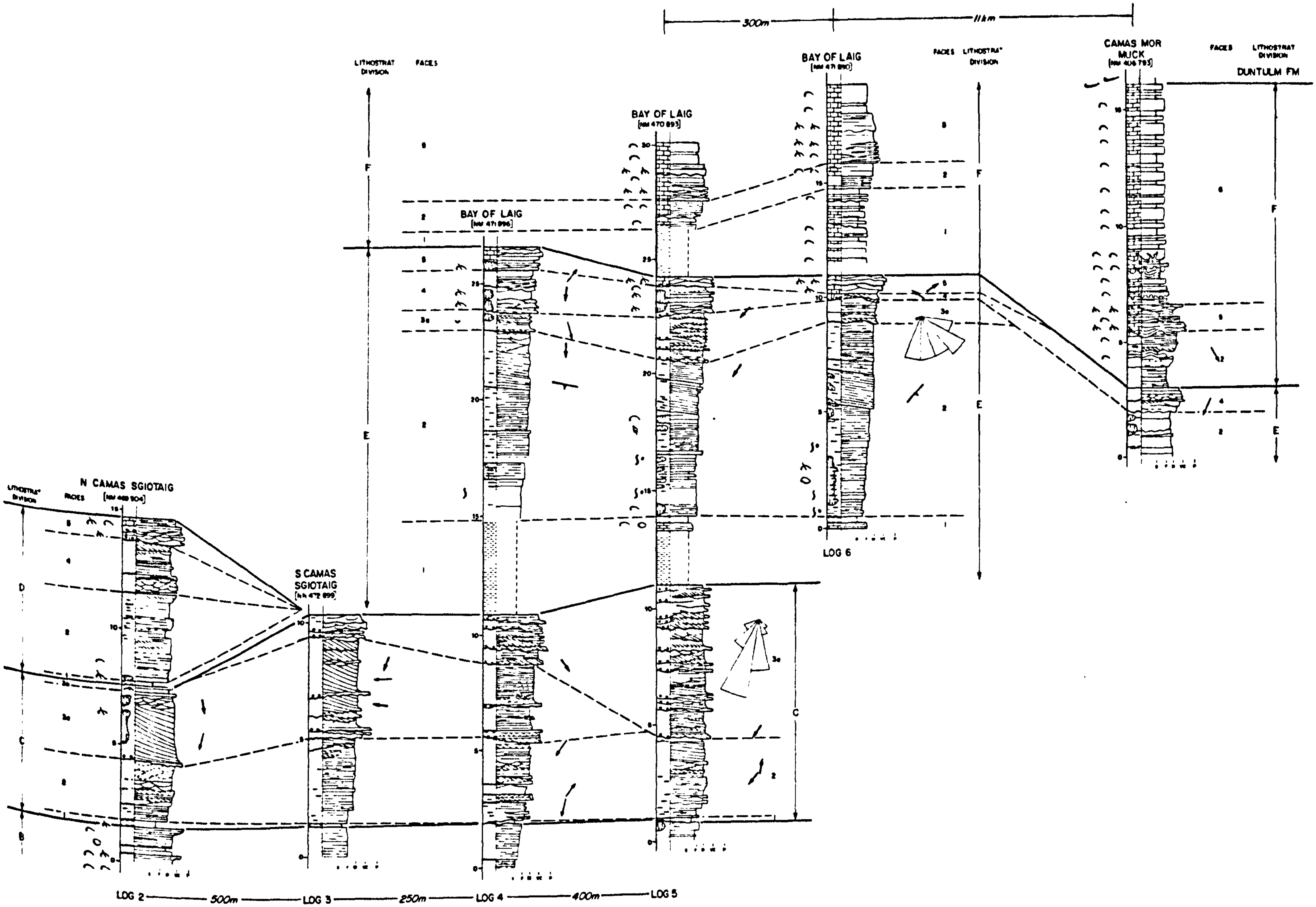


FIGURE 7 Graphic logs of divisions C,D,E and F Valtos Formation Camas Sgiotaig and Bay of Laig, Eigg and Camas Mor, Muck.

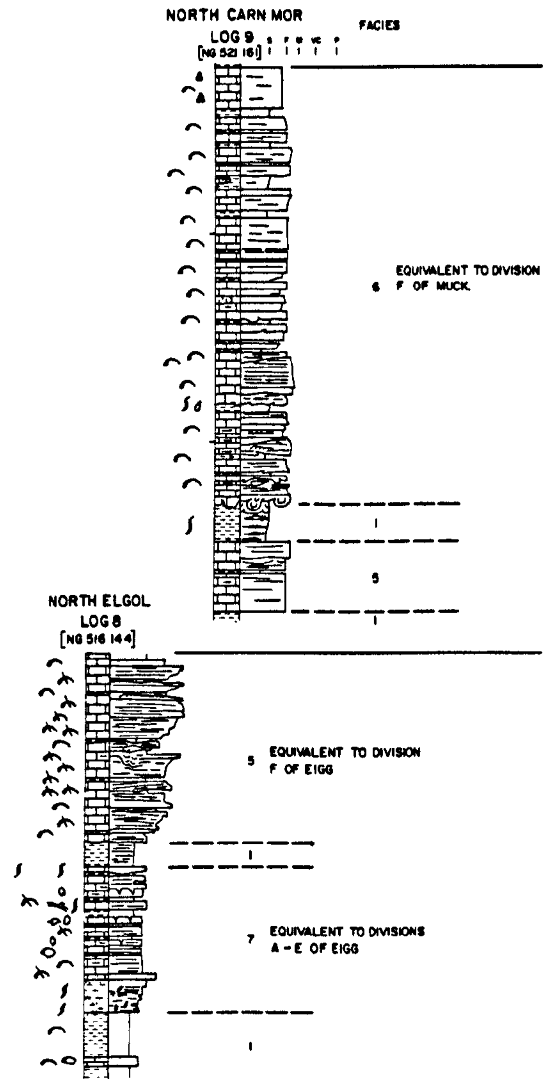


FIGURE 8 Composite log of the Valtos Formation in Strathaird.

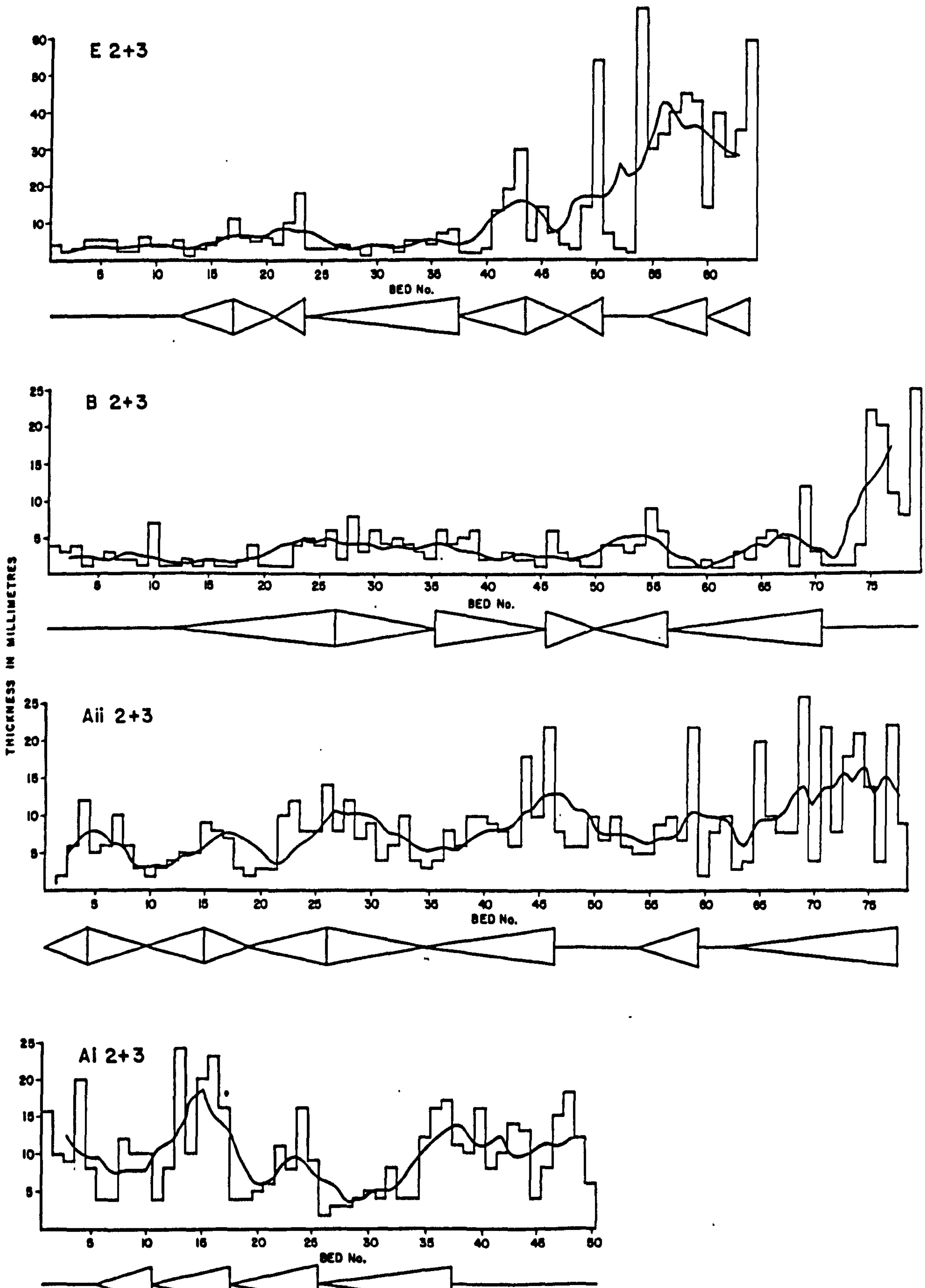


FIGURE 9 Bed thickness histograms and 5th bed moving average curves for Facies 2 and 3 in divisions Ai, Aii, B and E.

The limestones are either micritic and finely laminated (algal bound) with prominant desiccation cracks (Plate 5) or are sandy with Neomiodon valves and large complex Thalassinoides (Crustacean) burrows. The burrows are large horizontal winding and branching forms 1.5-3cm in diameter with short vertical sections. They occur with simple Planolites (Plate 6) are filled with shelly sediment (more shelly than matrix) and contain numerous mud pellets.

INTERPRETATION

The Valtos Formation in the Inner Hebrides basin comprises a highly characteristic sequence of genetically related facies (see stratigraphic section fig 5 graphic logs, figs 6, 7 and 8 and plate 7); interpreted as representing distinct lagoonal delta progradational phases (faces sequence 1-->2-->3 and 4) and transgressive phases (facies 5 and 6). The Formation also includes a basin margin facies (facies 7).

Progradational sequences comprise:

Facies 1: Neomiodon mudstone-siltstone facies, interpreted as offshore lagoonal, pro-delta muds at the base of each sequence.

Facies 2: Coarsening upward sandstone facies, interpreted as representing lagoonal delta front progradation.

Facies 3a: Coarse - pebbly sandstone facies, representing distributary channel and sand flat sequences transitional to facies 3b.

Facies 3b: Thin bedded and trough cross bedded sandstone facies, representing flood generated delta plain sheet sands locally with minor wave reworking at the delta shoreline.

Facies 4: Wave dominated sandstone facies, developed at the top of some sequences is interpreted as representing upper shore face - foreshore and backshore sediments defining wave dominated sections of the lagoonal delta shoreline.

Facies 5: Neomiodon debris limestone facies, probably representing nearshore and shoreface sediments deposited as the delta plain subsided and was transgressed.

Facies 6: Load cast facies, interpreted as representing shallow offshore lagoonal muds-silts and storm generated sublittoral sands post dating the brackish transgression which controlled sedimentation at the top of the Formation.

Basin margin deposits:

Facies 7: Crustacean burrow and desiccation crack facies, representing mud flats close to the basin margin in an area of low sedimentation rate.

1) Neomiodon mudstone-siltstone facies: - INTERPRETATION.

Facies 1 forms the basal part of a series of delta progradational sequences. Mud accumulation in this type of sequence is likely to represent either intertidal flats or offshore sheet deposits (Evans 1965). The apparent lack of desiccation cracks (cf Klein 1970) or rootlets and coals (cf Sellwood 1972) combined with the lateral persistance of the facies, probably indicates that it represents offshore lagoonal (pro deltaic) deposits. The presence of articulated and intact Neomiodon (life assemblages) demonstrates rapid salinity fluctuations as a low current velocity environment (see discussion below) and the shell beds probably represent areas or periods on minimal mud deposition or winnowing during storms (cf Futterer 1982).

2) Coarsening upward sandstone facies: - INTERPRETATION

Facies 2 sandstones represent an upward increase in flow velocity and are a consistent element in each of the progradational sequences. This upward increase in flow velocity, a lack of rootlets or desiccation cracks and the stratigraphic position of the facies between the offshore mudstones of facies 1 and shallow water, high current velocity deposits of facies 3a, 3b or 4 means that facies 2 represents the progradation of composite subaqueous bars which were up to 8.75m in amplitude (cf Klein 1974). The genetic relationship of this facies with facies 3 means that it represents repeated lagoonal delta front, progradational phases.

In division Ai, Aii and B thin sharp based sand beds are intercalated with thin mudstones and thicker muddy sands. These record bioturbation or wave reworking between individual depositional events. The sharp based sand beds are structureless or include faint horizontal lamination and rare current ripples. They resemble density current deposits and record the dominant SE and SSE direction of sediment transport (flow events). The flows probably held enough suspended sediment to behave as density currents although the elements of Bouma sequences are not recognized. Density current flow was probably initiated by a combination of high levels of suspended sediment load and the absence of a sharp salinity contrast between the flow (effluent) and the basin water (see discussion on hyperpycnal flow below).

In divisions D and E carbonaceous, argillaceous partings occur between bedding units and the tops of most beds are penetrated by simple <u>Planolites</u> type burrows demonstrating fluctuating or episodic flow. These flow conditions are probably broadly analogous to the system postulated for facies 2 in divisions Ai, Aii and B. However the large scale inclination of bedding units in division E is not apparent in Ai, Aii and B (although the outcrop of Ai and Aii on the wave cut platform is not conducive to the recognition of this type of structure). Depositional dip directions of the low angle inclined delta front sands in division E demonstrate the broad lobate configuration of the delta front and are directly related to the palaeocurrent pattern seen in the overlying channel sands of facies 3a. These low angle structures can be differentiated from the steeply inclined (20°-25°) delta front sands of Gilbert type deltas (Gilbert 1885) which are close to the angle of repose of the sediment (see discussion below).

In division C facies 2 is thinner and coarser grained than elsewhere. It represents a high current velocity equivalent of the sands described above. The upward transition from episodically deposited planar laminated and lenticular sands to coarser, plane bedded and trough and tabular cross stratified sands represents a sharp upward increase in current velocity. This demonstrates deposition from traction currents which generated low amplitude bar and dune bedforms. These bedforms represent consistent high current velocities in a shallow channelised area at the bar crest. Trough cross stratified cosets also occur in the top of facies 2 in division E which like its facies equivalent in division C is overlain by pebbly fining upward sandstones of facies 3a.

Palaeocurrent measurements indicate that the progradation direction of successive lagoonal delta front sequences was southerly (see graphic logs figs 6 & 7) and that the delta front at least in division E was broadly lobate in form. However facies 2 in division

C and E also includes a subordinate northerly component in the palaeocurrent distribution representing rare landward migrating bedforms. These are attributable to tidal or more probably storm induced current reversals.

3a & b) Coarse - pebbly sandstone facies: - INTERPRETATION.

Facies 3a sandstones truncate and are genetically related to the underlying delta front sands of facies 2. The fining upward sequence in division C records southerly palaeoflow directions and is interpreted as a major fluvial distributary channel fill. In division E similar but thinner sandstones are interpreted as representing a minor distributary channel which probably exhibits a lateral transition into facies 3b, sheet flood dominated, sand flat sediments. Facies 3b sandstones are interpreted as representing laterally extensive sand flats, fringing the distributaries on the delta plain and extending to the delta shoreline.

i) Major distributary channel fill sequences. Facies 3a.

The large scale tabular avalanche sets in division C (Plate 2 and logs 2 and 3) are interpreted as representing in-channel bar bedforms up to 2.5m in amplitude. They overlie a basal pebbly lag and are blanketed by topsets representing down current migrating (S and SSW) dunes and plane beds. Foreset dip directions of the large scale sets vary from S (the presumed down-channel direction) to W. giving a bar front configuration expected from alternate bar types.

The vertical sequence of sedimentary structures, complex palaeocurrent distribution and fining upward grain size profile has distinct similarities with the deposits of bed load dominated low sinuosity, sandy fluvial systems (eg. Harms and Fahenstock, 1965; Coleman, 1969; Collinson, 1970, N.D. Smith, 1970 p.167 fig 17 A & B and Cant and Walker, 1978). The basal lag deposit records very high current velocities and the large scale tabular sets resemble transverse - alternate bars, supplied with sediment by small scale dunes (top sets) occupying the bar top. The genetic association of facies 3a with delta front sands and pro delta muds means that this deposit (southward thinning wedge at base of facies 3a, div. C) represents a major low sinuosity distributary channel fill. It has similarities with the delta top, fluvial channels described by McCabe (1975) but is much smaller in scale.

South of Camas Sgiotaig the upper surface of this sand body (southward thinning wedge) is truncated by a second high current velocity system (logs 3 and 4). This northward thinning wedge records repeated scour and fill events. The scour surfaces in the basal 2m are laterally persistent and approximately horizontal while examples higher in the sequence are laterally impersistent and more closely spaced so that a thinning upward profile is apparent. Preserved between these pebble lined scour surfaces are planar laminated, trough and tabular cross stratified sands representing upper flow regime plane beds and low amplitude bar and dune bedforms, with reactivation surfaces in the absence of mud drapes) demonstrating rapidly fluctuating flow velocities.

This sequence also resembles some of the deposits of low sinuosity, sandy fluvial systems (eg N. D. Smith 1970, p167, fig 17, sequence C and F) where a vertical decrease in set size demonstrates a vertical decrease in flow power. Tabular and trough cross stratified sands with horizons of planar lamination are attributable to the deposition of upper flow regime plane beds and the migration of bar and dune bedforms at high or falling stage (cf Coleman 1969) to form in-channel longitudinal bars. The geometry of the deposit and the vertical and lateral variation in style of sedimentataon suggest in-channel deposition of the bars with a vertical and lateral gradation into broad, flood dominated sand flats. The thin trough cross stratified sands in log 3 could therfore be placed in facies 3b.

The sandstones in the top of division C (log 4 and 5) indicate deposition from high current velocities in close proximity to a major fluvial channel. these sands also include up to 5% of amorphous organic material (kerogen) which is probably humic in origin. this material probably indicates the operation of soil forming processes on sand flats fringing major fluvial distributary channels on the delta plain.

The distributary channel sandstones of facies 3a in division C using the terminology of Friend et al (1979) have a ribbongeometry and comprise two storeys separated by a scour. Together with the coarse grain size of the deposit and suite of in-channel bedforms this geometry indicates high flow velocities, a plentiful supply of clastic sediment and a widely and rapidly fluctuating flow regime.

ii) Minor distributary channel fill sequences. Facies 3a: -

Distributary channel fill sandstones of facies 3a in division E (log 4, 5 and 6), although thinner, are similar to those discussed above (northward thinning wedge, division C). The southerly palaeocurrent mode (SE in rose measured close to log 6) is parallel with the local depositional dip direction of the delta front sands of facies 2 indicating that powerful offshore directed (southerly) currents supplied sediment directly to the lobate delta front. These in-channel sandstones are probably also transitional to flood generated sand flat sediments and in log 6 could easily be placed in facies 3b.

iii) Sand flat deposits. Facies 3b

In division Aii planar laminated sands with current lineation in the top of facies 2 are truncated by a trough cross stratified coset of facies 3b. This demonstrates the progradation of a channelized area of the delta plain into very shallow water (plane bedded interval). Southerly flow directions (vector 172°) are recorded by trough axes and the prefered long axis orientation of numerous pieces of coniferous driftwood.

Facies 3b in division A1 also includes current orientated logs (long axis trend average 130°, sub parallel to palaeocurrents in facies 2) but comprises a series of coarse grained, erosively based current rippled sands. These demonstrate the rapid deceleration of high velocity currents and represent a series of discrete sheet flood events.

Wave ripples and single grain laminae or pockets of granules - small pebbles demonstrates wave winnowing at the tops of some of these beds. They are interpreted as sheet flood deposits, forming sand flats modified by wave processes at the delta shoreline. They probably represent the distal and lateral equivalents of the sand flat facies sediments discussed in this account with facies 3a (distributary channel sands).

4) Wave dominated sandstone facies:- INTERPRETATION

Sands of facies 4 include Neomiodon debris (preserved in calcite concretions) and consist of isolated trough sets and small wedge-shaped lenses of coarse sediment. Similar deposits have been documented from modern upper shore face environments (Reineck and Singh, 1973; Howard, 1972). Planar lamination with low angle planar cross lamination is probably analogous to the swash cross stratification of Harms et. al. (1975) with low angle discordances between sets representing adjustments of the beach face to changing wave energies. Similar sediments are documented from modern foreshore - beach ridge sediments by Clifton et. al., (1971); Howard and Reineck, (1972) and Dickinson et. al., (1972).

Facies 4 in places overlies minor distributary channel fill sandstones indicating that it probably represents the wave reworking of fluvially supplied sediment with the addition of shell debris after lateral migration and abandonment of the distributaries.

In division D fine muddy limestones with articulated Neomiodon overlie beach ridge sediments. These represent deposition in a low current energy area landward of the beach ridge and indicate that the beach ridge was probably a spit.

The stratigraphic position of facies 4 between facies 2 (delta front) and facies 5 (probable trangsressive limestones) and the facies relationships in division B indicate that it is part of the lagoonal delta progradation sequence. Alternatively, the wave dominated facies could be interpreted as part of the transgressive facies 5.

5) Neomiodon debris limestone facies: - INTERPRETATION

Facies 5 caps delta progradational sequences in divisions B, D and E and is overlain by offshore/prodelta Neomiodon mudstones of facies 1. In division F and in Strathaird the facies is thicker and is overlain by shallow offshore sediments of facies 6 at the top of the Formation. The facies is coarse grained and locally pebbly; it represents high current velocities and the availability of large quantities of shell debris (commonly abraded) - but the absence of a significant supply of sand. As such it either represents part of the regressive delta shoreline identified as facies 4 (such as a backshore beach ridge composed of storm generated shell debris) or is a transgressive shoreline deposit recording abandonment and subsequent inundation of the delta plain.

The overlying mudstones of facies 1 and the mudstones and sandy limestones of facies 6 contain no evidence of subaerial exposure so that the stratigraphic position of facies 5 between offshore sediments and progradational delta front or shoreline sediments of facies 2 or 3 strongly favours a transgressive origin.

In division F on Eigg and Muck facies 5 truncates a thin coarsening upward sandstone representing the eroded remnant or distal part of a delta progradational sequence. Very high current velocities are recorded by the basal erosion surface of the facies on Muck where the fining upward profile probably represents a storm surge channel fill. The coarsening upward unit which caps the facies includes a wave winnowed pebbly lag and probably represents a wave generated nearshore shoal.

Facies 5 in Strathaird is also interpreted as representing a nearshore shell debris shoal. It coarsens upwards and contains probable wave ripples and is capped by coarsening upward units like those on Muck. The large scale load like structures in facies 5 (Plate 3) comprise a sandy mudstone (originally low density material) and a muddy sandy limestone forming large scale intrusive bodies overlying a thick, virtually structureless, sandy, shell debris limestone (originally high density material). These therefore differ from true load structures attributed to gravitational instability (cf Allen 1970 p 86) where the high density sediment (sand) overlies low density sediment (mud).

In Strathaird the structureless sandy shell bed (facies 5) probably records fluidization (liquifaction) generated by increased pore fluid pressures built up beneath the impermeable mudstone, probably in response to rapid deposition. Liquifaction occurring beneath this permeability interface could cause the overlying semi-consolidated bed to deform plastically and displace the underlying fluidized sediment to form large scale 'load like' structures. A similar process is described by Lowe (1975).

6) Load cast facies:- INTERPRETATION

Facies 6 comprises an alternation of planar laminated and current rippled, sandy, shelly limestones and dark shales which occasionally include wave generated siltstone lenses (wavy flasers) and Planolites burrows. The bases of many sandy limestone beds are deformed by large scale load structures demonstrating very rapid deposition.

The facies represents a shallow basinal environment with episodic flood or storm generated clastic influxes resulting in rapid deposition of sands and Neomiodon shells (now sandy limestones) overlying unconsolidated muds.

On Muck large scale load structures (Plate 3) are truncated by aplane bedded sandy limestone recording the exhumation and partial erosion of the newly formed load structures. Very similar deposits are documented by Goldring et al (1978) from Eocene and modern estuarine and tidal flat sediments. However there is no evidence for the reactivation of the exhumed load structures in the manner reported by Goldring et al. (1978).

This depositional regime continued into the overlying Duntulm Formation where the increasing salinity of the basin water is recorded by the colonization of the basin floor by oysters. This increase in salinity corresponds with the decrease in, or cessation of fluvial supply of clastic sediment to the basin (see discussion below).

7) Crustacean burrow and desiccation crack facies:- INTERPRETATION

Facies 7 occurs at the base of the Formation in Strathaird and is only ca 6m thick. It is the stratigraphic equivalent of the delta progradational sequences discussed above (ca 51m) and therefore testifies to the very low levels of clastic supply to this region, close to the margin of the Inner Hebrides Basin.

The prominent desiccation cracks demonstrate frequent subaerial exposure of finely laminated, probably algal bound carbonate muds. These sediments and the mudstone intercalations are thought to represent mud flats at a fluctuating lagoon shoreline. The shelly limestones with ?Thalassinoides (Crustacean burrows) represent shallow water lagoonal sediments. The complexity of the burrow systems and their short vertical 'pipes' probably demonstrate very slow rates of deposition.

DISCUSSION

Controls and constraints on a depositional model for the Valtos Formation in the Inner Hebrides Basin.

The Valtos Formation on the Isle of Eigg is interpreted as representing 5 lagoonal delta, progradational phases (represented by distinct sequences of facies:- 1-2-3 or 4), separated by thin (locally absent), transgressive shell debris limestones (facies 5). These delta progradational sequences are absent from Strathaird where a thick transgressive limestone of facies 5 overlies thin mud flat sediments of facies 7. However in spite of this lateral facies variation in both Strathaird and on Muck the same sequence of facies occurs at the top of the Formation. (On Eigg the top of the Formation is not exposed).

A depositional model accounting for the genetic relationships of the progradational facies (1-2-3-4) and the major lateral facies/thickness variation between Eigg-Muck and Strathaird has to take into account the following controls and constraints.

1) Palaeogeography of the Inner Hebrides Basin; based on the structural map of Binns et al (1975) and the Triassic palaeogeography of Steel (1976), see fig 1, introduction above and the discussion in relation to the Elgol Formation (Chapter 2).

The basin was filled longitudinally giving a southerly progradation direction to the delta front sandbodies (see palaeocurrent data fig 5 & 6). This progradation direction conflicts with the sediment distribution pattern, based on heavy mineral distributions, invoked by Hudson (1964). Hudsons palaeogeography proposes a SE source for the Valtos Formation sandstones of Eigg in the Dalradian of the southern and eastern Highlands. Dominant NW palaeocurrent flow directions could therefore be expected in the basin. Subsequent work on heavy mineral suites (see Appendix 1) is in agreement with Hudsons (1964) data. However, in combination with recent regional structural data (Binns et al. 1975) and the palaeoflow directions proposed above, it suggests that the hinterland of the Inner Hebrides Basin contained weathered Old Red Sandstone (and possibly Carboniferous) sediments sourced mainly from the Dalradian and Moinian. The data also indicate that the hinterland was situated to the NE of the basin in the area of Wester Ross.

ii) Copious sediment supply; the sand bodies are all strongly regressive and include coarse, often pebbly, low sinuosity fluvial distributary channel and sand flat sediments. These demonstrate the availability of large amounts of weathered clastic material in the hinterland and sediment supply from short headed, energetic streams with widely fluctuating discharge patterns.

iii) Bipolarity of palaeocurrents; although having a complex palaeocurrent pattern dominated by a southerly mode (parallel to basin margins), the palaeocurrent distribution includes a subordinate northerly component (facies 2). These northerly palaeocurrents represent shoreward migrating bedforms which could be attributable to tidal (micro tidal) or more probably, storm induced flow reversals. The palaeocurrent distribution is however strongly fluvially (and ?ebb) dominated.

iv) The presence of beach ridges and beach spits demonstrating the occurrence of wave energies which were sufficient to redistribute fluvially supplied sediment.

v) An apparent lack of rootlets coals and desiccation cracks but abundant drifted wood debris. This indicates direct fluvial input from a nearby, densely vegetated hinterland with mature soil profiles but the non-development or rarity of subaerial soils in the basin. However, the stratigraphically highest sandstones in division C (sand flats of facies 3b) are homogeneous and contain up to 5% of finely divided humic material which possibly represents soil forming processes. Rootlets occur rarely in the top of two similar sand bodies in the Valtos Formation of Trotternish, Skye, in the Sea of the Hebrides basin (see Chapter 4).

The non occurrence or rarity of rootlets and soil profiles within the basin could be attributable to rapid deposition of clean sand which is poor in plant materials (cf. T. Harris 1976) or the erosion of the upper surface of the sandbodies during subsequent brackish transgressions (see discussion below). In addition all the sandbodies are succeeded by mudstones of facies 1 leading to poor exposure of their upper surfaces.

vi) A non-marine macrofauna; dominated by monotypic shell beds of the non-marine bivalve *Neomiodon* (Hudson 1963 a and b; Tan and Hudson 1974). Hudson (1980) describes *Neomiodon* as having a marine ancestry and isotopic composition but having its main faunal associations with nearly fresh water assemblages; although it only rarely occurs in the same bed as the freshwater faunas. Hudson interprets *Neomiodon* as an opportunistic bivalve adapted to tolerate environments of rapidly and widely fluctuating salinity, such that it could colonize and flourish in an environment which was extremely hostile to stenohaline organisms. *Neomiodon* possibly only laid down its shell during periods of near marine salinity but could adequately survive almost freshwater episodes (J.D. Hudson pers. comm.).

The palaeoecological constraints outlined above are in very good agreement with the copious clastic supply, rapidly fluctuating freshwater run off and the restricted area of the Inner Hebrides Basin. Together with minor wave reworking of fluvially supplied sediment and the possibility of a microtidal range these observations restrict the depositional environmentof the Formation to delta progradation in a large, elongate, non-marine lagoon (or estuarine embayment).

In this type of system salt water which would occupy the basin (given a marine connection) during low discharge periods (dry season?) could be displaced seawards/offshore (SW) over the entire basin area during periods of very high discharge (wet season?). The operation of this fluvial discharge dependant system would give the very rapid salinity fluctuations invoked above.

The Duntulm Formation (in the Inner Hebrides Basin) overlying the Valtos Formation represents brackish-marine and marine-hypersaline salinities (Hudson 1963; Hudson and Harris 1979; Hudson 1980) and is probably attributable to the long term invasion of salt water. This is possibly attributable to a decrease in fluvial discharge into the basin and correlates closely with the cessation of copious clastic supply to the basin recorded by a change in depositional regime (style) at the top of division E of the Valtos Formation.

DEPOSITIONAL MODEL: Lagoonal deltas and alternative models.

Valtos Formation sediments clearly record the two phase, progradational and abandonment history of deltaic sediments outlined by Scruton (1960). The Formation represents copious, rapidly fluctuating, coarse grained clastic supply, records minor reworking of delta front sediments into regressive beach ridges and exhibits a lobate delta front configuration. The progradational sequences therefore resemble modern, lobate, fluvial dominated deltas and share some characteristics with humid region, stable shelf, fan deltas.

However there are a number of other possible alternative interpretations of the Valtos Formation. These include:

i) Braid plain and mud plain deposits (cf P. Allen 1975).

ii) Simple non-deltaic shorelines of the type described by Clifton et al (1971), or Davidson-Arnott and Greenwood (1976).

iii) The progradation of an estuarine channel-shoal complex with associated swash bars. e.g. Howard and Reineck (1972), Greer (1975).

i) The progradational sequences bear some resemblance to the braid plain and mud plain deposits of the Wealden of the Weald (P. Allen 1975; 1976) but can be differentiated from these deposits by the lack of evidence for subaerial emergence of the coarsening upward sands of facies 2 (delta front in this interpretation).

Facies 2 could be the equivalent of the coarsening upward, rising stage component of Allens braid bars but facies 2 sandstones are burrowed rather than rootlet penetrated and contain evidence of minor wave reworking (division Ai, Aii), together with landward orientated sets of cross strata demonstrating storm or tidally induced flow reversals (division C and E). In addition facies 4 represents the reworking of fluvially supplied sediment into regressive beach ridges or spits (division B and E) demonstrating the stratigraphic position of the delta shoreline.

The occurrence of these features clearly differentiates the Valtos Formation from the Wealden of the Weald, although low sinuosity channel sands (distributaries) and sheet flood sands (sand flats) are identified.

ii) Simple non-deltaic shorelines are an unlikely interpretation because, although oscillation ripples and beach ridges with probable swash cross stratification have been identified they are comparatively unimportant. There is also abundant evidence of copious fluvial supply of clastic sediment, large amounts of drifted wood and finely divided plant debris and a distinct lobate shoreline configuration.

iii) The third alternative is implausible because this type of system is dependent on symmetrical or nearly symmetrical tidal current reversals. This control applies even to estuarine systems with a significant and important fluvial input, eg the Ossabaw Estuary, Georgia, (Greer 1975 p 108, 109). Although there is some evidence of current reversals in division C and in division E the system is very strongly fluvially dominated. The progradation of delta like sandbodies is therefore the most likely interpretation.

It has been established above that tidal current reversals are unimportant and that the current reversals are most probably the result of storms. Elongate tidal sand ridges of tide dominated deltas eg. the Ord (Coleman and Wright 1975) are not therefore represented. Similarly there is no evidence for the extensive beach ridges of wave dominated deltas, eg. the Griyalva and Sao Fransisco (Coleman and Wright 1975). There is also no evidence for the existence of elongate or birdfoot, Mississippi type deltas, although the deposits are clearly fluvially dominated.

The Formation, therefore, represents a lagoonal deltaic regime characterized by rapidly fluctuating coarse clastic supply from channelized, bed load dominated and non channelized fluvial systems with minor wave reworking of fluvially supplied sediment. This reworking is attributable to storms in a basin of reduced but rapidly fluctuating salinity. Wave energies were sufficient to generate minor beach ridges and spits. The interaction of these processes together with the sheet geometry of the delta front facies and its lobate shoreline configuration (division E) has close similarities with modern lobate fluvial dominated deltas. e.g. the Colorado Delta, Texas (Kanes 1970). Modern humid region fan deltas deposited in stable continental shelf systems also share some of these characteristics e.g. (McGowan 1970; Wescott and Ethridge 1980 p 393).

ANCIENT ANALOGUES

Ancient fan delta sequences described by Sykes and Brand (1976) from East Greenland have some characteristics in common with the Valtos Formation in Eigg but a closer ancient analogue is probably represented in the Wealden lagoonal deltas described by Stewart (1981). These delta sandstones occur within a lagoonal sequence recording similar salinity fluctuations to those in the Valtos Formation. They were supplied by a low sinuosity river system with a complex and variable suite of bedforms which are locally similar to those in facies 3a of the Valtos Formation. The low angle inclined delta front sands of facies 2 are similar to lacustrine delta front deposits in the Eocene Green River Formation, interpreted by Stanley and Surdam (1976) and Surdam and Stanley (1978) as Gilbert type deposits.

Lobate, fluvially dominated, lagoonal and lacustrine deltas are probably better analogues for the Valtos Formation (in the Inner Hebrides Basin) than are fan deltas because the sandbodies are not limited in their occurrence to a break of slope (usually fault controlled) at the basin margin. However, delta plain sediments are dominated by low sinuosity channels and flood generated sand flats.

The dominance of fluvial processes in generating lobate delta front sequences in the Valtos Formation of Eigg is the same as proposed for the Elgol Formation in Strathaird (Chapter 2). This degree of fluvial dominance in the Valtos Formation in the Inner Hebrides Basin contrasts with the fluvial-wave interaction system proposed for the Valtos Formation in the Sea of the Hebrides Basin (See Chapter 4).

FACIES RELATIONSHIPS

The depositional model (fig 10) is divided into a delta plain (facies 3a, 3b & 4), a delta front (facies 2) and a pro-delta/offshore area (facies 1) representing the components of each progradational phase. The diagram does not however attempt to illustrate the facies relationships of the mud flat and shallow lagoonal sediments of facies 7, or the transgressive sheet deposits of facies 5 and facies 6.

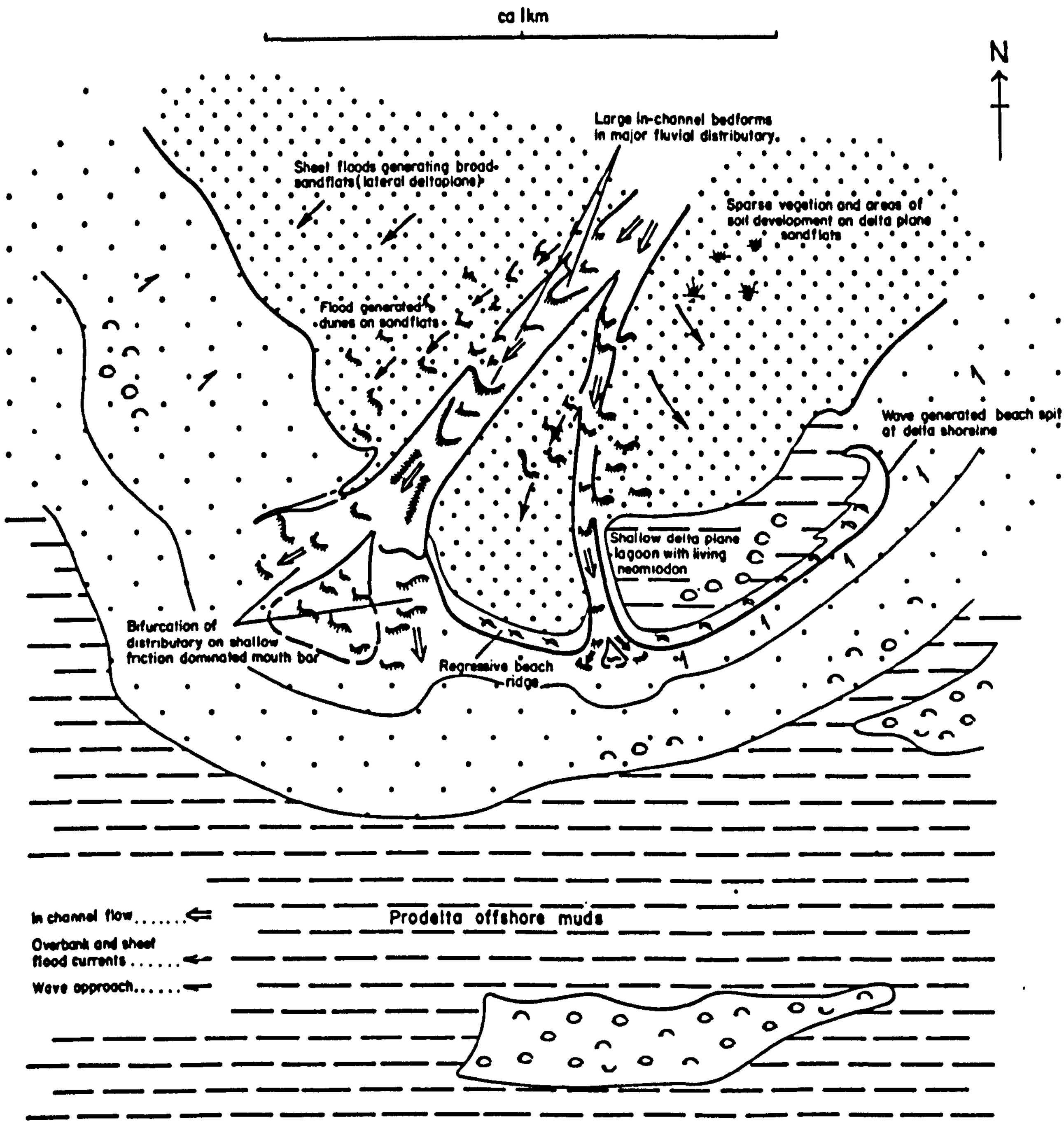


FIGURE 10 Plan illustrating facies relationships in an idealised Valtos Formation, progradational phase - Lobate, fluvially dominated lagoonal delta

DELTA PLAIN

The delta plain (see fig. 10) is dominated by a major low sinuosity fluvial distibutary system (facies 3a in divsion C). The coarse grain size of this deposit together with its suite of in-channel bedforms, its ribbon geometry and stacking probably implies high flow velocities and large scale fluctuations in flow power indicating an actively uplifted source area. The sequence in division C is similar to the Carboniferous distributary channel described by McCabe (1975) although it is much smaller in scale.

Minor channel fill sequences (division Aii and E) probably only functioned during flood periods; deposition taking place during falling stage plugging newly formed, shallowly incised channels and forming broad sand flats.

Sheet flood deposits of facies 3b demonstrate non-channelized run off probably corresponding to individual flood events. The wave ripples and granule-pebble armoured surfaces at the top of some of these individual sheet flood deposits probably represent wave reworking, in the shallow water of the partially inundated delta plain close to the delta shoreline. Flood generated overbank flow is probably also recorded by the pebbly deposits capping facies 3a in division C. These deposits also interpreted as representing broad sand flats and contain humic material which possibly indicates soil formation.

The depositional model chosen assumes that major distributary channel sequences represent an axial position in each lobate, lagoonal delta progradational system. The subsidiary minor distributaries and sheet flood deposits probably therefore represent lateral positions within successive prograding deltas. The distribution of these facies types in the logged sections is closely related to the nature of the underlying delta front deposits.

The beach ridge or spit deposits of facies 4 probably represent inter channel areas of the delta shoreline and record wave reworking of fluvially supplied sediment and Neomiodon debris) from the delta shoreline.

Abandonment of the delta plain is recorded by a return to the mudstones (facies 1) demonstrating subsidence and inundation. In divisions B, D and E coarse grained, pebbly and shelly deposits of facies 5 intervene between facies 4 and the suceeding mudstones. These deposits are interpreted as recording the passage of the shoreline as inundation of the delta plain occurred. The non occurrence of this facies in some sequences is possibly related to the speed of the transgression and available wave energy.

DELTA FRONT FACIES

The progradation of delta sand bodies into a non-marine basin with only a limited ability to redistribute fluvially supplied sediment has resulted in the preservation of the interval form and configuration of the delta front and mouth bar deposits. This therefore gives some clues as to the hydrodynamics of the delta front.

The delta front hydrodynamic regime in such deltas is largely dependant on the controls discussed by Wright (1977)

i) discharge rate, fluctuation and outflow velocity of the steam,

ii) water depth in and basinward of the river mouth,

iii) the volume and grain size of the sediment load and

iv) the sharpness of density contrasts between the river and basin waters.

Wright (1977) describes 3 primary processes resulting from the interaction of these controls:

i) Buoyancy; occurring in relatively deep river mouths through the invasion of a salt wedge causing the less dense river water to spread basinward as a discrete layer. This results in fine grained deposits with a gradational coarsening upward profile and an elongate or bar finger geometry.

ii) Inertia and associated turbulent diffusion; resulting from deep water basinward of the river mouth, small density contrasts and high outflow velocities. This causes inertial forces to become dominant and river water to behave as a fully turbulent jet. This type of outflow also has very low spreading angles (angle between the effluent centre line and effluent boundary) and is characterised by progressive basinward deceleration. The deposits formed from this regime are characteristically relatively 'coarse grained' have the classic Gilbert-type profile of topsets, foresets and bottomsets (Gilbert 1885) and a cone shaped geometry reflecting the low spreading angle of the effluent.

iii) Turbulent bed friction; resulting from high rates of bed load transport, high outflow velocity (coarse sediment supply) and shallow water basinward of the river mouth. This causes friction with the bed to become dominant and consequently lateral turbulent diffusion with very high spreading angles and rapid basinward deceleration. The interaction of these processes results in coarse grained deposits with a broad lenticular geometry reflecting high spreading angles. The deposits will characteristically contain high current velocity structures and be capped by a bar crest facies including shallow or incipient, bifurcating distributaries forming the 'middle ground' mouth bar type of Coleman et al (1964); Ardorfer (1973).

Water in the receiving basin of the Valtos Formation deltas was of reduced but fluctuating salinity (see discussion in relation to Neomiodon above) so that the long term operation of buoyant processes at the distributary mouths is unlikely. The basin immediately offshore from the distributary mouth was probably shallow (2.5-maximum 10m, based on Klein 1974) so that inertial processes giving rise to a Gilbert type profile could not operate fully. Turbulent bed friction with consequent high current velocity bedforms is therefore the most probable dominant process. The operation of friction dominated processes is demonstrated by scour surfaces, plane beds and trough and tabular cross stratified cosets in the bar front and bar crest deposits of facies 2 in division C, D and E. The broad lobate configuration of the delta front (facies 2, division E) probably reflects the high spreading angles of friction dominated outflow. High spreading angles and rapid basinward deceleration of the outflow results in sand deposition close to the distributary mouth so that it can be relatively easily reworked by waves and incorporated, along with shell debris into minor beach face sequences, such as that postulated in facies 4.

Discrete sharp based sand beds occurring in facies 2 (divisions Ai, Aii, B and parts of D & E) possibly record the density controlled underflow of turbulent, sediment laden effluent beneath less dense basin water (hyperpycnal flow of Bates 1953).

Facies distribution in an idealized delta lobe.

The character of mouth bar/delta front deposits in the Valtos Formation is probably directly related to the overlying delta plain facies. The high current velocity deposits of facies 2 (division C) occur in association with the major low sinuosity distributary channel deposits of facies 3 and probably represent an axial position in a delta lobe. In division E the apex of the lobate bar front occurs in log 5 and gives a SSE orientation. This corresponds with the thickest development of minor distributary channel fill sequences in facies 3a and suggests that log 5 occupies an axial position in a progradational lobe and that logs 4 and 6 are intermediate.

Facies 2 in division Ai and Aii (probably recording hyperpycnal underflow) corresponds to minor channel and sheet flood deposits of the overlying delta plain (facies 3) and are probably lateral. Although there is no evidence for the nature of the fluvial supply to division B the nature of the delta front facies suggests a lateral position.

Bed thickness profiles (fig 9) although poorly defined record the progradational history of the lateral and intermediate sequences. Rhythmic thickening upward sequences represent a progressive increase in sediment supply to the depositional site and possibly record phases of delta front progradation controlled by the lateral switching of distributaries on the delta plain. The cyclic sequences which are superimposed on these rhythms represent a fluctuation in sediment supply which could be seasonal.

PRO-DELTA AND OFFSHORE MUDS.

The muds and shell beds of facies 1 represent quiet water, offshore from the delta front between 2.5-10 deep (cf Klein 1974). All the deposits of facies 1 are thin, demonstrating the rapid progradational style of the Valtos Formation deltas and probably indicating relatively low levels of fine grained suspended sediment in the effluent water. The Neomiodon shell beds comprise unbroken single valves and include articulated specimens demonstrating that they are probably life assemblages. They indicate periods or areas of minimal mud deposition and are probably distal or lateral to an advancing delta front.

MUD FLATS AND SHALLOW LAGOONAL SEDIMENTS

Mud flat and shallow lagoonal sediments (facies 7, only occurring in Strathaird) are the stratigraphic equivalent of the 6 progradational sandbodies discussed above. The facies represents very slow deposition (and probably long periods or nondeposition) in the absence of coarse grained, clastic supply in an area close to the margin of the Inner Hebrides basin. This relationship is controlled by the configuration and subsidence history of the basin margin and is discussed below.

TRANSGRESSIVE FACIES

Because trangressive shorelines in a deltaic system represent an abandonment facies they are usually not actively supplied with sediment and characteristically therefore leave very little sediment to be preserved in the stratigraphic record. The thin, locally absent pebbly shell debris limestones of facies 5 record this type of depositional regime. They are interpreted as representing wave winnowing and reworking of delta plain sediments in shallow nearshore and trangressive shoreline environments. High current velocities are demonstrated by the deeply scoured channelized base of facies 5 on Muck. The stratigraphic equivalent of these rocks in Strathaird represents a very rapidly deposited shell debris shoal.

The load cast facies (6) occupies a stratigraphic position at the top of the Formation. It represents significant but episodic clastic supply to the basin and is probably not strictly a transgressive facies. Facies 6 records diminished clastic supply and fluvial run off and is probably directly related to an increase in salinity of the basin water leading ultimately to the colonization of the shallow basin floor by oysters, marking the base of the Duntulm Formation. However, this increase in salinity could also be related to the late Bathonian sea level peak of Vail and Todd (1981).

PALAEOGEOGRAPHY AND FACIES DISTRIBUTION

The structural controls on facies distribution (illustrated on the palaeogeographic map fig. 1 and discussed above) in combination with the depositional model can offer explanations of the facies distribution patterns in the basin. This approach also allows predictions as to likely lateral and axial facies developments. These palaeogeographic speculations and explanations are discussed under 3 headings.

i)Thickness and facies variation between Strathaird and Eigg-Muck:

The present day structurally controlled Inner Hebrides Basin is markedly assymetrical with a deep, down faulted western margin controlled by the Camasunary-Skerryvore fault. It is likely that this structure also characterised the Jurassic basin so that the thickest accumulation of Valtos Formation sandstones would be expected at this western margin. This however, is not the case; outcrops of the Formation in Strathaird are only 1-2 km east of the fault but are anomalously thin. The upper ca 20m is similar to the stratigraphic equivalent rocks on Muck towards the centre of the basin but the rest of the Formation (progradational delta front and distributary channel sandbodies) is missing. This anomalously thin basin margin sequence records very low subsidence rates and contrasts with the evidence for rapid subsidence of this part of the basin during deposition of the Bearreraig Sandstone Formation (Bajocian) and Elgol Sandstone Formation (close to the base of the Great Estuarine Group).

A possible explanation for this apparent anomaly is that the Camasunary Fault in the mid-Mesozoic could have been a more complex structure than the reactivated normal fault seen truncating Jurassic sediments today (downthrow ca 650m against Torridonian). Several parallel faults or step faults defining the basin margin would create a series of 'terrace' structures parallel to the basin margin. Each of these minor fault blocks could have different subsidence histories and therefore different sediment accumulations. The thickest development of Valtos Formation sandstones would therefore be expected east of the basin margin area. Figure 12 illustrates a conjectural model of basin margin fault movements, to account for observed facies distribution and thickness variations.

An additional factor involves clastic supply to the Strathaird area of the Inner Hebrides Basin. The structural map of Binns et al (1975) includes a structural high in the area of the Sleat Peninsula and Triassic debris flow sediments in Sleat (Steel 1974) indicate very close proximity to an uplifted basin margin. This structural high was probably represented in the Middle Jurassic and effectively

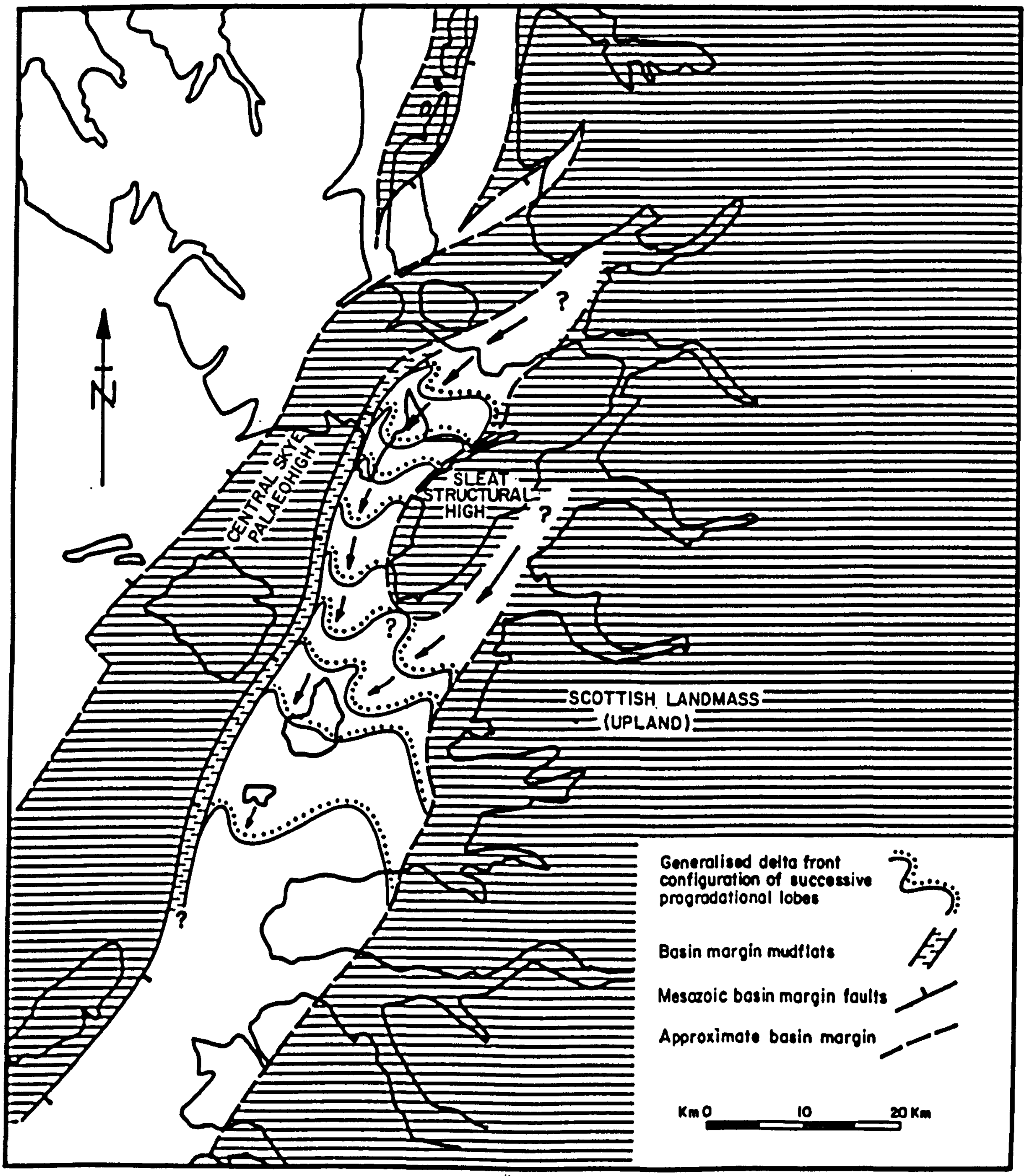


FIGURE 11 Palaeogeography of the Valtos Formation in the Inner Hebrides Basin.

FIGURE 12 Speculative diagram to show the possible relationship of terrace structures associated with the Camasunary-Skerryvore Fault to stratigraphic thickness of the Mid - Upper Jurassic sediments.

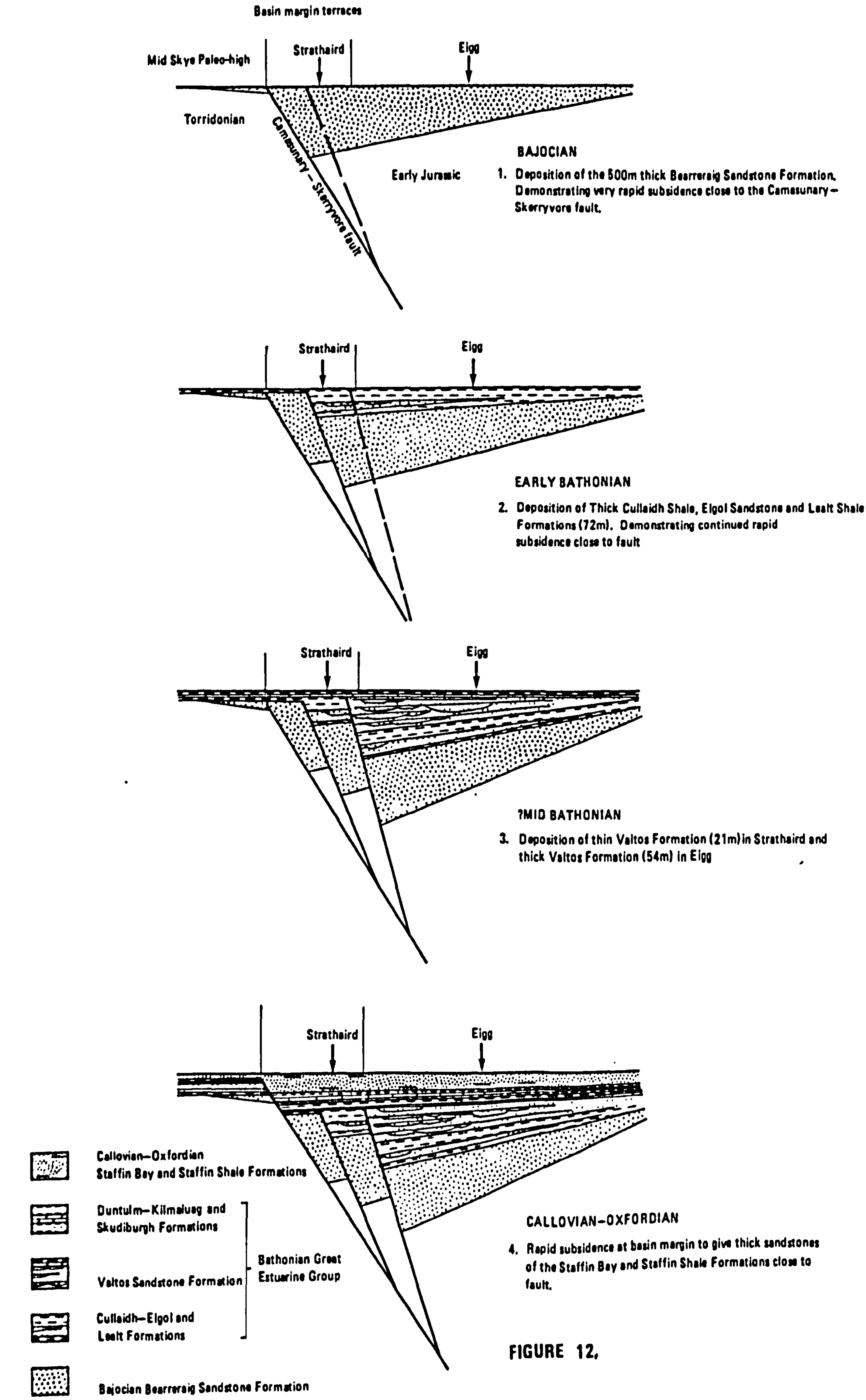

Basin margin terraces
Mid Skye Paleo-high
Strathaird
Eigg
Torridonian
Camasunary – Skerryvore fault
Early Jurassic
BAJOCIAN
1. Deposition of the 500m thick Bearreraig Sandstone Formation. Demonstrating very rapid subsidence close to the Camasunary–Skerryvore fault.
Strathaird
Eigg
EARLY BATHONIAN
2. Deposition of Thick Cullaidh Shale, Elgol Sandstone and Lealt Shale Formations (72m). Demonstrating continued rapid subsidence close to fault
Strathaird
Eigg
?MID BATHONIAN
3. Deposition of thin Valtos Formation (21m) in Strathaird and thick Valtos Formation (54m) in Eigg
Strathaird
Eigg
CALLOVIAN-OXFORDIAN
4. Rapid subsidence at basin margin to give thick sandstones of the Staffin Bay and Staffin Shale Formations close to fault.
Callovian–Oxfordian Staffin Bay and Staffin Shale Formations
Duntulm–Kilmaluag and Skudiburgh Formations
Valtos Sandstone Formation
Cullaidh–Elgol and Lealt Formations
Bathonian Great Estuarine Group
Bajocian Bearreraig Sandstone Formation

FIGURE 12.

divided the landward (NE) end of the basin into two (see palaeogeographic map fig 1). It is possible that only the eastern branch was a conduit of major clastic supply to the southerly part of the basin during deposition of the Valtos Formation, especially because the source of the sediments lay to the east and north east.

Lateral facies variation:

The Valtos Formation on Eigg is dominated by the lateral and intermediate elements of delta progradation sequences. Only one major fluvial distributary channel system is seen at outcrop, although there are 6 delta progradation sequences each of which will be related to a major distributary channel fill sequence which should therefore, occur somewhere in the basin.

The asymmetry of the Inner Hebrides Basin means that the area of most rapid subsidence during deposition of the Valtos Formation was probably west of the Isle of Eigg. Figures 11 and 12 show the main locus of distributary channel sand deposition at the axis of the basin in the area between Eigg and the western, basin margin faults (Camasunary-Skerryvore faults).

Axial facies variation and the character of the Hinterland.

The landward (NE) and seaward (SW) equivalents of the Valtos Formation, seen in the Inner Hebrides basin, are either eroded or not exposed. However the landward end of the basin and transition to the hinterland would probably involve a gradation from delta front and delta plain sediments (like those seen at outcrop), to alluvial plain and valley fill, low sinuosity fluvial sediments in the hinterland. The hinterland was probably actively uplifted and relatively humid with a seasonal climate (rainfall) and relatively dense vegetation cover, mainly of conifers. The hinterland probably also contained a thick regolith capable of supplying large amounts of sand sized clastic material. This sand was probably derived from Old Red Sandstone lying unconformably on the Moinian.

It is not known what underlies the Tertiary lavas and sediments between Mull and the Blackstones Bank in the south of the basin (Binns et al 1975). The depositional model for the Valtos Formation based on southerly progradation (controlled by subsidence) would predict reaching the depositional limit of the delta sand bodies in this region. This relationship can be demonstrated for the Elgol Formation, which in the Inner Hebrides Basin, is a similar progradational system with a depositional limit between Eigg and Strathaird.

Plate 1 Division E, south of Camas Sgiotaig, Eigg. Low angle inclined coarsening upward delta front sandstones of facies 2 with prominent calcite concretions overlain by probable shallow channel (facies 3a) and delta shoreline sandstones of facies 4. Cliff is capped by transgressive shell debris limestone of facies 5. Hammer at bottom left is 70 cm long.

Plate 2 Facies 3a, Division C, north of Camas Sgiotaig, Eigg. Large scale tabular cross stratification 2.5m in amplitude representing in-channel bar bed forms in a major low sinuosity distributary.

Plate 3 Facies 5, Strathaird, Large scale 'load like' structures formed in sandy shell debris limestones below a sandy mudstone bed. The structures probably record elevated pore pressures and liquifaction of the sandy shelly sediments below the sandy mudstone (laterally persistent permeability barrier).

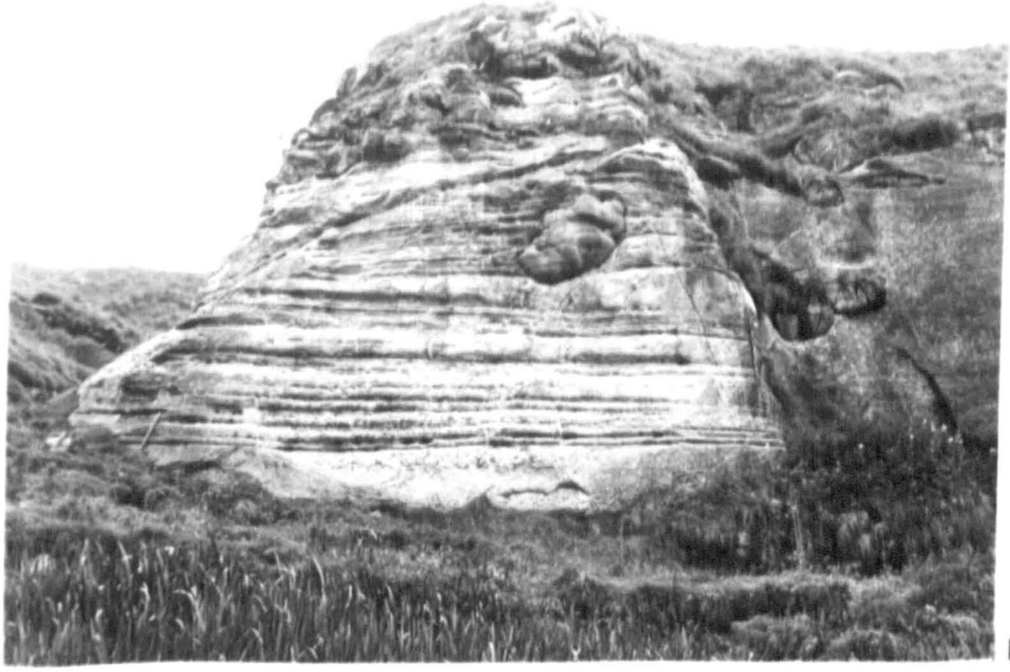


Plate 1


Plate 2


Plate 3

Plate 4 Facies 6, Division F, Muck. Large scale exhumed load casts truncated at the erosive base of a sandy limestone with shell debris.

Plate 5 Facies 4, Strathaird, Mud filled desiccation cracks formed in a laminated micritic limestone.

Plate 6 Facies 7, Strathaird. Thalassinoides burrows with shelly, mud pellet fill in a silty mudstone.

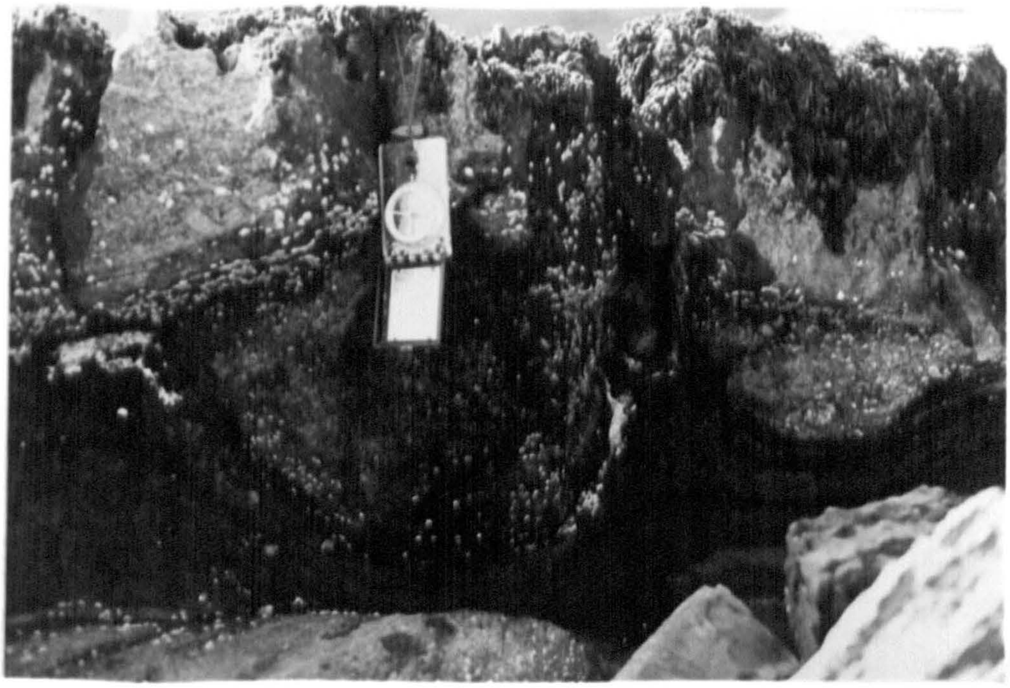


Plate 4

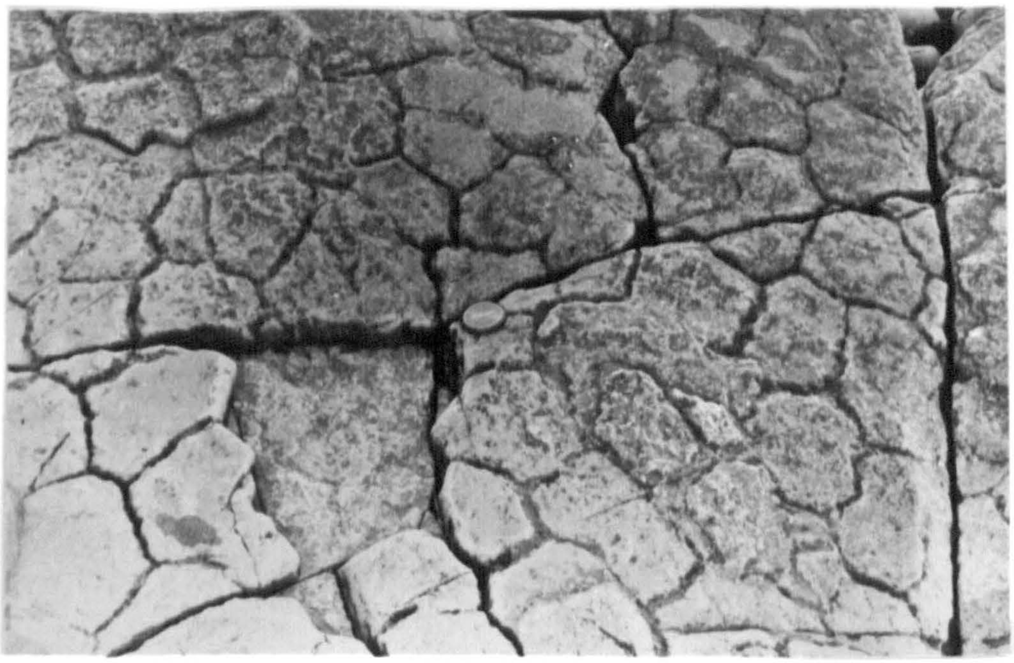


Plate 5


Plate 6

Plate 7 Division C,D and E, south of Camas Sgiotaig, Eigg. The lower cliff comprises a thin pro-delta muddy siltstone of facies 1 in the wave cut notch and coarsening upward delta front sands of facies 2 truncated by distributary channel sandstones of facies 3a. The unexposed section corresponds to pro-delta/offshore muds-silts. The upper cliff comprises a coarsening upward sequence with low angle offshore inclined delta front sands. These are overlain by probable shallow channel (facies 3a) and delta shoreline sandstones (facies 4). The cliff is capped by transgressive shell debris limestone of facies 5. Cliff is ca 27 m high.

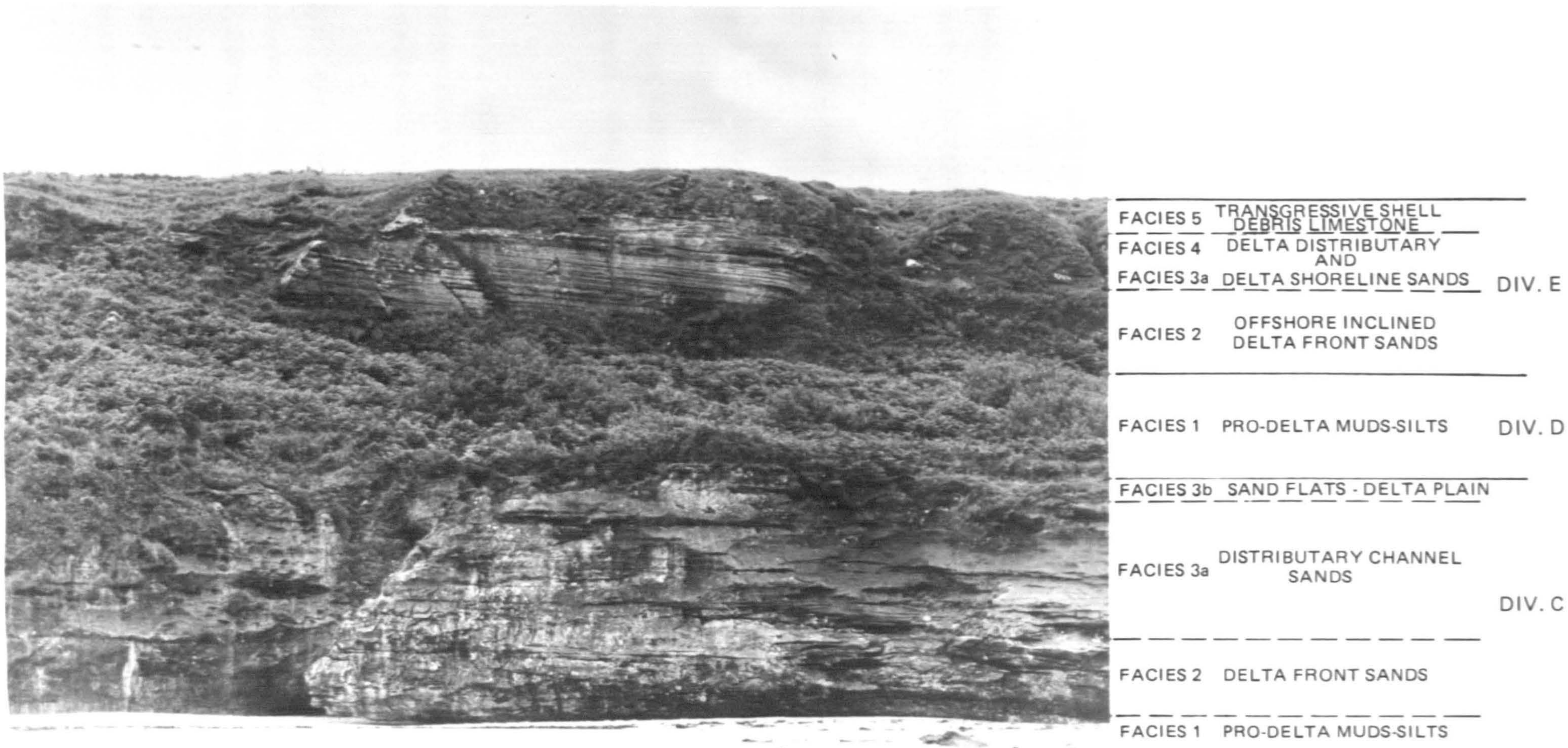

FACIES 5 TRANSGRESSIVE SHELL DEBRIS LIMESTONE
FACIES 4 DELTA DISTRIBUTARY AND
FACIES 3a DELTA SHORELINE SANDS
DIV. E
FACIES 2 OFFSHORE INCLINED DELTA FRONT SANDS
FACIES 1 PRO-DELTA MUDS-SILTS
DIV. D
FACIES 3b SAND FLATS - DELTA PLAIN
FACIES 3a DISTRIBUTARY CHANNEL SANDS
DIV. C
FACIES 2 DELTA FRONT SANDS
FACIES 1 PRO-DELTA MUDS-SILTS

Plate 7

CHAPTER 3

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CHAPTER 4 BATHONIAN FLUVIAL-WAVE INTERACTION LAGOONAL DELTAS AND LAGOON SHORELINE SANDSTONES, VALTOS FORMATION, SEA OF THE HEBRIDES BASIN AND THE PALAEOGEOGRAPHY OF THE HEBRIDEAN BASINS.

ABSTRACT

The Valtos Formation in the Sea of the Hebrides Basin comprises upper and lower sand dominated units and a middle limestone shale unit. In the sand dominated units low sinuosity fluvial distributaries define the axial areas of successive lagoonal delta progradational sequences. These pass laterally into beach face sequences representing wave dominated delta shorelines and interdeltaic lagoon shorelines. Each progradational sequence overlies offshore lagoonal muds and most are capped by transgressive shell debris (Neomiodon) limestones. The middle limestone shale unit represents low rates of clastic supply and comprises ?storm generated shell debris (Neomiodon) sheets and shoals interbedded with offshore lagoonal muds. The Valtos Formation in the Sea of the Hebrides Basin differs from that in the Inner Hebrides Basin in the dominance of wave over fluvial processes and corresponds with its greater size (hence fetch). As in the Inner Hebrides Basin the Neomiodon dominated fauna represents rapidly fluctuating salinities probably controlled by fluctuations in fluvial run off into a relatively small basin with a marine connection. Lithostratigraphic correlation allows the mapping of generalized depositional limits of successive lagoonal delta-lagoon shoreline progradational phases and with palaeocurrent data indicates NE-SW longitudinal basin fill. Most of the Valtos Formation sands were probably sourced in the ORS in the area of Wester Ross to the NE but the outcrops in west Skye include two easterly prograding phases with distinctive epidote dominated heavy mineralogy sourced in the Outer Hebrides landmass across the Minch Fault to the west.

CHAPTER 4

BATHONIAN LAGOONAL DELTA AND LAGOON SHORELINE SANDSTONES, VALTOS FORMATION, SEA OF THE HEBRIDES BASIN AND THE BATHONIAN PALAEOGEOGRAPHY OF THE HEBRIDES

I

INTRODUCTION

The type section of the Valtos Formation (ca 120 m) is defined by reference to outcrops in sea cliffs on the east coast of the Trotternish peninsula, north Skye (see Harris and Hudson 1980). Additional outcrops in north Trotternish occur in the Lealt River, Lonfearn Burn and south of Rubha Garbhaig. They provide the only complete section in the Valtos Formation in the Sea of the Hebrides Basin (ca 135 m) together with details of lateral facies variation. This account is therefore based primarily in north Trotternish. Incomplete sections occur elsewhere in the basin at Loch Bay (ca 22m) and Waterstein (ca 62m) in west Skye and on Raasay (ca 35m). Details of outcrop distribution are shown in figures 1 and 2 and each of the main sections is illustrated by means of graphic logs (figs 3-8 logs 1-10).

Although the type section of the Valtos Formation is defined in north Trotternish (because of thickness, diversity of facies and accessibility, Harris and Hudson 1980) the simplest facies sequences are on Eigg in the Inner Hebrides Basin. Because the genetic relationships of facies are not so readily apparent in north Trotternish the sedimentology of the formation has been discussed first in the Inner Hebrides Basin (see Chapter 3 above).

The Valtos Formation in the Sea of the Hebrides Basin in general repeats the facies association described from Eigg and Muck. In both basins the formation has a distinctive non marine fauna dominated by Neomiodon, and is interpreted as representing lagoonal muds with lagoonal deltas and associated shoreline systems. However, there are important differences reflecting differing rates of clastic supply, subsidence histories and basin energy regimes (waves and ?tides).

Facies in the Valtos Formation in the Sea of the Hebrides basin with the exception of 6b and 7b are the same as defined in the Inner Hebrides basin; these comprise:

1) Neomiodon Mudstone - Siltstone Facies, representing offshore lagoonal mudstones at the base of each facies sequence.

2) Coarsening Upward Sandstone Facies, representing delta front and lower - middle lagoon shoreface sands in lower part of each of the Valtos Formation sandbodies.

3) Coarse - 'Pebbly' Sandstone Facies, representing distributary channel and sand flat environments.

4) Wave Dominated Sandstone Facies, representing wave reworked (fluvially supplied), mid - upper shoreface, foreshore and backshore sands.

5) Neomiodon Debris Limestone Facies, representing transgressive deposits capping abandoned lagoonal delta and lagoon shoreline sandstones or shallow lagoonal shell debris, sheets and shoals intercalated with facies 1 mudstones - siltstones.

6a) Load Cast Facies, representing storm or flood generated shallow offshore/sublittoral sands intercalated with facies 1.

6b) Ripple Drift Cross Laminated Facies, representing a distinctive type of storm generated waning flow sandstone also intercalated with facies 1.

7a) Crustacean Burrow and Desiccation Crack Facies, representing periodically emergent lagoon shoreline mud flats.

7b) Rootlet penetrated Facies, representing vegetated areas of the delta plain, mudflats and sand flats.

The fauna, like that in the Inner Hebrides Basin, is dominated by the bivalve Neomiodon. It records rapid and wide salinity fluctuations (Hudson 1980), probably controlled by varying rates of fluvial run off (see discussion in Chapter 3 above). The fauna also includes the fresh water snail Viviparus and locally abundant fish debris including shark teeth and fin spines. Finely divided plant debris is common in all the sandstone facies and there are local accumulations of coniferous driftwood.

The Sea of the Hebrides Basin is larger than the Inner Hebrides Basin and probably therefore had a greater fetch. Consequently wave-formed structures and sequences are much more important than in the Inner Hebrides Basin.

The palaeocurrent pattern (recorded by means of rose diagrams and vector arrows included alongside the field logs) in the Sea of the Hebrides Basin is dominated by southerly flow directions demonstrating an axial sediment dispersal pattern with a copious supply of clastic sediment from the ENE. Occasional northerly flow directions record palaeocurrent reversals in the same manner as recorded for the formation in the Inner Hebrides Basin (Chapter 3, above). This palaeocurrent pattern could represent southerly fluvial and ebb currents with a subordinate northerly flood tidal component. However, this type of palaeocurrent pattern is not a diagnostic feature of tidality even when it occurs in fully marine sequences (Johnson 1978). The northerly paleoflow directions can be attributed to wind/storm driven currents. This is probably the most likely control on palaeocurrent reversals even though salinity fluctuations (recorded by the Neomiodon dominated fauna) would indicate a connection to the SW with the open sea.

Lithostratigraphy

The Valtos Formation is a sandy intercalation between the lagoonal muds and lagoon shoreline sediments of the Lealt Shale and Duntulm Formations. The Lealt Formation represents fresh-brackish and brackish marine salinities and the Duntulm Formation records marine-brackish salinities with occasional fresh water and hypersaline episodes (Hudson and Harris 1979).

The Valtos Formation is divided into 3 lithostratigraphic units in the type section in north Trotternish (Harris and Hudson 1980). These are; a lower sandstone dominated unit, a middle limestone-shale unit and an upper sandstone dominated unit. Parts of these units are recognisable in each of the sections and are illustrated graphically in figs 3-7.

The fence diagram (fig 8) illustrates the distribution and correlation of facies and facies sequences in north Trotternish. These define 12 divisions (I-XII) of the same status as the 7 lithostratigraphic divisions (Ai-F) defined in Eigg and Muck (Chapter 3).

In north Trotternish (fig 3 logs 1-4) the lower sandstone dominated unit comprises 5 coarsening upward sequences (divisions II-VI) with the facies sequence 1-->2-->5 and one (division I) with the facies sequence 1-->2-->4-->7b-->5. The middle limestone-shale unit (divisions VII-IX Log 4) is poorly exposed but comprises an intercalation of facies 1 and 5 (facies sequence 1-->5). The upper sandstone dominated unit in north Trotternish includes two divisions (X and XI Logs 4,5,6 & 7) with the facies sequence 1-->2-->3. Division XI is capped by facies 7b and 5 and is overlain by division XII comprising facies 1 mudstones-siltstones which intervene between the sandbodies of the Valtos Formation and the oyster bearing Duntulm formation.

In Raasay the lower sand dominated unit is very poorly exposed but probably comprises 1 division with the facies sequence 1-->2-->5 followed by an intercalation of facies 1 mudstone and facies 6 sandstone (Log 8 fig 4). The middle limestone-shale unit comprises intercalation of facies 1 and 5 (as in north Trotternish). The upper sandstone dominated unit is not exposed in Raasay.

In west Skye the equivalent of the lower sand dominated unit is exposed in Camas na Sithean, Waterstein (Fig 7 Logs 10 and 11). It comprises four divisions with the facies sequence 1-->2 (Log 10). Here the middle limestone-shale unit is only partially exposed. At Loch Bay in west Skye (Log 9) it comprises facies 1 muds and facies 7 limestones and at Waterstein (Logs 10 and 11) it includes facies 1 muds and Viviparus bearing sands. The upper sand dominated unit at Waterstein (An Stac) occurs as rafts in a Tertiary sill complex. It probably comprises 2 divisions; one with the facies sequence 1-->2-->4 and one in which faces 3 sandstones truncate facies 1 muds-silts (log 11).

Petrography and Provenance.

The results of heavy mineral analyses are included in appendix 1 and are discussed in Chapter 3 above. In the Sea of the Hebrides Basin the Valtos Formation comprises sub-feldspathic and locally feldspathic sandstones (5-26% feldspar) which are distinctly different from the equivalent feldspar poor rocks in the Inner Hebrides Basin.

Heavy mineral assemblages from the two basins are also different (see Hudson 1964 and Table 1 this Chapter and Chapter 3). The Valtos Formation in the Inner Hebrides Basin contains garnet poor, staurolite rich, rutile rich assemblages probably indicating a significant although indirect contribution of sediment from the Dalradian of the southern and eastern Highlands (Hudson 1964). In Raasay and north Trotternish the Valtos Formation contains garnet rich heavy mineral

	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Brookite	Tremolite
Inner Hebrides Basin Eigg & Muck	23	38	12	8	13	1	1	P	-	P	P	-	-
Sea of the Hebrides Basin Trotternish & Raasay	13	26	7	35	9	6	2	1	P	P	P	-	-
Sea of the Hebrides Basin Loch Bay	8	26	4	20	9	16	12	P	1	-	2	-	-
Sea of the Hebrides Basin Waterstein	7	2	P	4	2	3	69	2	1	3	2	3	4

Table 1 Average Heavy Mineral Composition (%) of Valtos Formation Sandstones
1.5–3.0 ∅ fractions, opaque grains omitted

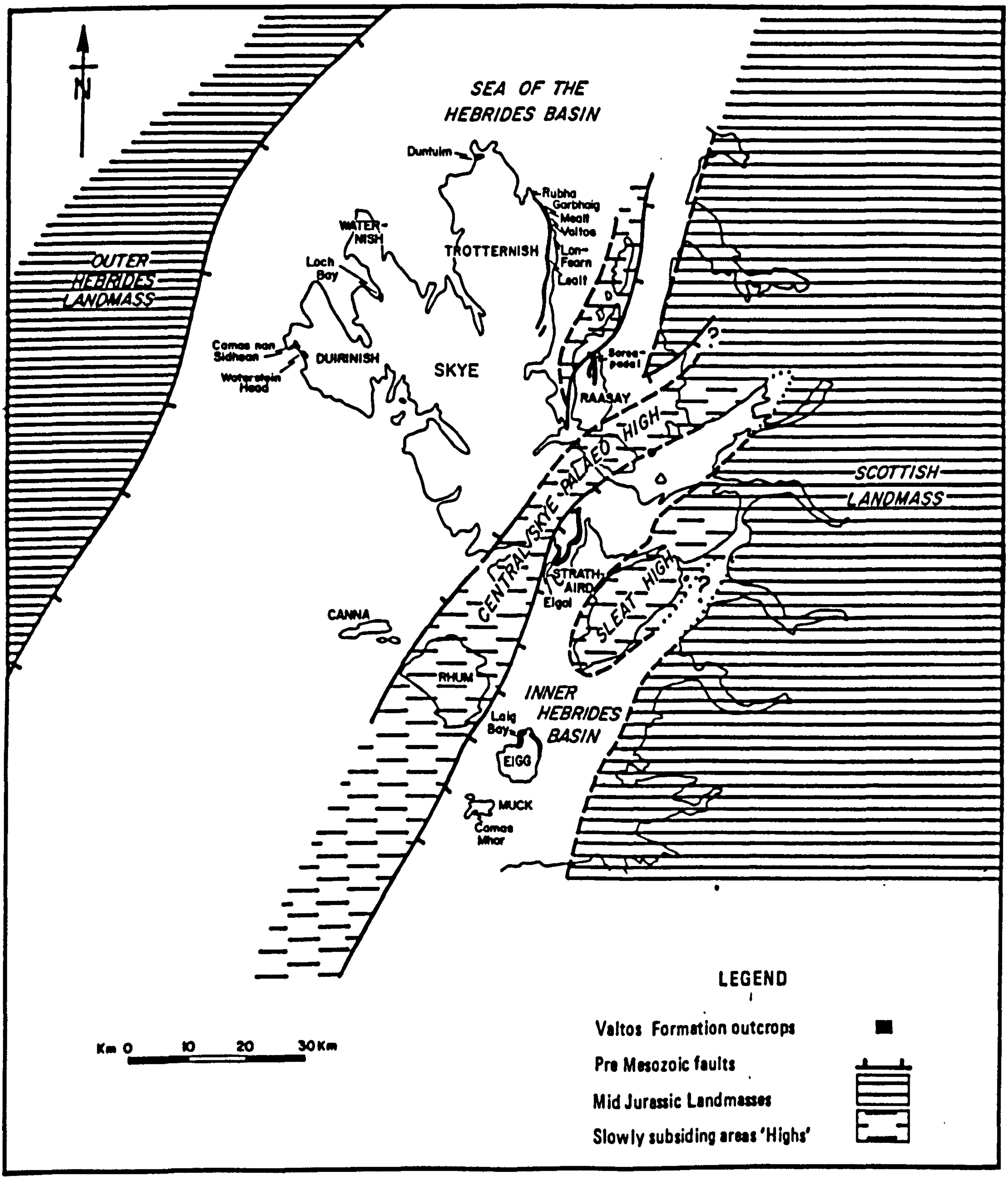

FIGURE 1 Major Mid-Jurassic structural controls on basin configuration (based on Binns et al., 1975; Steel 1976) and Valtos Formation outcrops

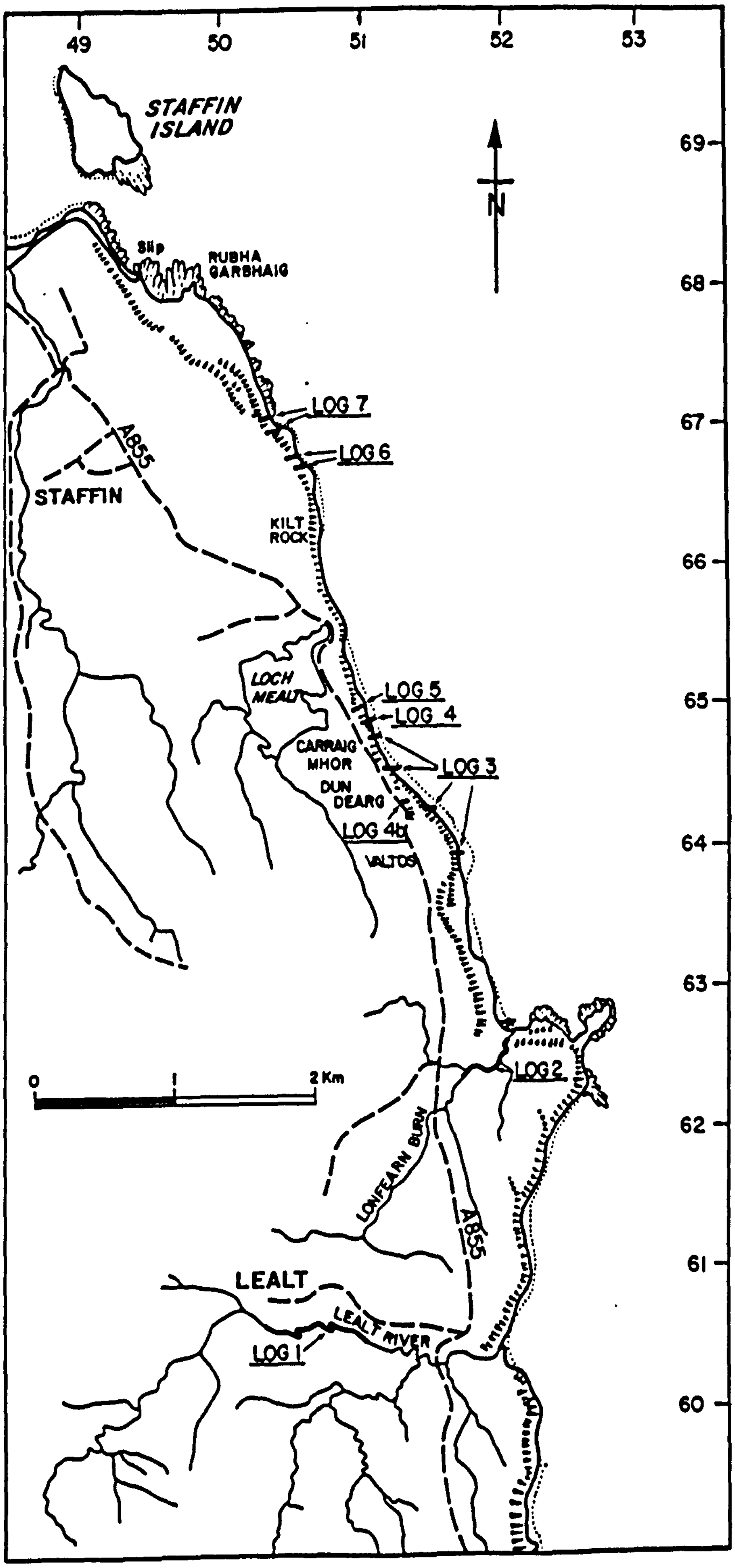

FIGURE 2 **Valtos Formation logged sections in North Trotternish**

assemblages with consistent amounts of kyanite and epidote, probably indicating a greater contribution of sediment from the Moines (Hudson 1964). Heavy mineral assemblages from the Valtos Formation in west Skye contain an average of 69% green epidote, probably derived from the Lewisian of the Outer Hebrides Landmass to the west (see table 1 and fig 10). This local dominance of Lewisian epidote is attributable to the position of the Waterstein outcrops, close to the western margin of the basin and coincides with local, easterly palaeoflow directions (see log 11 An Stac, Waterstein).

Because both the Hebridean/Minch basins have similar burial and diagenetic histories the differences in light and heavy mineralogy are attributed to differences in mineralogy of the source rocks exposed in the Hinterlands of the two basins. These source rocks for all but the west Skye outcrops were probably Old Red Sandstones overlying Moinian rocks in the area of Wester Ross to the NE and NNE of the Hebrides (see discussion in Chapter 3 above and Appendix 1).

Basin Configuration

The controls on configuration of the Middle Jurassic basin in the Hebridean area are illustrated in figure 1 and have been used to reconstruct the palaeogeographies shown in figure 11. These structural controls on sedimentation have been discussed in Chapter 3 and are based on the present day structural map of Binns et al (1975) and the Triassic palaeogeography of Steel (1976).

In the east the basins are controlled by the margin of the Caledonian fold belt giving a complex basin margin with numerous fault controlled embayments (cf Steel 1976). This margin approximates to the ancient deep basement structure discussed by Stewart (1982) in connection with structural controls on Torridonian sedimentation in Skye. The modern Sea of the Hebrides Basin has a deep downfaulted western margin controlled by the Minch Fault and is separated from the Inner Hebrides Basin by an elongate slowly subsiding ridge called the mid-Skye palaeohigh, Binns et al (1975). This structure is more fully discussed in Chapter 3. It probably accounts for important differences in sand body geometry and facies for most of the Mesozoic sandstones north and south of the structure while stratigraphy and facies in the limestone and shale formationsare remarkably consistent.

The northern limits of the ancient Sea of the Hebrides depositional basin were probably controlled by structures related to the Loch Maree Fault which separated the Sea of the Hebrides and North Minch Basins in the Triassic (McQuillin and Binns, 1973; Steel, 1976). The basin was possibly open to the south where it probably had a marine connection. However, the controls on basin configuration in this area (west of Coll and Tiree and in the area of the Stanton Banks) are not fully understood (Binns et al 1975).

KEY TO LOG SYMBOLS

LITHOLOGICAL SYMBOLS

- Sandstone
- Sandstone Pebbly
- Sandstone Shaly
- Sandstone Shale / Carbonaceous streaks
- Limestone
- Limestone Sandy
- Marl
- Dolomitic Limestone
- Intraformational Pebbles
- Oolitic Limestone
- Shale

LITHOLOGICAL LOG ABBREVIATIONS

CLASTICS

s - Shale / Clay
f - Fine Sand
m - Medium Sand
vc - Very Coarse Sand
p - Pebbles

CARBONATES

ml - Marl
cl - Calcilutites
ca - Calcarenites
cr - Calcirudites

PALAEONTOLOGICAL SYMBOLS

- Bivalve Molluscs Articulated
- Bivalve Molluscs Disarticulated
- Bivalve Molluscs Broken
- Oysters Articulated
- Oysters Disarticulated
- Gastropods
- Brachiopods
- Ostracods
- Estheriids (Cyzicus)
- Fish Teeth Scales & Bones
- Reptile Bones
- Allochthonous Lignite
- Driftwood
- Plant Fragments
- Nodular Algae
- Stromatolitic Algae

SEDIMENTARY STRUCTURES

- Trough Cross Stratification
- Planar Cross Stratification
- Low Angle Stratification
- Current Ripples
- Erosive Surfaces
- Loaded Surfaces
- Desiccation Cracks
- Desiccation Breccia
- Gypsum Pseudomorphs

BIOGENIC STRUCTURES

- Degree of Bioturbation
- Planolites
- Monocraterion
- Diplocraterion
- Thalassinoides
- Lockia / Pelecypodichnus

DIAGENETIC STRUCTURES

- Calcareous Concretions
- Septaria
- Fibrous Calcite Veins / Beef

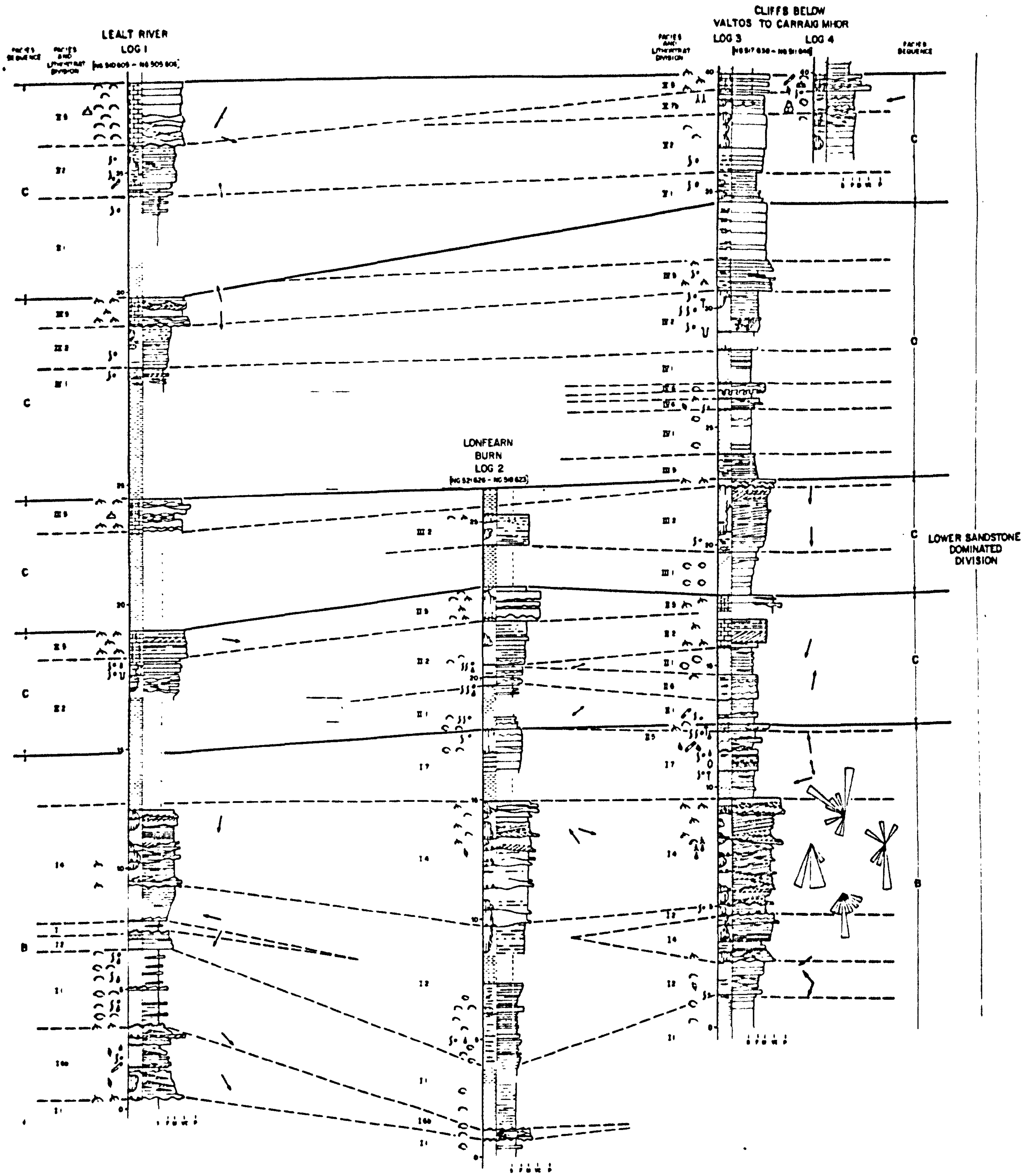

FIGURE 3 Graphic logs (1-4) of divisions I-V, lower sandstone dominated unit of the Valtos Formation, North Trotternish.

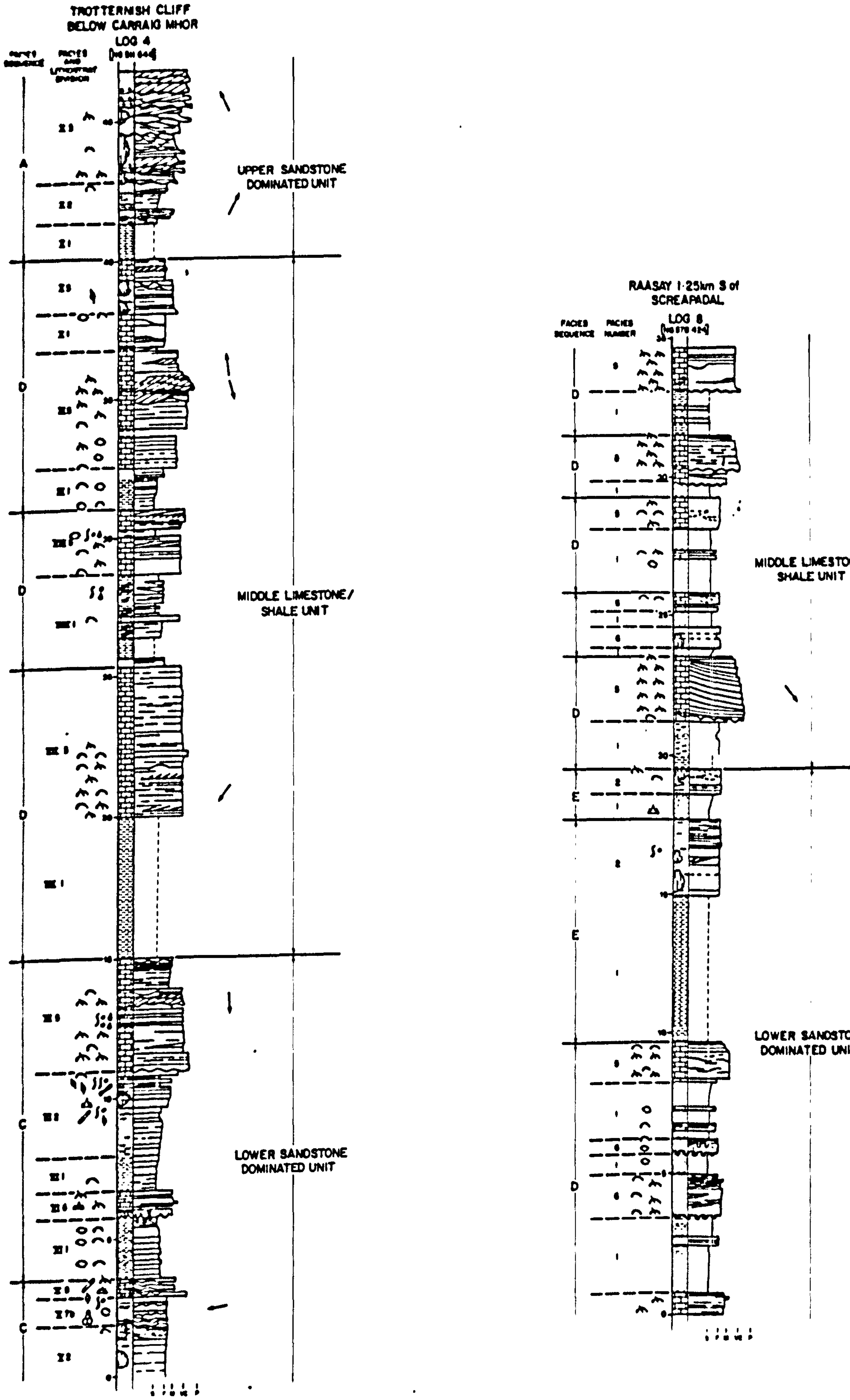

FIGURE 4 Graphic logs of divisions V-X, lower sand dominated, middle limestone shale and upper sand dominated units of the Valtos Formation, North Trotternish and the equivalent rocks of Raasay.

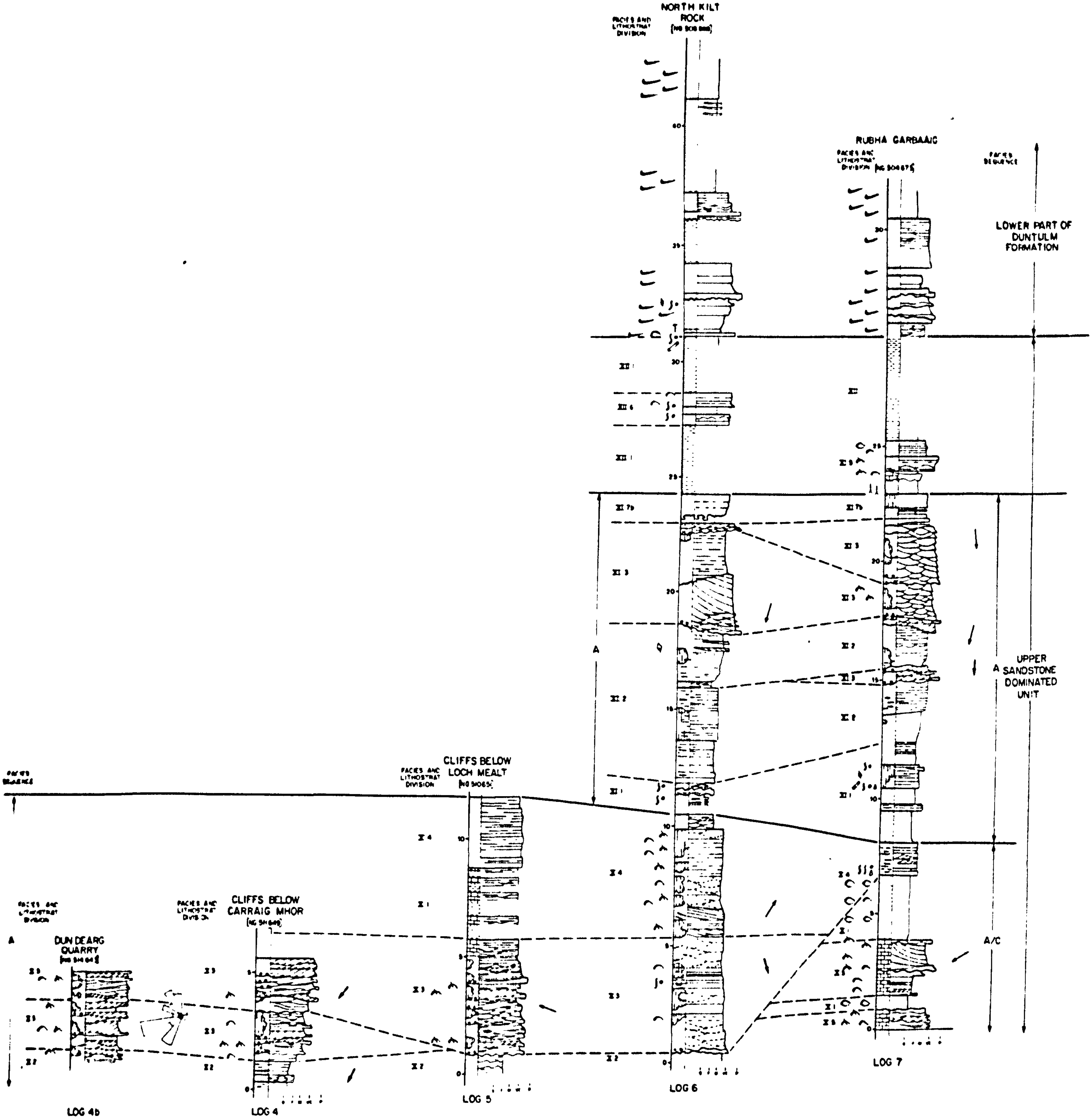

FIGURE 5 Graphic logs (4-7) of divisions X-XII, upper sandstone dominated unit of the Valtos formation and the basal Duntulm Formation, North Trotternish.

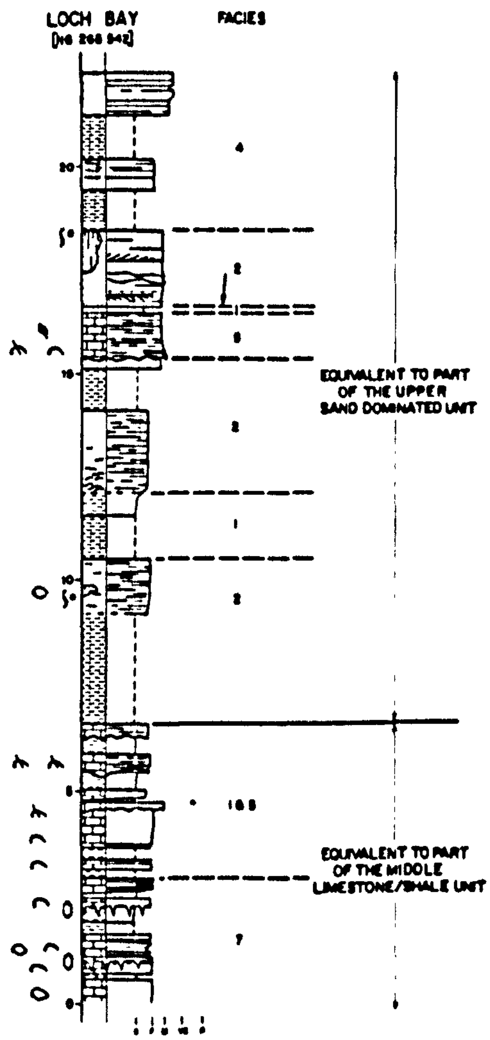

FIGURE 6 Graphic log of the Valtos Formation, Loch Bay, Waternish.

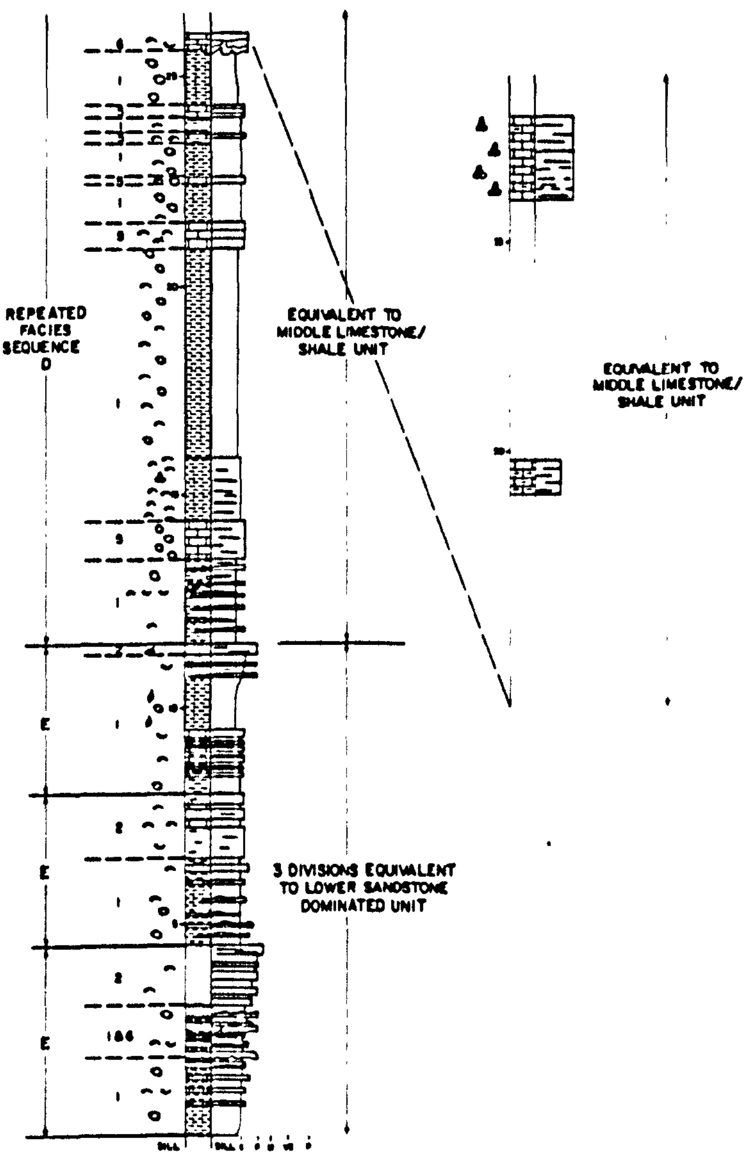

FIGURE 7a Camas Nan Sidhean, Waterstein, Duirinish, W.Skye log of rocks equivalent to the Lower Sand Dominated and Middle Limestone/Shale Units (NG 141 477).

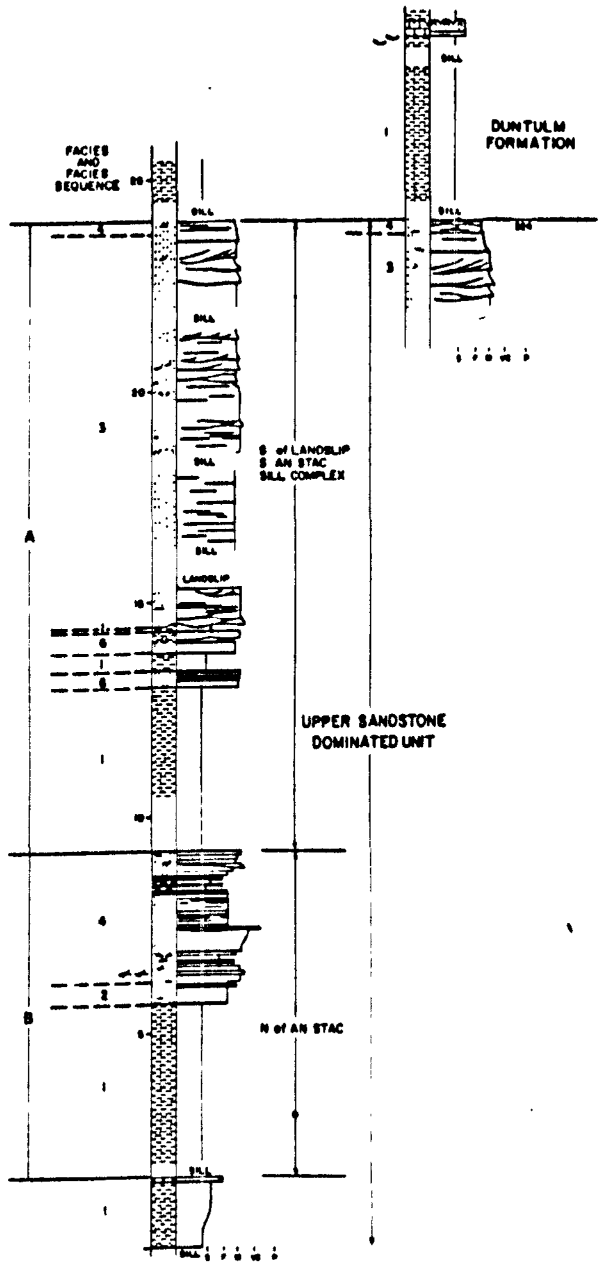

FIGURE 7b An Stac Waterstein, Duirinish, W.Skye, composite field log of the Upper Sandstone Dominated Unit preserved as rafts in a Tertiary sill complex (NG 144 468).

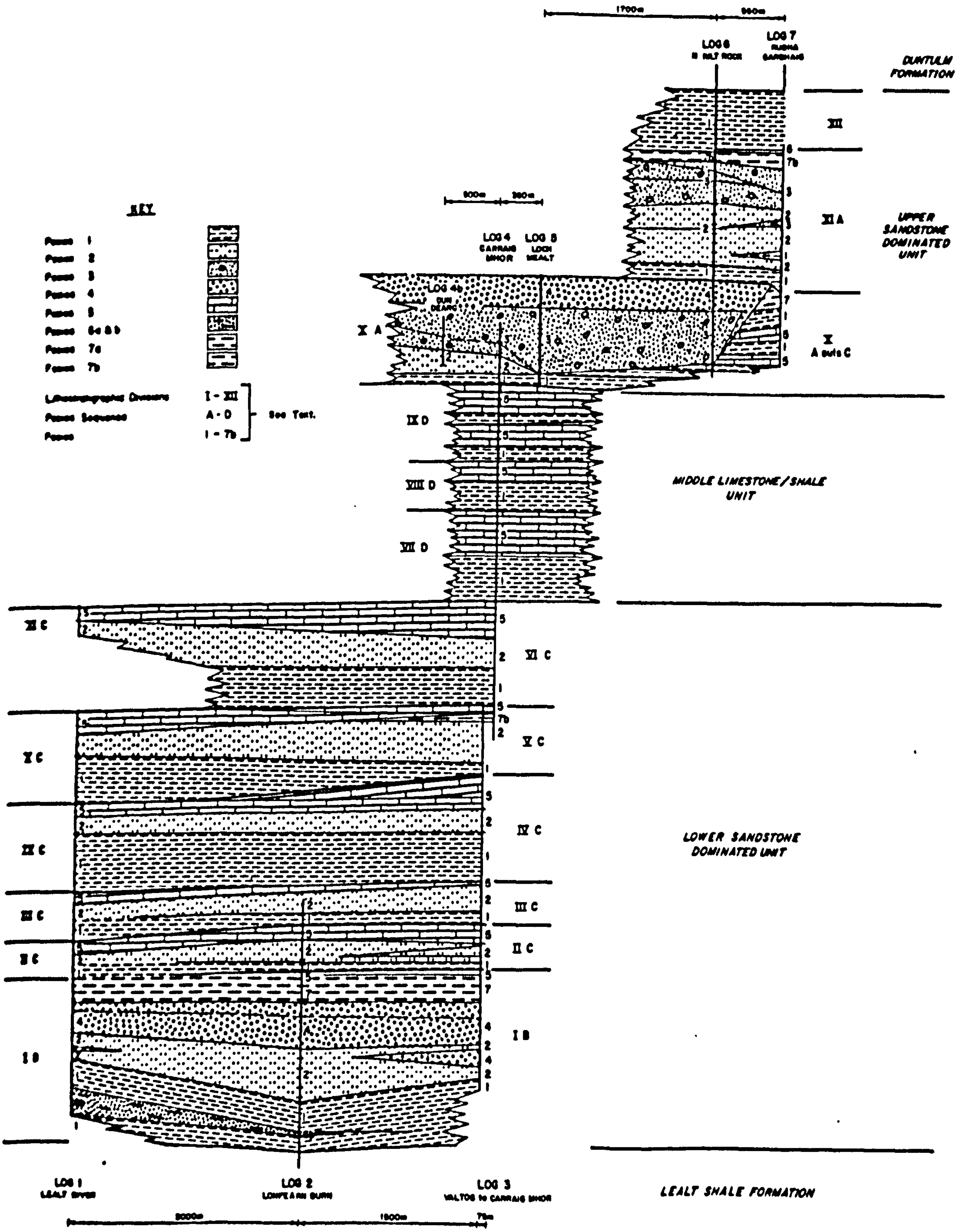

FIGURE 8 Lithostratigraphic correlation of the Valtos Formation in North Totternish, Skye.

FACIES DESCRIPTION AND INTERPRETATION

The facies defined above are based on distinct associations of lithology, grain size profile, sedimentary structures, trace fossils and macrofossils. The characteristics of these facies and facies sequences are illustrated in the graphic log (figs 3-7) and in the lithostratigraphic section (fig 9). Examples of localities providing good or typical sections in each of the facies are specified at the beginning of each description.

FACIES 1 Neomiodon Mudstone-Siltstone Facies (eg. Lealt River division. I & Valtos division III).

DESCRIPTION

Like its facies equivalent in the Inner Hebrides Basin these grey-greenish grey mudstones and siltstones include thin sands with wave and current ripples and interference rippled surfaces. The facies contains scattered Neomiodon and thin monotypic beds of Neomiodon occurring as intact single valves and articulated specimens. Shell orientations are probably random with very few convex up or imbricated specimens.

Facies 1 mudstones and siltstones are overlain by, or pass gradationally into facies 2 sands at the base of the coarsening upward sand bodies and are interbedded with limestones of facies 5 in the middle limestone-shale unit. They locally contain sheet sands of facies 6a and 6b.

INTERPRETATION

Facies 1 represents low current velocities with an insitu fauna of Neomiodon demonstrating rapid and wide salinity fluctuations. The facies records the establishment of shallow brackish lagoons with the lagoon floor above storm wave base; demonstrated by the thin wave rippled sands. Neomiodon concentrations show apparently random orientations and lack the 'edgewise' and imbricate relationships characteristic of wave and current processes defined by Futterer (1982). However, they occur in distinct lenticular beds and burrowing is ubiquitous so that they are probably bioturbated wave winnowed concentrations.

FACIES 2 Coarsening Upward Sandstone Facies (e.g. Lealt River division IV 2 Rubha Garbhaig division X1).

DESCRIPTION

Facies 2 sands occur at the base of each of the Valtos Formation sandbodies in north Trotternish and contain distinctive sub spherical and botryoidal calcite concretions. The facies comprises gradational coarsening upward sequences frequently composed of bioturbated structureless sands. Locally mud partings and thin interbeds occur. These commonly overly sharp based sands and drape wave rippled surfaces. Basal bedding plane surfaces preserve Pelecypodichnus (very probably formed by Neomiodon), Teichichnus (Plate 1) and rare 'U' burrows. Wave ripples are dominant in some sequences and others particularly in the upper sand dominated unit, include trough crossbed sets, coarse grained scour and fill structures and current ripples.

Articulated and intact single valves of Neomiodon occur in common calcite concretions but are rare in the thick facies 2 sands in the upper sand dominated unit. In west Skye facies 2 forms subdued coarsening upward sequences with gradational basal contacts with facies 1 mudstones-siltstones (log 10 fig 7).

INTERPRETATION

Facies 2 sands in the lower sand dominated unit contains both wave and current generated structures and are interpreted as representing the lower-middle shoreface of delta shoreline and interdeltaic lagoon shoreline sequences.

In the upper sandstone dominated unit the thicker developments of the facies probably represent mouth bar sands truncated by the overlying distributary channels of facies 3.

The facies records a progessive upward increase in flow velocities and numerous fluctuations in current energy allowing mud deposition or bioturbation to occur. Fluctuations in flow velocity in delta and lagoon shoreline sequences are attributed to storms (cf Kumar and Sanders 1976). Scour and fill structures and trough cross-bed sets in the mouth bar sands probably record deposition from waning currents representing individual flood events.

FACIES 3 Coarse - Pebbly Sandstone Facies (e.g. Rubha Garbhaig division XI)

DESCRIPTION

Major fining upward very coarse-medium grained moderately well sorted sandstones of facies 3 are the dominant components of division X and XI (fig 5) but are absent from outcrops of the Lower sand dominated unit.

In north Trotternish (division X and XI) facies 3 sandbodies contain pebble lined basal erosion surfaces defining the limits of fining upward sequences with channel like geometries (Plate 2 & 3). The facies also occurs with a coarsening upward profile at Dun Dearg and Carraig Mhor (logs 4a and 4b).

The simplest development of the facies comprises a composite fining upward sequence of trough cross stratified cosets with large scale planar cross bed sets. In logs 4b and 5 (Carraig Mhor and Loch Mealt) the lower parts of the fining upward sequences are dominated by thin clast supported conglomerates (vein quartz and quartzites) overlying scour surfaces (Loch Mealt and North Kilt Rock). In logs 5 and 6 the sequences are overlain by facies 4 sandstones with wave generated structures. Log 6 (north Kilt Rock, division XI) and log 7 (Rubha Garbhaig division XI) illustrate the relationships of successive channel form sands, each of which overlies a pebbly lag and forms part of another major multistorey sandbody (see Plates 2 & 3). Although the cliffs shown in Plates 2 and 3 only provide a single oblique

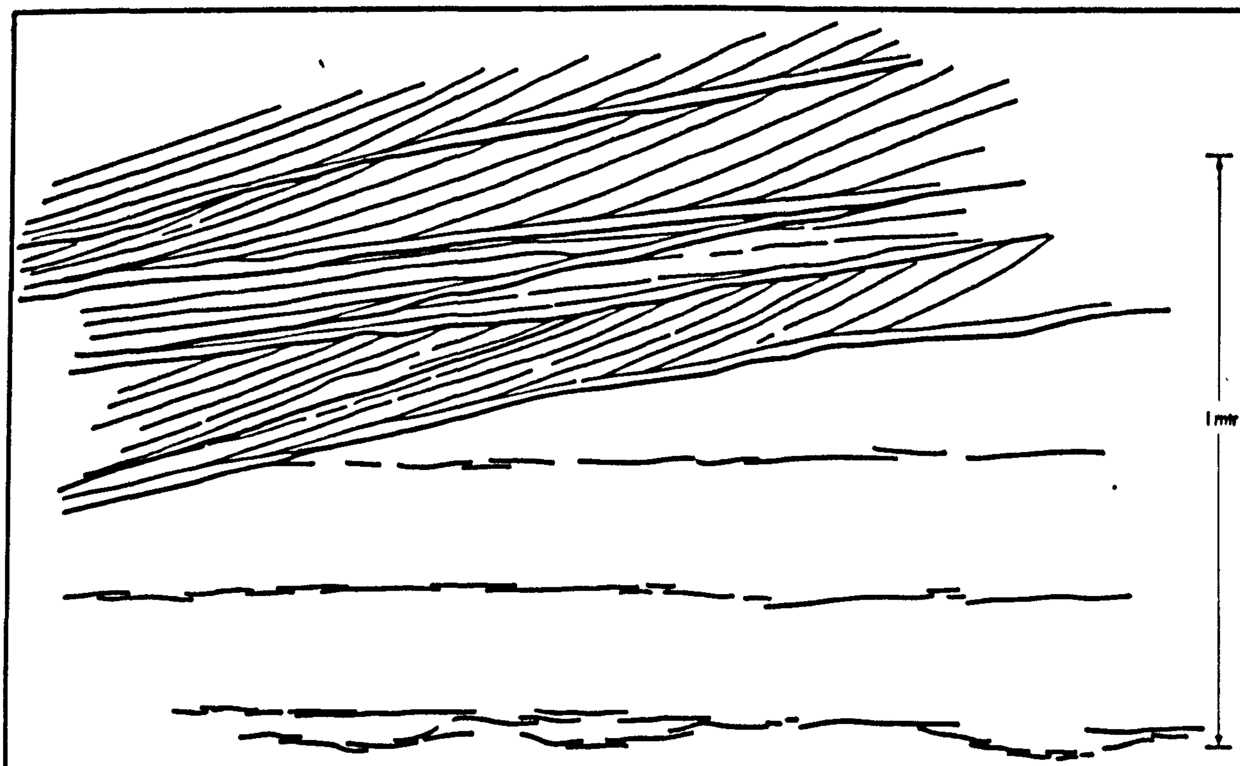

FIGURE 9 Field sketch to show basal erosion surface of facies 3, channel form sands with low angle inclined lateral accretion surfaces and reactivation surfaces.

section through the sandbody and access is difficult, it can be seen to comprise low angle (up to 12°) bounding surfaces to sets of trough and planar cross strata. North of the Kilt Rock (log 6 Plate 2) these surfaces are marked by accumulations of granules and small pebbles and represent reactivation surfaces separating 20-30 cm high avalanche sets (see field sketch fig 9). Large scale trough cross beds (amplitude up to 50 cm) locally overlie the pebble lined basal erosion surface. The fining upward profile in these sequences is subdued and often is only apparent at the top where fine and fine-medium grained sands are capped by mudstones (rarely rootlet penetrated) of facies 7b.

Facies 3 in log 4a & b (Carraig Mhor and Dun Dearg) comprises a coarsening upward sequence of pebbly scour and fill structures and trough and planar cross bed sets with reactivation surfaces. Neomiodon are preserved in ferroan calcite concretions but are absent from outside the concretions (Plate 4).

Palaeocurrent flow directions are predominantly S-SW but in the coarsening upward sequence illustrated in log 4b there is a wide spread of palaeoflow directions with a WSW mode but including flow to the ENE.

INTERPRETATION

Facies 3 sandstones are interpreted as distributary channel fill sequences and their associated, high current energy, channelised proximal mouth bar sands. The fining upward sequences include multistorey and multilateral channel forms.

In division X (logs 4b and 5) the repetition of scour surfaces and pebble lags demonstrates numerous fluctuations in river stage. This together with the texture of the sands (medium-very coarse grained) and the suite of sedimentary structures (trough and large scale planar cross stratification) representing in-channel dune and transverse bar bedforms, suggests low sinuosity channel types. The sand dominated, South Saskatchewan type of low sinuosity fluvial deposits (Cant and Walker 1976, 1978; Miall 1977, 1978) probably bear the closest resemblance to the divisions X sands although the facies relationships of the fluvial sands is obviously very different.

The coarsening upward sequences in logs 4a and 4b include a similar suite of sedimentary structures together with accumulations of disarticulated and broken Neomiodon. They represent fluctuating flow velocities and a general upward increase in current energy. These sands are interpreted as representing a friction dominated mouth bar with a channelized bar crest. This type of mouth bar is controlled by high rates of bed load transport, high outflow velocities and shallow water basinward of the river mouth (Wright 1977); see discussion in chapter 3 above). The high spreading angles of friction dominated outflows are probably recorded in the wide range of palaeoflow directions at Dun Dearg (log 4b).

The interpretation places the base of the channel fill sequence at 3.75 m in log 4b and indicates complete truncation of bar crest sands at the base of log 5. Erosion of Neomiodon bearing mouth bar sands is taken as the reason for the occasional occurrence of broken Neomiodon in some of the fining upward, distributary channel sequences.

The multilateral channel forms (log 6 in north Kilt rock, division XI and log 7, Rubha Garbhaig, division XI, Plates 2 & 3) include low angle bounding surfaces to sets of planar and trough cross strata demonstrating that they are at least in part side filled channel forms. This component of lateral accretion is not apparent in the axial areas of individual channel form sands where bounding surfaces are horizontal indicating in-channel vertical accretion. The low angle surfaces may record the development of the 'side bars' described from low sinuosity fluvial systems by Allen (1968), Collinson (1970). These bedforms slope gradually into the channel and are blanketed by dunes or sandwaves. These relationships could generate the structure sketched in fig 9. However, they also closely resemble the modified slipface sediments of scroll bars described from the coarse grained, high sinuosity Lower Wabash River (Jackson 1976). In this system fluctuations in flow velocity generate reactivation surfaces which are subsequently draped by avalanche sets recording movement of the scroll bar crest. Vertical profiles resembling division X and XI of the Valtos Formation are also recorded by Nijman and Puigdefabregas (1978) from an ancient coarse grained high sinuosity fluvial system. The presence of low angle lateral accretion surfaces and reactivation surfaces could therefore mean that facies 3 is in part the product of coarse grained high sinuosity rather than low sinuosity fluvial distributary system.

Although the facies 3 sandstones resemble fluvial sequences their association with Neomiodon bearing, mouth bar sands and offshore lagoonal muds demonstrates that they are delta distributary channels. They therefore represent the axial areas of individual lagoonal delta progradation sequences. The interaction of fluvial and basinal processes is probably responsible for the variability in style of channel fill in this part of the Valtos Formation and means that these channel sands may have some affinities with estuarine channel-sand flat environments. e.g. Bridges and Leeder (1976).

The correlation diagram (fig 8) indicates that fluvial distributary sands truncate offshore lagoonal sediments in division X, between logs 5 and 7. This implies a lowering of base level by contraction of the lagoon and correlates with the resumption of clastic supply which ended deposition of the middle limestone/shale unit.

FACIES 4 Wave Dominated Sandstone Facies (e.g. Valtos, division I, Lealt River division I)

DESCRIPTION

The facies varies from planar laminated and low angle cross laminated sands (probably swash cross stratified) with Neomiodon debris (e.g. division X) to thicker more complex sands in division I. The facies contains distinctive large scale calcite concretions (Plate 6)

In division I (figure 3 logs 1, 2 and 3) the facies shows considerable lateral variation but all three of the sections exhibit wave generated structures (including probable swash cross stratification cf. Harms et al 1975) and contain disarticulated Neomiodon preserved in ferroan calcite concretions. Logs 2 (Lonfearn) and 3 (Valtos) have a distinct coarsening upward profile but log 1 (Lealt) includes scour surfaces and coarse grained sands with scattered pebbles at the base.

In logs 1 and 2 the facies comprises massive and planar laminated sands with scour and fill structures containing accumulations of small pebbles. However below Valtos (log 3), the sequence is more complex including a diverse suite of current and wave generated structures and a complicated pattern of palaeoflow directions (see log 3).

At the base, a subsidiary coarsening upward sequence with current and wave generated structures is overlain by poorly sorted sands with scattered pebbles and Planolites type burrows associated with mud partings. Above this, planar laminated well sorted sands contain isolated planar and trough cross bed sets with unimodal S palaeocurrent directions (rose iv log 3). Above 6.5 m (Plate 5) low angle inclined planar lamination includes isolated scour and fill structures with palaeocurrents oblique to the consistent S dip of the inclined lamination. Also at this horizon is a planar laminated pebbly sandstone with a basal scour surface and vertical escape structures, probably of Neomiodon (see Plate 6).

Above a pebble lined scour surface at 7.75 m the facies includes swash cross lamination comprising alternating granule poor and pebbly granule rich laminae (Plate 7). Low angle discordances occur between sets which exhibit a consistent southerly inclination direction (rose ii log 3). 75 m north along the outcrop swash cross lamination is replaced by trough and high angle planar cross stratification with dominant S palaeoflow directions but including subordinate N palaeocurrents (rose iii log 3).

The top of the sand body comprises very pebbly calcite cemented sands with Neomiodon debris. These sands are dominated by high angle planar cross stratification giving N palaeocurrents (rose i log 3) and are overlain by mudstones-siltstones and thin sands with desiccation cracks of facies 7.

INTERPRETATION

Facies 4 contains a variety of current and wave generated sedimentary structures and in combination with the underlying facies 2, lower shoreface deposits (e.g. in division I) is interpreted as recording a complete beach face sequence. In division X, however, the facies overlies distributary channel sandstones and is interpreted as representing reworking in the upper shoreface-foreshore of fluvially supplied sediment at a prograding delta shoreline. Modern examples of this sequence have been documented from fluvial-wave interaction and fluvial-wave-tide interaction deltas e.g. (Oomkens 1967, 1970; Maldonado 1975 and Allen 1965; Weber 1971; Oomkens 1974; Elliott 1978).

In division I (logs 1 and 2) the repeated pebble lined scour and fill structures are similar to the storm generated middle-upper shoreface deposits described by Kumar and Sanders (1976). In the middle shore face, shoaling storm waves winnow the sediment generating pebble lined scours which are infilled as the storm wanes. The cross stratified and planar laminated sands with Neomiodon escape structures in log 3 (Plate 6) are also attributed to storm events. These demonstrate that

Neomiodon lived in, or was washed into the shoreface zone and could escape through ca 30 cm of sediment deposited in one event. Truncated escape structures demonstrate the repetition of these storm events.

The subsidiary coarsening upward sequence in the lower part of log 3 (2-5 m), includes wave and current generated structures and is capped by muddy bioturbated sands. This sequence is in general similar to the shore parallel, shoreface bar (outer bar) and trough sediments of Davidson-Arnott and Greenwood (1976). Higher in the sequence the scour and fill structures truncating planar laminated and bioturbated (probable fair weather) deposits are similar to the inner bar crest sands of Davidson-Arnott and Greenwood (1976). This sequence probably represents the ridge and runnel topography of a barred shoreface..

The top of facies 4 in division I contains probable swash cross stratification (Plate 7) in which the textural alternations and low angle discordances represent adjustments of the foreshore profile to changing wave energies. The consistent S dip of these structures defines an E-W shoreline trend with S progradation of the shoreline. The foreshore sands also include high angle landward orientated sets of planar cross strata. These are interpreted as recording the landward migration of a fair-weather bar or ridge (cf. Davies et al, 1972). Complex palaeocurrent distribution patterns present in the shoreface - foreshore sediments (roses ii, iii and iv, log 4) and in the overlying, probably storm generated backshore sediments are typical of beach face sediments (Davies et al, 1972; Reinson, 1979).

FACIES 5 Neomiodon Debris Limestone Facies (eg Lealt River and Valtos, division V)

DESCRIPTION

Facies 5 comprises disarticulated and broken Neomiodon mostly orientated parallel to bedding and predominantly convex up. The facies has a variably sandy matrix and commonly includes quartz pebbles lining shallow scours. It is always cemented with sparry calcite and is similar to its equivalent in the Inner Hebrides Basin.

The facies usually has a sharp or erosive base. It caps coarsening upward sequences in the lower sand dominated unit (1.25-2.5m thick) where imbricate stacks of shells are common and is intercalated with facies 1 shales in the middle limestone-shale unit (1-5.5m thick). It includes occas ional thin dark mudstones together with rare shark teeth and fin spines (Plate 8).

Sedimentary structures are generally indistinct but in addition to scour and fill it includes poorly defined cross stratification (giving bimodal generally N-S palaeocurrents but with a dominant S mode) undulose lamination and locally large scale low angle surfaces. However, most facies 5 limestones are structureless and some are probably bioturbated. In the middle limestone-shale unit facies 5 limestones occasionally include lenticular or broadly channel form bodies up to 2 m thick and large scale tabular avalanche sets inclined at 14°-20° (giving S palaeoflow directions). These overlie a pebbly basal erosion surface and truncate largely structureless limestones of similar texture so that they locally also truncate facies 1 mudstones (ses log 8, 21.5-25.5m).

In the lower sand dominated unit facies 5 limestones are locally reddish-brown weathering and include micritic intraformational limestone pebbles (Plate 9) reptile bones and abundant fish debris, including bones and scales and large numbers of Hybodont shark teeth.

INTERPRETATION

Facies 5 represents high current velocities but low rates of clastic supply leading to the concentration of shell and fish debris. In the lower sandstone dominated unit, the facies intervenes between progradational shoreline sediments (with evidence of subaerial exposure below the shell debris limestone in divisions I and V) and offshore lagoonal muds and is therefore interpreted as recording repeated, shallow, brackish transgressions of the delta and lagoon shoreline. Most of the shoreline-delta progradation sequences underlying facies 5 are incomplete indicating erosion of shoreline and coastal plain sediments during transgression with the subsequent addition of large amounts of Neomiodon debris.

These limestones represent small scale shell debris dunes blanketing pebbly scour surfaces with occasional dark shales recording widely fluctuating current energies. Imbricate stacks of Neomiodon valves occur locally and may represent wave generated concentrations as defined by Futterer (1982). Large scale low angle surfaces (inclined to SE in division V, log 1) may represent bar flank accretion surfaces (cf Johnson 1977) and although southerly palaeocurrents predominate, bimodal N and S flow directions demonstrate tidally or more probably storm induced flow reversals. Deposition of these shell debris limestones is thought to record shallow water with high current and wave energies on the subsiding delta plain.

The truncation surfaces and shell debris bars and dunes probably represent a sequence of events analogous to the delta destructive phase of marine deltas outlined by Scruton (1960) and Coleman and Gagliano (1964). A similar sequence of events is proposed for lacustrine deltas by Stanley and Surdam (1978 p562).

Although the red weathering limestones with fish debris and reptile bones in facies 5 are not true bone beds they have some similarities to the Rhaetic bone beds of SW Germany described by Aepler (1974). In this system some of the bone beds are interpreted as condensed sequences comprising pre-phosphatized bone material derived from the erosion of delta plain, lagoonal muds during transgression (Aepler 1974). The limestones with fish debris in facies 5 have similar stratigraphic and facies relationships and could represent a similar sequence of events although there is no direct evidence of pre-phosphatization.

In the middle limestone-shale unit, shell debris limestones representing high organic productivity and an absence of siliciclastic supply are intercalated with offshore-lagoonal mudstones. The presence of trough and tabular cross bed sets representing dunes and bars demonstrates the dominance of current over wave processes. The dominant texture of the limestones (disarticulated valves parallel to bedding or imbricated and predominantly convex up) also indicates deposition from currents rather than waves (cf Futterer 1982). The individual bioturbated beds record low current energy periods occurring between high current energy episodes responsible for the generation of shell debris bedforms.

These facies 5 limestones appear similar to the Carboniferous crinoidal grainstones and coquinas interpreted by Jeffery and Aigner (1982) as carbonate analogues of the shallow marine 'blanket sandstone' model developed by Anderton (1976). In Anderton's model dunes and sandwaves are formed by tidal (fair weather and moderate storm generated currents and are partially destroyed under intense storm conditions leading to the formation of pebbly lags and weak channel structures. This suite of structures is broadly analogous to those of facies 5 in the middle limestone-shale unit. The down current decrease in grain size and bedform size invoked in Anderton's (1976) model, may also be applicable to the Valtos Formation limestones (compare log 4, Carraig Mhor, Trotternish with the southerly, shale dominated equivalent rocks with fine grained, thin bedded limestones in log 10, Waterstein, West Skye).

<u>FACIES 6a</u> Load Cast Facies (eg Valtos division IV and Carraig Mhor division VI)

DESCRIPTION

Facies 6a comprises fine-very fine grained sandstones occurring as single beds (ca 10 cm - 1 m thick) or groups of beds intercalated with mudstones-siltstones of facies 1. Most of these sand beds have loaded bases, include transported Neomiodon, occasional shark teeth and are locally current rippled. As with facies 6 in the Inner Hebrides Basin these sand beds are usually calcite cemented but occur intermittently throughout the Formation rather than being limited to the top.

INTERPRETATION

Rapid deposition is demonstrated by the sharp loaded bases. The sands are interpreted as storm surge ebb, sublittoral sheet sands and are therefore genetically associated with the overlying lagoon shoreline sequences.

FACIES 6b. Ripple drift Cross Laminated Facies (eg Lealt River division I)

DESCRIPTION

Facies 6b occurs close to the base of the Valtos Formation in north Trotternish and is intercalated with facies 1 mudstones. The facies has not been recorded in the Inner Hebrides Basin. It comprises erosively based graded sandstones 10-30 cm thick occurring as a group of beds in the base of logs 1 and 2. Some are amalgamated to produce sandstones up to 1 m thick.

Individual facies 6b sandstones typically comprise shell debris and intraformational mud clasts overlying a basal scour surface followed by indistinct planar lamination overlain by ripple drift cross lamination. The ripple drift cross lamination usually exhibits an upward increase in the angle of climb and locally includes the transition from the type 'A' to type 'B' of Jopling and Walker (1968).

These structures are picked out by accumulations of finely divided plant debris in the lee of the ripples (see Plates 10 & 11).

The basal scour surface of some of the sand beds has a low angle cross stratified fill (Plate 12) and occasional slump structures occur. These comprise small scale recumbent folds with horizontal axial plane traces which are overturned to the S, parallel with the current direction indicated by the ripple drift cross lamination.

The upper ca 5 cm of some of these sand beds contains wave ripple lamination (Plate 11) and others include lenticular bedded probably wave winnowed accumulations of shell debris.

INTERPRETATION

Facies 6b represents episodic depositional events with high initial flow velocities resulting in sharp erosive bases and rapid flow deceleration. This is demonstrated by normal grading and by the upward increase in the angle of climb of ripple drift cross lamination giving the transition from type 'A' to type 'B'. This transition occurs because waning flow gradually increases the rate of fall out of sediment from suspension therefore steepening the angle of climb of the current ripples (Jopling and Walker 1968). Many of these waning flow events were followed by a period of wave reworking before mud deposition resumed.

Although these 'turbidite-like' sandstones resemble the crevasse splay sands described by Arndorfer (1973) and Elliott (1975): they areinterpreted as sub-littoral, storm surge ebb sands deposited offshore from the prograding lagoonal delta shoreline sequence recorded from higher in division I. They differ from facies 6a in the absence of large scale load casts and the presence of well developed ripple structures.

These sands are similar to facies 3 and 4 of Banks (1973) and have a modern analogue in the post Hurricane Carla graded sand bed described by Hayes (1967).

These sands are superficially similar to the sublittoral sheet sands of Goldring and Bridges (1973) and Hamblin and Walker (1979) but do not include hummocky cross stratification. Deposition in facies 6b of the Valtos Formation was from unidirectional, offshore flowing currents, carrrying sand which was probably put into suspension by storm waves impinging on the shoreline. Wave generated sedimentary structures are limited to wave ripples and lenticular lamination in the top ca 5 cm of the sand beds.

FACIES 7 Crustacean Burrow and Desiccation Crack Facies (eg Valtos division I and Loch Bay, middle limestone shale unit)

DESCRIPTION.

Facies 7 occurs above a coarsening upward sequence in division I in north Trotternish and occurs close to the top of the middle limestone-shale unit at Loch Bay, Waternish.

At Loch Bay the facies is very similar to facies 7 in Strathaird(Inner Hebrides Basin). Muddy micritic, Neomiodon bearing limestones with thin dark shale interbeds include prominent desiccation cracked surfaces and large complex *Thalassinoides* type burrows (Plate 13).

In North Trotternish the facies differs in that it is dominated by siltstones and sandstones. Grey muddy siltstones at the base with ?*Thalassinoides* burrows are overlain by current and wave rippled very fine grained sands with thin shale interbeds and desiccation cracks. The sequence is capped by highly carbonaceous-lignitic mudstone overlain by lenticular flaser bedded sands and silts which are cut by a thin channel form sandstone with current orientated drift wood. (Plate 14).

INTERPRETATION

The facies represents periodic emergence and therefore desiccation of lagoon margin mudflats which in north Trotternish are cut by a minor channel sandstone. The association of the facies with a shoreline progradation sequence in division I probably means that the basal siltstones are the deposits of a backshore lagoon with washover sand lobes.

The Loch Bay sequence records low levels of clastic supply, resulting in a carbonate dominated mud flat sequence.

FACIES 7b. Rootlet Penetrated Facies (eg Valtos, division V and Rubha Garbhaig division XII)

In the lower sand dominated unit, (below Valtos), rootlets occur in association with a grey-green mottled mudstone and thin *Viviparus* bearing sands below facies 5 limestones. In the upper sand dominated unit, rootlet penetrated muddy siltstones cap a series of sharp based sands interbedded with very carbonaceous almost lignitic shales at the top of division XI (log 7, Rubha Garbhaig).

INTERPRETATION.

Facies 7b represents vegetated areas of the delta or coastal plain. In division V the fresh water snail Viviparus associated with this mottled mudstone probably represent fresh water ponds bordered by vegetated sand flats. In the upper sand dominated unit the carbonaceous shales probably represent overbank or delta plain muds and the sands resemble sheet flood or crevasse splay deposits. Rootlets occur at the top of this sequence demonstrating a significant period of non deposition or abandonment before the next brackish transgression which culminated in the colonization of the area by Oysters (marking the base of the Duntulm Formation) probably in response to the development of almost marine salinities in the basin (Hudson 1980).

III

FACIES SEQUENCES AND DEPOSITIONAL MODEL.

Most of the facies discussed above have previously been defined for the Valtos Formation in the Inner Hebrides Basin. On Eigg in the Inner Hebrides Basin the coarsening upward facies sequence 1-->2-->3 or 1-->2-->4-->5 is repeated 6 times (division A1-E) so that it dominates all but the upper part of the Formation. These sequences are interpreted as representing the progradation of lobate, fluvially dominated lagoonal deltas. In this system the intervening brackish transgressive or delta destructive phases are recorded by Neomiodon limestones of facies 5 which are present at the top of 3 of the sequences.

In the Sea of the Hebrides Basin, facies sequences are more varied and the individual facies, although readily identified, are of slightly different character. These differences reflect a larger basin with a more varied history of subsidence and clastic supply (see discussion below).

Five facies sequence types can be delineated in the Sea of the Hebrides Basin. Facies shown in brackets in these sequences occur rarely or locally in an otherwise consistent sequence. These sequences are:

Facies sequence A is a coarsening upward sequence representing the axial part of the lagoonal delta systems. It includes proximal mouth bar sands truncated by fining upward distributary channel sands. The facies sequence is 1-->2-->3-->(4)-->(7b).

Facies sequence B differs from A in that it does not include mouth bar or distributary channel facies. It represents lagoonal delta shoreline progradation in the form of a wave dominated beach face with a backshore or delta plain lagoon. The facies sequence is 1-->2-->4-->7-->5.

Facies sequence C represents simple, interdeltaic lagoon shoreline Progradation. Like B the sequence is capped by transgressive erosively based coquinas. The facies sequence is 1-->2-->(7b)-->5.

Facies sequence D comprises shallow lagoonal shell debris sheets and shoals and lagoonal muds deposited during a period characterized by low rates of clastic supply. The facies sequence is a simple alternation of 1-->5.

Facies sequence E only occurs in west Skye and on Raasay. It probably represents the offshore or distal parts of successive lagoonal delta progradation sequences. The facies sequence is a simple alternation of 1-->2.

In addition to these distinct facies sequences, facies 6a and 6b (probably representing storm generated clastic influences) are intercalated with facies 1 mudstones at various horizons.

The block diagrams (figures 10.1-10.4) illustrate the probable genetic relationships of facies in the most important facies sequences (A-B-C-D). These are discussed in stratigraphic sequence (B-C-D-A) in order to account for the evolution of the Valtos lagoonal delta system as recorded in the main-north Trotternish outcrops. Figure 10 forms the basis of the following summary.

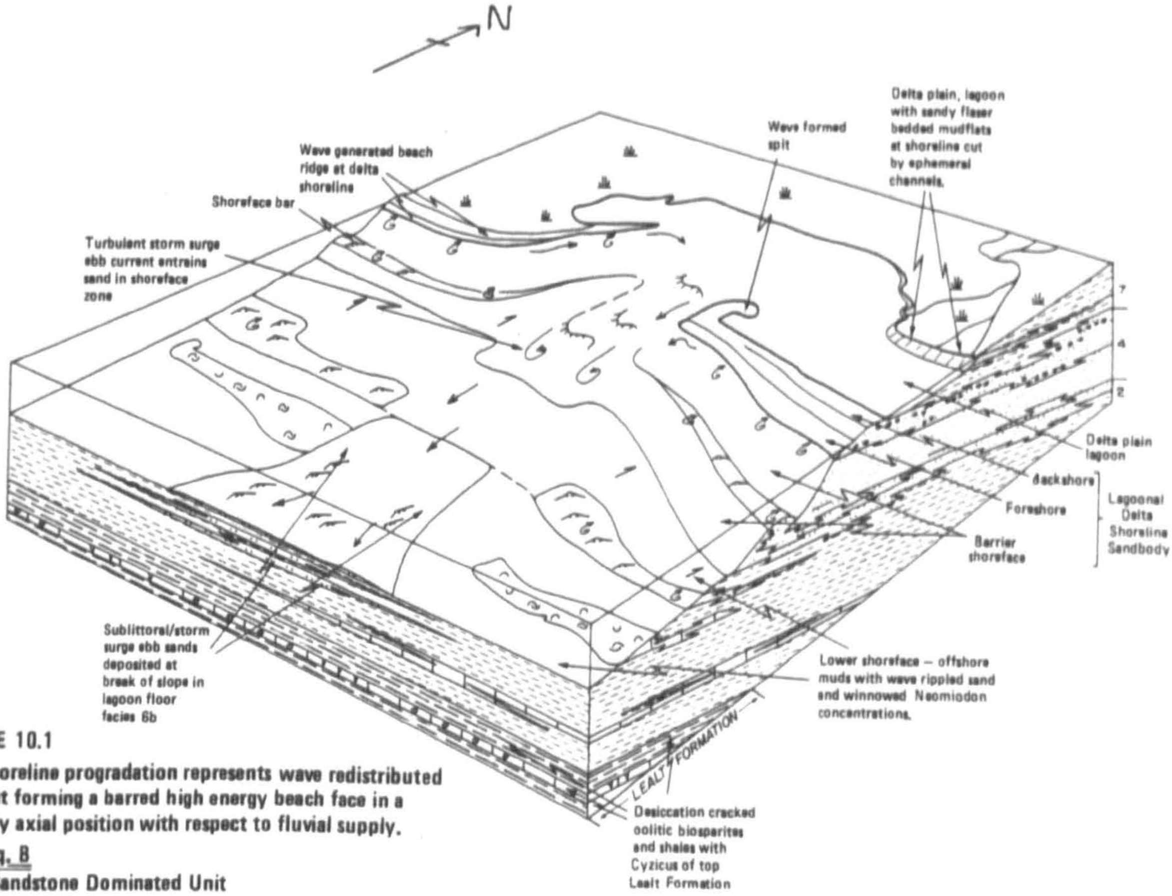

FIGURE 10.1

Delta shoreline progradation represents wave redistributed sediment forming a barred high energy beach face in a relatively axial position with respect to fluvial supply.

Facies sq. B

Lower Sandstone Dominated Unit

Division I

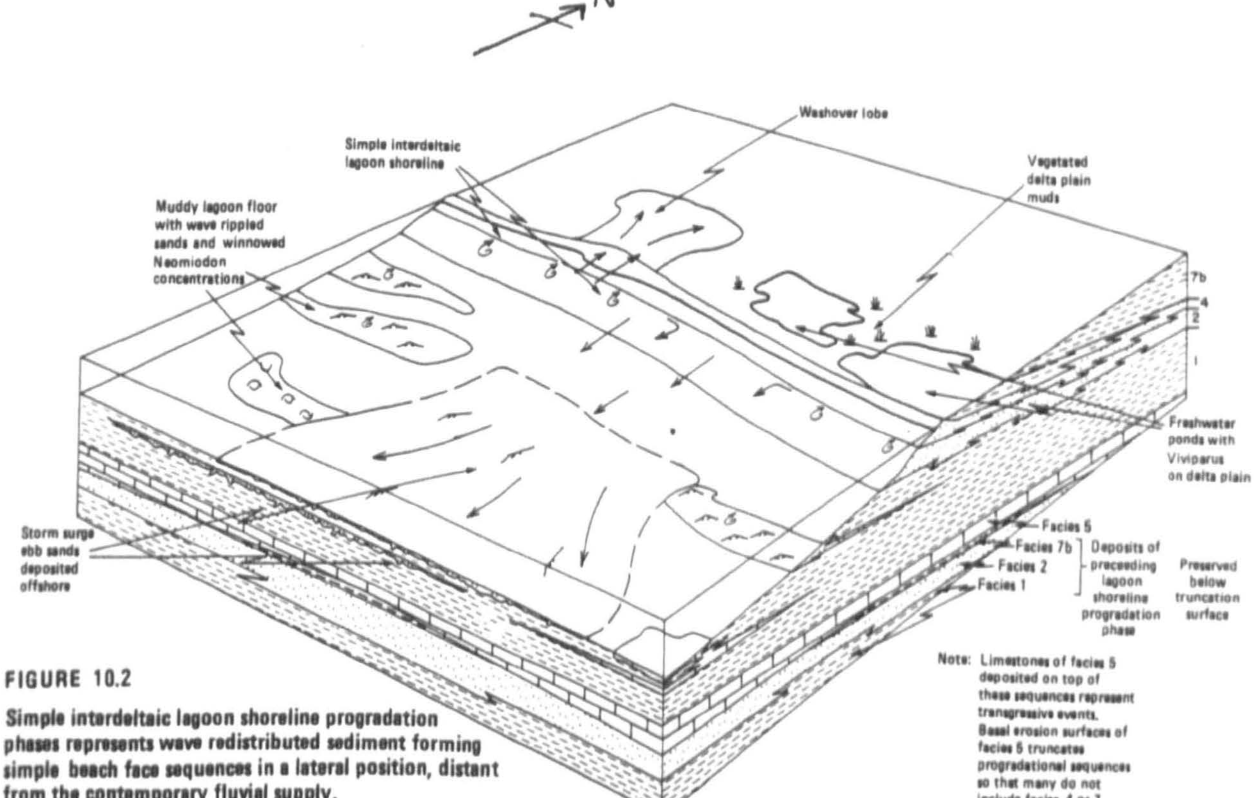

FIGURE 10.2

Simple interdeltaic lagoon shoreline progradation phases represents wave redistributed sediment forming simple beach face sequences in a lateral position, distant from the contemporary fluvial supply.

Facies sq. C

Lower Sandstone Dominated Unit

Divisions II, III, IV, V and VI

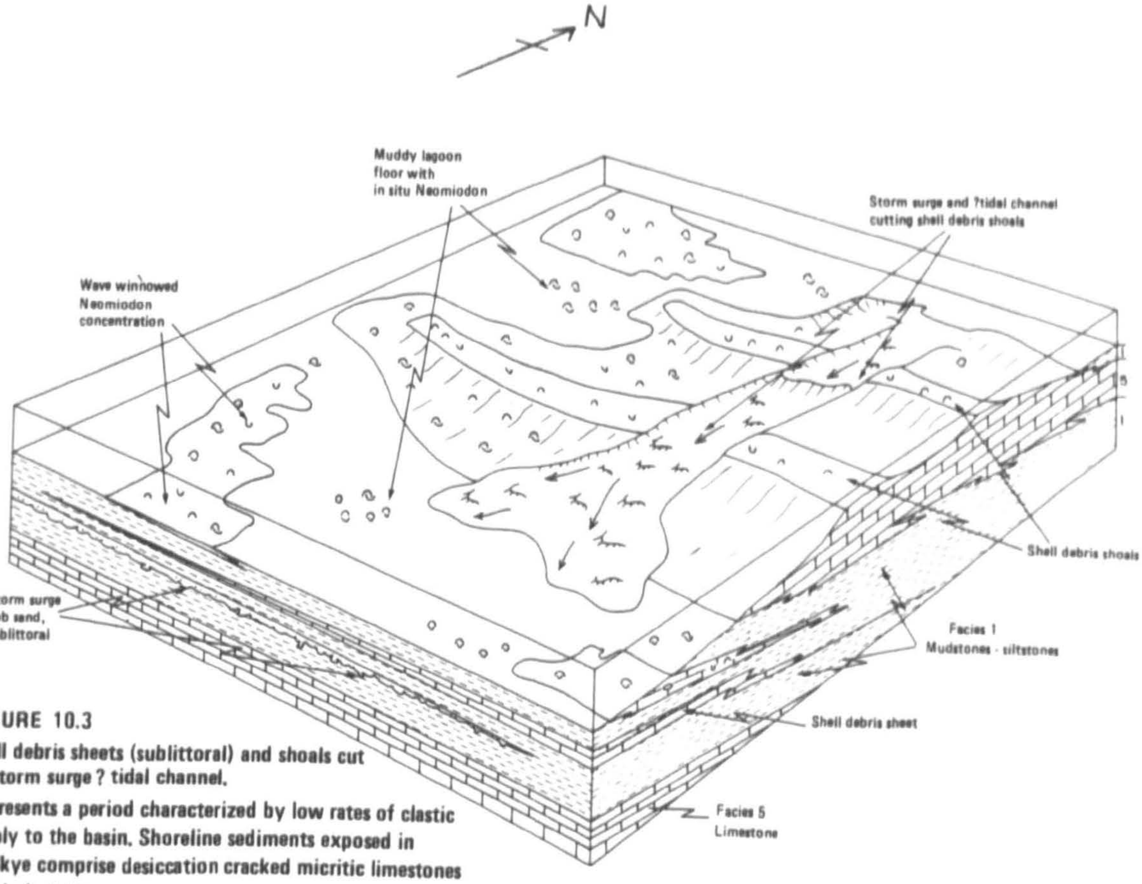

FIGURE 10.3

Shell debris sheets (sublittoral) and shoals cut by storm surge ? tidal channel.

Represents a period characterized by low rates of clastic supply to the basin. Shoreline sediments exposed in W. Skye comprise desiccation cracked micritic limestones and dark shales.

<u>Facies sq. D</u>
Middle Limestone Shale Unit
Dibisions VII, VIII and IX

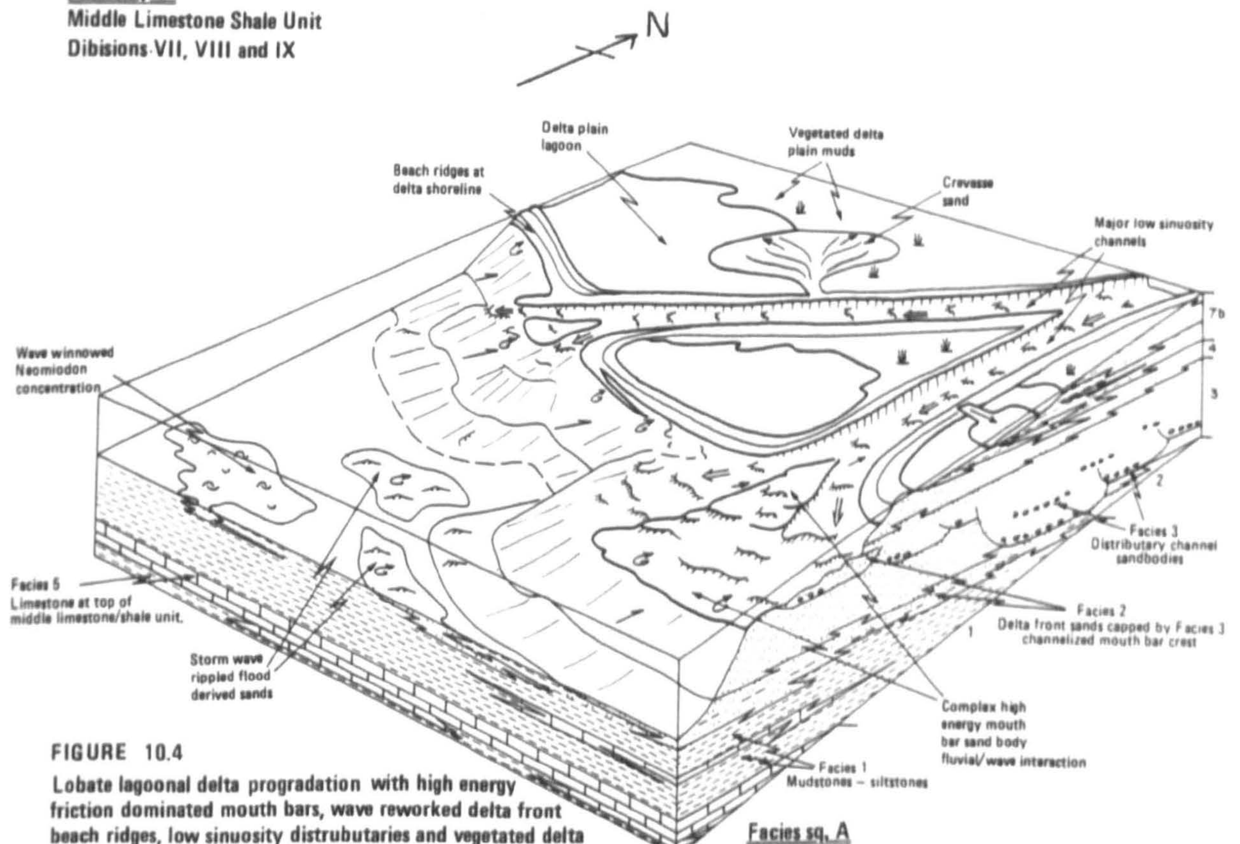

FIGURE 10.4

Lobate lagoonal delta progradation with high energy friction dominated mouth bars, wave reworked delta front beach ridges, low sinuosity distrubutaries and vegetated delta plain.
Represents the axial portion of each lagoonal delta progradation phase.

<u>Facies sq. A</u>
Upper SandstoneDominated Unit
Divisions X and XI

LOWER SANDSTONE DOMINATED UNIT

Facies Sequence B (1-->2-->4-->7-->5) Figure 10.1.

Deposition of the Valtos Formation in Trotternish commenced with the inundation of the coastal mudflats represented by the top of the Lealt Formation, resulting in the establishment of a shallow brackish lagoon in which mudstones-siltstones were deposited.

Copious clastic supply to the basin is recorded by the southerly progradation of a lagoonal delta system. This delta is represented by facies sequence B in division I (see fig 10.1). It records high wave energies which generated a beach spit system (facies 2 and 4) with shoreface bars (ridge and runnel topography), storm generated scour and fill structures and a well defined foreshore zone with swash cross stratification. The system was actively supplied with sediment, reworked by waves, probably from nearby fluvial distributaries.

Landward of the beach spit (fig 10.1) is a delta plain lagoon or bay bordered by wave rippled (flaser bedded) mudflats (facies 7) cut locally by ephemeral channels. The lagoon is infilled by muds and washover lobe sands, the top surfaces of which are occasionally subaerially exposed and desiccation cracked.

Storms which generated the washover lobes and scour and fill structures in the shoreface sands are also the presumed origin of the 'turbidite like' beds (facies 6b) in division I. These sands probably originate in the manner proposed by Banks (1973), Hamblin and Walker

(1979), and Walker (1979) based on the modern analogue described by Hayes (1967). In this system storm waves acting on the delta shoreline place large volumes of sediment in suspension and pile water in the shoreline and backshore area to give a storm tide effect (storm surge). As the storm abates, seaward return flow generates a storm surge ebb current which decelerates offshore (usually at a break of slope) depositing graded sand beds with a waning flow series of structures (facies 8b).

The facies sequence (B) is capped by a thin Neomiodon limestone (facies 5) and overlain by the facies 1 lagoonal mudstones of the next shoreline progradational sequence. The facies 5 limestone is interpreted as recording abandonment (cessation of clastic supply) of the delta, continued subsidence and a consequent brackish transgression of the delta plain. Deposition of transgressive facies 5 limestones is not illustrated in any of the diagrams in figure 10.

Facies sequence B in the base of the Valtos Formation is thicker and more complex than the facies sequence C, shoreline sandbodies which characterize the rest of the lower sand dominated unit in north Trotternish. It probably therefore represents the wave reworking of fluvially supplied sediment in a relatively axial position with respect to fluvial supply.

Facies Sequence C (1-->2-->(7b)-->5), Figure 10.2

The shoreline progradational sequences which make up the rest of the lower sandstone dominated unit in Trotternish represent repeated simple shorelines without shoreface bars. (Divisions II, III, IV, V, VI).

Offshore-lower and middle shoreface, regressive sediments (facies 1 & 2) are recognised in each sequence but most are truncated by transgressive facies 5 limestones (delta destructive) so that delta plain sediments are only rarely preserved (eg division V). The sequence is repeated 5 times in the lower sand dominated unit.

The depositional model for facies sequence C (fig 10.2) functions in a similar way to facies sequence B. Waves impinging on the shoreline redistribute sediment and cause southerly shoreline progradation by accretion of the beach face. Occasionally storm waves generate seaward flowing, storm surge ebb currents which cause the rapid deposition of sub-littoral sheet sands (facies 6a).

Sands in facies sequence C are all thinner and finer grained than the facies sequence B sands. They probably indicate deposition during a period of localised low subsidence rate and are interpreted as representing deposition further alongshore from the locus of clastic supply than facies sequence B. The sequences are therefore interpreted as simple, interdeltaic lagoon shorelines.

The truncation of these regressive shoreline sequences at the base of the facies 5 transgressive limestones is possibly also a function of local, low subsidence rate. This would also account for the occurrence of limestones with fish debris (occupying pockets on the truncation surfaces) probably derived from the erosion of lagoon shoreline or coastal plain sediments.

MIDDLE LIMESTONE-SHALE UNITS.

Facies Sequence D (1-->4) Figure 10.3

Facies sequence D represents a major change in depositional style and in north Trotternish is the only facies sequence type in the middle limestone-shale unit. It represents a period characterized by low rates of clastic supply and high organic productivity leading to the abundant availability of Neomiodon shell debris.

Wave and moderate storm generated currents probably concentrated shell debris into shoals which are locally draped by thin mud laminae or include bioturbated horizons. Intense storm generated currents were probably responsible for the truncation surfaces and shallow channel structures. This system is based on the shallow marine 'blanket sandstone' model of Anderton (1976) and is similar to the crinoidal grainstones and coquinas discussed by Jeffery and Aigner (1982).

Sand intercalations in the middle limestone-shale unit are all assigned to facies 6a and interpreted as distal storm generated, sub-littoral sheet sands.

UPPER SAND DOMINATED UNIT.

Facies sequence A (1-->2-->3-->(4)-->(7b)) Figure 10.4

Division X and XI in the upper sand dominated unit comprise lagoonal delta progradation sequences and record the resumption of clastic supply to the basin. These sequences are dominated by S or SW orientated bed load dominated distributary channels. The texture of these channel sandstones together with the suite of in-channel bedforms demonstrates the existence of an energetic fluvial system with major fluctuations in river stage and probably also illustrates the interaction of fluvial and basinal processes.

On the delta plain periodic floods are the origin of the crevasse splay or sheet flood sands which are intercalated with carbonaceous and occasionally rootlet penetrated muds. These represent delta plain lakes or lagoons with vegetated banks. The lateral migration of low sinuosity distributaries probably accounts for the small amounts of overbank, delta plain sediment preserved.

It is proposed that high rates of bedload transport and high outflow velocities in combination with shallow water in the receiving basin (lagoon) resulted in the dominance of frictional processes at the distributary mouths (see Wright 1977 and discussion in Chapter 3 above). Distributary mouth bars are therefore coarse grained, contain high current velocity structures in the bar crest and are probably broadly lenticular in form. This geometry means that sedimentation occurred very close to the delta shoreline so that sand could be readily reworked by waves into beach face sequences.

Depending on the extent of lateral migration distributaries these beach face sands may overly channel fill sequences (eg division X) or form complete beach face sequences (eg division I) defining the delta shoreline. Laterally these sequences should pass into finer grained, simple, interdeltaic lagoon shorelines (eg divisions II, III, IV, V, VI).

Basinward of the delta front/distributary mouth, low current energies result in the deposition of lagoonal muds which are interrupted by occasional sharp based current rippled sands. These could be interpreted as the result of high discharge at the river mouths but are indistinguishable from the storm derived, facies 6a sands discussed above. Shallow water depths in the lagoon are indicated by wave ripples on the top surface of thin lenticular sands.

Facies sequence A is repeated twice in the upper sand dominated unit with the establishment of rootlet penetrated (Rubha Garbhaig log 7) or desiccated cracked (Cairidh Ghlumaig, Duntulm) delta plain sands and muds close to the top of the Formation. The occurrence of Oyster dominated faunas marking the base of the Duntulm Formation corresponds with a reduction in clastic supply to the basin and a marked increase in salinity of the basin water allowing brackish-marine faunas to become established.

WEST SKYE AND RAASAY LOWER SANDSTONE DOMINATED UNIT.

Facies Sequence E (1-2)

This simple alternation of facies is not illustrated in figure 10 and is limited in its occurrence to the lower sandstone dominated unit on Raasay and at Camas nan Sidthean in west Skye. The series of subdued coarsening upward sequences (facies 1-2) could be interpreted as muddy lagoon shoreline progradation sequences but do not contain any evidence of subaerial emergence. They are therefore interpreted as the offshore equivalents of lagoonal delta/shoreline progradation sequences and therefore approximate to the depositional limits of those sequences.

DISCUSSION

The facies sequences defined above are interpreted as genetically related elements of a lagoonal delta-shoreline system (see fig 10). The distributary channel and mouth bar sands of facies sequence A (fig 10.4) are inferred to pass laterally via facies sequence B (fig 10.1) into thin, simple lagoon shoreline sequences (facies sequence C fig 10.2) recording the redistribution of fluvially supplied sediments by waves.

The importance of waves in this system differentiates the Valtos Formation in the Sea of the Hebrides Basin from the equivalent rocks in the Inner Hebrides Basin (discussed in the preceeding chapter) and corresponds with the greater size of the Sea of the Hebrides Basin.

The character of delta plain sediments in the two basins is also different. In the Inner Hebrides Basin facies 3b records sheet flood processes which together with low sinuosity fluvial channel sandstones (facies 3) makes the delta plain analogous to the sand flats of some fan deltas (eg McGowan 1970). In this type of system wave reworking of sediments is limited to restricted abandoned sections of the delta shoreline. The dominance of in-channel sands over sheet flood sand-flat deposits in the Sea of the Hebrides Basin and the evidence for extensive redistribution of sand by waves indicates that the Sea of the Hebrides lagoonal delta system is more closely analogous to fluvial-wave interaction systems eg. the Copper River fan delta of Alaska (Galloway 1976). The Copper River delta is supplied by a low sinuosity river and is fronted by a wave formed barrier shoreface and therefore shares some characteristics with the Valtos Formation model (fig 10). However, there are important differences; the receiving basin for the Valtos Formation deltas was a non marine lagoon and tides were probably negligible.

Ancient analogues of the Valtos Formation deltas occur in the Eocene Green River Formation, Wyoming (Stanley and Surdam 1978; Surdam and Stanley 1979). However, this lacustrine system includes true Gilbert-type delta lobes which are not represented in the Sea of the Hebrides Basin although it does exhibit the lateral transition from fluvially dominated delta lobes to interdeltaic shoreline sands in the same way as proposed for the Valtos Formation.

The Valtos Formation also has some similarities with the Late Jurassic

- Early Cretaceous fan deltas discussed by Sykes and Brand (1978) from East Greenland but better analogues are probably represented in the Wealden rocks of the Hastings area described by Stewart (1979, 1981).

Fan delta analogues are applied by Stewart (1982) in the interpretation of Wealden lagoonal deltas which have similarities with the sandy fringes of the Recent, Red Sea fan deltas described by Sneh (1979). However, this Wealden lagoonal delta system and the Valtos Formation in the Sea of the Hebrides Basin do not fit readily into a fan delta classification because there is no evidence of true alluvial fans although these may have been small and limited to non exposed areas at the margins of the basins. Additionally neither of these lagoonal delta systems are limited in their occurrence to fault controlled basin margin positions at a break of slope into their respective basins (cf. Wescott and Ethridge 1980).

The Valtos Formation is therefore classified as a fluvial-wave interaction lagoonal delta system.

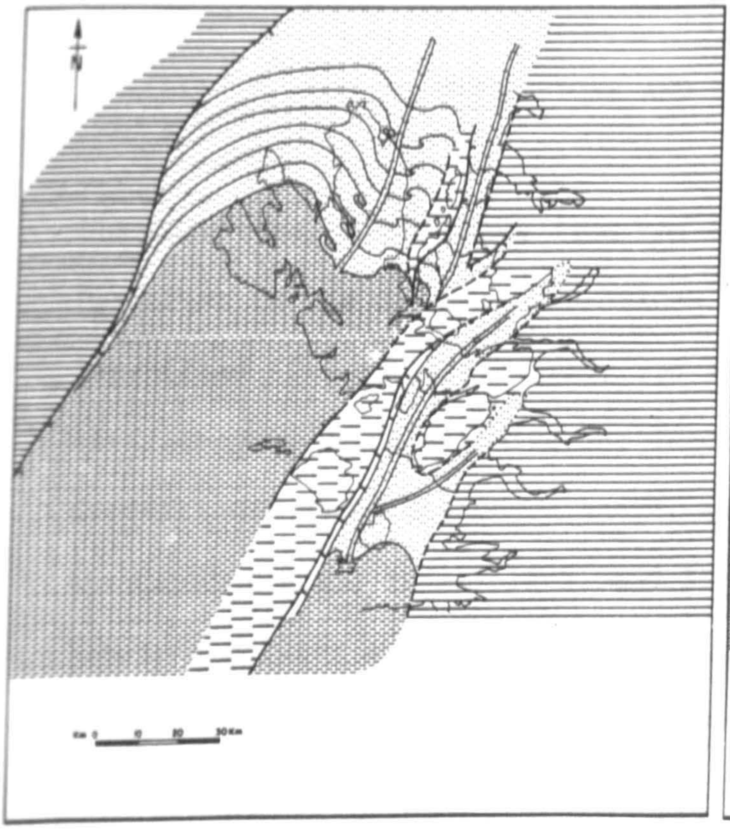

FIGURE 11.1 Probable maximum extent of 1st lagoonal delta/shoreline progradation phase, lower sandstone dominated unit.

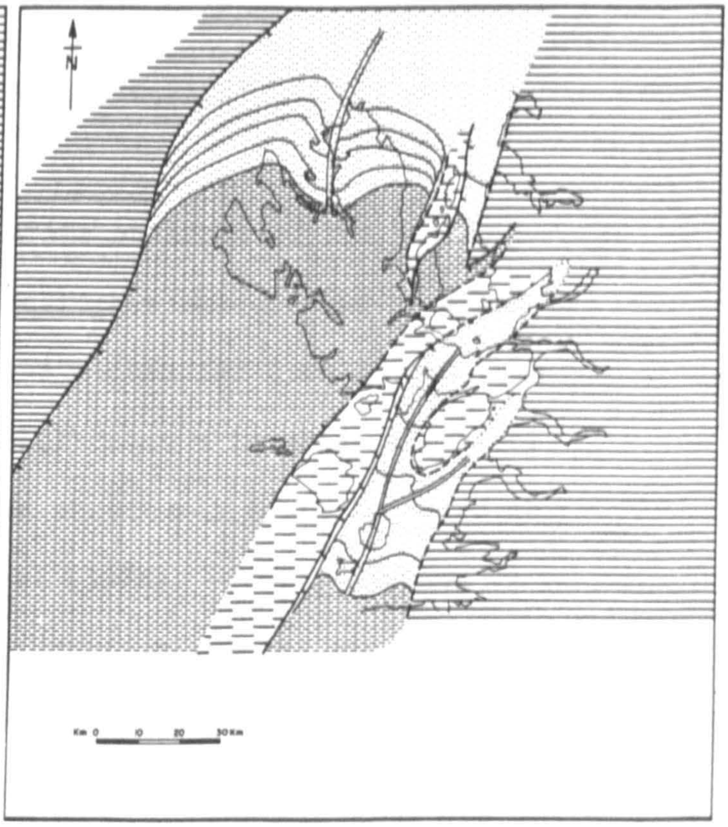

FIGURE 11.2 Probable maximum extent of 5 successive lagoonal delta/shoreline progradational phases lower sandstone dominated unit. Division II, III, IV, V and VI

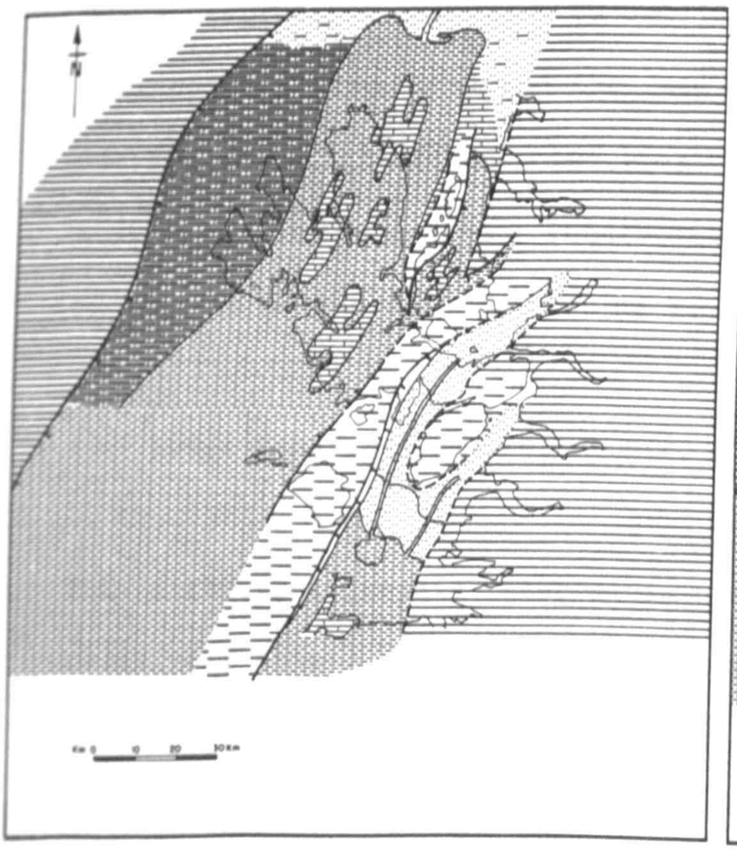

FIGURE 11.3 Possible shoreline configuration in the middle Limestone/Shale Unit. Divisions VII VIII and IX with sublittoral shell debris shoals

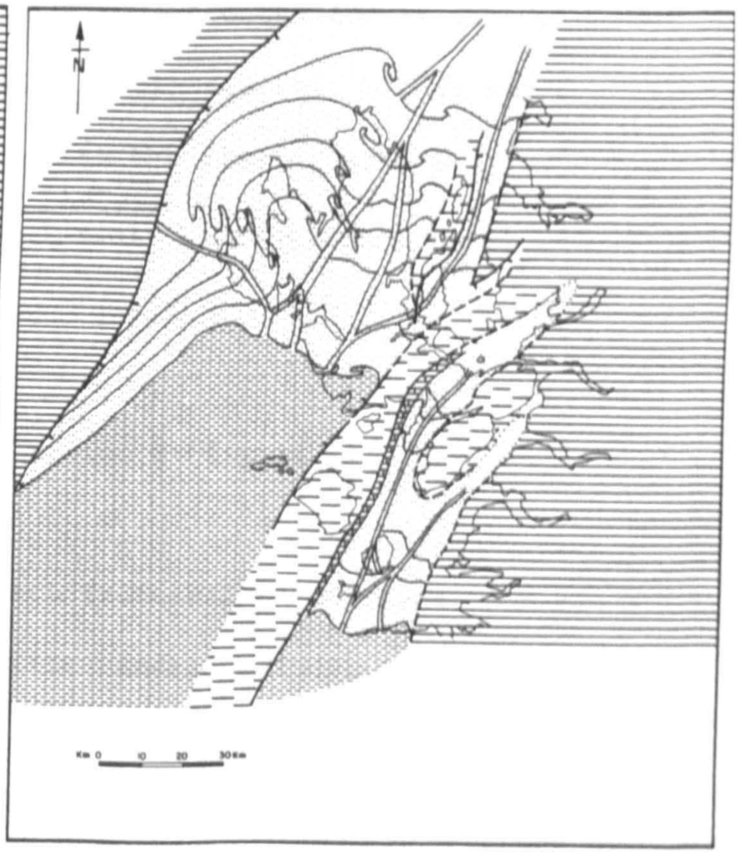

FIGURE 11.4 Possible maximum extent of 2 lagoonal delta progradation phases, upper sandstone dominated unit. Divisions X and XI.

LEGEND

- Upland areas
- Slowly subsiding 'high s'
- Lagoonal delta and Lagoon shoreline sands
- Offshore, lagoonal muds-silts
- Shell debris and Lime muds

CONCLUSIONS AND PALAEOGEOGRAPHY

The main conclusions drawn from the facies analysis of the Valtos Formation in the Sea of the Hebrides Basin are embodied in a series of maps (figs 11.1 to 11.4). They are constructed for each of the main stratigraphic units assuming the lagoonal delta - lagoonal shoreline depositional model discussed above, and structural controls based on the maps of Binns et al (1975) and Steel (1976). Some questions remain regarding some of the facies interpretations and the validity of using a combination of Triassic and present day structural information for Middle Jurassic time. Some of these questions are discussed below.

The distribution of facies sequence types in the Sea of the Hebrides Basin is probably dependant on subsidence rate (controlled by the contemporary structure) and the rate of clastic supply. Within any one lithostratigraphic unit the proximity to the fluvial system supplying clastic sediment (controlled largely by subsidence rate) is thought to be the main control on facies development.

i) Lower sandstone dominated unit, division I (fig 11.1)

This lithostratigraphic interval in north Trotternish comprises relatively thick, coarse grained shoreline sandstone indicating southerly shoreline progradation. Thickness, grain size and sedimentary structures indicate that the sequence (B) is a lagoonal shoreline system and probably therefore represents a near axial position with respect to fluvial supply. A major NNE-SSW trending distributary system just to the west of the north Trotternish outcrop is therefore inferred (fig 11.1).

The presence of thin offshore lagoonal sands and muds (facies sequence E) in west Skye (ca 5 m) is used to define the approximate depositional limits of this delta shoreline system.

On Raasay outcrop of this lithostratigrphic interval is poor but probably comprises a thin (<10 m) lagoon shoreline sequence (facies sequence C). This places the progradational limit of the division I lagoonal delta with its associated interdeltaic lagoon shoreline south of the Raasay outcrop.

ii) Lower sandstone dominated unit, divisions II, III, IV, V and VI. (fig 11.2)

These divisions comprise 5 E-W orientated interdeltaic lagoon shoreline sequences (facies sequence C) indicating a lateral shift in the locus of distributary channel and mouth bar deposition away from the area of the north Trotternish outcrop. The channel system has therefore been drawn further to the west than indicated in fig 11.1, (i.e. closer to the axis of the Sea of the Hebrides Basin). The repetition of 5 similar lagoon shoreline progradational episodes in north Trotternish demonstrates the fairly long term establishment of this palaeogeographic scheme.

The depositional or progradational limit of these successive lagoonal deltas and associated lagoon shorelines (seen at outcrop), is controlled by the occurrence of offshore lagoonal mudstones and storm derived sandstones in western Skye and Raasay. The differences between the Raasay and north Trotternish sequences over this lithostratigraphic interval are probably supporting evidence for the existence of the small 'high' separating the Raasay area from the main basin. This structure probably also accounts for the differences in stratigraphy of the Bajocian, Bearreraig Sandstone Formation discussed by Morton (1965).

iii) Middle limestone-shale unit, divisions VII, VIII, IX (fig 11.3)

The middle limestone-shale unit records a period characterized by low rates of clastic supply to the basin so that lagoonal deltas and sandy lagoon shoreline sequences are not seen at outcrop. This lithostratigraphic interval is dominated by shell debris shoals and channels with intervening offshore lagoonal muds. However, evidence of subaerial exposure in west Skye (desiccation cracked lagoon shoreline limestones at Loch Bay) demonstrates the existence of the sand starved lagoon shoreline tentatively drawn in fig 11.3.

iv) Upper sandstone dominated unit, divisions X, XI, XII (fig 11.4)

In the upper sandstone dominated unit S and SW orientated distributary channel and proximal mouth bar sandstones occur at outcrop in Trotternish and represent the axial parts of 2 lagoonal delta progradation sequences. The onset of clastic supply is marked by truncation of facies 1 mudstones and facies 5 limestones at the base of distributary channel sandstones in division X.

Coarse grained delta shoreline and distributary channel sandbodies (18 m) outcropping in west Skye (An Stac, Waterstein) have a very distinctive heavy mineralogy, probably derived from the Lewisian of the Outer Hebrides. These rocks represent 2 minor eastwardly prograding lagoonal delta systems sourced from the Outer Hebrides Landmass to the west of the Sea of the Hebrides Basin.

The upper sandstone dominated unit therefore represents 2 major phases of lagoonal delta progradation. None of the outcrops (not exposed on Raasay) provide any evidence of depositional or progradational limits so that the line shown in fig 11.4 is arbitrary.

Desiccation cracked (Duntulm) and rootlet penetrated delta plain sands (south Rubha Garbhaig, log 7) occur at the top of the Division XI. These are associated with flood derived sands and were probably deposited before the reduction in clastic supply which marks the top of the formation had occurred. This reduction in clastic supply probably indicates reduced fluvial run off and corresponds with a change in fauna indicating increased (almost marine) salinities in the base of the Duntulm Formation. The basal Duntulm Formation comprises oyster bearing muds and stromatolitic and nodular algal limestones representing marine-brackish salinities and shallow water depths on the inundated delta plain.

v) Probable hinterland characteristics and controls on palaeosalinity

The hinterland of the Sea of the Hebrides Basin in the area of Wester Ross to the north east of the basin was probably like that proposed for the Inner Hebrides Basin (Chapter 3); an intermittently uplifted area of weathered probably Old Red Sandstone overlying the Moines, with a cover of conifers and a seaonal rainfall. However, the mineralogy of the probable Old Red Sandstone source rocks in the hinterlands of the two basins probably differed. The more feldspathic sands of the Sea of the Hebrides Basin were probably derived ultimately from granulites of the Moinian and possibly Torridonian arkoses whereas the Valtos Formation in the Inner Hebrides Basin probably comprises sands sourced in part from Dalradian Quartzites. Low sinuosity-braided rivers with widely fluctuating discharge probably supplied the Valtos Formation lagoonal delta system.

On entering the basin these rivers could have generated a type of fan delta (cf. Sneh 1979) but the distance of progradation of the successive delta sequences S and SW into the basin together with the importance of waves in reworking fluvially supplied sediment into lagoon shoreline sequences precludes the application of a fan delta classification.

Widely fluctuating salinities within the basin were probably controlled by seasonally fluctuating run off from the hinterland leading to the predominance of Neomiodon in the fauna. During the two episodes of repeated lagoonal delta progradation (lower and upper sandstone dominated units) facies sequences like that of the middle limestone shale unit were probably established in the basin to the SW of Skye. This hypothesis is used to establish the relationship shown in figure 10.3 where a lagoonal delta system is proposed in the area NE of Skye during deposition of the middle limestone shale unit.

Given a marine connection to the SW fluvial discharge into the basin could displace salt water seawards (SW) so that it would be possible to establish more saline brackish and brackish-marine facies like those of the overlying Duntulm Formation to the SW of Skye. Although there are no boreholes and therefore no direct evidence these rocks could be transitional to normal marine facies to the SW of the Sea of the Hebrides Basin in the area of Berneray and Hawes Bank.

vi) Comparison with the Valtos Formation of the Inner Hebrides Basin.

There are obvious similarities between the Valtos Formation in the two basins and both are interpreted as representing the progradation of types of lagoonal delta. The absence of the middle limestone/shale unit in the Inner Hebrides Basin is probably attributable to differing subsidence histories in so far that the Eigg outcrops are in a more proximal position in the Inner Hebrides Basin than are the Trotternish outcrops in the Sea of the Hebrides Basin.

The major difference between the facies developed in the two basins is in the dominance of wave generated lagoon shoreline and wave dominated delta shoreline sequences in the Sea of the Hebrides Basin. Although wave generated beach ridges have been identified in the Valtos

Formation in the Inner Hebrides Basin they are relatively unimportant. This corresponds with the relative size of the two basins (fig 10) and is reflected in the general form of the shorelines shown in figure 10.

The Inner Hebrides Basin delta shoreline are drawn with a broadly lobate fluvially dominated configuration whereas the Sea of the Hebrides delta and lagoon shorelines have been drawn with smooth-wave dominated shapes giving an arcuate shoreline including wave generated spits.

FIGURE CAPTIONS

FIG 1. Map to show the major structural controls on Mesozoic basin configuration from Binns et al (1975) and Steel (1976) with the location of the main Valtos Foramtion outcrops.

FIG 2. Location map of the Valtos Formation sections in north Trotternish, Skye.

FIG 3. Graphic field of logs of divisions I-V, logs 1,2 and 3, lower sandstone dominated unit, Trotternish, North Skye.

FIG 4. Graphic field logs of divisions VI-IX, log 4 lower sandstone dominated unit and middle limestone shale unit, Trotternish, north Skye and log 8 of approximately the same lithostratigraphic interval, Raasay.

FIG 5. Graphic field logs of divisions X, XI and XII log 4b, 5, 6 and 7 upper sand dominated unit and the base of the Duntulm Formation, Trotternish north Skye.

FIG 6. Graphic field log of the Valtos Formation section in Loch Bay, Waternish, west Skye.

FIG 7. Graphic field log of the Valtos Formation sections at Waterstein, Duirinish, west Skye.

FIG 8. Lithostratigraphic correlation of the Valtos Formation divisions in Trotternish, north Skye, showing the distribution of facies and facies sequences. These divisions I-XII are of the same status as the 7 lithostratigraphic divisions Ai-F identified in the Valtos Formation on Eigg in the Inner Hebrides Basin.

FIG 9. Field sketch illustrating the truncation of horizontally bedded facies 2 - mouth bar sands at the base of facies 3 - distributary channel facies and complex low angle inclined, laterally accreted channel fill.

FIG 10. Depositional models to illustrate the genetic relationships of facies in the main facies sequences: these in part correspond to the main lithostratigraphic divisions in north Trotternish.

FIG 10.1 1st progradational lagoonal delta phase, facies sequence B. in north Trotternish.

FIG 10.2 Rest of the lower sandstone dominated unit in north Trotternish, facies sequence C repeated to form 5 lithostratigraphic divisions.

FIG 10.3 Middle limestone shale unit, Trotternish and Raasay, facies sequence C.

FIG 10.4 Upper sandstone dominated unit, Trotternish and Waterstein, facies sequence A.

FIG 11. Palaeogeographic reconstruction of the Sea of the Hebrides and Inner Hebrides Basin for the same lithostratigraphic units as illustrated in fig 4.

FIG 11.1 1st lagoonal delta/shoreline progradation phase.

FIG 11.2 5 successive lagoonal delta/shoreline progradation phases with a repetition of facies distribution pattern; lower sandstone dominated unit.

FIG 11.3 Possible shoreline configuration in the middle limestone/shale unit unit with offshore, sublittoral shell debris sheets and shoals.

FIG 11.4 Final lagoonal delta progradational phases in the upper sand dominated unit recording increased rates of clastic supply to the basin.

PLATE CAPTIONS

PLATE 1a Trace fossils, *Teichichnus*? and *Pelecypodichnus* on lower surface of a thin sand bed (Hypichnia) which at outcrop overlies a thin mud lamina draping a wave rippled surface (facies 2). Field of view 340x240 mm.

PLATE 1b Similar preservation of *Pelecypodichnus* to that in Plate1a.

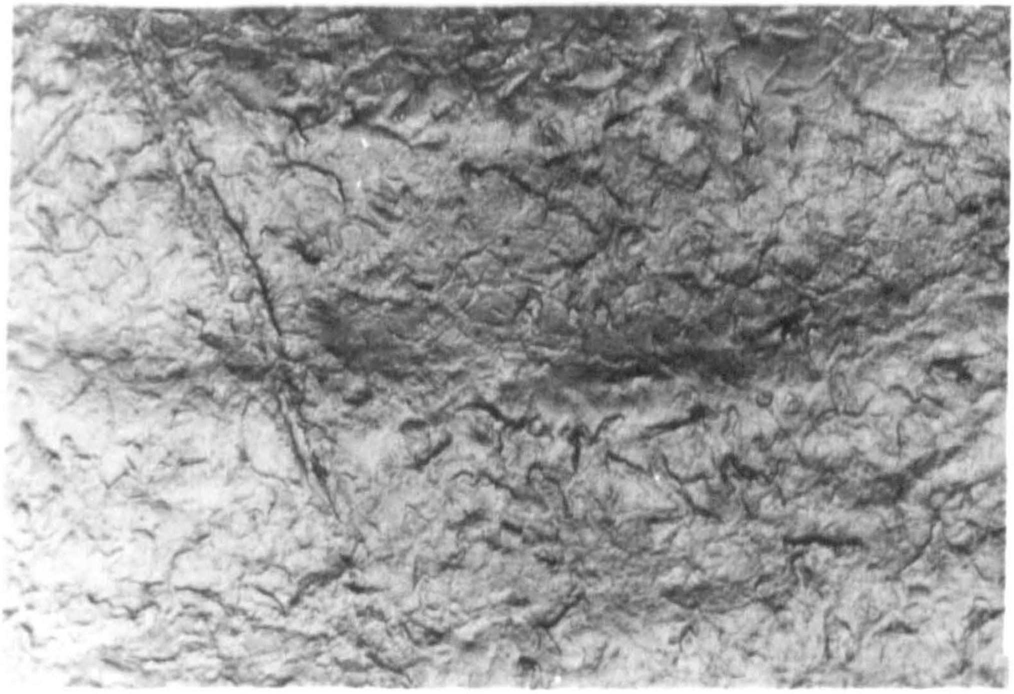

Plate 1a

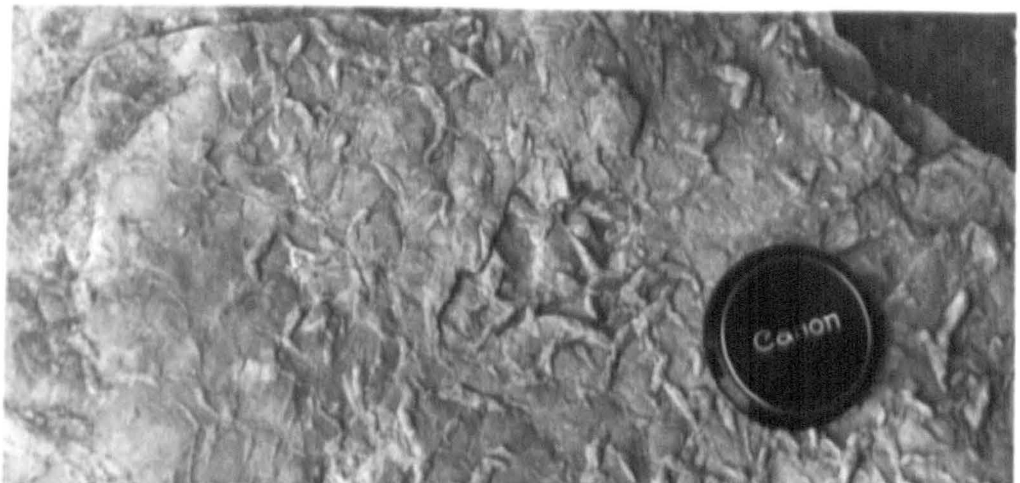

Plate 1b

PLATE 2 Panoramic view of distributary channel and mouth bar sands in division X and XI, north Kilt Rock Trotternish, cliff is 22 m high.

1 Multistory distributary channel sandstone of Facies 3 capped by Neomiodon bearing beach face sands of facies 4

2 Thin lagoonal sands of facies 1 at base of division XI

3 Coarsening upward mouth bar sand - facies 2

4 Multilateral and multistorey distributary channel sands of facies 3; basal truncation surfaces define channel-form sand bodies, but oblique section makes these and low angle-lateral accretion surfaces indistinct.

5 Delta plain muds and flood derived sands facies 7.


V
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DIV XI
III
II
DIV X
V
IV
DIV XI
III

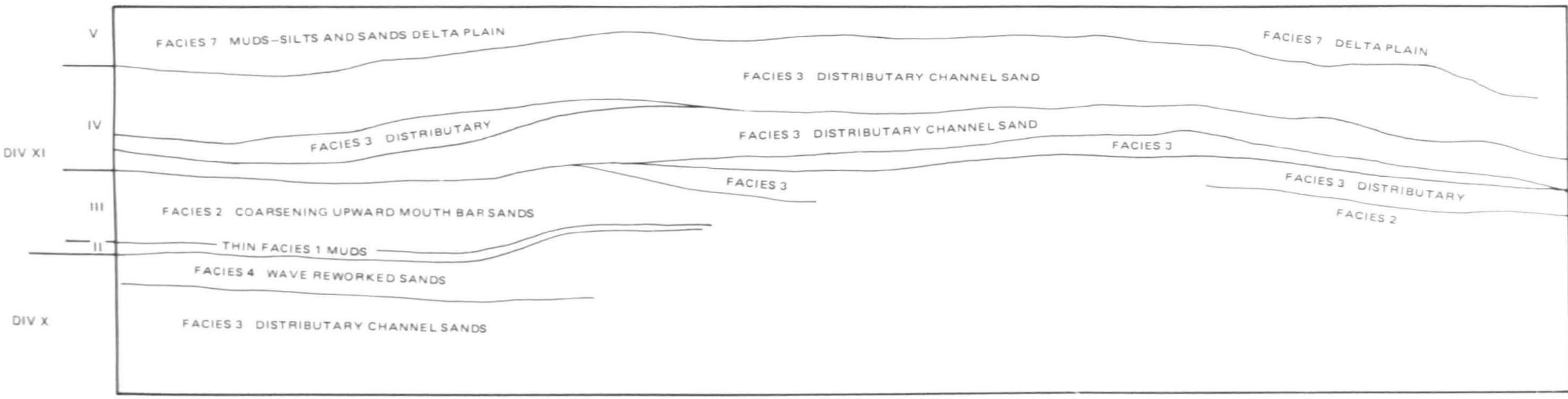
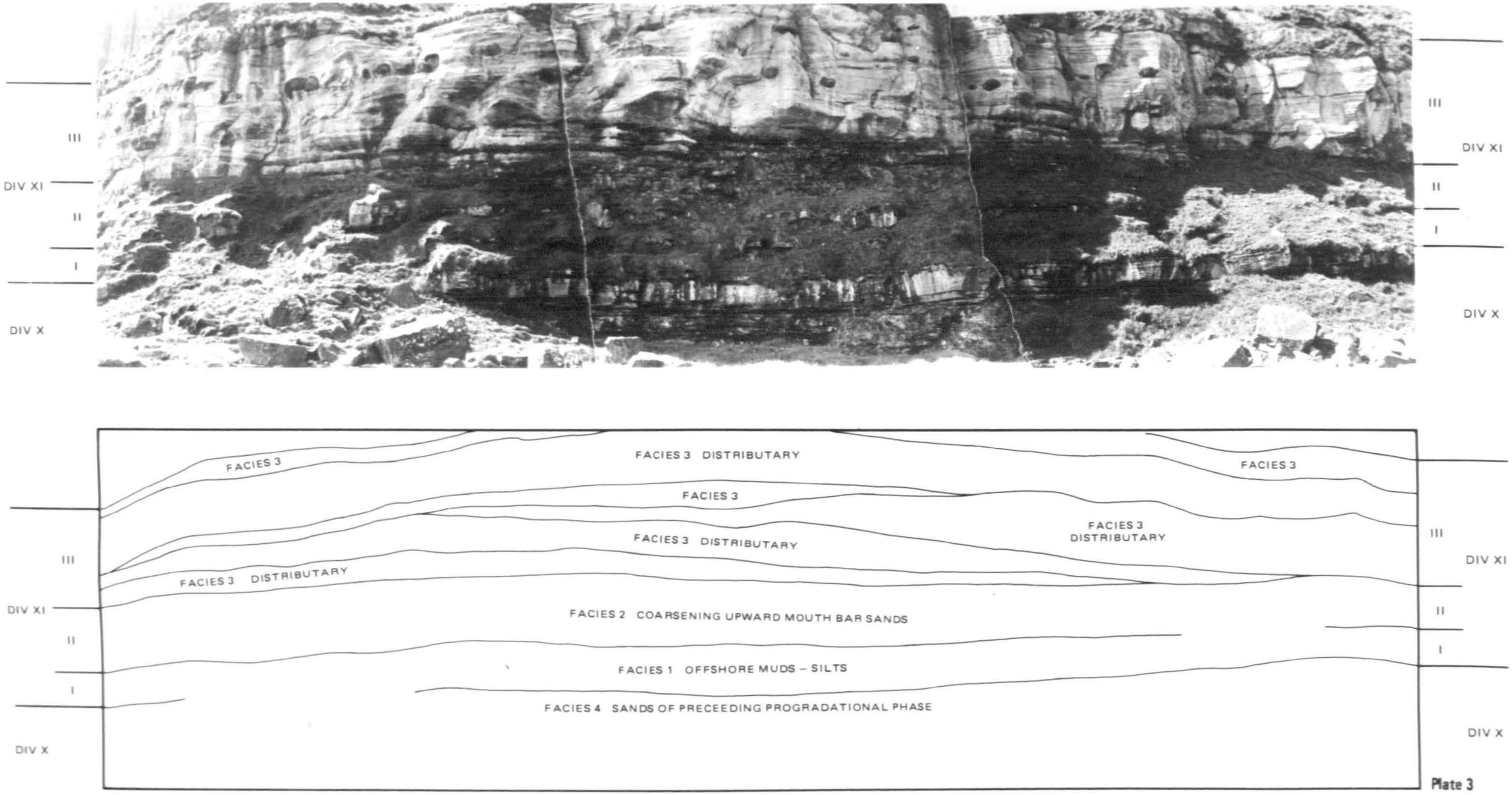

V
IV
DIV XI
III
II
DIV X
FACIES 7 MUDS–SILTS AND SANDS DELTA PLAIN
FACIES 7 DELTA PLAIN
FACIES 3 DISTRIBUTARY CHANNEL SAND
FACIES 3 DISTRIBUTARY
FACIES 3 DISTRIBUTARY CHANNEL SAND
FACIES 3
FACIES 3
FACIES 3 DISTRIBUTARY
FACIES 2
FACIES 2 COARSENING UPWARD MOUTH BAR SANDS
THIN FACIES 1 MUDS
FACIES 4 WAVE REWORKED SANDS
FACIES 3 DISTRIBUTARY CHANNEL SANDS
V
IV
DIV XI
III

Plate 2

PLATE 3 Panoramic view of lagoonal muds (facies 1) mouth bar sands (facies 2) and multilateral distributary channel sands (facies 3) division XI south Rubha Garbhaig, Trotternish, Cliff is ca 18m high.


DIV X
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FACIES 3 DISTRIBUTARY
FACIES 3 DISTRIBUTARY
FACIES 3 DISTRIBUTARY
FACIES 2 COARSENING UPWARD MOUTH BAR SANDS
FACIES 1 OFFSHORE MUDS – SILTS
FACIES 4 SANDS OF PRECEEDING PROGRADATIONAL PHASE

Plate 3

PLATE 4a Dun Dearg, Trotternish. Calcite concretions in Neomiodon bearing proximal mouth bar sands facies 3, overlying coarsening upward rocks of facies 2. Sedimentary structures are deformed around the concretions demonstrating displacive crystal growth probably in conjunction with post concretion compaction.

PLATE 4b Dun Dearg, Trotternish. Trough cross stratified facies 3 sandstone with calcite concretions (arrow 1 and 2). Friable brown weathering zone (arrow 3) around the concretions probably indicates decalcification at the margins of the concretions.

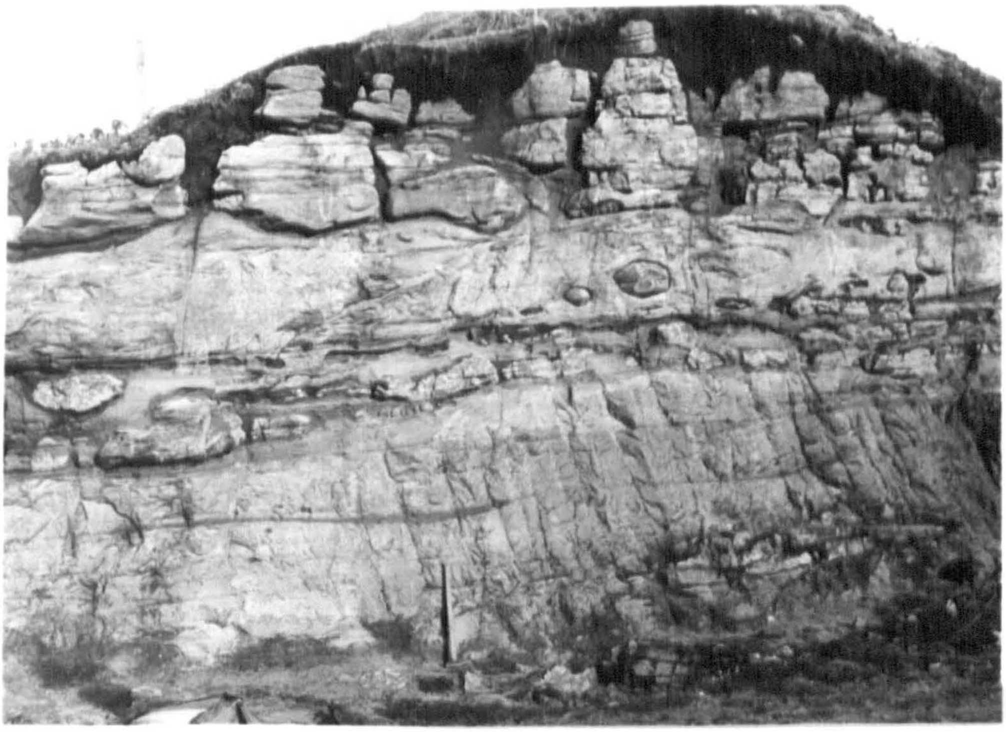
Plate 4a

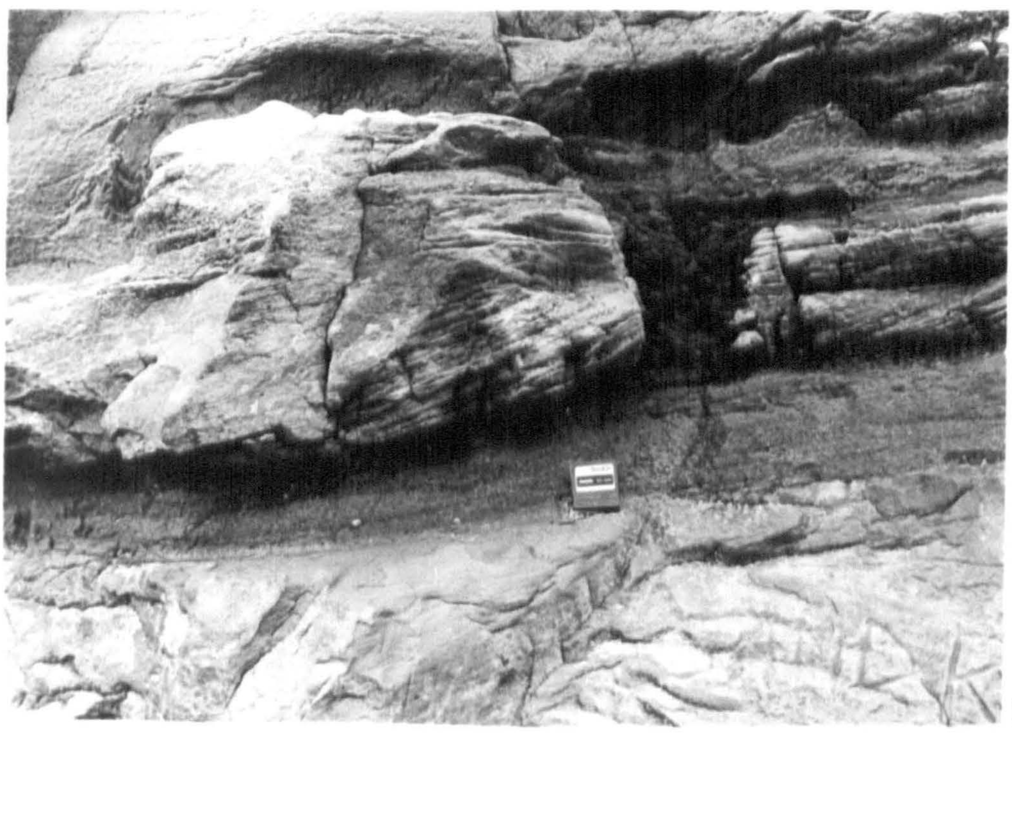
Plate 4b

PLATE 5 Large, botryoidal calcite concretion in facies 4, Valtos, Trotternish. Planar laminated and low angle planar cross laminated sands with pebble lined scours represent middle - upper shore face of a progradational delta shoreline. Hammer is 70 cm long.

Plate 5

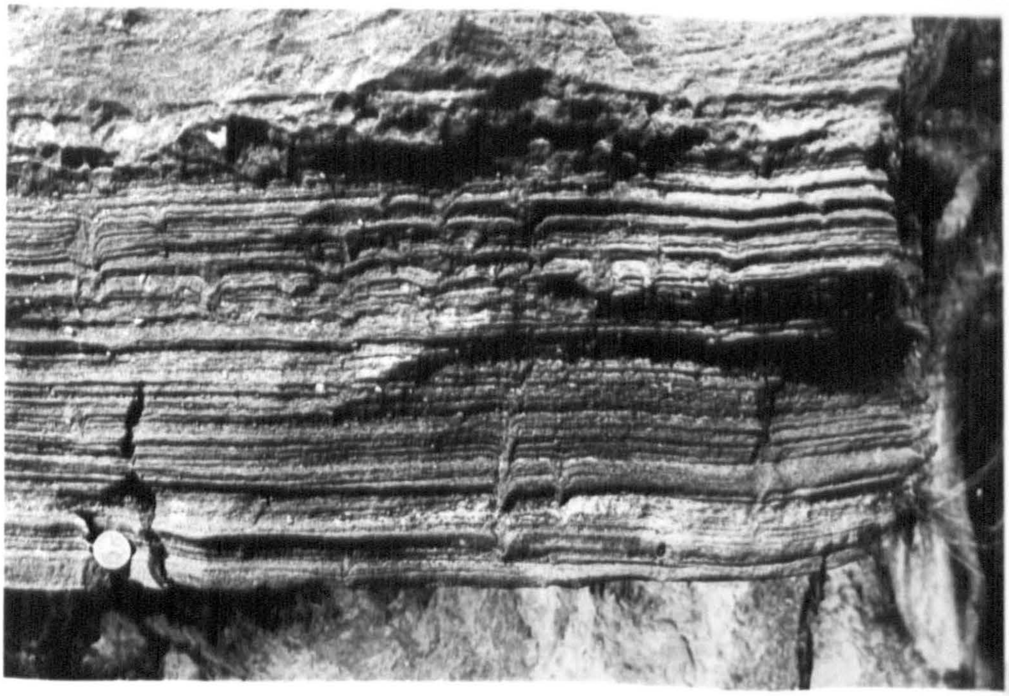
Plate 6

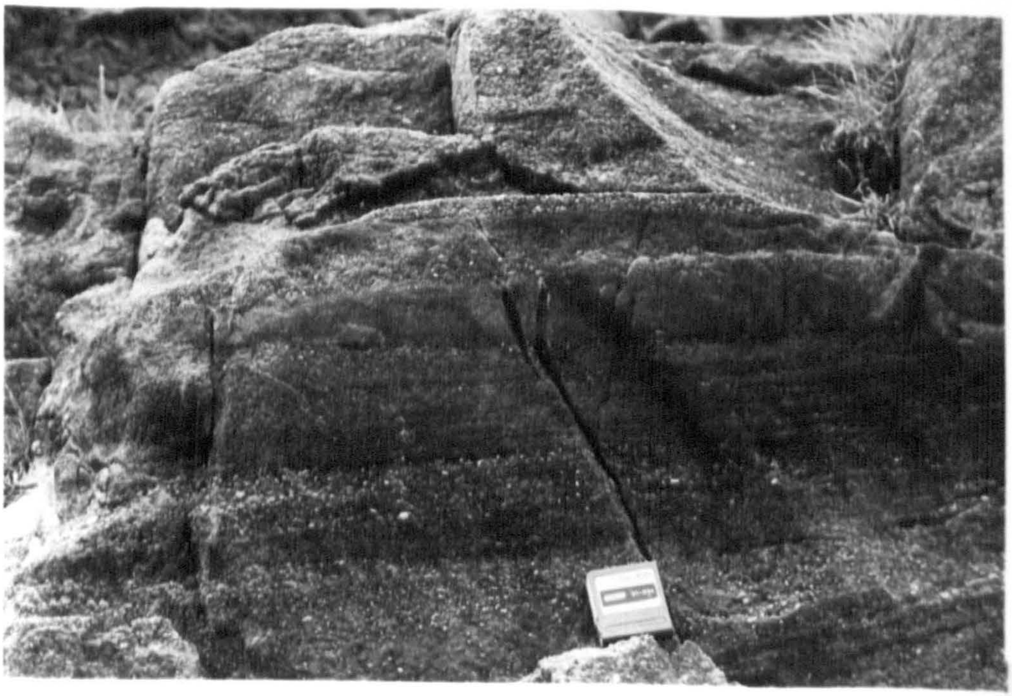
Plate 7

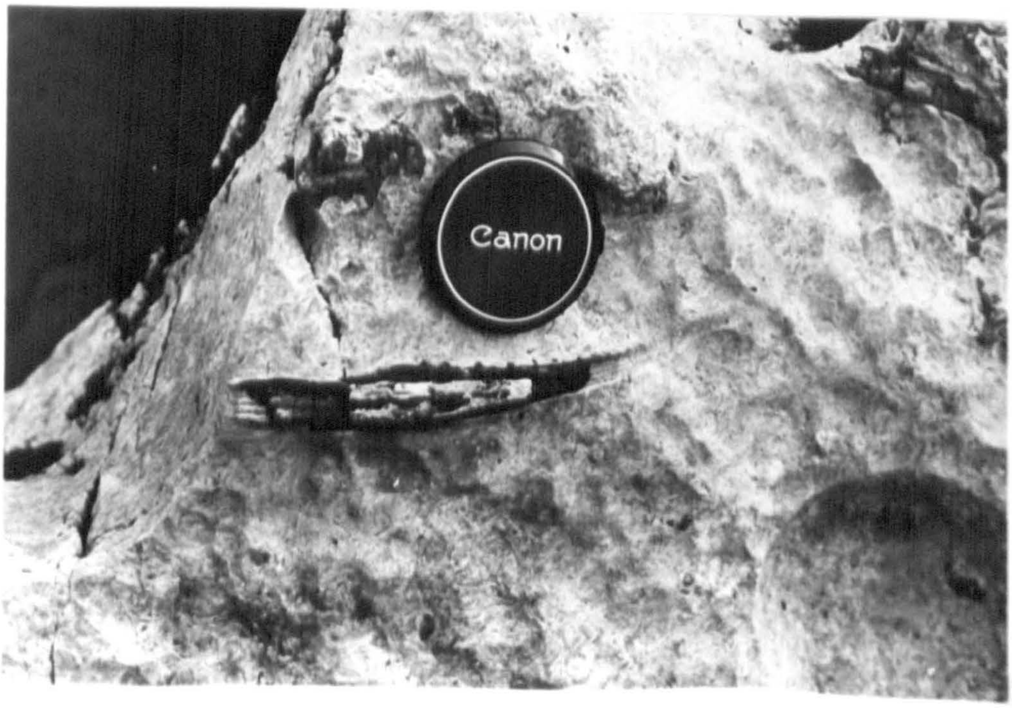

Plate 8

PLATE 6 Laminated pebbly sands with Neomiodon escape structures recording storm events in the middle shoreface (facies 4) division I Valtos, Trotternish. Scale is a 10 p coin diameter 28 mm.

PLATE 7 Pebbly, Neomiodon bearing sands interbedded with planar laminated and low angle planar cross laminated sands with low angle discordances between sets. Structures interpreted as swash cross lamination, top of facies 4 division I, Valtos, Trotternish. Scale is 50 mm in diameter.

PLATE 8 Probable shark fin spine in Neomiodon debris limestone, facies 5, division V Lealt River, Trotternish. Scale is 55 mm in diameter.

PLATE 9a Photomicrograph (x125) of Neomiodon debris with probable aggregated algal 'lumps' in a sandy matrix. Facies 5, (transgressive shell debris limestone) division V, cliffs below Valtos, North Trotternish.

PLATE 9b Photomicrograph (x50) of intraformational micritic limestone pebble in sandy Neomiodon debris limestone of facies 5.

Plate 9a

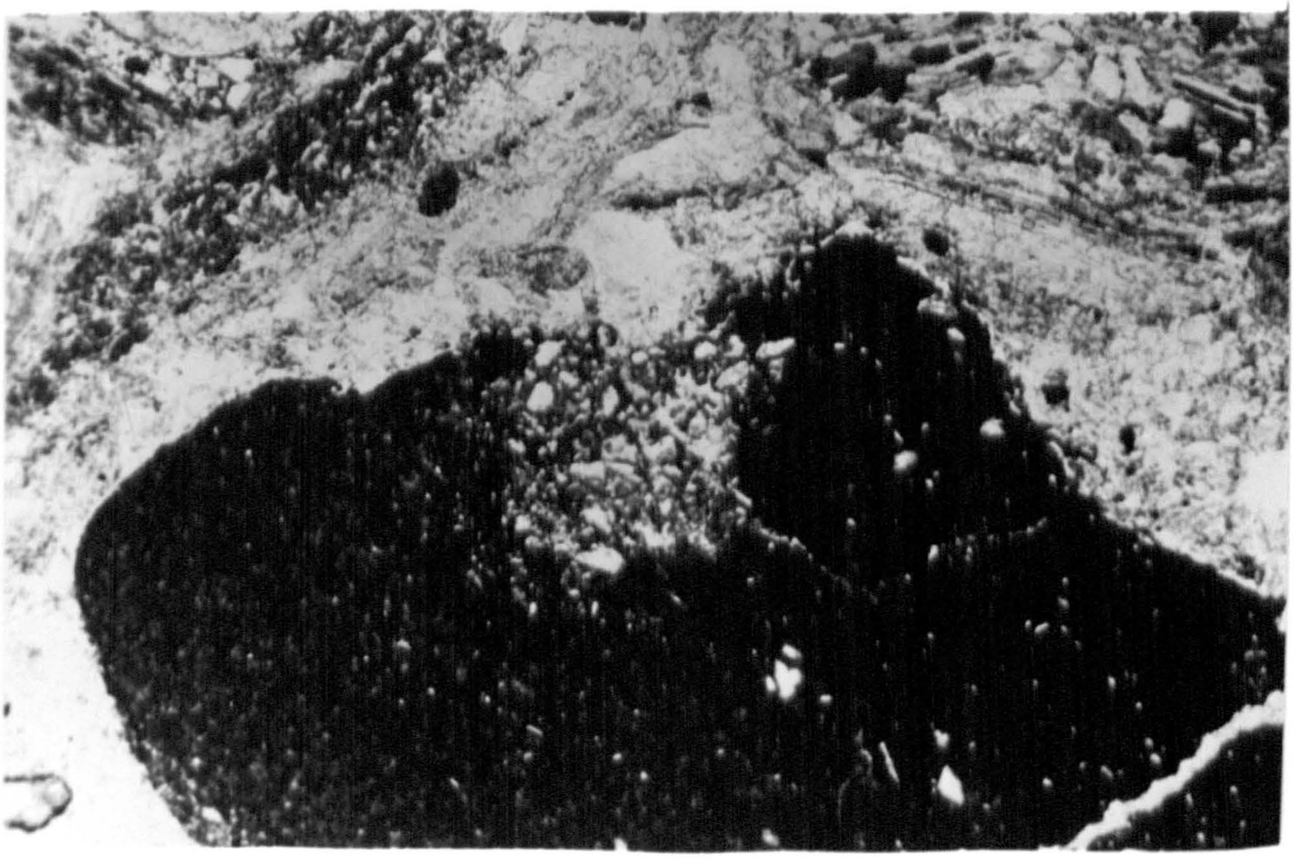

Plate 9b

PLATE 10 Ripple drift cross laminated, fine grained sandstone infilling a shallow scour in sublittoral sheet sand. Increasing angle of climb records the transition from type 'A' to type 'B' climbing ripples of Jopling and Walker (1968). Facies 7b. Lealt, Trotternish. Scale - 10 p coin dia 28 mm.

PLATE 11 Detail of ripple drift cross lamination in Plate 10.

PLATE 12 Undulose probable wave ripple lamination in the top 1-2cm of a facies 6b sublittoral sheet sand. Lonfearn Burn. Lower part of sand bed contains planar lamination and current ripple lamination. Scale is 55 mm in diameter.

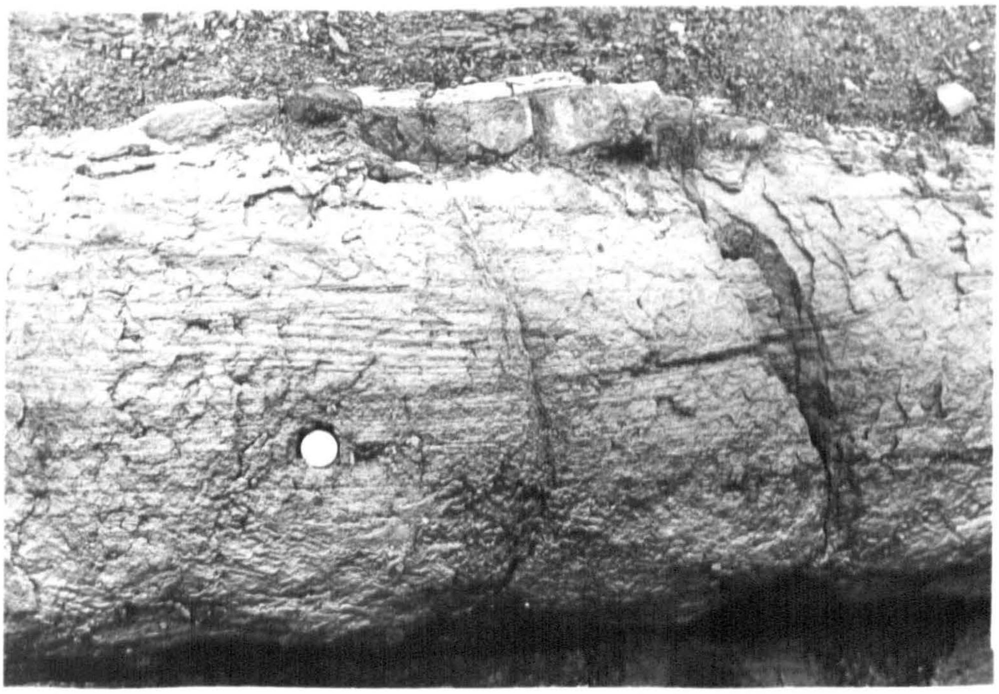

Plate 10

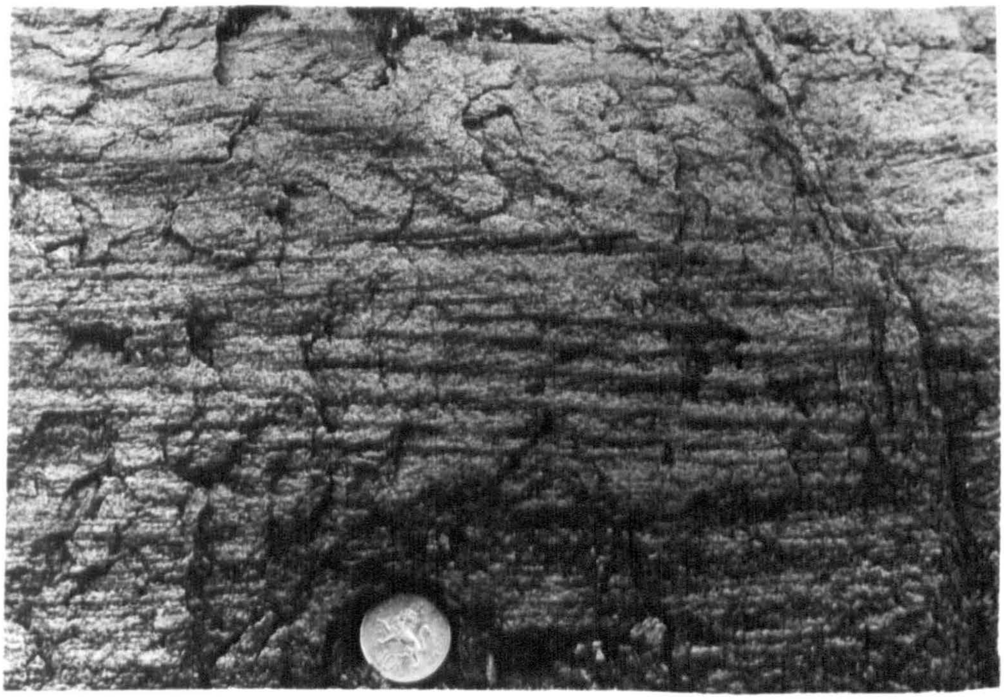

Plate 11

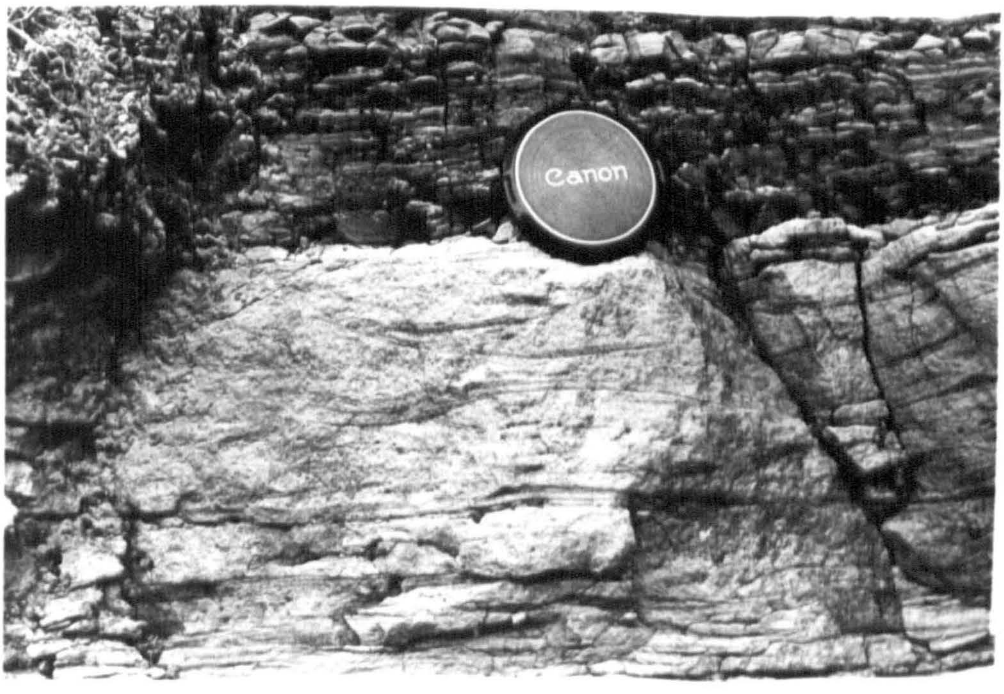

Plate 12

PLATE 13 Thallassinoides burrow in micritic limestones forming part of muddy, sand starved lagoon shoreline sequence. Middle limestone/shale unit Loch Bay, Waternish.

PLATE 14 Sandy lignitic mudstone (arrow 1) overlain by carbonaceous mudstones with sand flasers representing mudflats cut by a minor channel fill sand (arrow 2) with current orientated driftwood. This sandy delta plain lagoon shoreline sequence (facies 7) is capped by a thin, probably transgressive shell debris limestone (facies 5).

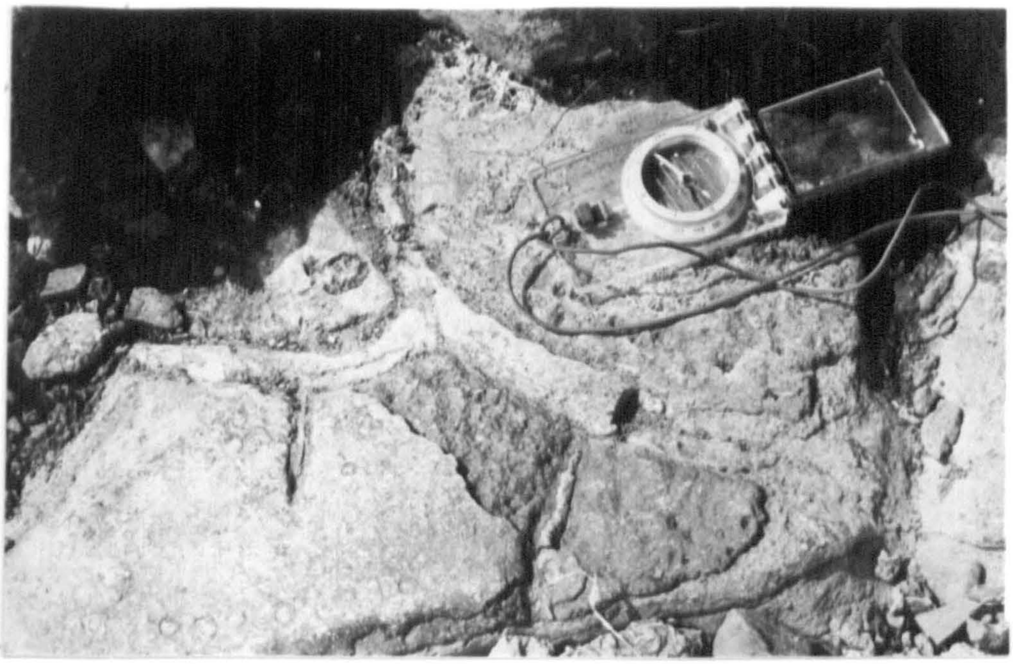

Plate 13

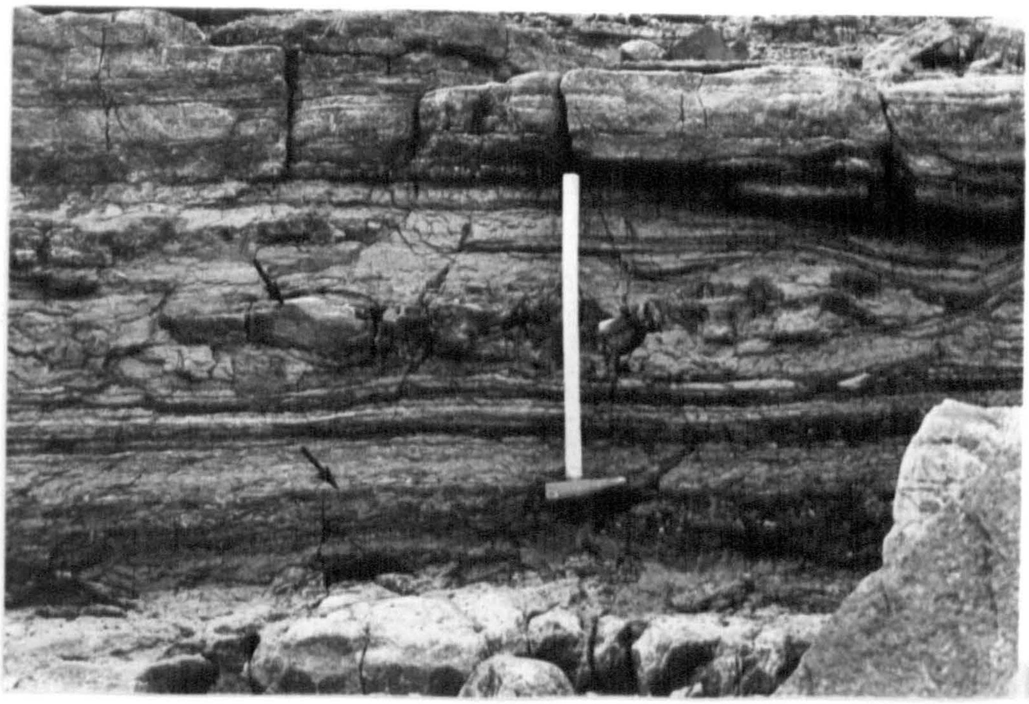

Plate 14

CHAPTER 4

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WRIGHT, L.D., 1977. Sediment transport and deposition at river mouths: a synthesis. Bull. Geol. Soc. Am., 88, 856-868.

CONCLUSIONS

The seven Formations of the Great Estuarine Group comprise distinct groups of genetically related facies. The recognition of facies relationsips allows the definition of lithostratigraphic boundaries and provides a framework for the facies analysis of the two sandstone dominated Formations. The conclusions of this work on the Elgol and Valtos Sandstone Formations are presented as a series of controls and constraints and as sequences of events to account for the stratigraphy and lateral variation seen in the outcrops of the two Formations

CONTROLS AND CONSTRAINTS ON THE DEPOSITIONAL MODELS

The Elgol and Valtos Formations are interpreted as a series of repeated lagoonal delta and associated lagoon shoreline systems. The main controls on thickness and facies development are:

i) The nature of the Hinterland
ii) The configuration of the basins and subsidence rate
iii) The rate of clastic supply and proximity to the main distributaries
iv) The size of the basins hence wave energy available in the basins
v) The salinity of the basin water and the presence or absence of a connection with the open sea.

The sandstones comprise quartz arenites and sub-feldspathic arenites the texture of which indicates derivation from a hilly hinterland. The hinterland probably contained Old Red Sandstone largely derived from the

Moines and Dalradian in the area of Wester Ross to the north east and weathered Lewisian in the area of the Outer Hebrides across the Minch Fault to the west.

The characteristics of the sandstones and the palaeoecology (Hudson 1980) and stable isotope geochemistry (Tan and Hudson 1974) of the intervening limestones and shales indicates a warm climate with seasonal rain-fall.

The fauna and microflora of the sandstone Formations demonstrates deposition in basins of reduced salinity and rapidly fluctuating salinity. Only in the north of the area (at Invertote and Rigg) are the Elgol Formation sandstones associated with normal marine salinities.

Thickness and facies distibution patterns for the two Formations correspond very closely with the basin configuration established for Triassic rocks by Steel (1976(and the structure maps presented by Binns et al (1975). It is concluded that in the Mid Jurassic the Inner Hebrides/Minch area comprised two elongate fault bounded basins. These comprise the Sea of the Hebrides Basin in the west and the smaller Inner Hebrides Basin in the east. These two basins were separated by a narrow, slowly subsiding ridge, termed the Mid-Skye palaeo-high. Within this context the Elgol and Valtos Formations represent axial sediment dispersal systems with repeated SSW progradation of lagoonal deltas and lagoon shorelines. This axial or longitudinal type of depositional system is the norm for fault bounded rift basins in the related North Sea and East Greenland areas.

ELGOL FORMATION

The base of the Great Estuarine Group is marked by the establishment of non marine, anoxic conditions leading to oil shale deposition over most of the outcrop area. The following sequence of events is proposed to account for the deposition of the Elgol formation after the initial establishment of this non-marine system.

1) The reestablishment of a marine connection and the SSW progradation of a delta system in north Trotternish containing a marine fauna and micro-flora. Bimodal N-S palaeocurrents at Invertote and Rigg are attributed to tidal processes. Wave generated sedimentary structures demonstrate the importance of waves in controlling the configuration of the delta shoreline of this fluvial-wave-tide interaction delta.

2) The continued southward progradation of the Elgol Formation delta into the area of south Trotternish. Here the Elgol Formation is a fluvial dominated system and lacks any evidence of tidal currents. It contains mouth bar sands which probably indicate bouyant distributary mouth processes which are dependant on near marine salinities in the basin water.

3) The deposition in the Inner Hebrides basin of a fluvial dominated delta system. Mouth bar processes in this basin were dominated by frictional processes (density underflow) leading to the preservation of depositional dips recording the lobate configuration and progradation direction of the delta front. This

probably indicates fresh or fresh - brackish salinities in the basin water.

4) A decrease in the rate of clastic supply to the Elgol Formation delta in the Inner Hebrides Basin causing the delta to reach a depositional limit between Strathaird and Eigg.

VALTOS FORMATION

Following the deposition of lagoonal mudstones, algal limestones and oolites recording brackish, fluctuating salinities in the Lealt Formation; the Valtos Formation represents the resumption of a clastic supply to both basins. The light and heavy mineralogy of the sandstones in the two basin differs. The rocks have a similar burial and diagenetic history so that these differences are attributable to variations in the source rocks exposed in the hinterlands of the two basins. The fauna of the Valtos Formation is dominated by Neomiodon which demonstrates very rapidly fluctuating salinities. The following sequence of events is proposed to account for the stratigraphy and lateral facies variation seen in the Valtos formation outcrops.

1) The SSW progradation of lagoonal delta systems in both the Sea of the Hebrides and Inner Hebrides Basins. In the Sea of the Hebrides Basin wave energies were high so that a wave dominated delta shoreline sequence was deposited in the Valtos (north Trotternish) area. In the smaller Inner Hebrides Basin wave energies were lower so that a lobate fluvial dominated delta developed.

2) A lateral shift westwards away from the Valtos (north Trotternish) area of the main distributary channels resulting in the deposition at Valtos of relatively thin lagoon shoreline sequences. The lower part of the Formation includes 5 of these sequences each of which is capped by a Neomiodon shell debris limestone recording transgression of the shorelines in the absence of clastic supply. In the Inner Hebrides Basin on Eigg this lower part of the Formation comprises 3 lagoonal delta progradation phases and includes major low sinuosity distributary channels.

3) A decrease in the rate of clastic supply to the Sea of the Hebrides Basin resulting in the deposition of lagoonal shales and Neomiodon shell debris sheets and shoals. Lagoonal delta progradation continued in the Inner Hebrides Basin but this phase probably reached a depositional limit at Camas Sgiotaig on Eigg.

4) A resumption of clastic supply to the Sea of the Hebrides Basin with the deposition of major distributary channel and proximal mouth bar sands forming two progradational sequences in north Trotternish. A similar style of sedimentation occurred in west Skye at this time. However, these rocks have a distinctive heavy mineralogy demonstrating derivation from the Lewisian of the Outer Hebrides. Lagoonal delta sandstones on Eigg in the Inner Hebrides Basin include distinctive low angle inclined delta front beds recording the configuration of the lobate fluvially dominated delta. These sediments contrast with shell debris limestones, desiccation cracked mudstones and thin flood derived sands exposed

in Strathaird (also in the Inner Hebrides Basin). This thin development of the Formation represents a sand starved system and is thought to record deposition on a terrace like structure developed by faulting in association with the main Camasunary basin margin fault.

5) A marked reduction in the rate of clastic supply to both basins. This reduction in fluvial run off is probably related to the deposition of dark shales with oyster beds recording brackish - marine salinities in the base of the overlying Duntulm Formation.

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APPENDIX 1

HEAVY MINERAL ANALYSIS

The results of 69 heavy mineral analyses are presented as tables and as ternary diagrams. The samples analysed comprise:

29 samples from the Valtos Formation in the Sea of the Hebrides Basin; (Trotternish, Raasay, Waternish and Duinnish).
21 samples from the Valtos Formation in the Inner Hebrides Basin, (Eigg and Muck).
13 samples from the Elgol Formation in Trotternish and Raasay.
6 samples from close to the top of the Bearneraig Sandstone Formation in Trotternish.

METHODS

Heavy mineral separations were prepared using the gravity fall through tetrabroemethane method described by Carver (1971). All samples were crushed and disagregated by immersion in cold 10% HCl for 48-72 hours irrespective of cement types. The mineral separations only therefore include the relatively acid, insoluble forms. This particularly affects apatite which is completely removed from many of the samples. Disaggregated samples were split to a convenient size by the cone and quarter method.

Heavy mineral separates were mounted on gridded slides in Canada Balsam. Where sufficient grains were recovered 300-350 non opaque grains have been counted. Any samples which produced less than 70 identifiable non opaque grains are rejected and do not appear in the accompanying tables.

Because heavy mineral assemblages are influenced by grain size and sorting all the samples were sieved to produce a 1.5Ø-3.Ø(.35-.125mm) size fraction. This method removes the 'flood' of tiny zircon grains which dominate heavy mineral assemblages from all fine - very fine grained sandstones in the Great Estuarine Group (Hudson 1964) and allows observation of the more variable coarser sand sized minerals. However, the use of this size fraction precludes direct comparison with the findings of Hudson (1964), which are based on the entire sand fraction. Some of the samples with high zircon percentages particularly from the Elgol Formation are the result of sieve clogging and therefore the retention of large numbers of grains finer than 3.Ø. The rest of the samples were wet sieved to minimize this problem.

In order to investigate the effects of carbonate cementation and diagenetic dissolution of heavy minerals, some samples were taken in pairs; one from a calcite concretion and one from strata immediately adjacent to the concretion. These samples are delineated (c & nc) on the tables below. All the other calcite cemented samples are suffixed (cem).

RESULTS

The heavy mineral percentages shown in the table belows illustrate the same petrographic provinces established by Hudson (1964). These comprise i) Trotternish and Raasay in the Sea of the Hebrides Basin

ii) West Skye also in the Sea of the Hebrides Basin and iii) Eigg and Muck in the Inner Hebrides Basin.

Trotternish and Raasay samples contain more garnet and kyanite and epidote occurs more consistently than in the Inner Hebrides Basin. West Skye samples are dominated by epidote and can clearly be distinguished from the rest although mineral assemblages from Loch Bay indicate mixing of epidote dominated assemblages like those from Waterstein with assemblages typical of Trotternish-Raasay. In the Inner Hebrides Basin staurolite and rutile are more common than in Trotternish-Raasay. The triangular diagrams included in this appendix illustrate some of these points and are also included in the preceeding chapters.

The pairs of specimens, one taken from a concretion and the other from strata immediately adjacent to that concretion indicate that staurolite and kyanite and where present epidote and hornlende are more common within concretions than outside. This suggests the dissolution of staurolite, kyanite, epidote and hornblende either during burial or modern weathering diagenesis. Conversely garnet has a tendency to be more common in uncemented samples from outside concretions than within concretions.

Table 1 — Valtos Formation Sea of the Hebrides Basins

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Indent
	Valtos – Dun Dearg, Trotternish												
	Tr 120	10%	16%	8%	55%	10%					P		
	Tr 121(cem)	13%	3%	4%	30%	6%	40%	3%				P	
	Tr 123(cem)	10%	37%	6%	32%	4%	3%	2%	2%		2%	P	1%
188	Tr 142	3%	23%	3%	47%	6%	14%	4%					
71	Tr 136	42%	18%	8%	24%	4%							3%
181	Tr 350(cem)	14%	33%	4%	22%	7%	11%	8%				P	1%
264	Tr 131(cem)	4%	20%	5%	54%	8%	7%	2%				1%	1%
	Dun Dearg, Quarry Trotternish												
116	Tr 19	9%	49%	4%	29%	7%	2%	2%	1%				
344	Tr 20(nc)	12%	40%	12%	32%	3%	P		P		1%		
120	Tr 21(c)	8%	29%	7.5%	17%	7%	14%	10%	2%			5%	
	Lealt River, Trotternish												
348	Tr 197	12%	18%	3%	57%	8%	1%		P			P	P
310	Tr 203(cem)	5%	27%	3%	48%	7%	6%	1%					1%
	Raasay												
262	Ra 33	14%	10%	5%	52%	15%	1%	2%	2%	P			P
330	Ra 35	12%	12%	2%	49%	18%	3%	2%	1%	2%			1%

Table 1

Loch Bay, Duirinish

n Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Anatase	Indent
213 W 10	2%	35%	2%	2%	15%	36%	3%	P	2%		2%		
297 W 8	6%	32%	8%	33%	7%	5%	1%		7%			P	P
194 W 9	16%	12%	3%	24%	5%	6%	31%		P		3%		

Waterstein, Waternish

n Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Brookite	Tremolite	Hornblende
217 W 16	6%	3%	1%	1%	3%	3%	62%	1%			6%	11%	2%
239 W 17	4%	2%	P	5%		2%	83%	2%	P			2%	1%
252 W 22	11%	1%		5%	3%	4%	62%	2%	3%		3%	P	5%
Average Composition Loch Bay	8%	26%	4%	20%	9%	16%	12%	P	1%		2%		2%
Average Composition Waterstein	7%	2%	P	4%	2%	3%	69%	2%	1%		3%	4%	2%

Table 1 (contd)

Kilt Rock - Rudha Garbhaig, Trotternish

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Indent
250	Tr 238	14%	44%	10%	17%	12%	3%		P				
161	Tr 243(cem)	12%	32%	9%	12%	25%	3%	4%	1%		1%		
	Tr 324(cem)	31%	21%	16%	19%	5%	2%	3%				1%	
215	Tr 325(c)	11%	26%	1%	42%	5%	7%	8%				1%	
308	Tr 326(nc)	10%	14%	7%	64%	1%	P	P	1%				
	Tr 328	7%	56%	14%	14%	6%	2		P				

S. Staffin Slip, Trotternish

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Indent
303	Tr 161	16%	12%	3%	66%	1%			3%				
214	Tr 166	12%	38%	8%	14%	21%	1%	1%	1%		P	1%	1%
333	Tr 171	19%	18%	18%	8%	27%	8%		3%				P
	Sea of the Hebrides Basin Average Composition	13%	26%	7%	35%	9%	6%	2%	1%	P	P	P	P

Table 2 — Valtos Formation, Inner Hebrides Basin

Bay of Laig, Eigg

Division E

Spec No	n	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende
Ei 203(c)	130	11%	41%	8%	6%	27%	P	4%		P	P	2%
Ei 204(nc)	89	14%	60%	5%	11%	8%						
Ei 200(c)	140	11%	62%	5%	9%	12%	1%					
Ei 201(nc)	160	19%	66%	4%	9%	2%						
Ei 20(cem)	127	20%	40%	6%	12%	22%						
Ei 17	122	21%	57%	6%	5%	9%						

Division C

Spec No	n	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende
Ei 111	115	18%	39%	13%	1%	25%	2%	2%				2%
Ei 54	160	19%	31%	14%	4%	32%						
Ei 10	142	32%	25%	21%	1%	19%			P			
Ei 8	118	22%	50%	10%	2%	12%						
Ei 105	136	9%	40%	14%	2%	10%	6%	15%				3%
Ei 50	169	19%	33%	19%	8%	18%			1%			1%
Ei 103	192	52%	8%	22%	4%	3%	1%	5%				4%
Ei 5	92	8%	40%	15%	9%	24%	2%					
Ei 4	136	55%	21%	17%	7%	3%						

Table 2 (contd)

Division B

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende
131	Ei 48	35%	30%	10%	16%	5%					1%	
93	Ei 46	13%	41%	13%	16%	15%	2%					
165	Ei 3	65%	10%	18%	7%		1%					

Division Ai & Aii

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende
147	Ei 44(cem)	14%	27%	13%	23%	10%	12%					P
76	Ei 42	22%	55%	12%	8%	3%						
87	Ei 37	11%	13%	10%	23%	13%						
	Eigg, Inner Hebrides Basin Average Composition	23%	38%	12%	8%	13%	1%	1%	P		P	P

Table 4

Elgol Formation

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Indent
	Trotternish												
224	Tr 35	28%	41%	11%	12%	4%	5%	4%	4%			4%	2%
211	Tr 40	14%	36%	12%	18%	11%	4%	1%	1%			1%	
269	Tr 111	18%	24%	11%	14%	32%	1%						
269	Tr 112	12%	16%	13%	16%	39%	3%	P			P		
	Rigg Burn												
310	Tr 223	56%	7%	24%	2%	1%	P					P	
286	Tr 222	49%	22%	23%	2%	2%		P	P				1%
	Invertote												
305	Tr 126	64%	2%	33%	P	P							
275	Tr 25	20%	47%	9%	19%	4%					P		
288	Tr 108	52%	11%	23%	9%	4%		P					P
324	Tr 103	12%	41%	11%	25%	6%		1%	4%				
316	Tr 105	25%	28%	32%	11%	1%			P				3%

Table 4 (contd)

n Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Indent
Raasay Stream Section N. of Dun Caan												
409 Ra 3	55%	14%	14%	10%	5%			1%		1%		
366 Ra 14	57%	12%	23%	5%	2%			1%		P		
Elgol Formation Average Composition	36%	23%	18%	11%	9%	1%	1%	1%		P		P

Table 5 — Bearreraig Sandstone Formation, Trotternish

n	Spec No	Zircon	Tourmaline	Rutile	Garnet	Staurolite	Kyanite	Epidote	Apatite	Sphene	Monazite	Hornblende	Anatase	Indent
	Invertote													
340	Tr 18	21%	40%	26%	9%	2%		2%	P		P		P	
344	Tr 29	47%	24%	19%	8%	2%		P					P	P
	Rigg													
320	Tr 213	12%	28%	8%	40%	10%		P					P	1%
422	Tr 218(cem)	54%	12%	12%	20%	1%		P	P				P	
	Torvaig													
229	Tr 319(c)	2%	27%	7%	61%	P		2%			P	P	P	
279	Tr 320(nc)	10%	39%	7%	44%							P		
	Average Composition	24%	28%	13%	30%	3%		1%	P		P	P	P	P

Key

(cem) Sample Cemented with Calcite

(c) " " " ") notation for specimens from ferroan

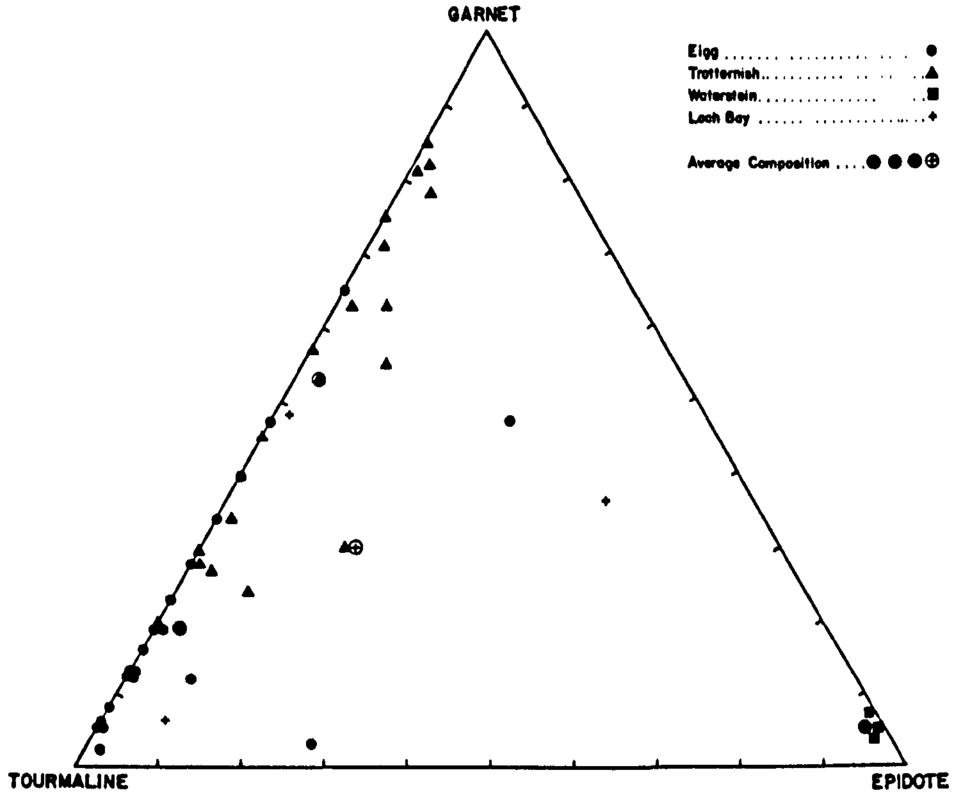
(nc) Uncemented-friable sample) calcite concretions and adjacent uncemented friable sand

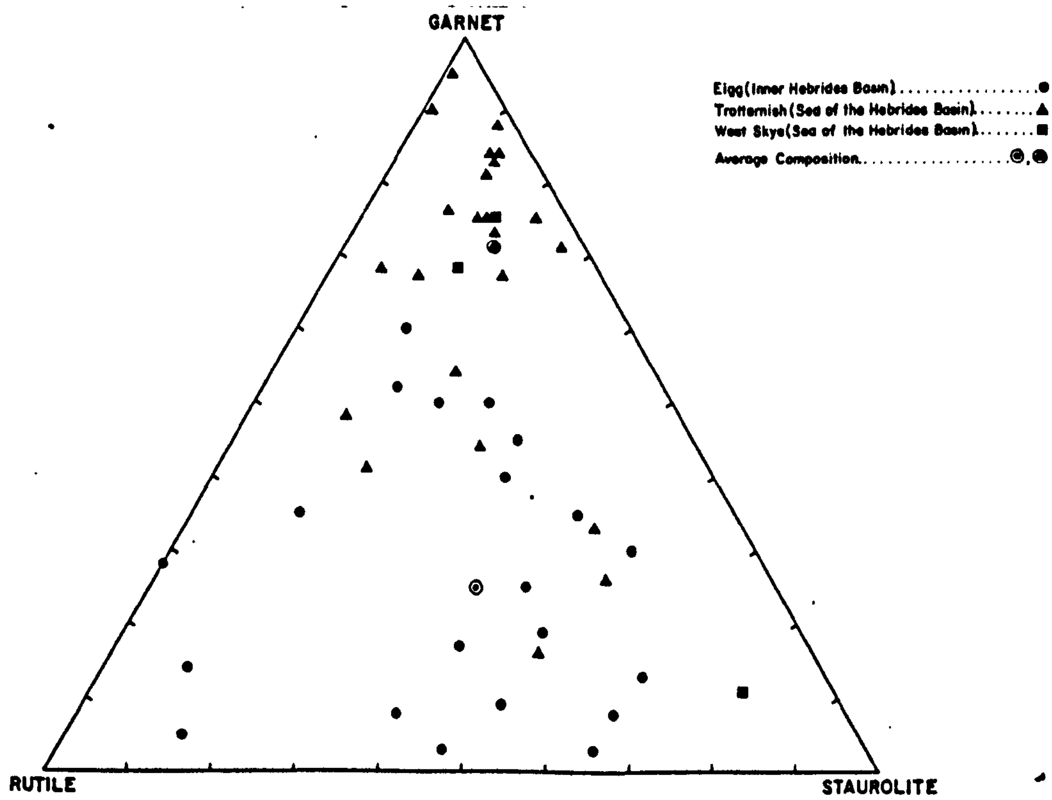
Tr = Trotternish

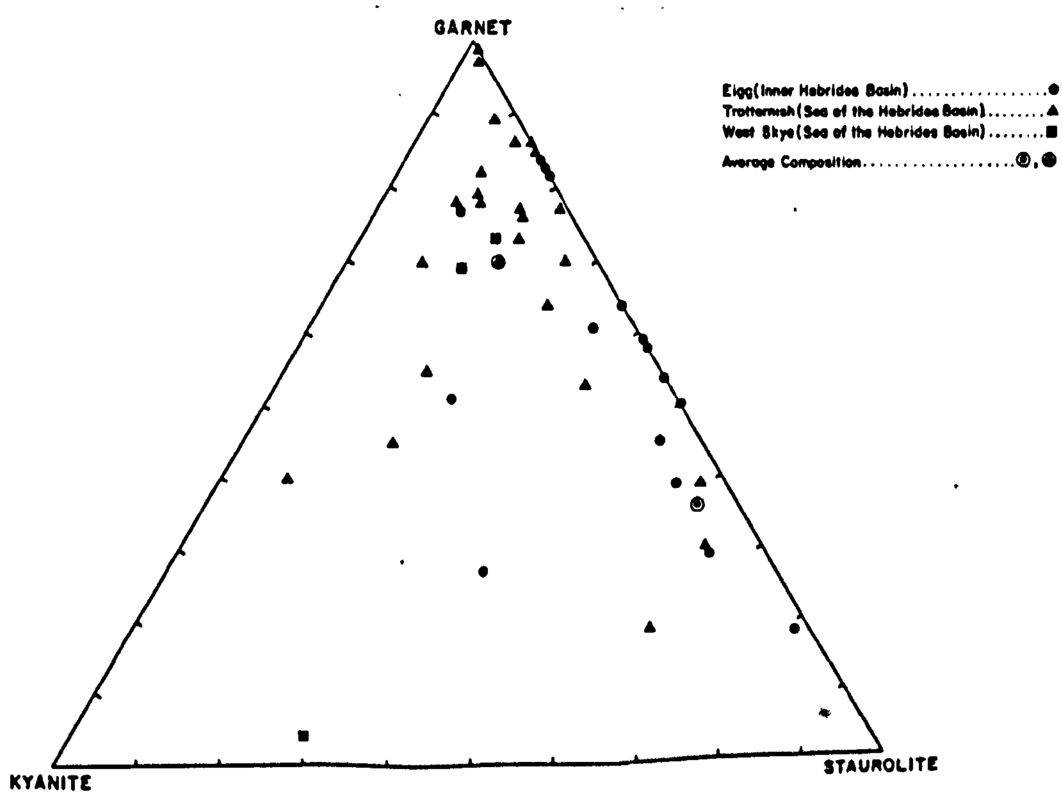
W = West Skye

Ra = Raasay

Ei = Eigg


GARNET
TOURMALINE
EPIDOTE
Eigg
Trotternish
Waterstein
Loch Bay
Average Composition


GARNET
RUTILE
STAUROLITE
Eigg (Inner Hebrides Basin)
Trotternish (Sea of the Hebrides Basin)
West Skye (Sea of the Hebrides Basin)
Average Composition


GARNET
KYANITE
STAUROLITE
Eigg (Inner Hebrides Basin)
Trotternish (Sea of the Hebrides Basin)
West Skye (Sea of the Hebrides Basin)
Average Composition

APPENDIX 1 REFERENCES

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APPENDIX 2

GUIDE TO THE MAIN ELGOL AND VALTOS FORMATION OUTCROPS

In the preceeding chapters reference to outcrop localities and logged sections is made by local place names and grid references. The following provides a brief description of the main outcrops and access to them.

ELGOL FORMATION: SKYE AND RAASAY

ELGOL FORMATION: ELGOL SHORE, STRATHAIRD. Log 1 Chapter 2 [NG 5164 1380]

The section comprises hard, thermally metamorphosed sandstones forming low sea cliffs at the northern side of Port na Cullaidh. These cliffs are dissected by dyke gulleys which provide excellent 3 dimensional outcrops off the whole formation. The basal transition to shales of the Cullaidh Formation occurs among mobile boulders of the storm beach in the bay (Port na Cullaidh).

Access to the section is by walking down the road from the car park below Elgol, past Elgol School and turning north across the beach.

ELGOL FORMATION: SCARP FACE SECTIONS SOUTH OF KILMARIE, STRATHAIRD. Logs 2-7, Chapter 2 [NG 5222 1354 - NG 5430 1595]

The escarpment formed by the Elgol Formation extends between the above grid references and provides intermittant exposure of the middle and upper parts of the formation. The best and most accessible of these are figured in Chapter 2 (logs 2-7). Rocks close to the top of the formation are exposed on the dip slope of the escarpment as slabs of hard white sandstone dipping NE into a series of peat bogs so that the contact with the overlying Lealt Formation is never exposed. The base of the formation and the transition to the Cullaidh Formation is only exposed in road side quarries north of Elgol.

Access is by walking north along the base of the escarpment from Glasnakile path [NG 525 138] and continuing north along the A881 road.

ELGOL FORMATION: SCARP FACE SECTIONS NEAR KEPPOCH, NORTH OF KILMARIE STRATHAIRD. Logs 8 and 9, Chapter 2 [NG 5610 1855 - 5634 1920]

The scarp face at Keppoch north of Kilmarie provides sections similar to those described from south of Kilmarie.

Access is by walking north along the base of the escarpment from a disused quarry next to the A881 road [NG 562 184].

ELGOL FORMATION: SOUTH TROTTENISH, CLIFFS BELOW FIURNEAN. Chapter 2 [NG 5110 4640 - 5157 4980]

The Elgol Formation forms a subsidiary cliff or terrace above the high (ca 650') cliffs formed of the Bearreraig Sandstone Formation.

This terrace provides almost continuous exposure of the middle and upper parts of the formation although access to the cliff face is limited. The base of the formation and the transition to the Cullaidh Formation is exposed in several small gulleys north of NG 5168 4900. More extensive outcrops of the upper part of the formation occur in the stream at NG 5157 4980 and between here and the cliff face. The south end of the outcrop is controlled by truncation of the Middle Jurassic rocks at the base of the overlying Tertiary agglomerates and lavas.

Access to the section is by walking east from the A855 to the saddle between Fiurnean end Craig Ulatota or by walking south along the cliff top from Bearreraig power station.

ELGOL FORMATION: RAASAY: STREAM SECTION N. OF DUN CAAN. Chapter 2
[NG 5812 4206 - 5805 4196]

The Elgol Formation forms a low terrace extending for 3 kms north of Dun Caan and is exposed in the south bank of a stream 2½ kms north of Dun Caan at the above grid references. These low river cliffs form the only complete section in the Elgol Formation on Raasay.

Access to the section is by walking east from the road (parking space at NG 562418) up a stream valley (which contains a section in the Garantiana Clay, Cullaidh Shale and basal Elgol Formation (300 m E of the road) and across the moors to the east facing cliffs.

ELGOL FORMATION: RIGG BURN, NORTH TROTTENISH. Chapter 2 [NG 5169 5628 - 5162 5623]

In the Rigg Burn the Elgol Formation crops out as a series of low river cliffs overhung by trees on both north and south banks of the stream. These provide a complete but composite section including the basal transition to the Cullaidh Shale Foramtion.

Access to the section is by walking down the stream from the A855 road [NG 513 562].

ELGOL FORMATION: INVERTOTE, NORTH TROTTERNISH. Chapter 2, section 1. [NG 5219 6028 - 5231 6003 and 5198 6040] section 2 [5209 6065].

At Invertote the Elgol formation crops out in a continuous 12-20 m high cliff at the south end of the bay [NG 5219 6028 - 5231 6003], in a low river cliff close to the mouth of the Lealt River [NG 5198 6040] and in a section at the top of the beach 150 m north of the river mouth [NG 5209 6065].

The section at the south end of the bay comprises a lower cliff and wave cut platform composed of the Bearreraig Sandstone Formation a wave cut notch occupied by the Garantiana Clay and Cullaidh Shale Formation and an upper cliff composed of the Elgol Formation. Access to this section is tide dependant and although a series of rock falls allows access to the cliff face the upper part of the Formation is largely inaccessible. However, this upper part of the Formation is easily accessible in the south bank of the Lealt River close to the mouth of the stream and 150 m north of the river mouth.

Access to Invertote is by walking down a foot-path on the south side of the Lealt River gorge from the A855 road.

VALTOS FORMATION: SEA OF THE HEBRIDES BASIN

VALTOS FORMATION: CLIFFS BELOW VALTOS, NORTH TROTTERNISH

Type section, lower sandstone dominated unit and middle limestone shale unit, logs 3 & 4, Chapter 4 [NG 5174 6396 - 5114 6475]

Below Valtos the Valtos Formation dips WNW so that by traversing NW along the foreshore successively higher parts of the formation can be examined at beach level to give an almost complete section in the lower sandstone dominated unit. The unexposed sections on the foreshore all correspond to facies 1 mudstones-siltstones; outcrops of which frequently occur as scars higher in the cliffs. At the northern end of the section [NG 5114 6475] the cliffs include sections in the middle limestone-shale unit but the sequence is difficult to reconstruct because of talus cover of the mudstones and complex transgressive sills which are intruded prefferentially into these mudstone horizons.

Access to the southern end of the section is by a cliff path which leaves the A855 road at Culnacknock [NG 514 636]. The cliffs at the northern end of the section can be ascended by a dyke gulley at NG 5090 6532, 300m south of Mealt waterfall.

VALTOS FORMATION: CLIFFS SOUTH OF RUBHA GARBHAIG AND NORTH OF THE KILT ROCK, NORTH TROTTERNISH. Upper sandstone dominated unit. Chapter 4. Logs 6 & 7 [NG 5035 6726 - 5034 6707 and 5065 6673 - 5060 6684]

The section south of Rubha Garbhaig comprises baked limestones and shales on top of the Rubha Garbhaig sill and a cliff providing a very good laterally continuous section in the sandstones of lithostratigraphic division XI. Above the level of this cliff is a separate section in the basal part of the Duntulm Foramtion. The cliff north of the Kilt Rock provides a similar section in lithostratigraphic division XI and the basal Duntulm Formation. The lower part of the cliff also includes sandstones of division X but the cliff face is largely inaccesible.

Access to the sections is by walking south from the slipway at Rubha Garbhaig [NG 495 682] across the raised beach to the cliffs south of Rubha Garbhaig continuing south across fallen blocks of dolerite on the foreshore to the section north of the Kilt Rock. The cliffs above this section can be ascended by a dyke gulley [NG 5057 6673].

VALTOS FORMATION: DUN DEARG, NORTH TROTTERNISH. Upper sandstone dominated unit, Chapter 4, Log 4b [NG 5134 6426].

This excellent section in part of the upper sandstone dominated unit has been obliterated during 'improvements' to the A855 road, but a series of small outcrops are still exposed alongside the road south of Dun Dearg.

VALTOS FORMATION: LONFEARN BURN, NORTH TORTTERNISH. Lower sandstone dominated unit, Chapter 4, log 2 [NG 5209 6267 - 5175 6236].

The base of the Valtos Formation occurs in a small waterfall close to the mouth of the Lonfearn Burn. The rest of the section occurs as a series of separate outcrops in both banks of the Burn between this waterfall and a waterfall [NG 5176 6236] 300 m to the SW.

Access to the section is by walking down a footpath leading from the settlement of Lonfearn [518 627] down to the mouth of the Lonfearn Burn.

VALTOS FORMATION: LEALT RIVER, NORTH TROTTERNISH. Lower sandstone dominated unit, Chapter 4, log 1 [NG 5100 6052 - 5034 6066].

The section comprises a series of low river cliffs on the outside of seccessive bends in the Lealt river (entrenched meanders) areas of non-exposure between these river cliffs mainly correspond to mudstones of facies 1. This relatively poorly exposed section contrasts with the sea cliffs described from elsewhere in north Trotternish and from Eigg.

Access to the section is by walking upstream from the road bridge on the Lealt River [NG 5155 6137].

VALTOS FORMATION: LOCH BAY, WATERNISH, WEST SKYE. Chapter 4 [NG 2659 5422 - 2642 5420]

The section comprises a series of separate outcrops on the beach and in low cliffs extending for 170 m along the beach at the head of Loch Bay. Unexposed sections between the outcrops mainly correspond to facies 1 mudstones.

Access to the section is by walking down a track leading from village of Bay [NG 268 539] to the shore.

VALTOS FORMATION: CLIFFS IN CAMAS NAN SIDHEAN, DUIRNISH. Rocks equivalent to the lower sandstone dominated unit and middle limestone/shale unit, Chapter 4, [NG 1410 4768]

The section comprises faulted and folded sandstones and silty limestones exposed in sea cliffs and a waterfall at the head of the bay. The section along the coast to the west includes rafts of Lealt Formation within a transgressive sill complex.

Access to the section is by descending the cliffs and landslips to the beach on the east side of the waterfall.

VALTOS FORMATION: CLIFFS AND FORESHORE AT AN STAC, WATERSTEIN HEAD, DUIRNISH. Upper sandstone dominated unit. Chapter 4 [NG 1425 4696 & 1439 4690]

North of An Stac below Waterstein Head sandstones of the Valtos Formation form a low sea cliff partly obliterated by a major landslip. South of An Stac the upper part of the formation and the basal Duntulm Formation are preserved as rafts in a Tertiary sill complex. These rafts provide a composite section exposed on a series of 'benches' cut in the cliffs.

Access to these sections is by walking south from Camas nar Sidhean along the beach and across the landslip mentioned above.

VALTOS FORMATION: INNER HEBRIDES BASIN

VALTOS FORMATION: FORESHORE NORTH OF ELGOL AND CLIFFS NORTH OF CARN MOR, STRATHAIRD. Chapter 3, logs 8 and 9 [NG 5165 1434 - 5166 1460 and 5205 1590 - 5200 1618]

The section 700 m north of Elgol comprises a series of outcrops of mudstones with Neomiodon (marking the base of the Formation) and Viviparus and desiccation cracked limestones. The rest of this section is exposed as a stack on the forshore composed of sandy Neomiodon debris limestones.

The section north of Carn Mor occurs in a ca 12 m high cliff composed of interbedded sandy limestones and mudstones-siltstones and on the beach immediately north of the cliff section. Here a promontory composed of Viviparus bearing limestone extends across the wave unit platform and out to sea and marks the top of the formation. These two thin mudstone-limestone dominated sections demonstrate the differences between the Valtos Formation in Strathaird and the thick sandstone dominated sections exposed elsewhere in both the Inner Hebrides and Sea of the Hebrides Basins.

Access to both these sections is by walking north along the beach from Elgol School [NG 517 138]. When the tide is high the north Carn Mor section can be reached by a poorly defined cliff path which starts at the end of a track north of Elgol Village [NG 519 141].

VALTOS FORMATION. FORESHORE AND CLIFFS NORTH OF CAMAS SGIOTAIG, EIGG. Divisions Ai,Aii,B,C and D, Chapter 3, log 1 and 2 [NM 4686 9042 - 4674 9033 (foreshore) and 4689 9037 (cliffs)]

The section is exposed on the ~~wave~~ cut platforms and in the south west facing cliffs forming Blar Mor north of Camas Sgiotaig. The section on the foreshore extends for ca 160 m across the wave cut platform so that access is limited to low tide. The section is parly obscured by seaweed and is cut by numerous Tertiary dykes most of which occupy minor faults. The cliffs on the SW side of Blar Mor are relatively easily ascended and provide a complete vertical sequence in divisions Aii, B, C and D. The north facing cliffs of Blar Mor duplicate this section but are largely inaccessible.

Access to the locality is either by walking north along the beach from the Bay of Laig, or by walking across the moors from the end of the track at Howlin [NM 477 898] north of Cleadale.

VALTOS FORMATION: BAY OF LAIG, EIGG. Divisions C,D and E Chapter 3, logs 3,4,5 and 6 [NM 4718 8988 - 4732 8849]

The cliffs on the east side of the Bay of Laig provide the best sections in the Valtos Formation in the Hebrides. Numerous embayments and indentations in the cliffs together with outcrop on the wave cut platform provide relatively easy access to excellent 3 dimensional outcrops. The formation dips SW at less than 10" so that by traversing from N to S each successive division of the formation can be examined at sea level. However, the sequence is repeated by minor faults many of which are occupied by Tertiary dykes. The baked sandstones at the margins of these dykes form a series of double ramparts which cross the wave cut platform and extend seawards as minor promontories.

Access to the section is by walking north along the beach from the end of the track [NM 472 914] leading from Cleadale to the shore.

VALTOS FORMATION: CAMAS MOR, MUCK. Divisions E and F and the base of the Duntulm Formation [NM 4083 7913 - 4066 7927].

The wave cut platform (Sgeir Fhada) at the head of Camas Mor provides a section from the upper part of division E of the Valtos Formation into the Duntulm Formation. The section is partly covered by loose boulders on the storm beach but provides a good relatively continuous section. Outcrop of this stratigraphic horizon is poor elsewhere in the Inner Hebrides Basin.

Access to the section is by walking south through the fields from the farm a Cnoc nan Calmon [NM 404 800].

SEDIMENTOLOGY OF THE GREAT ESTUARINE GROUP (MIDDLE JURASSIC) OF NORTH-WEST SCOTLAND

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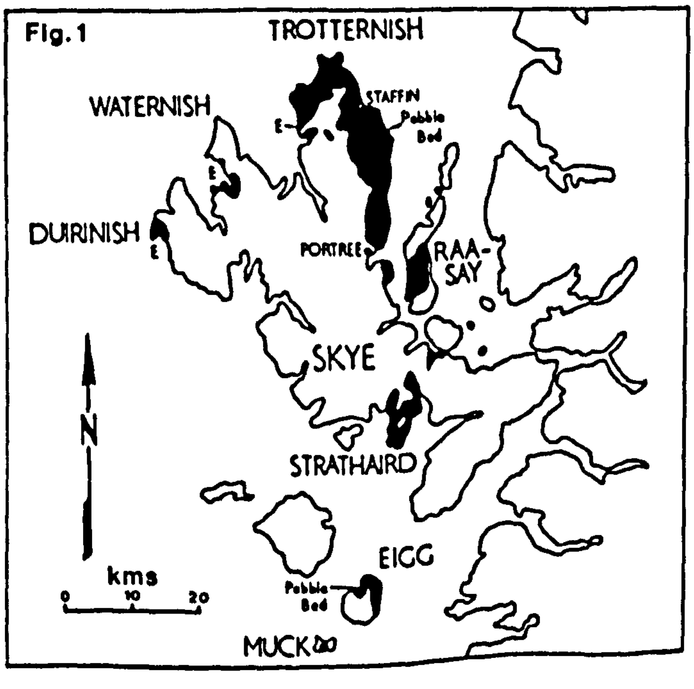
SUMMARY : A sequence of formations of paralic facies form the Great Estuarine Group, intercalated conformably within the otherwise marine, clastic-dominated Jurassic section in the Minch Basin off North-West Scotland. The predominant lithologies are silty shales with shell-beds and thin biosparites, and coarsening-upwards sequences of sandstones, a few 10's of m thick. The abundant faunas of bivalves and gastropods are of low diversity and indicate abnormal, mainly brackish, salinity. Supra-tidal stromatolites occur at two horizons. Deposition was in restricted, but marine-influenced, lagoons of low tidal range; the sandstones may represent prograding small deltas and marginal facies. Marine influence in general declined up the succession until a transgressive lagoon-bar sequence re-introduced marine sedimentation in the Callovian. Diagenetic grade is generally low despite burial beneath thick Tertiary lavas.

RESUME : Dans le bassin de Minch, au large de la côte NW de l'Ecosse, les formations paraliques qui constituent le "Great Estuarine Series" sont intercalées en concordance dans les sédiments marins à composition essentiellement terrigène . Les schistes silteux et des grès renferment des mollusques peu diversifiés, indiquant une salinité saumâtre . Des stromatolithes supratidaux sont également présents . La sédimentation a eu lieu dans un milieu à marée faible . Des grès reflètent probablement l'existence de petits deltas de progradation . L'influence marine qui diminue progressivement vers le sommet, se termine par une transgression callovienne . Les modifications diagénétiques sont relativement faibles malgré un enfouissement sous des laves tertiaires épaisses .

Fig.1



Symposium "Sédimentation jurassique W européen".
Assoc.Sédimentologistes Français; Publication spéciale N°I, Mai, 19
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General Setting. The islands of the Inner Hebrides (Fig. 1.) expose Mesozoic, mainly Jurassic, rocks that rest on Precambrian and Palaeozoic basement and are overlain by Tertiary volcanics. A similar succession is found in the submarine area of the Minch between the mainly Precambrian rocks of the Scottish mainland and the Outer Hebrides (1). Although direct evidence of palaeo-shorelines is lacking, we believe that the Inner Hebrides-Minch region approximates to a depositional Minch Basin, bordered on either side by swells. The main source of sediment was probably the Scottish swell (2), and the major Jurassic exposures (Fig. 1.) probably parallel the depositional north-south strike. Limited evidence indicates westward thinning in Skye. Some of the shales are very rich in montmorillonite (Boyd, personal communication) of probable volcanic origin.

The Great Estuarine Group is a paralic episode in an otherwise marine Jurassic section. During the accumulation of some 250 m of sediment the depositional surface was never more than a few metres from sea level, and despite the great variety of facies the vertical succession is remarkably constant along the 90 km of outcrop from North Skye to Eigg and Muck (Figs. 2-4) and probably originally further. The degree of diachroneity of facies cannot be accurately assessed because of lack of good zone fossils. Between the Upper Bajocian (Garantiana Zone) and Lower Callovian (Macrocephalus Zone) there are neither fully marine faunas (e.g. cephalopods) nor fully terrestrial deposits such as the coals and rootlet beds that occur in roughly contemporaneous deposits in the North Sea basin and in England. An origin in extensive shallow lagoons with a low tidal range, as in many modern lagoons, is envisaged (3). The occurrence of thick lagoonal deposits in a subsiding basin, rather than at its margins, has a parallel in the Purbeck Beds of southern England.

Climate. The palaeolatitude was about 35°N (4). Oxygen isotope studies suggest temperatures of about 22°C with marked seasonality (5). Climate was humid on the hinterland, at times at least, leading to strong run-off and abundant coniferous driftwood in the basin; at times the basin itself may have been semi-arid.

Stratigraphical Sedimentology. This is illustrated by logs (Figs. 2-4) of the main sections; see Fig.1. for locations. A field guide is given in (6). Points of particular interest in the various formations are noted below. We cannot as yet explain all the observations in terms of simple sedimentary models.

(1) Initiation of non-marine basin. Thick, open-marine Bajocian sandstones are succeeded by a thin (3 m) clay with ammonites. This passes gradationally into a black, laminated shale (Basal Oil Shale) with a sparse fauna including articulated fish, recording stagnation of the basin. Both argillaceous formations pass into sandstones northwards.

(2) White Sandstone. Bioturbated fine argillaceous sandstones pass up into cross-bedded sands capped by a pebbly granule-conglomerate, forming a classic coarsening-upwards sequence particularly well seen at Elgol, Strathaird (Fig. 3.), but present throughout the northern part of the region. This may represent a prograding delta with prominent delta-margin facies. There is no clear marine to non-marine polarity in the facies above and below, such as would be expected for an offshore bar. The White Sandstone thins out southwards.

(3) Mytilus Shales. Mainly silty shales alternating with shell-beds and biosparites; these formed by wave-winnowing of shells from muddy sediment, followed by progressive, mainly biological, breakage and rounding. Biosparites with high concentrations of shark's teeth and plesiosaur bones occur (7). Excellent evidence of salinity variations from freshwater to probably hypersaline, but mainly brackish (Fig.5; see ref.5). Algal stromatolites with gypsum pseudomorphs at the top (8).

(4) Estheria Shales. Unusual facies of laminated paper-shales with variably-brackish faunas (ostracods, '<u>Estheria</u>', bivalves, gastropods) interbedded with thin bio- and oo-sparites. These formed by intensification of the winnowing process described above, followed by chemical precipitation of carbonate. Ooliths and intraclasts are now ferroan dolomite. Fibrous calcite veins ("beef") prominent. Most similar described rocks are shore-phases of the Green River Formation (9).

(5) Concretionary Sandstones. Dominated by coarsening-upwards sandstone cycles indicating similar depositional conditions to those of the White Sandstone; much coniferous driftwood. Fig. 7 illustrates details from Eigg showing lateral facies variation on a small scale. Regional variations in thickness and facies also become important; thin succession with mudcracks, indicating frequent emergence, in Strathaird. Petrography indicates different sand sources in Trotternish and Eigg (2; compare 10, fig.6). Large calcite concretious formed during burial diagenesis (5).

(6) Lower Ostrea Beds. All the higher formations are much thicker and sandier in Trotternish than in the south. Marine influence increases again (oysters, rhynchonellids, crustacean burrows) and hypersaline carbonate mudflats were at times colonized by blue-green algae (8). Fresh-to-brackish intercalations still occurred in the north (e.g. Fig.6). In the south, the formation is thinner and lacks freshwater episodes; oyster biosparites are dominant (11).

(7) Ostracod Limestones. Marls and argillaceous calcilutites, some dolomitic; shales and biosparites are minor. Faunas (ostracods, '<u>Estheria</u>', gastropods) of very low diversity and freshwater-brackish affinity; desiccation features (mudcracks, dolomitic breccias) frequent. Fish and reptile bones common; mammals occur (12). Very shallow pools largely isolated from the open sea and frequently drying up.

(8) Mottled Clays. Red silts with calcareous nodules; thin, lenticular calcareous sandstones, probably channels. Probably alluvial silts but no definite soils or rootlet horizons.

(9) Top of Great Estuarine Group. In Trotternish, the Staffin Bay Formation represents a transgressive lagoon-barrier bar complex (6,13) overlying the Mottled Clays. In Strathaird they are overlain directly by the open-marine Carn Mor Sandstone, representing re-worked bar sands. Marine shales with ammonites follow.

<u>Diagenesis</u>. Early-diagenetic precipitation of carbonates confined to algal limestones, concretions etc; otherwise no evidence of early submarine or beachrock lithification as in the Persian Gulf, nor of early freshwater diagenesis as described from Bermuda. Early dolomite at some horizons (14). No hardgrounds. Burial-diagenetic cementation of all biosparites and thin sandstones by sparry ferroan calcite. Aragonite mollusc shells generally preserved in shales; replaced by neomorphic ferroan pseudospar in limestones. Incomplete calcite cementation of thicker sands, giving ellipsoidal concretions commonly 1-2 m. across. No obvious diagenetic alteration of feldspars apart from corrosion by calcite cement. Fibrous calcite veins in shales possibly formed during over-pressuring episodes. All this diagenesis probably pre-Upper Cretaceous and under less than 500 m. burial.

Tertiary burial beneath perhaps 1000 m. of basalt lavas had little obvious effect away from plutonic centres and thin contact-metamorphic zones. Vitrinite reflectivities between 0.23 and 0.50 are found at several outcrops (Hudson and B.S. Cooper, unpublished data). In Strathaird, near the Skye plutonic centre, alteration is evident in blackening and loss of fissility in shales, recrystallization of fossils and istopic exchange of calcite with circulating waters (14); the White Sandstone is cemented by quartz.

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Key to abbreviations, Fig. 2, Trotternish

Stratigraphy:

Ox C "Oxford Clay" = basal part of Staffin Shales Fm., Callovian (Ref.15)

BL S Belemnite Sands Mbr., Staffin Bay Fm., Lower Callovian

UOB Upper Ostrea Mbr., Staffin Bay Fm.,? Lower Callovian

Great Estuarine Group; Bathonian to ? Upper Bajocian; the units are, in effect, Formations but have not yet been formally designated as such:

MC Mottled Clay

OL Ostracod Limestones

LOB Lower Ostrea Beds

CSS Concretionary Sandstones

ES Estheria Shales

MS Mytilus Shales

WS White Sandstone

BOS Basal Oil Shale

Bearreraig Sandstone Group, Bajocian:

GC Garantiana Clay

BrS Sandstones of Bearreraig Group

Environments:

MfA Mudflat and alluvial (freshwater)

Lagoonal facies subdivided using key fossils as listed; see also Figs. 5, 6.

FW Freshwater Unio, Viviparus, 'Estheria'

FB Freshwater-Brackish 'Estheria', Neomiodon, tiny gastropods.

B Brackish Neomiodon in monotypic beds, small Praemytilus (in MS only); this category also used where only general interpreation is possible as in poorly fossiliferous beds in the generally lagoonal facies.

BM Brackish-Marine Praemytilus (MS) or Praeexogyra (LOB) in more or less monotypic shell beds; also Placunopsis, Cuspidaria, Corbula.

MHs Marine to Hypersaline Abundant Placunopsis etc. (MS); Praeexogyra with Kallirhynchia, Modiolus, Corbula, Myopholas etc. (LOB)

Spt Supratidal carbonate mudflat (hypersaline) Stromatolites & gypsum pseudomorphs.

Ano Anoxic basin. Bituminous shale, sparse benthic fauna, articulated fish.

Marine facies:

Bar Offshore or beach bar.

OM Open marine.

Degree of certainty of assignment indicated by solid or hachured column.

Key to Fig. 3, Strathaird: As Fig. 2, except

CMS Carn Mor Sandstone MBr, Staffin Bay Fm, Lower Callovian (Ref.15).

Key to Fig. 4, Eigg: As Fig. 2, except

CRET Upper Cretaceous Laig Gorge Beds, disconformable on Ostracod Limestones (Ref. 3, 1962).

Key to Figs. 5 and 6. Environmental interpretations of critical sections, showing evidence of rapid fluctuations of salinity. General discussion refs. (3, 5, 11).

Fig. 5. Type section of Mytilus Shales, north of Kildonnan, Isle of Eigg (Refs. 5, 7, 8).

Fig. 6. Sections in the Lower Ostrea Beds near Duntulm, Trotternish, Skye (Refs. 5, 6, 8). Correlation between the two columns is uncertain, but the preferred version is shown.

Fig. 7. Lateral variation in the Concretionary Sandstones, Eigg, over a distance of 1 km.

Key to Log. Symbols — **Lithological Symbols:** Standard

Sedimentary and Biogenic Structures

- Trough cross stratification
- Cross stratification
- Loaded bedding surfaces
- Erosion surfaces
- Burrows
- Desiccation cracks
- Gypsum pseudomorphs
- Algal laminations
- " stromatoliths
- " nodules

Diagenetic Structures:

- Concretions calcereous
- Septaria

Palaeontological Symbols:

- Bivalve molluscs articulated
- " " disarticulated and/or broken
- Gastropods
- Brachiopods
- Belemnites
- Ammonites
- Porifera
- Echinoderms
- Fish teeth scales and bone
- Reptile bone.
- Drift wood
- Estheriids
- Ostracods

Key to Lithological Log. Abbreviations:

i) Clastics

- Shale/Clay
- Fine sand
- Medium sand
- Very coarse sand
- Pebbles

ii) Carbonates

- Marls
- Calcilutites
- Calcarenites
- Calcirudites

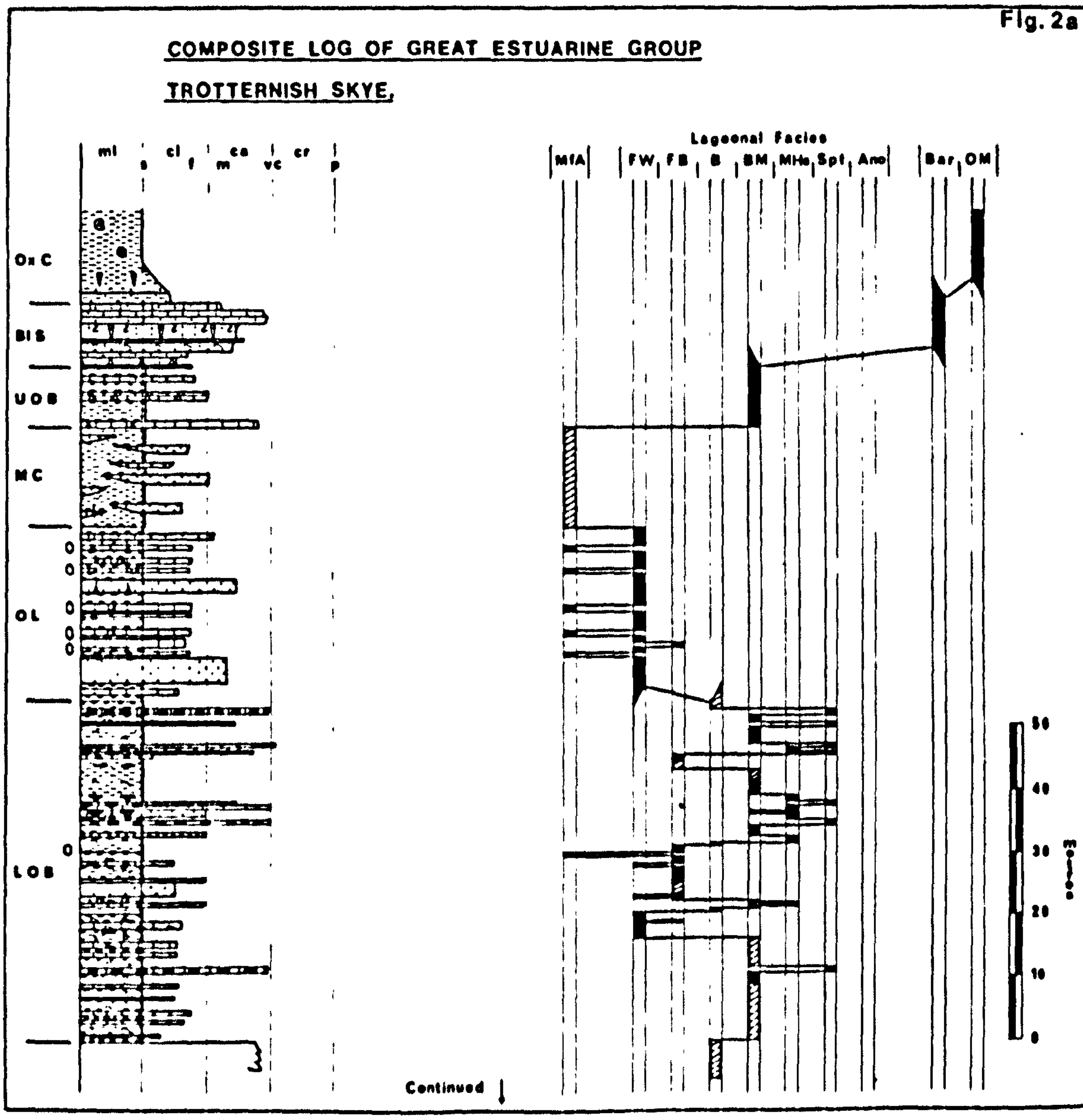


Fig. 2a

COMPOSITE LOG OF GREAT ESTUARINE GROUP

TROTTERNISH SKYE,

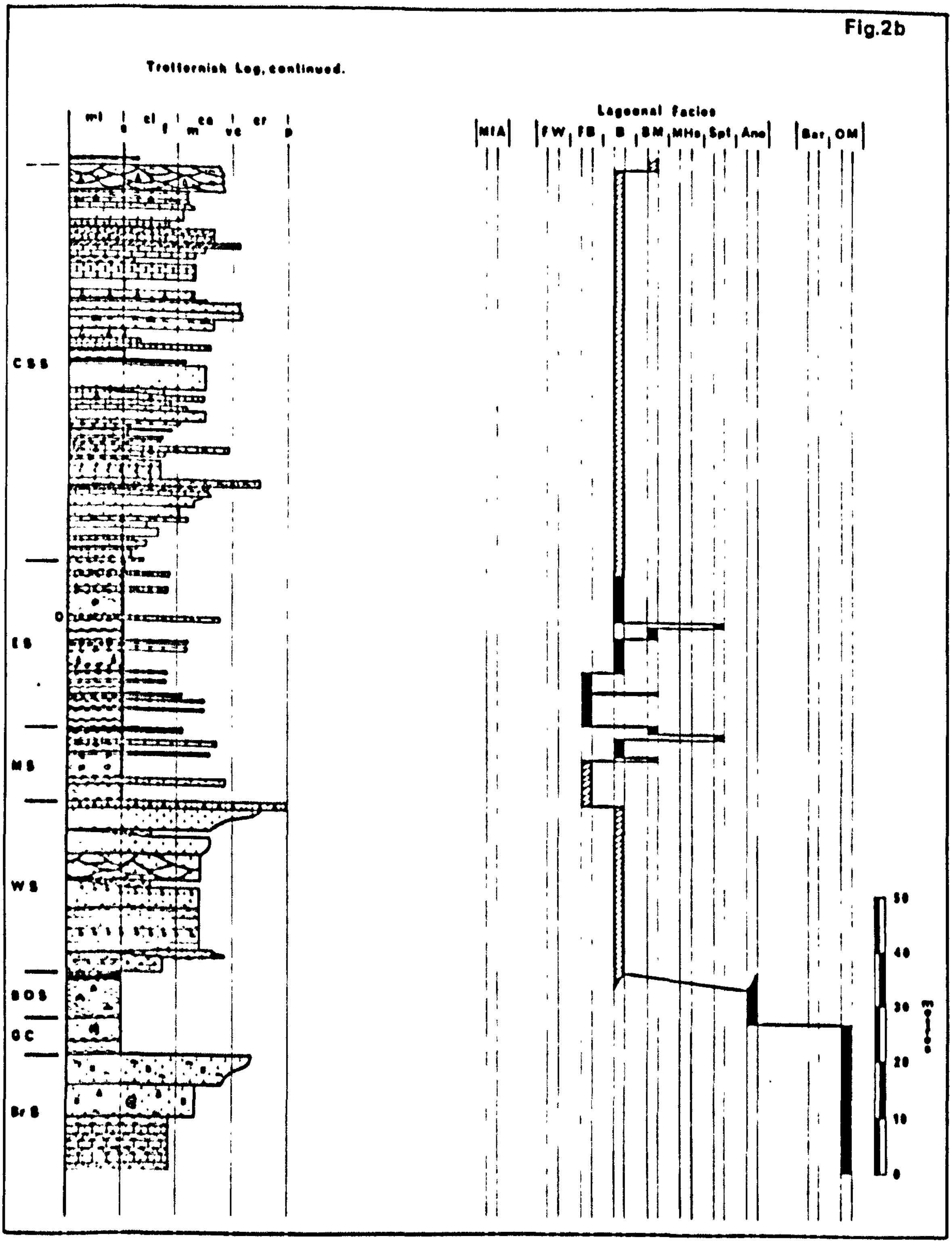


Fig.2b
Trotternish Log, continued.
ml
s
cl
f
m
ca
vc
cr
p
Lagoonal facies
M/A
FW
FB
B
BM
MHs
Spl
Ano
Bar
OM
CSS
ES
MS
WS
BOS
OC
BrS
50
40
30
20
10
0
metres

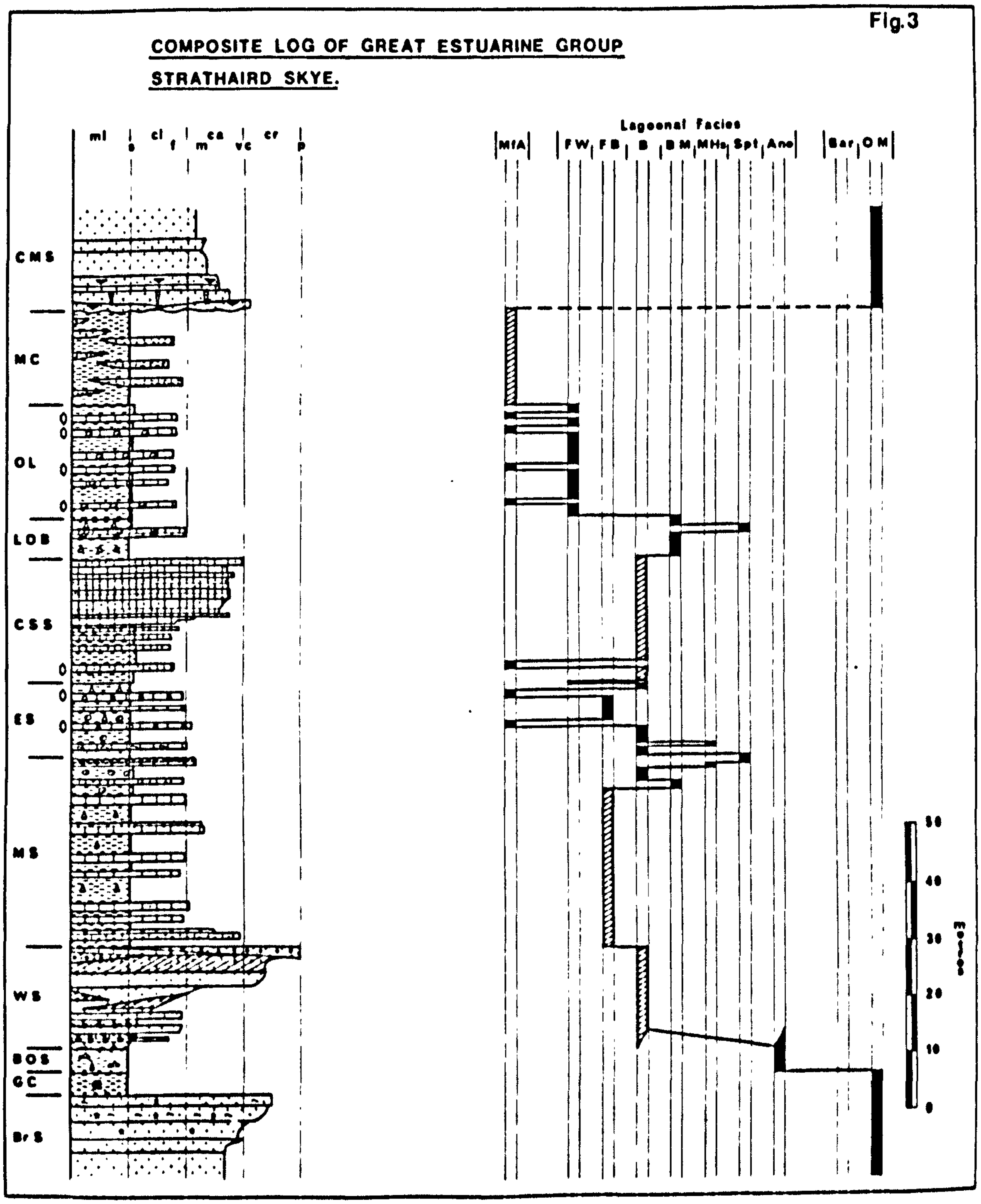


Fig.3
COMPOSITE LOG OF GREAT ESTUARINE GROUP
STRATHAIRD SKYE.
Lagoonal Facies
CMS
MC
OL
LOB
CSS
ES
MS
WS
BOS
GC
Br S

Fig.4

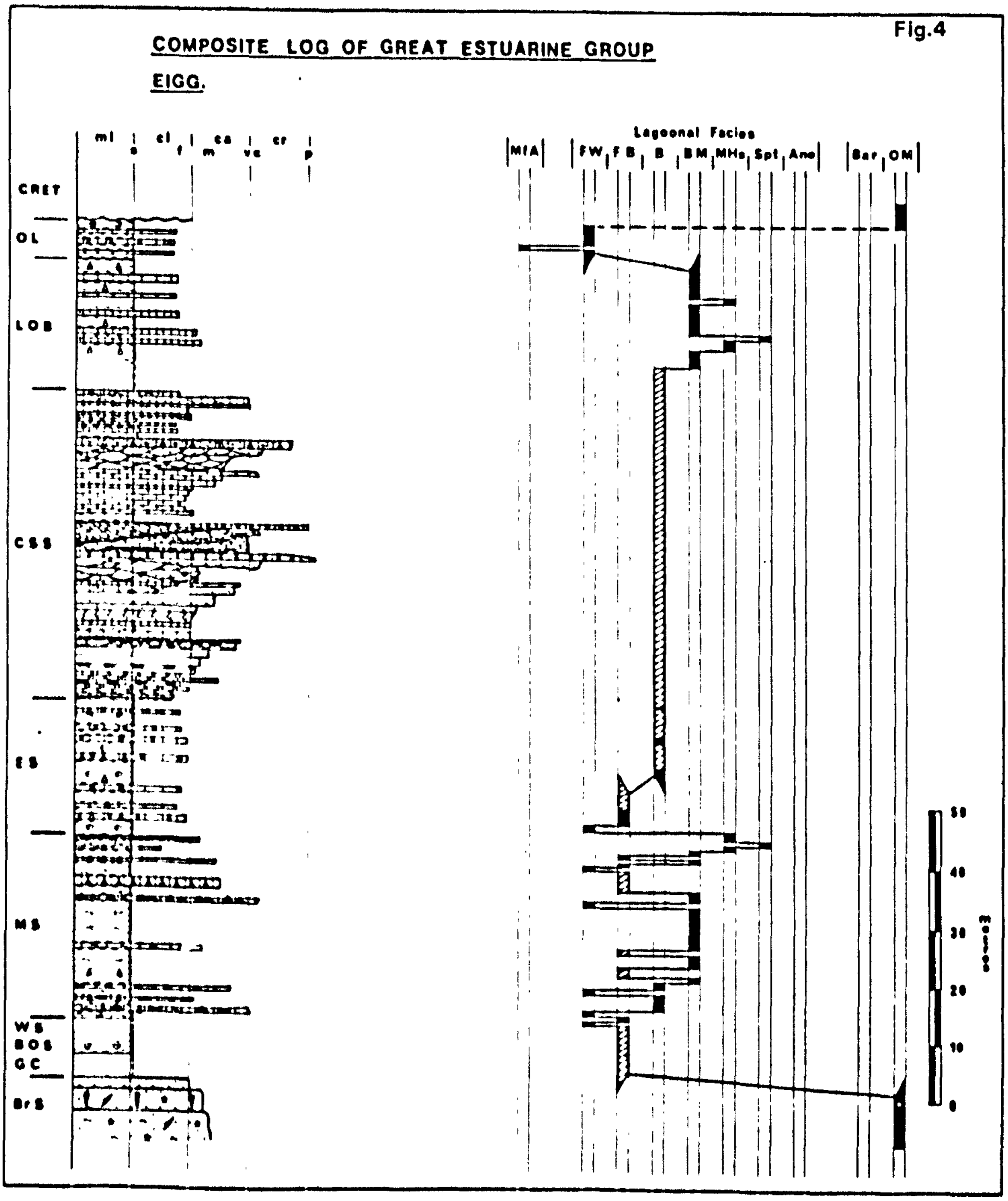
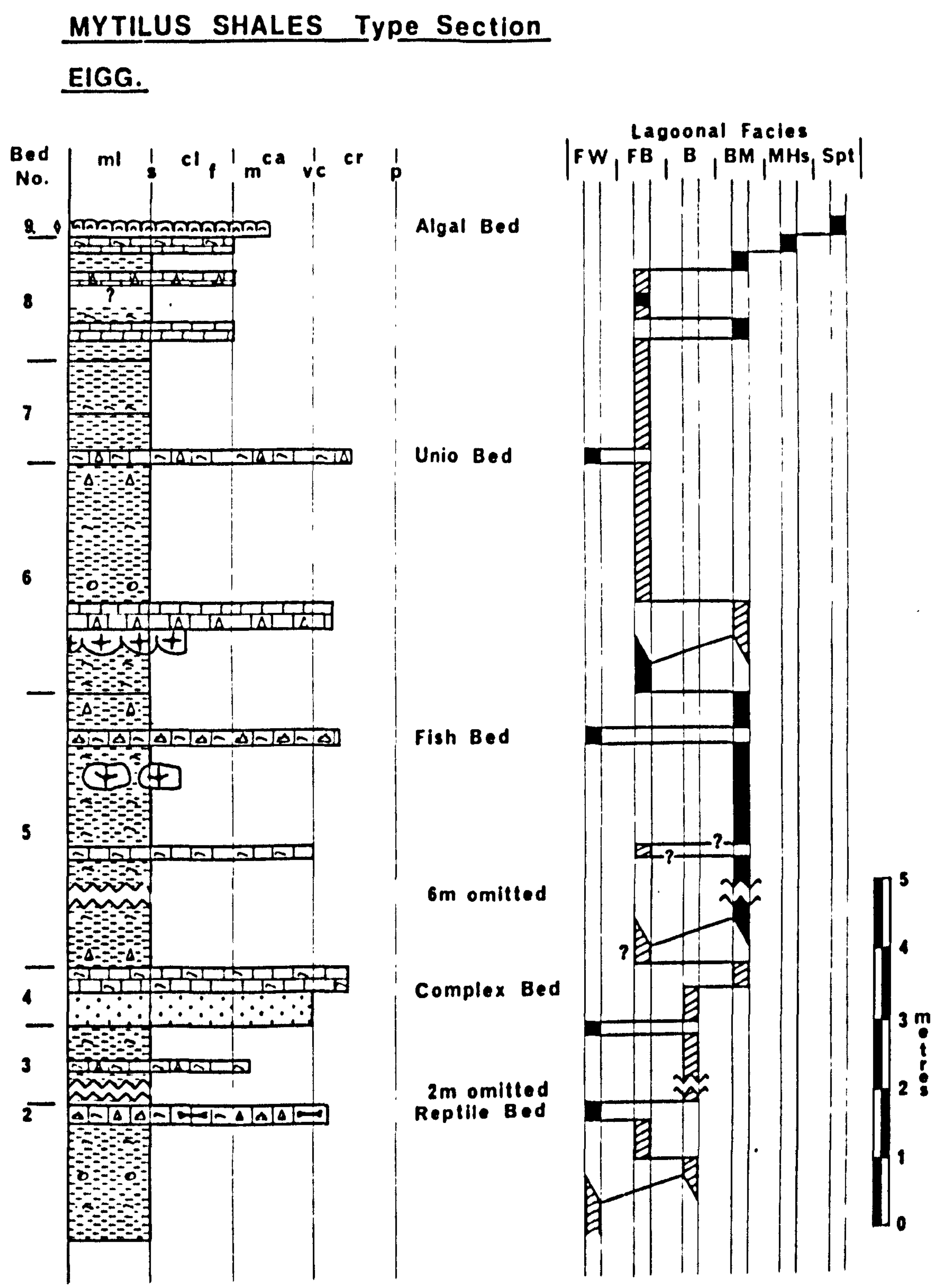

COMPOSITE LOG OF GREAT ESTUARINE GROUP
EIGG.
Lagoonal Facies
MfA
FW
FB
B
BM
MHs
Spt
Ano
Bar
OM
CRET
OL
LOB
CSS
ES
MS
WS
BOS
GC
BrS

Fig.5


MYTILUS SHALES Type Section
EIGG.
Bed No.
ml
s
cl
f
m
ca
vc
cr
p
Lagoonal Facies
FW
FB
B
BM
MHs
Spt
Algal Bed
Unio Bed
Fish Bed
6m omitted
Complex Bed
2m omitted
Reptile Bed
9
8
7
6
5
4
3
2
metres
0
1
2
3
4
5

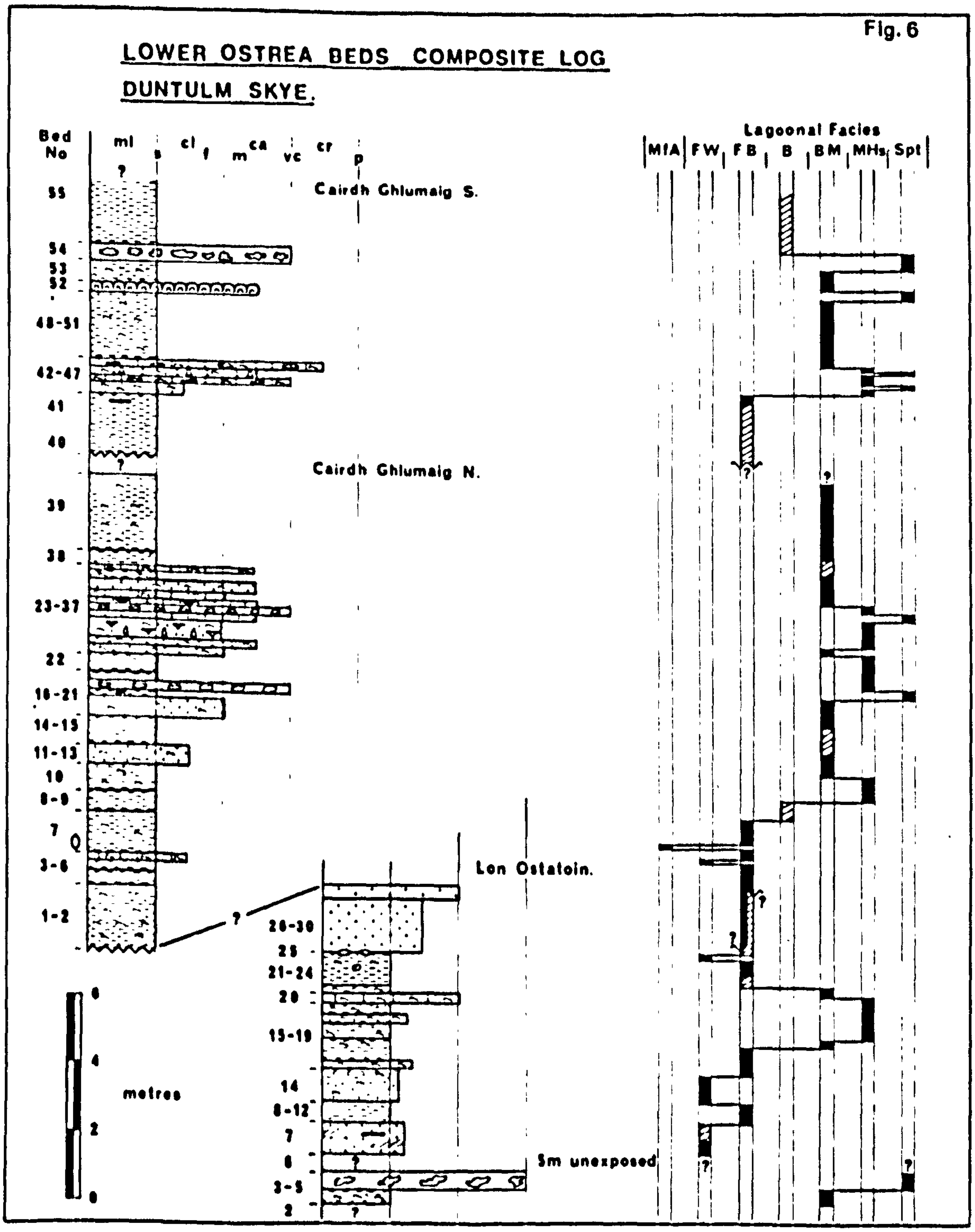


Fig. 6
LOWER OSTREA BEDS COMPOSITE LOG
DUNTULM SKYE.
Bed No
ml s cl f m ca vc cr p
Cairdh Ghlumaig S.
Cairdh Ghlumaig N.
Lon Ostatoin.
Sm unexposed
metres
Lagoonal Facies
MfA FW FB B BM MHs Spt

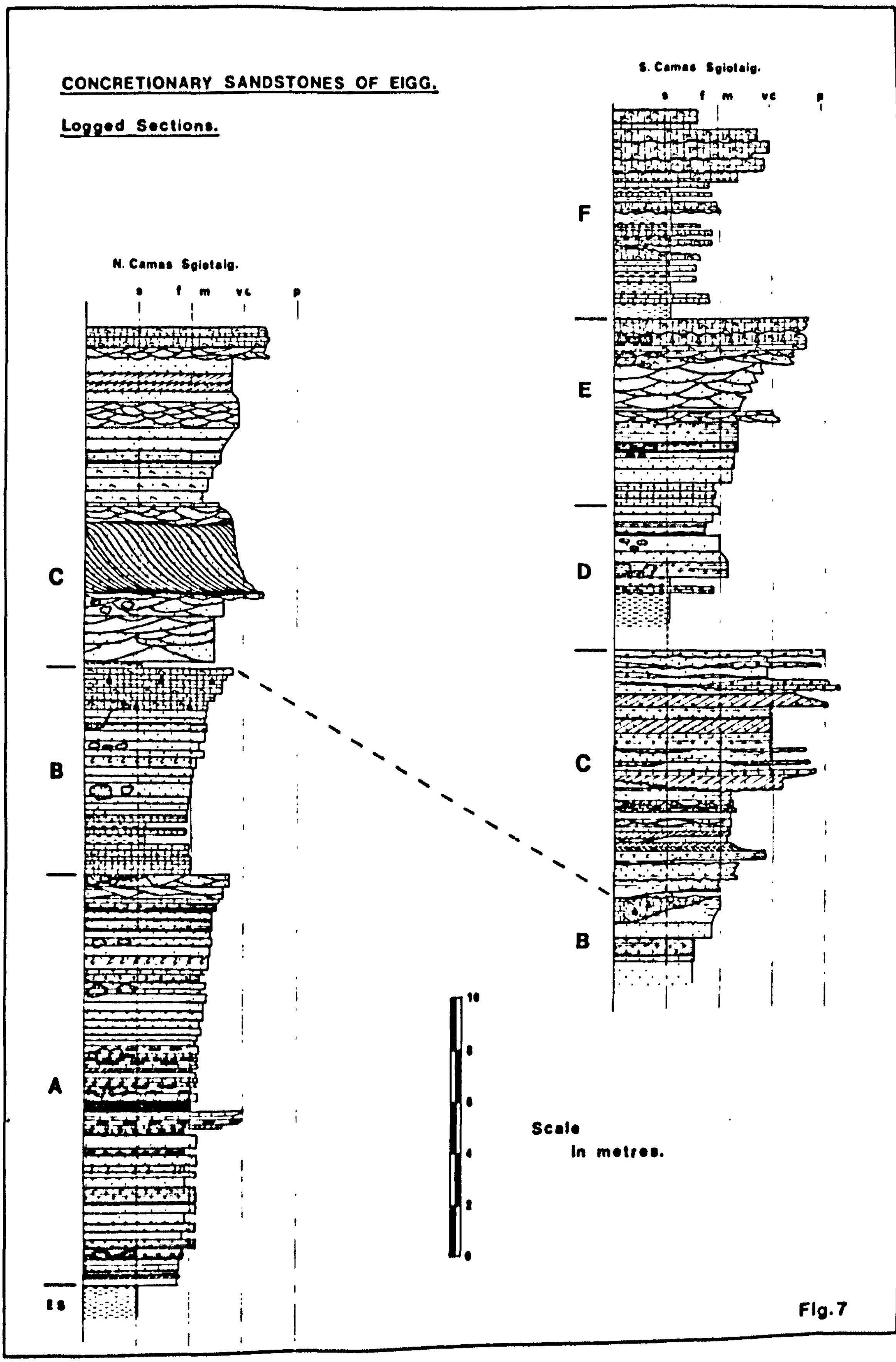

CONCRETIONARY SANDSTONES OF EIGG.
Logged Sections.
N. Camas Sgiotaig.
s f m vc p
C
B
A
ES
S. Camas Sgiotaig.
s f m vc p
F
E
D
C
B
10
8
6
4
2
0
Scale
in metres.

Fig.7