The response of lake margin sedimentary systems to climatically driven lake level fluctuations: Middle Devonian, Orcadian Basin, Scotland

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ABSTRACT

Lake margin sedimentary systems can provide highly sensitive records of sedimentary response to climate change. The Middle Old Red Sandstone of Northern Scotland comprises a thick succession of cyclic lacustrine sediments. Within this succession the deepest lake phase, the Achanarras fish bed, allows bed-scale correlation over 160 km across the basin. This provides a unique opportunity to examine the character of synchronous lake margin deposits, and their response to climatically driven lake level fluctuations, across a large continental basin. Detailed characterisation of two separate lake margin systems was carried out utilising multiple sections in western Orkney, in the north, and Easter Ross, in the south. Seven facies have been recognised, which include upper and lower shoreface, deep lake, shallow lake, playa, turbidite and fluvial facies. Differences in vertical and lateral facies stacking patterns reflect the response of these systems to climatically driven fluctuations in lake level. Comparison of the northern and southern systems examined highlights the variable response of lake margin systems to the same climatic change and related lake level fluctuations. In the south, a greater fluvial influence is recognised on the development of the lake margin successions, whereas in the northern example, which lay on the downwind margin of the lake, shore zone facies are more commonly developed. The variability recognised can be accounted for by regional variations in sediment supply, coastal physiography, lake size, bathymetry and potential fetch. Lake level stability is also recognised as a major control on the development of lake margin sedimentary systems, as is

the linked or unlinked relationship of the catchment and the lake basin climate for which a conceptual model is proposed.

INTRODUCTION

Understanding the controls on the development of lake margin sedimentary systems has important implications for the prediction of aquifer and reservoir distribution in lacustrine petroleum plays and furthermore can provide insights into the interaction of catchment and basin climatic regimes in closed basins. Lacustrine basins are particularly sensitive to climatic change, providing high resolution sedimentary records. An important part of the lacustrine system is the lake margin deposits which are highly sensitive to climatically driven lake level fluctuations. The high resolution correlation possible in this study allows the response of two widely separated (160 km) lake margin sedimentary systems to the same climatically controlled lake level fluctuations to be compared. Few examples of clastic lake shoreline facies have been described in detail from the rock record (Allen, 1981a; Allen, 1981b; Castle, 1990; Martel and Gibling, 1991) although a number of studies do consider the interaction of fluvial and lacustrine systems (eg. Rajchl et al., 2008; Sáez et al., 2007). This study characterises two contemporaneous lake margin systems (Fig. 1) with facies reflecting a wide range of environments, including shore zone, fluvial/deltaic and associated turbidite systems. The aims of this study are to describe and characterise the wide variety of lake margin facies that have been identified in the two systems examined, discuss the local architecture and response of these systems to climatically driven lake level fluctuations, and to assess the controls on the development of lake margin facies including variability recognised across the basin.

GEOLOGICAL BACKGROUND

The Middle Old Red Sandstone (MORS) of northern Scotland was deposited in the predominantly internally drained Orcadian Basin which stretched from Inverness, in the south, to Shetland, in the north (Fig. 1). The Orcadian Basin formed following collapse of the Caledonian Orogen (McClay et al., 1986) which resulted in the formation of a number of half graben basins which were intermittently linked hydrologically. The MORS fill of the basin comprises cyclic lacustrine deposits towards the basin centre and alluvial and fluvial facies towards more marginal regions (Trewin and Thirwall, 2002). The interface between these two settings is the focus of this study. Cyclicity within the lacustrine succession resulted from regular fluctuations in lake levels which are interpreted to reflect cyclic perturbations in climatic conditions which occurred with precessional and eccentricity periodicities (Andrews and Trewin, 2010). The cycles recorded largely comprise deep lake (fish bed), shallow lake and playa facies (Andrews and Trewin, 2010; Donovan, 1980), which are summarised in figure 2, as well as the lake margin facies which are described in detail here. Deposition took place in an arid to semi-arid climate with the north of Scotland positioned in the southern arid belt, between 20˚ and 30˚S (Tarling, 1985).

High resolution correlations across the Orcadian Basin are possible due to the occurrence of deep lake facies, often termed fish beds, which were deposited during periods of lake highstand (Fig. 3). The sections described here can be correlated on the basis of their fish fauna with the Achanarras fish bed, locally termed the Sandwick fish bed in Orkney, the most extensive episode of deep lake conditions found in the MORS succession. Detailed palaeontological and sedimentological studies have been made of basin centre sections (Andrews et al., 2010; Trewin, 1986) which contain thick units of seasonally laminated carbonate rich mudstones (Fig. 4). Correlations have been made with the Sandwick fish bed in Orkney utilising the characteristic fish fauna (Trewin, 1976), and further north to the Melby fish beds in Shetland (Mykura, 1976). Correlations have also been made with more marginal deposits in the Inverness region using palynology (Marshall and Fletcher, 2002). Correlation with the Easter Ross sections, described here, was suggested by (Andrews, 2008) and subsequent identification of the characteristic Achanarras fauna including *Coccosteus cuspidatus*, *Pterichthyodes milleri*, *Cheiracanthus latus*, *Diplacanthus crassisimus* and *Glyptolepis* has confirmed this correlation. The correlation of the fish bearing deep lake facies provide the framework for the more detailed lithological/palaeoenvironmental based correlations that are made.

FACIES

Six sections have been examined from Orkney and Easter Ross (Fig. 1). These regions are significantly different in terms of sediment supply, lake margin gradient and proximity to the basin margin (Andrews and Trewin, 2010) and therefore offer a wide range of potential variables in the generation of shore zone features. Seven facies have been recognised and are described below (summarised in Table 1). Particular attention is given to those more characteristic of the lake margin position and process. A synthesis of this lake margin system and its response to climatically forced lake level fluctuations is then presented.

Deep lake facies

The deep lake facies comprises dark grey, organic rich, laminated mudstones. Individual laminae average 0.5 mm in thickness and are often formed from clastic, clay, carbonate and organic components. These elements are found most commonly as carbonate-organic or clay-organic couplets but triplets are also recognised where clastic material, up to coarse silt, grades up into the clay component. The laminae are often bundled on a 4-10 mm scale although the organisation of this bundling varies throughout the individual sections (Fig. 5a). This facies commonly yields abundant fossil fish material, which allows accurate regional correlation and leads to the informal term of fish bed. Where early carbonate cementation and, in some instances, replacement occurs fish material can be preserved in three dimensions. One further feature which is recognised in the Easter Ross examples within the deep lake facies are sub horizontal, discordant, largely massive, sandstone beds up to 0.8 m thick (Fig. 5b & c), some of which contain angular clasts of the host deep lake facies.

Interpretation: The fine grained nature of this facies and the development of sub-millimetre lamination reflect its deposition in a very low energy environment. Furthermore, the preservation of organic material and fish remains suggest an anoxic setting. Such conditions are consistent with deposition in a deep lake environment within which the development of thermal stratification favoured the development of anoxic bottom waters, below the thermocline. The development of the couplets and triplets described bears close similarity to annual non-glacial varves described from modern lake settings (Anderson and Dean, 1988; Cooper et al., 2000; Dean et al., 1999). Previous studies have also favoured this interpretation (Andrews et al., 2010; Donovan, 1980; Rayner, 1963; Trewin, 1986). The individual laminae components reflect seasonal variations in sediment input within the lake. Variable lake temperature, salinity, catchment run off and lake turn-over events will all have influenced the deposition of the different laminae components observed (Kelts and Hsü, 1978; Sturm and Matter, 1978). Where best developed the laminae form clear bundles which have been shown to occur with periodicities which can be related to solar forcing of the climate (Andrews et al., 2010). The features described characterise a deep lake setting, below wave base and distal to significant clastic input. The discordant nature of the sandstone beds identified in the Easter Ross examples of this facies and the entrainment of portions of the deep lake facies are most consistent with an interpretation as injectites. This style of injection and their scale is characteristic of shallow depth injection systems (Jolly and Lonergan, 2002). It is likely that the early cementation of the laminites contributed to the development of overpressure in underlying sandstones which was released by some form of disturbance which resulted in injection through the deep lake facies.

Shallow lake facies

Intercalated mudstone and very fine sandstone/siltstone characterises this facies. The mudstone component forms laminae and beds 1-10 mm thick although some thicker examples up to 60 mm thick are recorded. The thicker examples commonly appear massive but lamination on a 0.5-5 mm scale has been recognised in the thinner occurrences. The mudstone components in Orkney are dominantly dolomitic, weathering to a characteristic buff to orange colour, but where fresh exposures occur a grey to dark-grey colouration is observed. The coarser grained sand and silt laminae are 1-10 mm thick and are commonly normally graded. Loaded and erosive bases are common and more rarely mudstone rip-up clasts are recorded. Thicker, sharp based, sandstone beds, up to 0.1 m thick containing horizontal lamination and displaying current and oscillation ripples on bed tops are also observed in the Easter Ross sections (Fig. 5e). In Orkney the dolomitic mudstone and coarser siltstone/sandstone components often form couplets 4 to 20 mm thick which are in turn stacked into regular bundles, 20-100 mm thick, containing an average of 5 couplets (Fig. 5d). Such finely developed sequences are less commonly developed in the Easter Ross examples. Syneresis cracks are abundant throughout this facies and rare desiccation cracks are also observed. Rare oscillation and current ripples are recorded in some of the thicker sandstone laminae. A wide variety of stromatolitic forms, including stromatolitic sheets, domal mounds, aligned mounds (and associated runnels), sand-cored mounds and reefal build-ups, are common in this facies throughout the Stromness Flagstone formations and are described in detail by Andrews and Trewin (2014).

Interpretation: The shallow lake facies forms the transition between the deep lake and playa environments and as such shares affinities with both of these. Dominantly low energy conditions are indicated by the predominance of mudstone which reflects the settling of fine sediment in a standing body of water. The formation of fine lamination and the dark colouration suggests periods of deeper water conditions where the preservation of fine lamination and organic material was possible. The presence of abundant syneresis cracks are indicative of regular fluctuations in salinity (Donovan and Foster, 1972; Plummer and Gostin,

1981) which may also have aided carbonate precipitation and are also likely to have been associated with regular climatically driven low amplitude variations in lake level. The sandstone/siltstone laminae reflect periods of increased energy. Erosive and loaded bases, alongside grading and the presence of mudstone rip-up clasts are characteristic of small scale lacustrine turbidite deposits (Sturm and Matter, 1978). Thinner examples without erosive bases may represent more dilute overflow and interflow events. The thicker examples recognised in the Easter Ross sections are interpreted to reflect greater sediment supply. This may have further restricted the development of the more finely interlaminated intervals described from Orkney. Bundling of mudstone-sandstone/siltstone couplets is interpreted as the consequence of climatic perturbations with cooler, wetter periods resulting in increased, thicker sand/silt components and warmer, drier periods being recorded by mudstone dominated intervals. The development of various stromatolitic forms within this facies has been related to reduced sediment supply, particularly during transgressive periods (Andrews and Trewin, 2014). This facies reflects deposition in a shallow, largely perennial, lake. Previous workers (Rogers and Astin, 1991) have suggested a more ephemeral interpretation for this facies with the syneresis cracks interpreted as desiccation features and gypsum pseudomorphs, and the sandstone components as wind blown sand sheets. However, the graded nature of the sandstone components and the inclusion of mudstone rip up clasts favour a subaqueous depositional setting as described here and furthermore the preservation of organic material, resulting in the dark colouration of the mudstone components, is more likely to have occurred in the poorly oxygenated bottom waters of a lake. Further discussion on the origin of the syneresis cracks can be found in Trewin (1992).

Playa facies

The playa facies is similar to the shallow lake facies, with intercalations of mudstones and coarser siltstone/very fine sandstone components which are commonly arranged in couplets. However, the individual components tend to be thicker, with mudstones 1-40 mm and more rarely up to 80 mm thick and silt to very fine sand laminae 1-10 mm thick and in some instances up to 30 mm. Thicker sandstone beds averaging 0.1 m thick are recorded in this facies in Easter Ross (Fig. 5f). The mudstones in the Orkney examples weather a characteristic buff colour due to their high dolomite content (Fig. 5g) whereas those in Easter Ross are commonly red and contain only minor carbonate. The siltstone/very fine sandstone components often have erosive bases and horizontal lamination capped by current and oscillation ripples are common in thicker examples. The couplets recognised here, as in the shallow lake facies, are bundled forming cycles 30-100 mm thick (Fig. 5g) which can be continuous through sections of several metres. A sandstone component dominated lower portion is capped by a mudstone component dominated upper portion. Desiccation cracks penetrate from the upper surface of each cycle and are ubiquitous throughout this facies. These cycles are less well developed where this facies is observed in Easter Ross. Syneresis cracks are also common and also recognised are rain drop impressions and stromatolitic sheets.

Interpretation: The predominantly fine grained nature of this facies, predicates a largely low energy environment of deposition occurring within a standing body of water. Oscillation ripples provide further evidence for standing water and the abundant desiccation cracks attest to its ephemerality. As in the shallow lake facies, the presence of syneresis cracks suggests that fluctuations in salinity occurred. Periodic higher energy depositional events are recorded by the siltstone/sandstone laminae. These are similar to those described from the shallow lake facies with erosive bases and current ripples both recorded which suggests a similar genesis as lacustrine turbidites. However, more commonly these sandstones overlie desiccated surfaces suggesting they were laid down as largely unconfined fluvial flood events likely to have led to the filling of the ephemeral lake during which wave reworking and the formation of oscillation ripple could occur. Both these flow types record evidence for decelerating flow in their gradation from horizontal lamination to current ripples. The bundling of the couplets is suggested to result from climatic forcing. The continuity of these cycles through several metres favours such an explanation over an autocyclic or tectonic control which would be unlikely to occur with such regularity over such an extended period of time. The features described are consistent with a shallow, ephemeral lacustrine, or playa, setting.

Lower shoreface facies

The characteristic feature of the lower shoreface facies is the presence of hummocky cross stratified sands interbedded with laminated mudstones and siltstones similar to those of the shallow lake facies (Fig. 6a). The hummocky cross stratified sandstones are commonly composed of very fine sand and form intervals from single beds up to 0.05 m, to stacked beds up to 0.3 m thick consisting of multiple sets (Fig. 5h). Individual sets within the stacked examples are commonly draped with mudstone or siltstone. In some instances the thicker accumulations form bar features with convex upper surfaces which are subsequently draped with mud and silt. The λ of the hummocks varies between 0.1 and 0.2 m and the amplitude reaches 20 mm in some examples. Both loading and grading are common in rare thicker beds (up to 0.2 m thick) which also commonly contain convolute lamination. Interbedded grey to dark grey mudstone and siltstone beds vary between 0.1 and 0.5 m thick and are laminated on a 1-5 mm scale. Syneresis cracks are recorded within this finer grained lithology. Sand interlaminations are present in some instances with very fine grained sand forming laminae 2-20 mm thick. Some examples resemble the sand streaked mud (M1) of De Raff et al. (1977). The mudstone and siltstone interbeds closely resemble the deposits of the shallow lake facies.

Interpretation: Deposition of the siltstone and mudstone intervals reflect periods of low energy conditions during which fine grained sediment was deposited from suspension within a standing body of water. Periodic fluctuations in salinity are indicated by the presence of syneresis cracks (Donovan and Foster, 1972; Plummer and Gostin, 1981). The general lack of sediment agitation is consistent with a position below wave base, however, variability in lake level and depth of wave action would depend on prevailing climatic conditions at the time of deposition. Where sandstone interlaminae are recorded, an increase in depositional energy can be inferred. De Raff et al. (1977) interpreted similar lithotypes (M1) as the fallout of sediment from suspension below wave base. The sediment may have been introduced in suspension from flood waters or washed into suspension during storm activity. Similar lithotypes have been recognised in the lowermost deposits of lacustrine shore face successions (Dam and Surlyk, 1993; Martel and Gibling, 1991). Further evidence for a lower shore face environment, and a characteristic feature of this facies, is the presence of hummocky cross stratification (HCS) which is classically associated with the lower shore face in marine environments (Dott and Bourgeois, 1982). Allen (1981b) described undulatory cross stratification from Devonian lake margin environments in Shetland and attributed its formation to high intensity oscillatory flow. Such flow is consistent with storm waves and the interbedded nature of the HCS, described here, with mudstone and siltstone intervals suggests only intermittent activity such as would be expected at storm wave base. HCS is commonly positioned within a lower shore face setting where described from other lacustrine successions (Dam and Surlyk, 1993; Martel and Gibling, 1991). Allen (1981b) argued for the generation of HCS immediately lakeward of the breaker zone, in shallow water, however the presence of laminated mudstones and siltstones in this example suggests a position further offshore. Sediment input similar to that recognised in the shallow lake facies, with the presence of turbidites, is likely to have occurred which was then reworked by wave action. Possible long-shore re-distribution of sediment may also have contributed to sediment supply.

Upper shoreface facies

The upper shoreface facies shows considerable variation across the sections examined. The most characteristic feature is very low angle cross-bedding (Fig. 7b) which is often accompanied by horizontal lamination, oscillation rippling and minor hummocky cross stratification (Fig. 6a). The cross-bedding within the low angle cross-bedded sandstones rarely exceeds 10° with bed thicknesses varying between 0.1 to 0.4 m. Some examples display subtle variations in the dip of the cross bedding throughout the interval indicative of re-activation/re-organisation of the bedform. The horizontally laminated sandstones form beds of similar thickness to those containing low angle cross-bedding and are also texturally similar, commonly composed of very fine moderately to well sorted sand. Oscillation rippled and hummocky cross-stratified sandstone beds are largely thinner (<0.1 m) and are often interbedded or draped with finer grained sediments. The scale of the HCS is largely similar to that described from the lower shore face facies but larger scale examples with λ of 1-1.5 m have been recognised in the Easter Ross successions, where they are often found in association with channel fill sandstone units. Sandstone beds up to 0.25 m thick, composed almost entirely of climbing ripples (Fig. 7b) are also present in association with the low angle cross-bedded, horizontally laminated and oscillation rippled sandstones. Syneresis and desiccation cracks are recognised in the finer grained intervals. In some instances the described lithotypes form large scale gently dipping foresets (Fig. 7c) which may reflect the attitude of the preserved shoreline or represent bar features several tens of metres wide by 0.5-1 m thick.

Interpretation: The low angle cross-bedding and associated horizontal lamination is interpreted as indicative of sedimentation in the high energy swash-backwash and breaker zone. Inclined bedding containing oscillation rippling and HCS are interpreted as occurring below the swash-backwash/breaker zone. Low angle cross-bedding with associated horizontal lamination, from the Devonian of Shetland, has been interpreted similarly as reflecting deposition in the foreshore and backshore environments, dominated by the breaker zone and the zone of swash and backwash (Allen, 1981a). Similar interpretations of low angle cross-bedding and horizontal lamination from lacustrine settings have been made by Dam and Surlyk (1993) and similar facies have been attributed to a shoreface environment by Link and Osbourne (1978). Some examples may reflect the deposition of accretionary bars similar to those described by De Raff et al. (1977) from shallow marine deposits. During calmer, lower energy periods, possibly related to increased lake level, finer grained interbeds were deposited which drape the ripple structures.

The larger composite features are most likely to be bar forms similar to beach bar/barrier ridge features described from modern environments such as Lake Bogoria (Renaut and Owen, 1991) and the Quaternary Lake Lahontan (Adams and Wesnousky, 1998). The internal structure of barrier ridge features recognised in the Lake Lahontan example is suggested to largely reflect their external form. Similar internal structure is described from the beach bar forms of Lake Bogoria example, with low angle cross-sets accreting on the shoreward side of the bar from bar washover and steeper sets forming in the swash zone on the lakeward aspect. Some similarities are recognised within the upper shoreface facies with, in some instances, the internal structure reflecting the convex upper surfaces, however a greater number of examples and greater clarity within the exposures would be needed to draw detailed comparisons.

Sediment delivery for reworking by shore zone processes probably occurred through flood generated sheet flows with the redistribution of sediment by longshore currents as occurs in the shore zone environments of Lake Bogoria in Kenya (Renaut and Owen, 1991). The interaction of fluvial systems with the shore zone environments also generated greater variability within the upper shoreface facies. The presence of climbing ripple dominated beds and clinoforms are suggestive of fluvial input resulting in progradation of a sand dominated lobe into the lake which was then intermittently reworked by wave action. In this association the climbing ripples are likely to reflect deposition in terminal lobes or in deltaic mouth bars, similar to those described by Sáez et al. (2007) from Palaeogene fluvial fan systems in the Ebro Basin. Flow was intermittent and allowed the deposition of mudstone and siltstone interbeds.

Turbidite facies

The turbidite facies is composed of: massive/convolute sandstones; convolute interlaminated mudstones, siltstones and thin sandstones and, massive mudstones/siltstones (Fig. 6b). Massive/convolute sandstones form beds between 0.05-0.90 m thick, composed of very fine sand. Bed bases are often erosive and well developed flute marks have been observed (Fig. 7d). Loading is also recorded (Fig. 7e), and in some instances has led to pseudonodule development. Convolute lamination is variably developed with some examples having lost much of their original structure and only retaining traces of contorted lamination. Rippling and poorly developed horizontal lamination is recognised towards bed tops and angular mudstone rip-up clasts are present at the base of some beds. Grading into overlying mudstone/siltstone beds is also present in some examples. Bedding is laterally continuous across the outcrop (25-40 m) with little variation in bed thickness. Rare examples of channels are present up to 6 m wide and 1 m deep with a largely massive fine to very fine sand fill. These narrow sand bodies have often undergone significant loading leading to the development of upturned channel margins. The channels recognised are loaded into the underlying sediment resulting in the generation of convolute lamination at the channel margins and rounded terminations to the channel wings. The fill of the channels recognised tends to be largely massive with some traces of convolute lamination at the channel margins.

The convoluted intercalated mudstones, siltstones and sandstones form intervals up to 0.5 m thick, some of which are composed of a number of discrete deformed packages. Within the convoluted horizons slide planes, folding and faulting are all recorded (Fig. 7f). The deformation tends to be more intensely developed in the thinner bedded/laminated examples. A spectrum of deformation is recognised with some intervals only containing gentle folds and minor faulting. Where the deformation is more severe the original lamination and structure of the sediment is lost.

The massive mudstones/siltstones form beds up to 1 m thick, with composite intervals reaching 2.5 m. This sub-facies is characterised by a lack of internal structure and the presence of a hackly fracture (Fig. 7g), however, poorly defined irregular, discontinuous lamination is present in some examples. Where present the lamination is often inclined at angles up to 90°. Rare sandstone pseudonodules are also recognised in some examples.

Interbedded with the sandstones are mudstone and siltstone intervals similar to those described from the shallow lake facies but desiccation is absent and oscillation rippling is rare. Lamination is well developed on a 1-5 mm scale. Bundling of silt and sand laminae is also recognised. Within these horizons plant fragments, surrounded by oxidation haloes, are common. Syneresis cracks are also seen where the regular introduction of sand laminae has aided their preservation.

Interpretation: The introduction of the thicker, laterally continuous sandstone beds, described above, to a perennial lake environment is most easily accounted for as the product of high energy turbidite deposition. Small scale turbidites have already been described in the shallow lake facies. Such laminae/beds tend to become more common preceding and in association with the intervals described here.

The massive nature of the massive/convolute sandstone beds is indicative of rapid deposition with traces of convolute lamination reflecting the dilute nature of the flows and subsequent dewatering. The commonly erosive bases and the presence of mudstone rip-up clasts evidence the high energy nature of the turbidite deposition, however evidence for waning flow is also recorded in some examples where grading is recognised. The presence of rippling and horizontal lamination towards the bed tops also reflects waning flow. This suite of structures is similar to those commonly recognised from marine turbidite deposits (Bouma, 1962; Talling et al., 2012), displaying evidence for initial high energy conditions with subsequent rapid deceleration. Initial high energy flow resulted in the development of erosive bases and due to the high water content of the mudstone loading was common. As the flow slowed a grading into silt/mudstone with plant fragments frequently resulted. The entrainment of plant fragments may provide evidence for the turbidite flows being triggered by stormy conditions, with increased fluvial input washing in greater amounts of sediment and plant material which settled out following the turbidite flow. Turbidite deposits, up to 1.5m thick, displaying a similar set of characteristics have been recorded from Lake Brienz (Sturm and Matter, 1978). Channel forms are rare in the turbidite facies and where present are heavily loaded. The development of a channel feature recorded in the Burraquoy section on Hoy (Fig. 4) may have been controlled by the topography generated by an underlying slump similar to examples reported from marine turbidites (Shultz et al., 2005). Such topography may also have initiated the channelisation of the turbidite flow.

The convoluted intercalated mudstones, siltstones and sandstones form a continuum with the massive mudstones/siltstones. The slide planes, folding and faulting record movement within the sediment pile. Erosion into the top of some deformed horizons reflects the shallow nature of dislocation. The features recorded are consistent with slump processes. With increased transport the deformation first becomes more intense, then degradation of the original structure occurs and finally massive mudstones/siltstone intervals are produced. The massive mudstone/siltstone facies are interpreted as subaqueous mud flows, triggered by initial slumping. Such flows may have travelled considerable distances. The poorly defined irregular, discontinuous lamination and inclined lamination may be the products of sliding within the mudflows during deceleration and arrest, or dewatering artefacts.

Fluvial facies

This facies is not widely developed in the sections examined but is most commonly found in association with playa, shallow lake and turbidite facies. The fluvial facies comprises 0.2-1.5

m thick erosively based medium to coarse grained sandstones which form units 1-5 m thick. Convolute lamination is common. Planar and trough cross bedding, and horizontal lamination are also widely developed (Fig. 6 b). Thinner sandstones commonly form laterally extensive sheets whereas the thicker examples often fill channel features. Mudstone rip up clasts are recorded at the base of some channels which show up to 1 m of incision. The nature of the outcrop does not allow their full lateral extent to be gauged.

Interpretation: Intercallations of desiccated playa mudstones demonstrate that this facies was deposited subaerially, however, the prevalence of dewatering structures suggests deposition often occurred in water saturated conditions. The development of trough cross bedding is indicative of periods of sustained flow. This occurred in channels with occasional overbank deposition leading to the development of sheet sandstones, often interbedded with the playa facies. The interaction of this facies with the playa, shallow lake and turbidite facies, forming a fluvial dominated shore zone association, will be described below where the spatial and temporal relationships of the facies and sedimentary systems are considered.

NORTH WEST BASIN MARGIN

Three sections were examined from the west coast of mainland Orkney and one from the island of Hoy which lies a short distance to the south (Fig. 1). These are positioned on the north west margin of the basin. The sections examined contain three complete climatically driven lacustrine cycles, each punctuated by the development of deep lake, ‘fish bed’ lithologies which allow the robust correlation presented (Fig. 4). These transgressive-regressive cycles are numbered 1 and 2 from the base of the section. A third cycle is recorded but not discussed in detail. The lowermost two fish beds comprise the Achanarras fish bed. The transgressive phase of the cycles examined is characterised by the simple transition through playa facies and shallow lake facies to reach the deepest lake interval. The regressive succession is often more varied with the transition to shallow lake facies regularly including turbidite intercalations before the appearance of lower and upper shore face facies. The playa facies represents conditions of the lowest lake level recognised and minor fluvial deposits are recorded capping the successions described. Lacustrine cycles described from more central regions of the basin tend to be less complex and be dominated by deep lake, shallow lake and playa facies (Andrews and Trewin, 2010; Donovan, 1980).

Spatial and temporal trends

The sections examined in the western region of Mainland Orkney run north south and palaeocurrents data suggest that the palaeoshoreline ran east southeast – west southwest (Andrews, 2008). Therefore the logged sections provide a transect through the shore zone sedimentary systems (Fig. 4). Evidence for three complete climatically driven lacustrine cycles is recognised, each punctuated by the development of organic rich deep lake deposits during their deepest phase. Previous work on the climatically driven cycles developed throughout the Middle Old Red Sandstone has demonstrated that a precessional (19,866 year) control is dominant (Andrews and Trewin, 2010) which suggests a ≈60 ka period for the deposition of the ≈70 m thick sections examined. Considerable variation in depositional rate occurred through the succession and is discussed below.

Cycle 1

Initial deepening through playa and shallow lake faces is recorded as a relatively thin succession across all four of the examined sections prior to a thick development of deep lake facies. In the northern sections, from the Point of Buckquoy, the deep lake facies are overlain by a thick succession of turbidite facies and intercalated shallow lake facies. A southward thinning can be recognised in the thicker turbidite units. These are in turn overlain by a transition through lower shore face to upper shoreface facies which record the shallowest water conditions during this cycle. Although in the southern of these two sections a stacked transition through lower to upper shoreface facies is recorded, a more complex situation is present to the north where the transition is broken by intervals of shallow lake facies. This is most easily accounted for by the development of a lake shore bar to the south and more sheltered back bar conditions in the north limiting the development of lower shore face facies. The lateral scale of this transition (400 m) seems reasonable although lacustrine barrier beach complexes have been described from extensive subsurface data sets up to 5 km wide and 15 km long (Castle, 1990). In the sections which lie 20 km, and a further 2.5 km, to the south no trace of the turbidite or shore face facies is recorded with continuous deposition of shallow lake facies reflecting the shallowest lake conditions and in turn overlain by the next deep lake phase. It is interesting to note that no evidence for incision during the previous lowstand is recognised but this is perhaps due to the relatively low amplitude of the lake level oscillation.

A depositional rate for the deep lake facies can be gained due to its annually laminated character. Measured examples from the equivalent Achanarras fish bed from

Achanarras Quarry in Caithness average 0.41 mm a^{-1} and similar facies in the Wick region average 0.5 mm a^{-1} (Andrews and Trewin, 2010). Using the Achanarras figure the total period of deposition for the lowermost deep lake interval is 13,170 years. This figure is consistent with the precessional periodicities (19,886 years) calculated for the lacustrine cycles documented throughout the Middle Old Red Sandstone succession (Andrews and Trewin, 2010). Assuming a broadly symmetrical climatic cycle, and environmental response, this suggests a rapid rate of deposition for the overlying regressive succession which comprises turbidites and shore face deposits (20.3 m) which can be calculated to have been laid down over a period of 3,348 years (half the remaining portion of the precessional period). This provides a depositional rate 60 mm a^{-1}, reflecting hugely increased sediment input in the north, compared to only a moderate increase up to 1 mm a^{-1} in the more distal sections that the turbidite systems did not reach at this time. This situation is repeated in the overlying cycle but with the depocentre shifted southwards.

Cycle 2

In the northern two sections the deepening into the next cycle is recorded by a relatively thin succession prior to the onset of deep lake facies deposition (Fig. 4). Overlying the deep lake facies is a succession of turbidite facies intercalated with shallow lake facies. This succession thickens markedly from the northern sections to those in the south but within these, two distinct phases of turbidite activity can be clearly correlated. The more distal sections contain evidence for the development of deep water channel systems at this time and a general progradation of the system can be recognised, filling accommodation which remained following the first deep lake phase. The subsequent shallowing is complex. The initial indication for a reduction in lake level is the appearance of an interval of lower shore face facies development. This can be traced between all four sections and appears to indicate a uniform infilling of accommodation in this region, the disparity in thicknesses of the underlying units having been balanced. Above this, interval intermittent playa conditions are intercalated with shallow lake facies. The playa facies is most thickly developed in the northern sections, with initial regressive events reaching as far south as the Noust of Netherton section. In the southern sections, the development of a number of lower shore face facies intervals record the lowering lake level prior to lake lowstand where playa facies can be traced across all four sections. Around this time incisional features were developed in all the sections examined. Simple channel features, 1-4 m deep and up to 8 m wide, with a predominantly lacustrine fill are developed in the north but more complex steep sided channels, cutting up to 8 m in to the lacustrine succession and up to 60 m wide, are developed in the south. Significant bank collapse is recognised in the latter and evidence for successive re-use of these features is provided by the terraced nature of some examples (Fig. 7h & 8). These features would suggest a prolonged period of down-cutting through the lake margin systems, perhaps associated with much lower amplitude lake level fluctuations, which did not inundate the western Orkney region. Such an explanation could account for the generation of the terraced nature of the erosive features. The final lacustrine cycle is of a more symmetrical form with a transgressive and regressive succession of similar thickness across all three sections.

SOUTH WEST BASIN MARGIN

Two sections which contain the two deep lake phases of the Achanarras fish bed, and can therefore be correlated precisely with those sections described from Orkney, were examined in detail on the Easter Ross coast and therefore the cycles are numbered similarly. The first is located at Jessie Port, just to the north-east of Hilton of Cadboll and the second lies 3 km to the north-east in Tarrel Bay (Fig. 1). These sections lie towards the south-west margin of the Orcadian Basin, adjacent to the Great Glen Fault. The MORS in this region is dominated by fluvial sandstones which almost entirely suppress lacustrine deposition in the succession which overlies the Achanarras fish bed.

As in the cycles described from Orkney, the transgressive successions appear as a simple transition through fluvial, playa and shallow lake facies which culminates in the deposition of deep lake facies (Fig. 4). The presence of extensively developed fluvial facies is considered to be due the position of the sections close to a major drainage conduit. The regressive successions are more complex with the addition of turbidite facies and fluvial dominated shore zone facies associations, and the occurrence of erosional cut out.

Spatial and temporal trends

Palaeocurrents recorded in the sections described, and the adjacent strata, indicate predominantly east north-east directed flow (Andrews, 2008) which is sub-parallel to the Great Glen Fault and supports the suggestion that, although not active, this feature had a significant expression in the landscape. The sections examined in this region are aligned similarly to the recorded palaeocurrents and therefore provide a south west to north east, proximal to distal transect through the basin margin sedimentary systems. Two complete transgressive-regressive cycles, which represent the Achanarras fish bed and correlate directly with those described from Orkney, are developed in this region of the basin and these are overlain by a thick succession of fluvial sandstones. The two intervals of deep lake facies can be correlated with the lowermost two deep lake phases described from the Orkney sections (Fig. 4).

Cycle 1

As is the case in the succession described from Orkney the initial transgressive phase is relatively condensed with thin developments of playa and shallow lake facies prior to the onset of deep lake sedimentation. These are however thicker than observed in Orkney, probably as a result of the greater sediment supply.

Overlying the deep lake facies is a 17 m thick succession which reflects a fluvial dominated shore zone facies association (Fig. 4) and is worthwhile describing in some detail. An initial thickening upward succession of turbidite facies interbedded with grey mudstones and siltstones of the shallow lake facies includes rare hummocky ripple cross lamination. This grades upwards into erosively based fluvial sandstones which often contain convolute lamination and, further up section, well developed cross bedding. Interbedded with these channel sandstones are playa facies mudstones. The turbidite and shallow lake facies recorded in the lower part of the succession are interpreted as deposits of the offshore transition zone. Turbidite deposition was triggered by periods of high flow in adjacent fluvial systems leading to the input of dense, sediment laden, flows to the lake. Up-section an increased frequency of turbidite beds reflects the progradation of the fluvial dominated shore zone. Rare hummocky ripple cross stratification indicates that some storm wave influence did occur. Overlying the turbidite deposits are medium to coarse grained, cross bedded and horizontally laminated sandstones which are interpreted as distributary channel deposits similar to those described by Dam and Surlyk (1993) from the Kap Stewart Formation of Greenland. The thicknesses of the initial distributary channel deposits vary from 1-5m and in some instances are immediately overlain by a succession of fluvial facies. More commonly the distributary channel sandstones are succeeded by desiccated laminated mudstones interbedded with sheet sandstones and occasional channel sandstones. These sequences are interpreted as the deposits of distributary channels and interdistributary bays with intermittent splays. It should also be considered that due to regular fluctuations in lake level the association described here may at times of lake level retreat acted as a terminal fluvial system. Similarities can be drawn with the Neales and Douglas Creek systems that terminate in Lake Eyre (Fisher et al., 2008).

The succession described here reflects the interaction of a fluvial system with a lake that was subject to regular fluctuations in its level. Published examples of fluvial-lacustrine interactions fall in to three categories: ‘Gilbert-type’ fan deltas, recorded from high gradient lake margins; wave dominated deltas and fluvial dominated deltas, both from low gradient settings. ‘Gilbert-type’ deltas are characterised by thick, depositionally inclined, coarse grained bedding (Smoot, 1991; Wood and Ethridge, 1988). The sand bodies within wave dominated deltas are characterised by intensive wave reworking (Allen, 1981a; Dam and Surlyk, 1993) and evidence for mouth bars is not reported. Fluvial dominated deltas tend to contain significant developments of mouth bars deposits (Rajchl et al., 2008; Sáez et al., 2007). The geometry of these deltaic deposits is governed by the accommodation available (lake depth) and stability of the lake level, with maximum progradation occurring during periods of lake-highstand when the climate is sufficiently humid to allow sustained sediment delivery. Although similarities can be drawn with these lacustrine deltaic systems and that described in this study the relatively minor development and preservation of mouth bars may favour a definition as a fluvial influenced shore zone rather than a delta. Regular fluctuations in lake level and reworking, largely by fluvial processes, may have limited the formation of mouth bars.

The shallow lake and turbidite facies of this regressive succession thicken to the north east whereas the fluvial portion of the regressive succession thins northwards where it contains a greater proportion of playa facies intercalations. This may be, in part, due to erosion at the base of the fluvial dominated portion of the overlying facies association but also due to the progradation of the fluvial dominated shorezone system from the south west. It should also be noted that the thickness of the individual turbidite beds decreases to the north east. Decreasing bed thicknesses in the turbidite facies is consistent with a transition to a more distal position with respect to the sediment input, and the basin ward thickening of this succession can be interpreted as a northward increase in accommodation alongside the regression of the shoreline by the progradation of fluvial and associated deltaic systems. Further evidence for the development of shallower conditions to the south is provided by the presence of shore face facies in the Jessie Port section (Fig. 4).

Cycle 2

The transgressive succession, including playa and shallow lake facies, which leads to deposition of the upper interval of deep lake facies occurs over a similar thickness as recorded in the lower cycle, however, the regressive succession is significantly different. In the proximal section desiccation cracks penetrate the deep lake facies for over 2 m and the playa facies from which they originate are only thinly preserved beneath a thick succession of fluvial facies. In the distal section the upper deep lake interval is overlain by turbidite facies and shallow lake facies in a broken exposure before the thick overlying fluvial deposits are encountered. The development of such extensive desiccation features in the proximal example are likely to have taken some time to form and may have been accompanied by localised incision during the rejuvenation of fluvial systems.

DISCUSSION

Controls on Sedimentation

A broadly similar response to the climatically driven lake level fluctuations of the Achanrras fish bed cycles is recorded in both the Easter Ross and Orkney regions. However, some significant differences are apparent. These and the underlying controls are summarised in Table 2. Deposition of deep lake facies is curtailed more quickly in the Easter Ross sections. This is likely to result from higher sediment input due to its position closer to the basin margin highlands. Furthermore, although it is unlikely that the Great Glen Fault was active at this time it is likely that a topographical expression of this long lived feature existed, acting as a sediment conduit. Palaeocurrent data and the lack of features suggestive of active tectonism in the adjacent Devonian succession support this assertion (Andrews, 2008). This is further evidenced by the rapid progradation of fluvial systems across the region following the deposition of the Achanarras fish bed lacustrine cycles. A more subdued topography has previously been suggested for the Orkney region (Andrews and Trewin, 2010) and this is consistent with the very fine grained nature of the succession. However, the thick turbidite succession does indicate that a significant sediment source was reaching the basin margin. Two distinct progradational phases are recognised with the first infilling the Birsay area and the second filling the remnant depocentre to the south (Fig. 4). The Orkney region lacks significant fluvial deposition at this time but, instead shore zone reworking of sediments producing upper and lower shore face facies is common. The development of these facies has a number of controls which will be discussed fully below but a significant factor in the development of these features in the Orkney region and not in the Easter Ross succession is the position of northern Scotland, between 20° and 30° south, during the Middle Devonian. Positioned in the south east trade wind belt the prevailing wind in the Orkney region would have been offshore and therefore resulted in increased wave action in this region which would have promoted the development of shoreface facies. The Achanarras succession forms the most widespread lacustrine interval to have developed in the Orcadian Basin and one of the only phases where significant progradational sedimentary systems formed. The return to less widespread lacustrine development led to the abandonment of these progradational features and incision through them. The controls on the development of the lake margin sedimentary systems, including both shoreface and fluvial dominated shore zone facies, are complex.

The development of shore zone facies is the product of the large number of variables which influence the lake shore environment including: sediment supply, lake level stability, coastal physiography and the combination of wind strength, direction and fetch. Probably the most important factor is the lake level stability since the features which characterise shore zone facies, and in particular the upper shoreface facies, require time to form, however Adams & Wesnousky (1998) have shown that lake shore bars can form in periods of less than 7 months. The greatest stability in lake level is likely to occur during periods of lake highstand when an outflow can form, regulating lake level. To develop shore zone facies during lowstand, a balance between inflow and evaporation must be achieved. Regular fluctuations in lake level will limit the time available for the development of shore zone facies.

The morphology of the shoreline deposits appears to reflect the grain size of the sediment available for reworking, with coarser grained deposits forming features of greater relief (e.g. Red Point in Caithness, Trewin (2009)) and lower gradient features more common in finer grained intervals. The sediment grain size and availability is largely controlled by the proximity of the basement and fluvial systems. The extent to which the sediment is reworked is in turn controlled by wind strength, fetch and the orientation of the shoreline to the prevailing wind. Further physiographic influences include the coastal configuration, including the influence of fluvial/deltaic and aeolian systems, and the lake margin gradient.

The development of progradational successions within closed lacustrine basins depends heavily on the relationship between run off and lake level. These, in turn, are controlled by the catchment and basin climatic conditions which can be either linked or unlinked (Fig. 9). Once a lacustrine basin becomes open, which can occur intermittently due to fluctuating lake level, progradation of lake margin systems is more easily achieved. The successions described in this study allow these relationships to be investigated.

Conceptual model for deposition

Progradational sedimentary successions are rare within the cyclic lacustrine succession of the MORS. This can be explained in the context of what was predominantly a closed basin. In this setting during transgression, sedimentary systems were pushed back towards the basin margin, limiting the potential for progradation and during the subsequent climatically controlled regression the reduction in run off led to the retrogradation of fluvial systems. These relationships are summarised in figure 9.

However, major progradation of sedimentary systems characterise the successions described in this study. Progradation is exclusively recorded in the regressive portion of the sedimentary cycles, although this is likely to have occurred during lake highstand. During transgression, sediment inputs were pushed back towards the basin margin by rising lake levels, and were only able to prograde once the lake level stabilised. During the deposition of the Achanarras fish bed it has been suggested that the Orcadian basin developed an outflow and was hydrologically open (Marshall et al., 2007; Trewin, 1986). Therefore a more stable lake level allowed the progradation of sedimentary systems out into the basin, and the more widespread development of shore zone facies. The timing of the development of incisional features towards the top of the Achanarras fish bed cycles also requires discussion. Similar incision is recorded during lowstand periods by Keighley et al. (2003) from the Eocene Green River Formation and were regarded as part of their lowstand systems tract, however, Andrews and Trewin (2010) recognised that incision is more likely to be related to the rejuvenation of fluvial systems during initial cooling and the onset of transgressive conditions. Which of these occurs is, in fact, controlled by the relationship between the catchment and basin climate (Fig. 9). Where the catchment (run off) and basin climate (precipitation-evaporation) are linked or unlinked, but catchment dominated, it is likely that the reduced lake level will be coincident with reduced run off and therefore progradation or incision of the fluvial/deltaic systems at this time is unlikely (Fig. 9a & c). However, if the catchment and basin climate are unlinked and basin dominated the fluvial systems are likely to prograde and potentially incise due to the drop in baselevel (Fig. 9b). These different scenarios could potentially co-exist in the same basin as can be observed in Lake Chad where; in the north no incision is recorded on the Angamma Delta (Drake and Bristow, 2006; Schuster et al., 2005) suggesting that run off from the Tibesti Plateau had ceased to reach the lake prior to the lake level dropping, and in the south the Chari, which drains from highlands to the southwest, has incised through its Mega Lake Chad highstand delta and is constructing a lowstand delta in the remnant Lake Chad (Fig. 10).

CONCLUSIONS

A diverse range of environments are recognised in two lake margin successions between which high resolution correlation can be made. This study has characterised the deposits of these environments, including lower and upper shoreface facies and the fluvial dominated shore zone facies association.

The development of the shoreface facies is controlled by sediment supply, lake level stability, coastal physiography and the combination of wind strength, direction and fetch. Lake shoreface facies are well developed in the sections examined in Orkney due to the greater lake level stability at this time afforded by the likely development of an outflow from the Orcadian Basin, and the position on the north west margin of the basin, a position where the maximum fetch could be utilised for the wave reworking of lake margin sediments.

The development of large scale progradational systems is controlled by the sediment supply, lake level stability and the relationship between catchment run of and the evaporation/precipitation ratio in the basin. The relationship of these factors in the example described varies significantly with time due to eccentricity modulated precessional climatic cyclicity (Andrews and Trewin, 2010). The development of large scale progradational successions is rare in the cyclic sequences which underlie and overlie those described here. This is probably due to the closed nature of the basin during these periods and therefore the lack of a stable lake level. Furthermore, during transgressive periods sediment input points would be forced back towards the basin margin and the following regression would be driven by the aridification of the climate and therefore the retrogradation of fluvial systems is likely (Fig. 9). The succession described here contains the most significant progradational package recorded in the Middle Old Red Sandstone of the Orcadian Basin. This is likely to have resulted from a period of stable lake level caused by the establishment of a lake outflow. Progradation did not occur during the transgressive phase, when sediment input points were being forced back towards the basin margin but rather, are found in the regressive succession with initial shallowing likely to reflect the infilling of accommodation rather than the lowering of lake levels. In fact, it is likely that once the climate started to move towards more arid conditions progradation ceased and fluvial systems retrograded. It is therefore suggested that incision occurred during subsequent periods of climatic cooling where rejuvenated fluvial systems downcut through the earlier lake margin systems. Entrenchment of these systems limited the extent of incision and re-use during successive lake level fluctuations resulted in the development of terraced margins.

ACKNOWLEGEMENTS

M.J. Newman is gratefully acknowleged for his identification of fossil fish specimens from the Easter Ross coast which helped in confirmation of the position of the Achanarras fish bed in this region. The Inverness Field Club and the Carnegie Trust are thanked by S.D.A. for financial support of fieldwork undertaken. Nigel Trewin is acknowledged for inspiring a long-lived interest in the Devonian of Northern Scotland which has led to some fantastic journeys. Gary Nichols and Alberto Sáez are thanked for constructive reviews.

FIGURE CAPTIONS

Table 1. Summary of facies.

Table 2. Comparison of lake margin systems.

Fig. 1. Locality map (a) with inset illustrating the position of the more detailed MORS palaeogeography (b). Half graben basins have been clearly identified west of Orkney (Enfield and Coward, 1987) but are less clearly discernible within the Moray Firth due to later structural overprinting. (B) Birsay, Point of Buckquoy; (S) Stromness, Noust of Netherton; (Ho) Hoy, Burraquoy-Yellow Rock; (A) Achanarras; (T) Tarrel Bay; (H) Hilton of Cadboll, Jessie Port; (GGF) Great Glen Fault.

Fig. 2. Summary of facies which comprise the climatically controlled lacustrine cycles which are developed widely though out the Middle Old Red Sandstone succession of Northern Scotland. During periods of lower amplitude lake level fluctuations the deeper lake facies are not developed.

Fig. 3. Regional stratigraphy of the Devonian of northern Scotland (Modified after Andrews, 2008 and Trewin and Thirwall, 2002). The MORS comprises the Upper and Lower Strath Rory Groups of Easter Ross, the Upper and Lower Caithness Flagstone Groups of Caithness and the Upper and Lower Stromness Flagstone Groups of Orkney.

Fig. 4. Correlation of the Achanarras fish bed which comprises two climatically driven lacustrine cycles in both Easter Ross and Orkney, numbered 1 and 2. The overlying cycle is included in the Orkney sections. The fish bearing deep lake facies mark the deepest lake phases and provide the regional correlation framework for the more detailed lithological/palaeoenvironmental based correlations that are made. Correlation of the lake lowstand is also made and marked with a dashed line. The true spacing of the sections can be seen in Figure 1. The Achanarras section is redrawn from Trewin (1986). See Figure 2 for the key to lithological/sedimentary features.

Fig. 5. (A) Annually laminated deep lake facies. Bundling of the laminae, reflecting solar forcing of the climate, can be recognised. (B) Carbonate rich deep lake facies cut by a sub

horizontal discordant sandstone injectite. (C) More detailed view of (B) illustrating the preservation of some original structure within the injectite body. (D) Interlaminated graded sandstones and dark grey mudstones with abundant syneresis cracks of the shallow lake facies. (E) Shallow lake facies comprising grey mudstones and thin sandstones. (F) Red, often desiccated, mudstones and intercalated sheet sandstones of the playa facies. (G) Playa facies comprising intercalated sandstone and dolomitic mudstone laminae, containing wave and current rippling and desiccation cracks. Fining upwards cycles, of which an idealised example is illustrated, are common. (H) Micro hummocky cross stratification, characteristic of the lower shoreface facies, developed in thin bedded sandstones which are intercalated with thin mudstones.

Fig. 6. (A) Example of lower and upper shoreface facies from the Point of Buckquoy, South, section. (B) A portion of the logged section from Tarrel Bay containing examples of both the turbidite facies and fluvially dominated shoreface facies association. See Figure 2 for the key to sedimentological structure and Figure 4 for the position of the sections.

Fig. 7. (A) Very low angle cross bedding characteristic of swash and backwash processes in the upper shoreface, here overlain by extensively developed climbing ripples interpreted as a mouth bar deposit and illustrating the complexity of the upper shoreface setting. (B) Climbing ripples transitional to plane bed within a mouth bar deposit. (C) Inclined strata forming bar features in the shore zone facies. (D) Well developed flute marks on the base of a thick turbidite bed. (E) Typical loaded and graded turbidite bed which is laterally continuous across the outcrop. (F) Complex brittle and ductile deformation structures developed in the early stages of slumping. (G) Massive siltstone, resulting from slump processes, with characteristic hackly fracture and inclined deformation surfaces. (H) A steep sided and narrow incisional feature towards the top of the Achanarras cycles on Hoy.

Fig. 8. A terraced incisional feature developed on Hoy at a similar level to figure 7H.

Fig. 9. Conceptual model for the linkage between catchment climate and lake basin climate (precipitation/evaporation), resulting in a cyclic fluctuation in lake level. Scenarios illustrated are where the catchment and lake basin are (A) linked, (B) unlinked, basin dominant and (C) unlinked, catchment dominant. Each plot represents one complete orbitally forced climatic cycle.

Fig. 10. Sketch map of Mega-Lake Chad illustrating the two major deltaic systems and their response to lake level fall.

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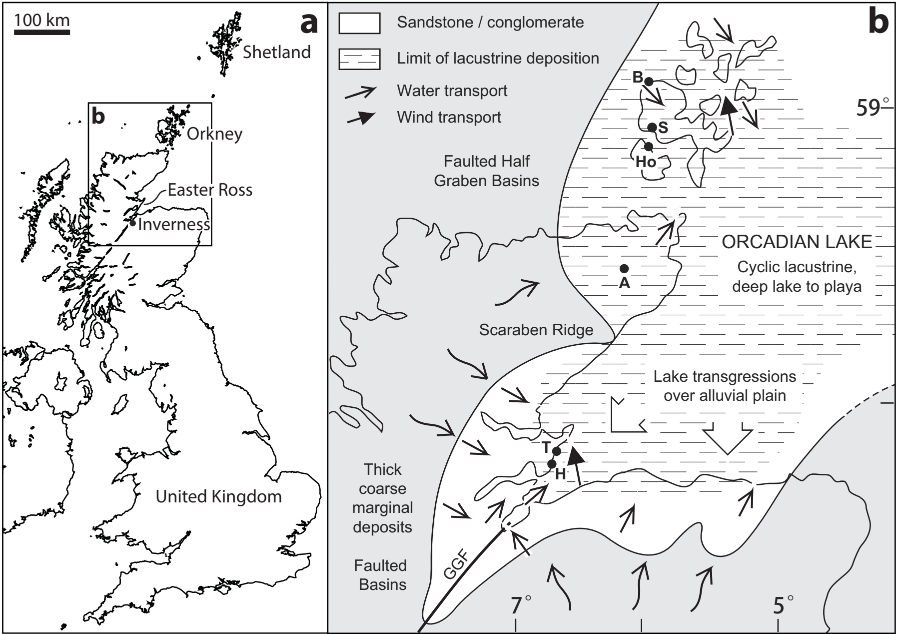
Table 1. Summary of facies

Facies	Lithology	Key sedimentary structures	Interpretation
Deep lake facies	Dark grey organic rich mudstone.	Laminated/varved (0.5 mm); seasonal clastic, clay, carbonate & organic components; fish material common.	Deep stratified lake with largely anoxic bottom waters.
Shallow lake facies	Intercalated very fine grained sandstone/ siltstone (1-10 mm) and grey to dark grey mudstone (1-10 mm).	*Sandstone* : sharp to mildly erosive bases, often graded, mudstone rip up clasts; current & rare oscillation ripples . *Mudstone* : laminated (0.5-5 mm), abundant syneresis cracks.	Shallow lake with fuctuating chemistry & depth. Regular sand input through turbidity flows.
Playa facies	Intercalated very fine grained sandstone/ siltstone (1-10 mm, more rarely up to 0.1 m) and mudstone (1-40 mm).	*Sandstone* : erosive bases, current ripples and oscillation ripples. *Mudstone* : desiccation and syneresis cracks common; laminated.	Ephemeral lake. Turbidite & sheet flood generated sand input; wave reworking.
Lower shoreface facies	Very fine grained sandstone (0.05-0.3 m) & grey to dark grey mudstone/ siltstone intercalations (0.1-0.5 m)	Hummocky cross stratification (λ - 0.1-0.2 m, amplitude up to 20 mm), grading, convolute lamination; syneresis in mudstone/siltstone.	Wave reworking in the lower shoreface. Finer grained portions record periods of calm/increased lake level
Upper shoreface facies	Very fine grained sandstone (0.1-0.4 m)	Low angle cross bedding, hummocky cross stratification, oscillation & climbing ripples; sometimes form larger scale gently dipping foresets (0.5-1 m thick and 10's of m wide).	Upper shoreface, in the swash-backwash & breaker zone. Larger features form beach bars/barrier bars.
Turbidite facies	Very fine grained sandstone (0.05-0.9 m) & mudstone/siltstone up to 1 m.	*Sandstone* : massive & convolute bedding; fluted & loaded bed bases common; Horizontal lamination & current ripples towards bed tops; some channels. *Mudstone/siltstone* : subtle to intense deformation, massive.	Turbidite and slump deposits.
Fluvial facies	Medium to coarse grained sandstone (0.2-1.5 m)	Convolute lamination, planar & trough cross bedding. Thinner sandstones form sheets but channels are also recorded	Fluvial. Often intercalated with playa, shallow lake & turbidite facies which forms a fluvial dominated shore zone association.

Table 2. Comparison of lake margin systems

Easter Ross		Orkney	
Characteristics	Controling factors	Characteristics	Controling factors
- Reduced thickness of deep lake facies due to sediment input - Progradation of fluvial systems during highstand - Coarser grained fluvial sediment	- Adjacent to significant basin margin relief - Major sediment input point	- Regular development of lower and upper shore face facies - Localised incision of highstand deposits during subsequent, low amplitude, lake level/climatic fluctuations - Progradation of turbidite systems during highstand	- NW basin margin (exposed to SE trade winds) - Low sediment input - Low relief

Figure 1



100 km
a
Shetland
b
Orkney
Easter Ross
Inverness
United Kingdom
b
Sandstone / conglomerate
Limit of lacustrine deposition
Water transport
Wind transport
Faulted Half Graben Basins
B
S
Ho
59°
ORCADIAN LAKE
Cyclic lacustrine, deep lake to playa
A
Scaraben Ridge
Lake transgressions over alluvial plain
T
H
Thick coarse marginal deposits
Faulted Basins
GGF
7°
5°

Fig. 2

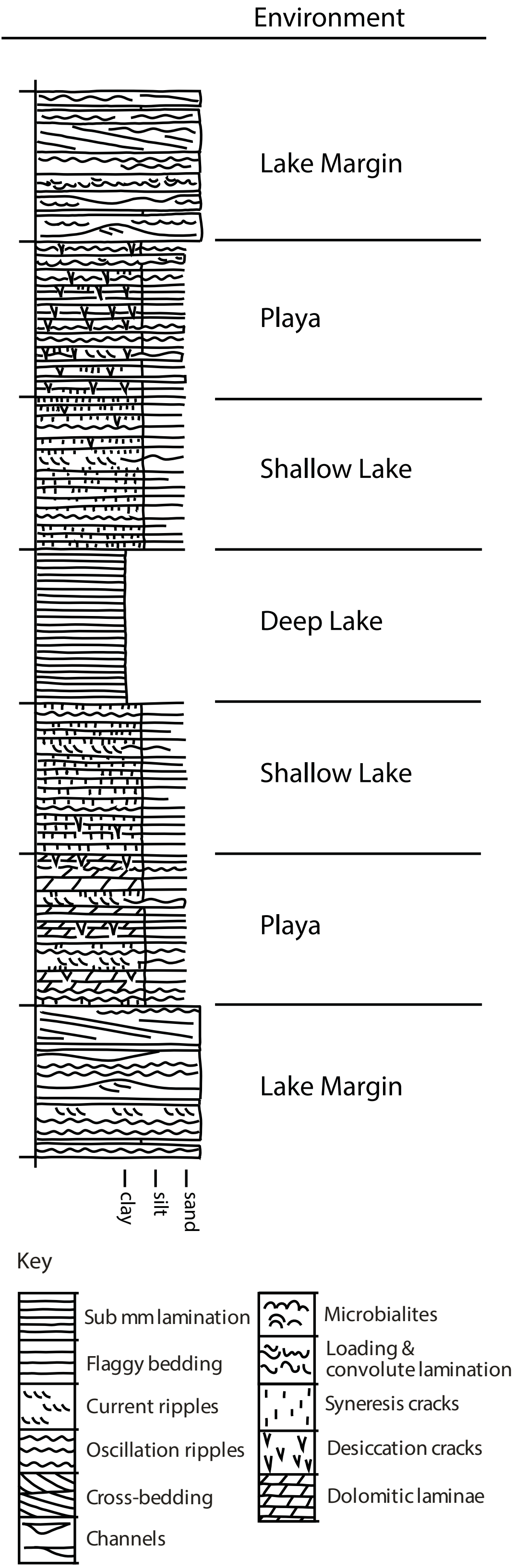
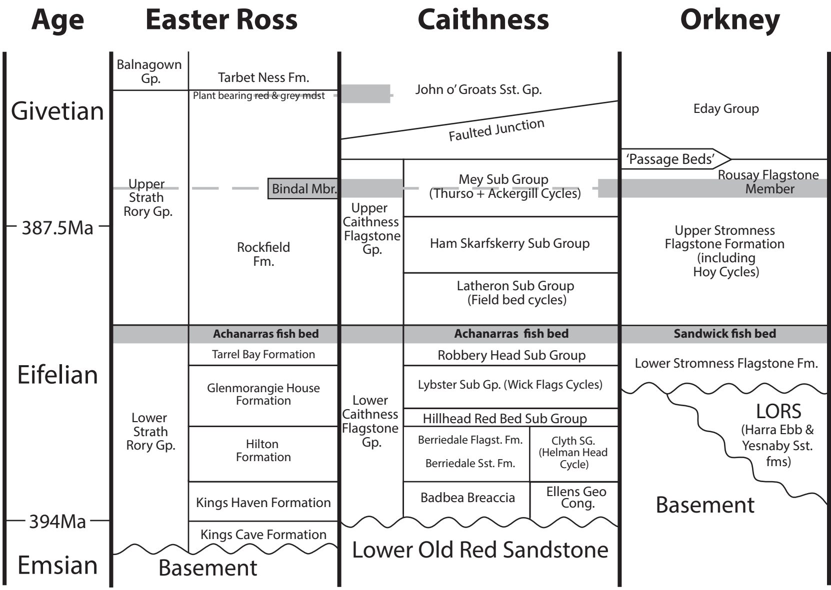

Environment
Lake Margin
Playa
Shallow Lake
Deep Lake
Shallow Lake
Playa
Lake Margin
clay
silt
sand
Key
Sub mm lamination
Flaggy bedding
Current ripples
Oscillation ripples
Cross-bedding
Channels
Microbialites
Loading & convolute lamination
Syneresis cracks
Desiccation cracks
Dolomitic laminae

Fig. 3


Age
Easter Ross
Caithness
Orkney
Givetian
387.5Ma
Eifelian
394Ma
Emsian
Balnagown Gp.
Tarbet Ness Fm.
Plant bearing red & grey mdst
Upper Strath Rory Gp.
Bindal Mbr.
Rockfield Fm.
Achanarras fish bed
Tarrel Bay Formation
Glenmorangie House Formation
Hilton Formation
Kings Haven Formation
Kings Cave Formation
Lower Strath Rory Gp.
Basement
John o' Groats Sst. Gp.
Faulted Junction
Upper Caithness Flagstone Gp.
Mey Sub Group (Thurso + Ackergill Cycles)
Ham Skarfskerry Sub Group
Latheron Sub Group (Field bed cycles)
Achanarras fish bed
Robbery Head Sub Group
Lybster Sub Gp. (Wick Flags Cycles)
Hillhead Red Bed Sub Group
Lower Caithness Flagstone Gp.
Berriedale Flagst. Fm.
Berriedale Sst. Fm.
Clyth SG. (Helman Head Cycle)
Badbea Breaccia
Ellens Geo Cong.
Lower Old Red Sandstone
Eday Group
'Passage Beds'
Rousay Flagstone Member
Upper Stromness Flagstone Formation (including Hoy Cycles)
Sandwick fish bed
Lower Stromness Flagstone Fm.
LORS (Harra Ebb & Yesnaby Sst. fms)
Basement

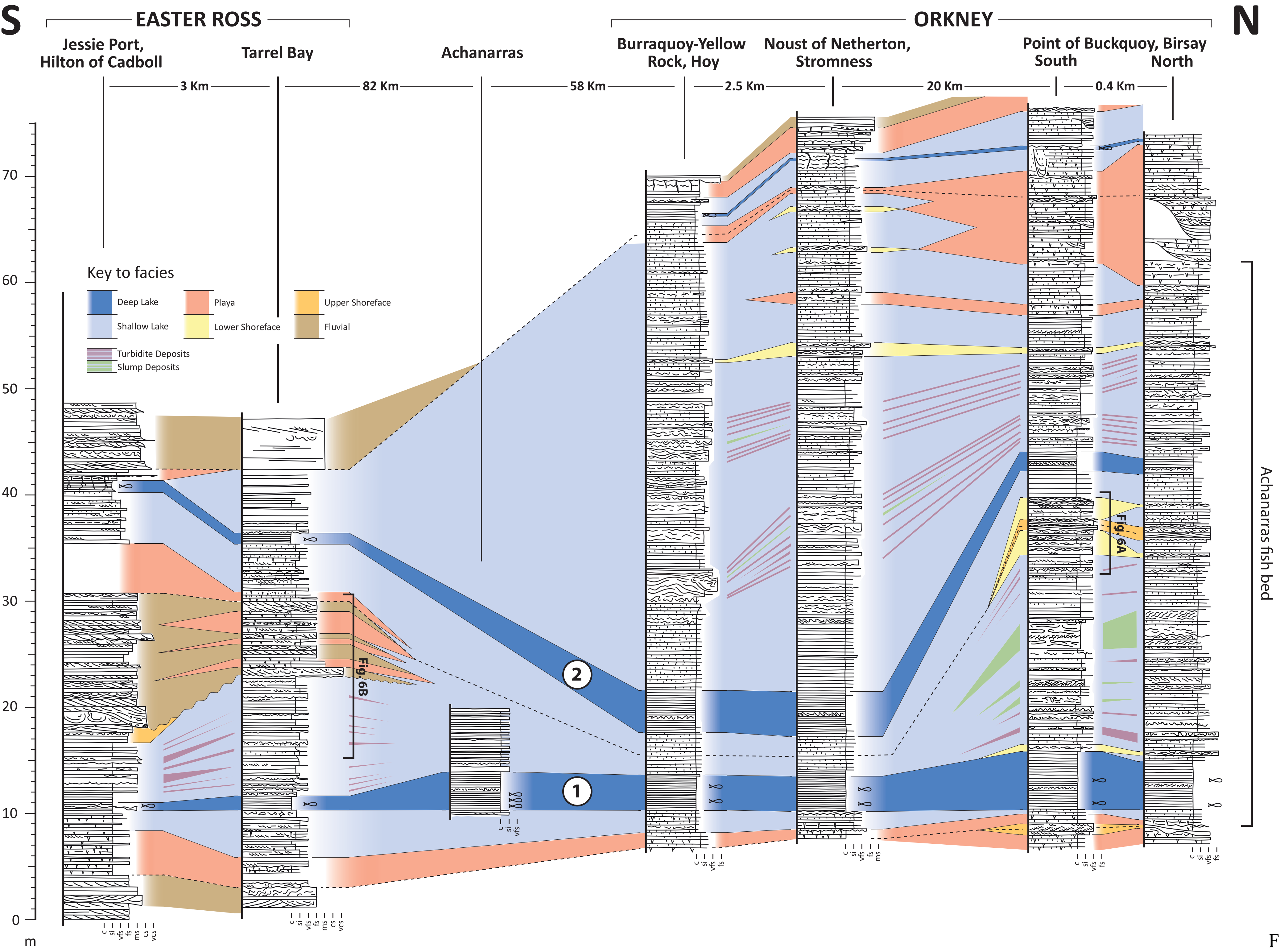

S
EASTER ROSS
ORKNEY
N
Jessie Port, Hilton of Cadboll
Tarrel Bay
Achanarras
Burraquoy-Yellow Rock, Hoy
Noust of Netherton, Stromness
Point of Buckquoy, Birsay South
North
3 Km
82 Km
58 Km
2.5 Km
20 Km
0.4 Km
Key to facies
Deep Lake
Playa
Upper Shoreface
Shallow Lake
Lower Shoreface
Fluvial
Turbidite Deposits
Slump Deposits
m
0
10
20
30
40
50
60
70
c
si
vfs
fs
ms
cs
vcs
①
②
Fig. 6B
Fig. 6A
Achanarras fish bed

Fig. 4

Figure 5

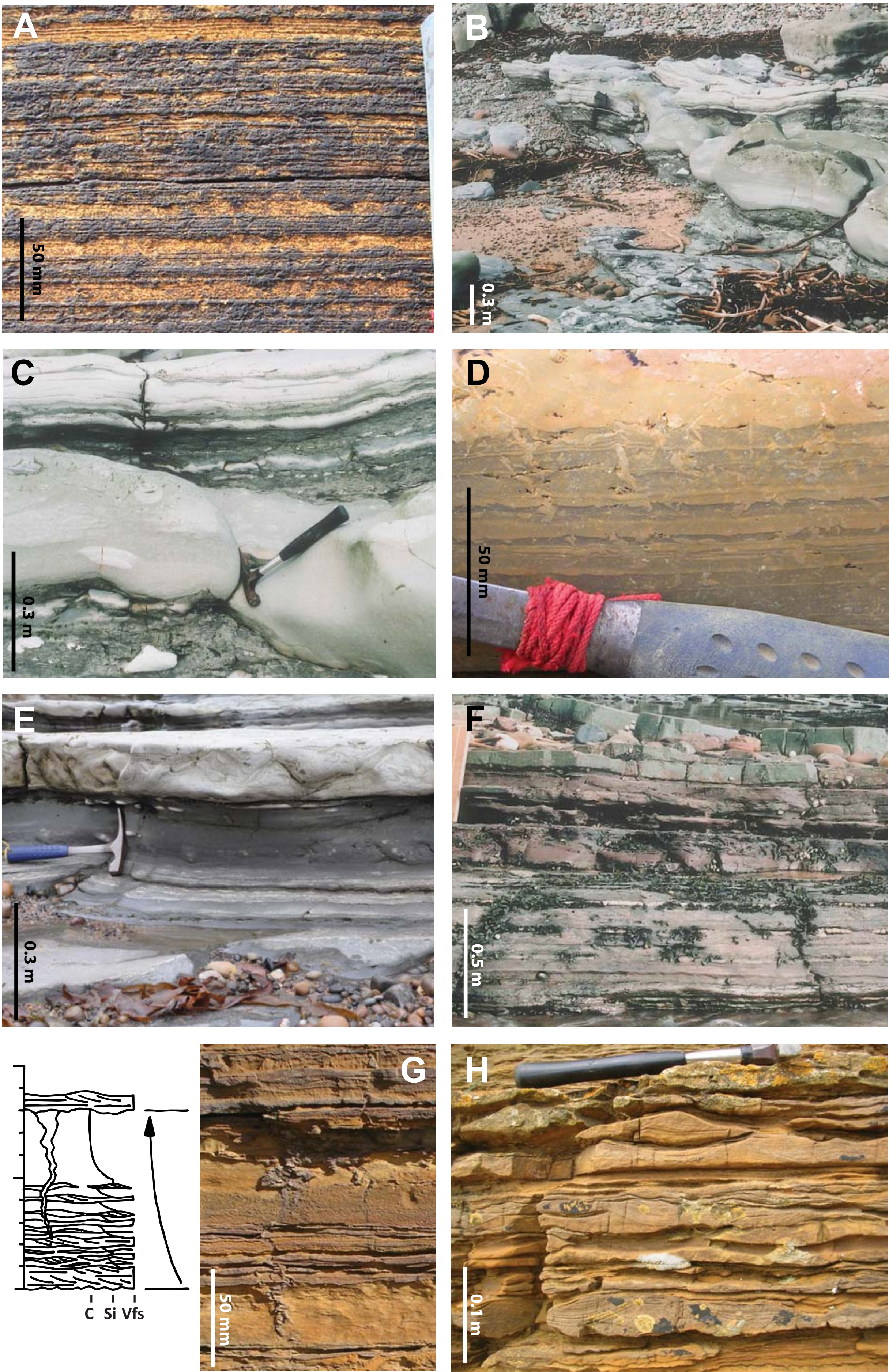


Figure 6

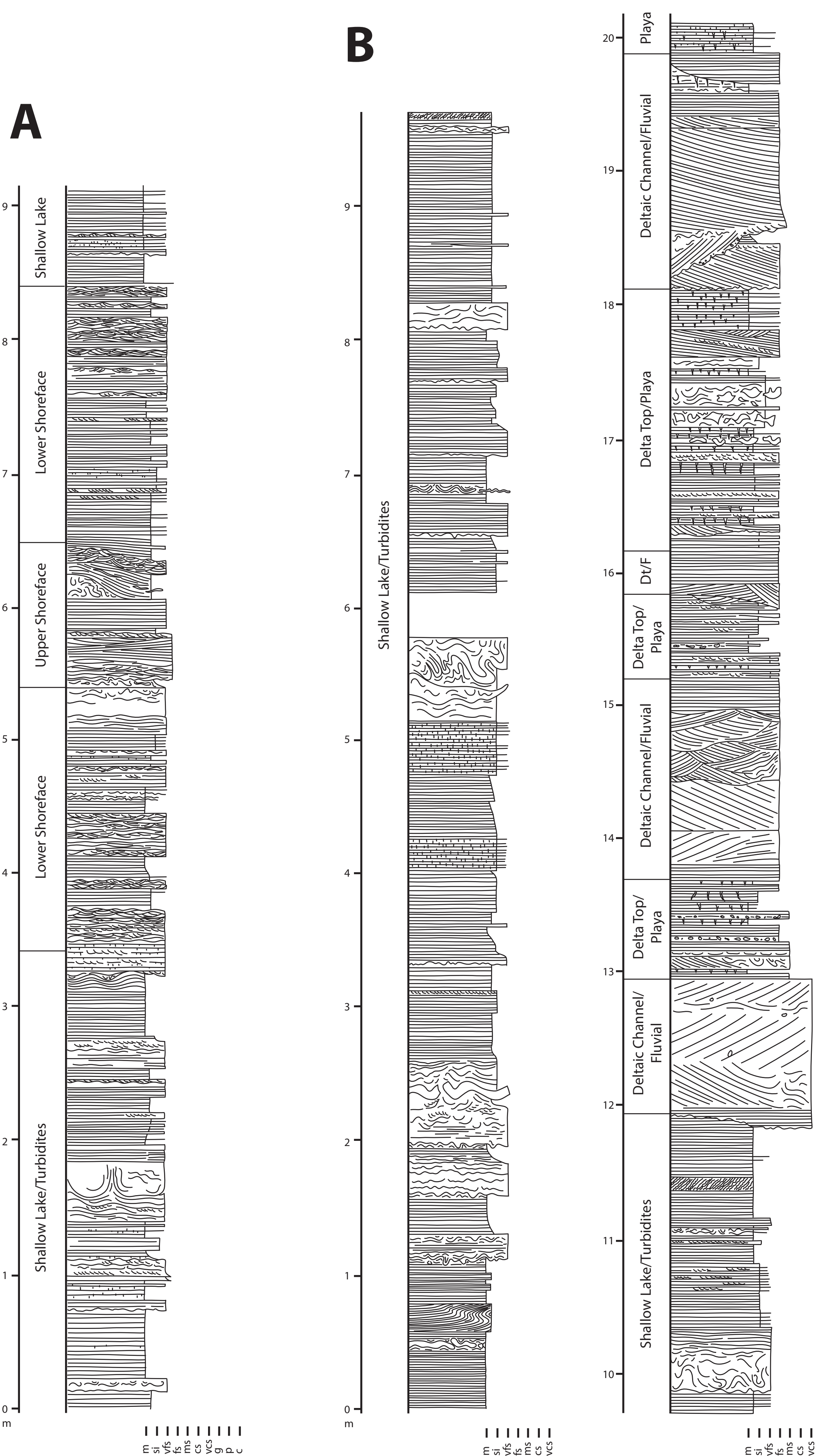

A
B
Shallow Lake
Lower Shoreface
Upper Shoreface
Lower Shoreface
Shallow Lake/Turbidites
Shallow Lake/Turbidites
Playa
Deltaic Channel/Fluvial
Delta Top/Playa
Dt/F
Delta Top/ Playa
Deltaic Channel/Fluvial
Delta Top/ Playa
Deltaic Channel/ Fluvial
Shallow Lake/Turbidites
m
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
m si vfs fs ms cs vcs g p c
m si vfs fs ms cs vcs
m si vfs fs ms cs vcs

Figure 7

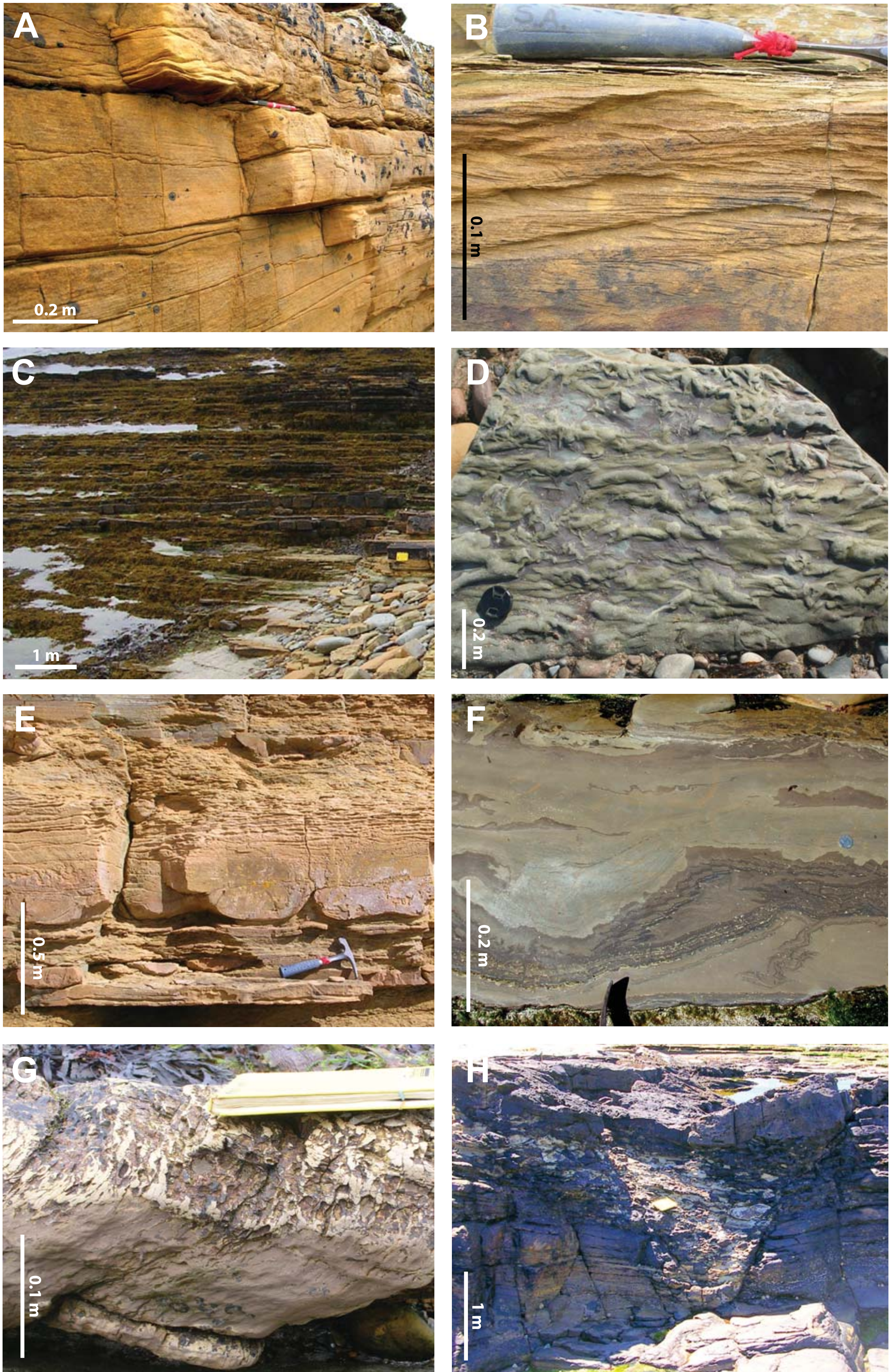


Figure 8

Figure 9

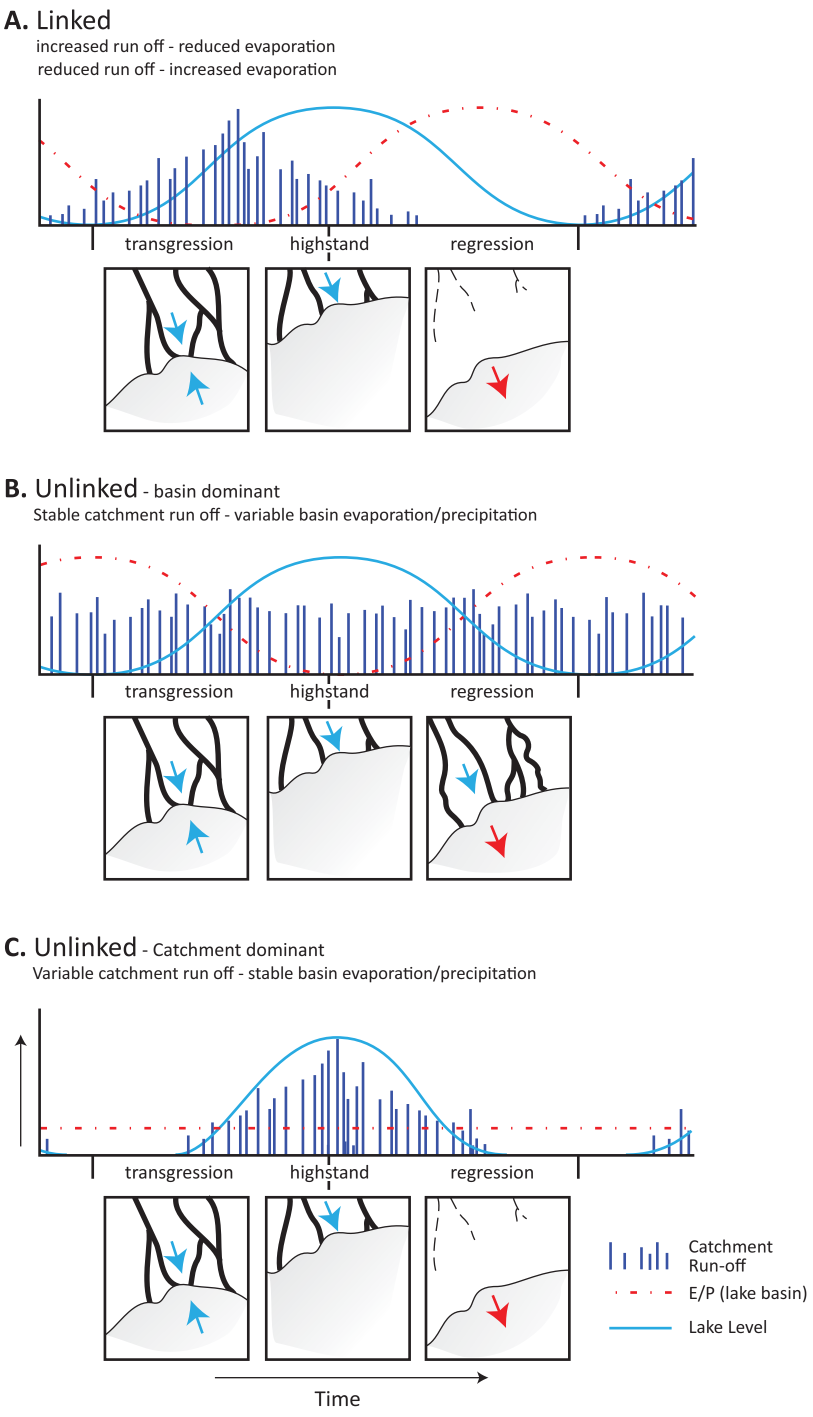
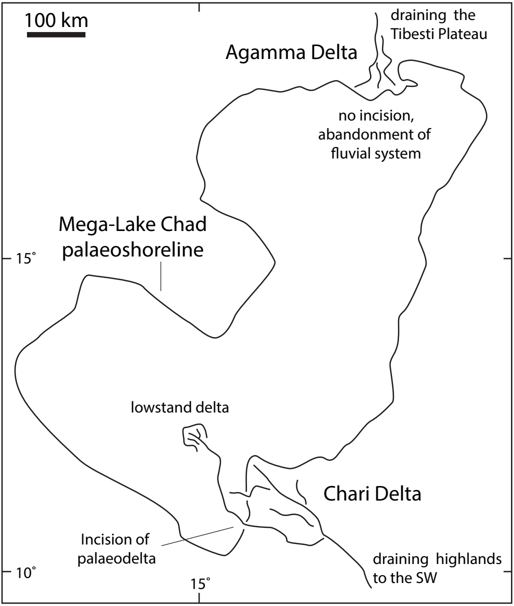

A. Linked
increased run off - reduced evaporation
reduced run off - increased evaporation
transgression
highstand
regression
B. Unlinked - basin dominant
Stable catchment run off - variable basin evaporation/precipitation
transgression
highstand
regression
C. Unlinked - Catchment dominant
Variable catchment run off - stable basin evaporation/precipitation
transgression
highstand
regression
Catchment Run-off
E/P (lake basin)
Lake Level
Time

Figure 10


100 km
draining the Tibesti Plateau
Agamma Delta
no incision, abandonment of fluvial system
Mega-Lake Chad palaeoshoreline
15˚
lowstand delta
Chari Delta
Incision of palaeodelta
draining highlands to the SW
10˚
15˚