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Lower Permian deposits of the Huab area, NW Namibia: a continental to marine transition

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Understanding the facies development of the Huab area is important as this area provides a bridge between the Permian deposits of South Africa and southern Namibia and those of the Paraná Basin in Brazil.

Post-glacial Permian environments in the Huab area were initiated by widespread, meandering river systems recorded by sandy point bar and coal-bearing floodplain deposits of the Verbrandeberg Formation. The base of the Tsarabis Formation is dominated by laterally amalgamated braided channel sandstones. These fluvial units interfinger upwards with wave-dominated deltaic and shoreface deposits bearing a variety of marine trace fossils. The overlying Huab Formation contains large-scale stromatolite ridges with flat pebble conglomerates formed in tidal channels between the ridges. The entire succession was later buried by landward-onlapping marine mud- and marlstones recording the peak of an overall transgressive development. Facies architecture varies considerably in cross-section perpendicular to the present-day continental margin, which is interpreted to reflect syn-depositional normal faulting during early South Atlantic rifting. This requires detailed palaeo-environmental analyses because it is assumed that marine-influenced Karoo-aged rocks in Namibia and Brazil trace the axis of a broad southern South Atlantic intracontinental rift zone.

Introduction

The initial fragmentation of the Gondwanan supercontinent around southern Africa is recorded in numerous Karoo-aged depositories comprising both foreland basins and intracontinental rift basins (Daly *et al.*, 1983; Dingle *et al.*, 1983; Veevers *et al.*, 1994). Basin fills of marine and terrestrial environments register progressive climatic change from glaciogenic to desert conditions over a time span lasting from Carboniferous-Permian to Jurassic and Early Cretaceous (Stollhofen, 1999). The basins yield the potential for various mineral and energy resources such as coal, molybdenum, uranium, gas and oil. Therefore, an improved knowledge of both their sedimentary and stratigraphic records and their structural styles is important for future exploration.

In this study we focus on Lower Permian strata in the Huab area of NW-Namibia that accumulated in a fault-controlled, Late Palaeozoic depository contemporaneously with Lower Permian strata in the Paraná Basin, South America, and the main Karoo Basin, South Africa (Fig. 1). Similar facies signatures, biostratigraphic records and the occurrence of aquatic fossils endemic to these depositories (Hallam, 1972; Ledendecker, 1992; Rohn, 1994) suggest that they were joined during the Late Palaeozoic to form an elongate, NW-SE-trending seaway between southern Africa and South America (Martin, 1975; Stollhofen, 1999). However, this basinal depression was repeatedly affected by northerly directed marine incursions (Fig. 1) following the Carboniferous interglacial sea level highstands (Martin, 1975; Visser, 1997; Bangert *et al.*, 2000). It is our aim to document such a marine-influenced succession and to place it in a geodynamic context.

The pre-breakup succession in Namibia can be subdivided into three megasequences, each bounded by unconformites: (1) Carboniferous-Lower Permian, (2) Latest Permian-Jurassic, and (3) Cretaceous age (Stanistreet and Stollhofen, 1999). Only the Carboniferous-Lower Permian megasequence will be considered in this paper (Fig. 2). This developed with a pronounced unconformity on top of deformed Proterozoic metamorphic and granitic basement rocks and achieves a maximum cumulative thickness of about 280 m. Carboniferous glacial and fluvioglacial Dwyka Group deposits initiate the sedimentary succession and are conformably overlain by fluvial deposits of the Verbrandeberg Formation, fluvial to shallow marine deposits of the Tsarabis Formation and marine deposits of the Huab Formation (Fig. 2).

Glacial deposits of the Carboniferous Dwyka Group

New radiometric ages derived from tuff beds interlayered with Dwyka and Ecca Group sediments in Namibia and South Africa assign the majority of the Dwyka Group to the Late Carboniferous (Bangert *et al.*, 1999). The Dwyka successions in both outcrop areas are comprised of up to four vertically stacked, upward-fining, deglaciation sequences, individually between 10 and 350 m thick and characterised by a mudstone-dominated top (Visser, 1997; Bangert, *et al.*, 2000). In southern Namibia, several of these mudstone units preserve evidence of marine incursions most probably coinciding with a maximum rate of glacial ice margin retreat (Martin and Wilczewski, 1970; Martin *et al.*, 1970; Bangert *et al.*, 2000).

In the Dwyka Group of the Huab area, Horsthemke (1992) distinguished four major lithofacies, grouped in an upward-fining arrangement of only 15 m thickness: (1) massive, clast-rich diamictites interpreted as lodgement tills, (2) layered, clast-rich diamictites with thin interleaved conglomerate and sandstone layers representing subaqueous outwash fan deposits, (3) current-ripple cross-laminated fine- to medium-grained sandstones and thin interbedded conglomerate layers of a distal outwash plain, and (4) rhythmically laminated mudstones with highly variable laminae thicknesses. The latter contain an ichnofossil assemblage dominated by

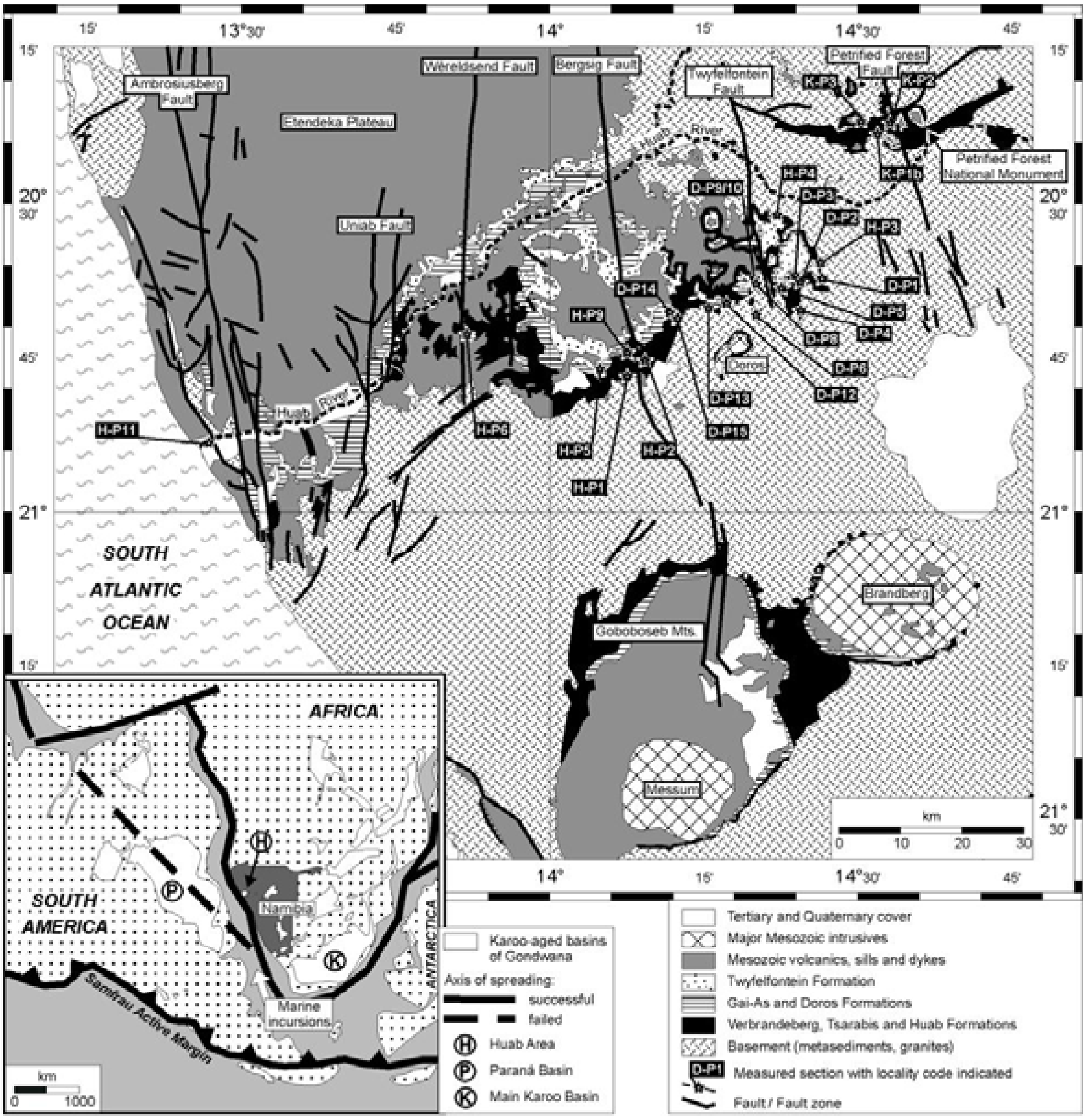

Figure 1: Geological map of the Huab area in NW Namibia (based on Miller and Schalk, 1980). Shown are the distribution of Lower Permian deposits of the Verbrandeberg, Tsarabis and Huab Formations and enclosing strata along with the locations of measured sections. The inset locates the Huab area in a southern Gondwanan context and shows the axis of spreading in the Paraná domain, both reactivating pre-existing basement structures (Stollhofen, 1999).

Diplichnites isp. and *Umfolozia sinuosa* which Ledendecker (1992) related to a glaciolacustrine prodelta environment. However, new discoveries of *Helminthopsis* isp., *Teichichnus* isp., *Chondrites* isp., *Thalassinoides* isp. and ?*Cruziana* isp. in the laminated fine-grained sandstones include those genera of the marine-influenced Dwyka deposits of the Aranos Basin in southern Namibia (Bangert *et al.*, 2000) and the main Karoo Basin in South Africa (Savage, 1971). Both facies architecture and palaeocurrent measurements suggest that the Huab area was occupied by an incised glacial valley (Martin, 1953, 1975, 1981) draining westward into the Paraná Basin (Santos *et al.*, 1996) where a more complete glacial record is preserved by the time-equivalent Itararé Group. Only during sea-level highstands, which coincided with peaks of deglaciation, were the incised glacial valleys flooded by marine incursions as indicated by the ichnofossil assemblage.

Coal-bearing fluvial deposits of the Permian Verbrandeberg Formation

Following the glacigenic Dwyka Group deposition, widespread meandering fluvial systems occupied the post-glacial landscape. Three major facies associations (Fig. 3) are developed: (1) an arkosic sandy point bar facies association grades upward into (2) a coal-bearing floodplain facies association interlayered with (3) a scoriaceous basalt which provides a useful horizon for correlation. The succession is up to 70 m thick and characteristically upward fining with an upward decreasing organic content.

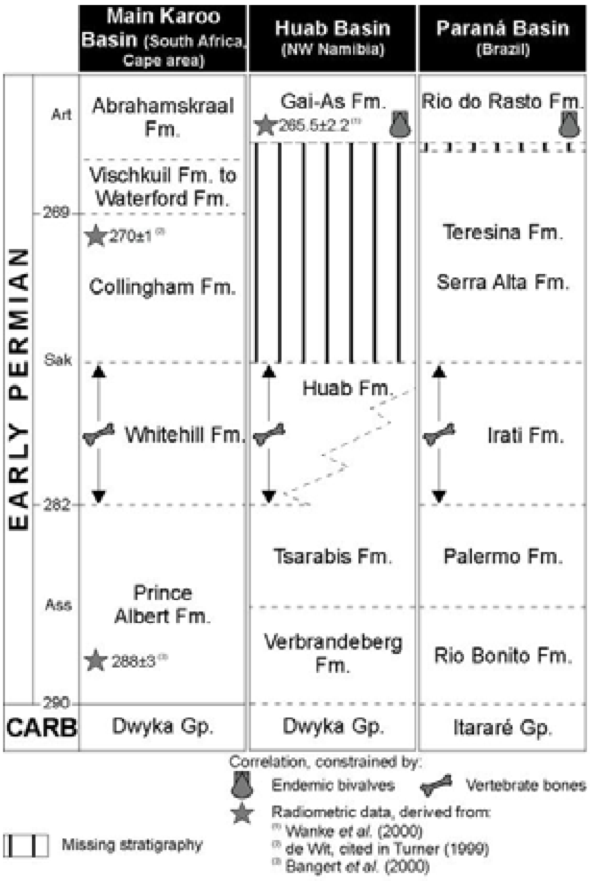

Figure 2: Stratigraphy of the Early Permian succession in the Huab area, the Paraná Basin and the main Karoo Basin (based on Ledendecker, 1992; Stollhofen *et al.*, 2000). Biostratigraphic constraints provide a basis for correlation and radiometric ages relate the succession to the numerical time scale of Gradstein and Ogg (1996).

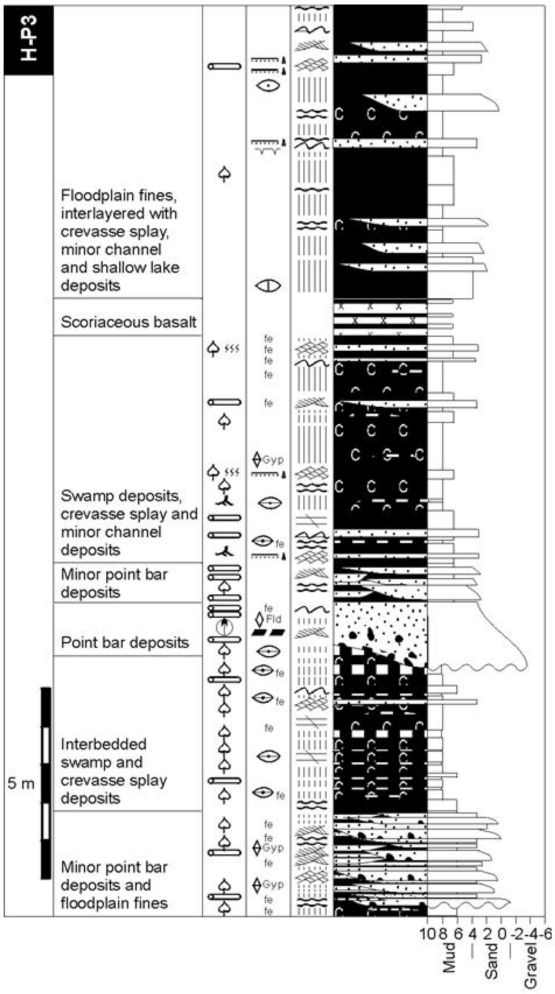

Figure 3: Section 'H-P3' shows the characteristic facies development of the Verbrandeberg Formation in the eastern Huab area (legend contained in Fig. 4). See Fig. 1 to locate the section.

Arkosic sandy point bar facies association

This facies forms about 15 % of the entire succession and consists of erosionally based, pebbly, fine- to coarse-grained sandstones forming isolated single-channel or subordinate multiple-channel bodies, 0.5 - 4.5 m thick and up to 50 m wide. Bases often contain concentrations of rounded quartz and alkali feldspar cobbles as well as various softclasts (e.g. sandstone, siltstone and coal). These are overlain by, coarse-grained, trough cross-bedded sandstones and, above these, medium-grained, plane-bedded and current-ripple cross-laminated sandstones. Trough cross-beds reveal highly variable palaeocurrent directions with a vector mean towards the NNW.

Channel geometries, the variable palaeocurrent directions and the presence of abundant floodplain fines reflect deposition in well confined fluvial channels within a meandering river system. Lateral migration developed typical upward-fining units consisting of coarse, erosionally based, channel lag deposits overlain by sandy deposits of the lower to upper point bar (Jordan and Pryor, 1992).

Coal-bearing floodplain facies association

Fine-grained, grey deposits characterise this facies association which forms about 85 % of the whole succession. Four interbedded lithofacies are present (1) floodplain deposits, (2) crevasse splay deposits, (3) shallow floodbasin lake deposits, and (4) coal-bearing swamp deposits.

(1) Floodplain deposits: normally graded and parallel to wavy laminated beds of fine-grained sandstone to claystone amalgamate to form units up to 20 cm thick. Small-ripple lenses and wave-rippled top surfaces locally occur in the sandy interbeds. Desiccation cracks are developed in the mudstone-dominated parts. Clay nodules and calcareous concretions occur throughout.

(2) Crevasse splay deposits: these are flat, lens-shaped bodies of fine-grained sandstone to siltstone 0.1 - 1.2 m thick with slightly erosive to sharp planar bases. They have a lateral extent of up to 12 m and interfinger with floodplain and floodbasin fines. Some of the beds contain a thin basal pebble layer containing mainly quartz

and mudstone pebbles. Typically, beds have normal grading and climbing ripples with an angle of climb decreasing upwards. Parallel lamination and current ripples are associated with bed tops.

(3) Shallow floodbasin lake deposits: sharp planar based, laminated claystone layers which contain abundant pyrite. They grade upward into thin, wavy laminated to ripple bedded siltstone and fine-grained sandstone layers amalgamating to coarsening-upward units, 0.7 - 3.2 m thick.

(4) Coal-bearing swamp deposits: dark grey claystone and siltstone beds which are rich in plant debris and haematised wood along with streaks, lenses and some small seams of coal, the latter up to 30 cm thick and of more than 10 m lateral continuity. They display parallel to wavy lamination or occur as massive layers. Both contain abundant clay nodules, up to 1 m in diameter, and small mm-sized ferrugineous concretions. Dispersed pyrite has weathered to secondary jarosite and gypsum.

The lateral extent and sedimentary structures of the fine-grained lithofacies indicate flood-stage deposition of suspended material in floodplain areas. Crevasse splays generated thin, lobe-shaped sandstone bodies on the floodplain. Where crevasse splays inundated shallow floodbasin and oxbow lakes, thin coarsening-upward cycles were produced by combined mouth bar/crevasse splay couplets. Abundant plant remains, the formation of coal and high iron-contents suggest poorly drained, densely vegetated swamp areas. Comparative present-day periglacial swamps are known from western Siberia, for instance. These developed overall anoxic low-pH conditions, favouring the reduction of iron, while marginal freshwater incursions support widespread iron precipitation (Walter, 1977). Such a mechanism would explain the restriction of haematised wood to the eastern margin of the Huab area.

Palaeobiological constraints

Beside coal, the lower half of the Verbrandeberg Formation in particular, contains abundant plant remains. Thin rhizolith horizons are best developed beneath the coals, and numerous fragments and impressions of leaves and bark occur in the claystone units, whereas silicified, calcified and haematised plant material (leaves, twigs, trunks and fructifications) are concentrated at the tops of sandstone units. Identified material is of *Glossopteris* sp. and *Noeggerathiopsis* sp. (written comm. Adendorff, 1998). Ledendecker (1992) further illustrates a lycopod bark impression, that he relates to *Cyclodendron leslii*. Fauna is exclusively recorded by bioturbation of the coal-bearing floodplain facies association, with the highest density in the crevasse splay facies and a complete lack in the coal-bearing swamp facies.

Verbrandeberg Basalt

Several thin scoriaceous basalt layers occur in the basal Verbrandeberg Formation. At the Verbrandeberg type locality (H-P3 in Fig. 1) these layers are 0.1-1.2 m thick, but pinch out over a distance of 11 km towards the SW and 8 km towards the NW. The original plagioclase and pyroxene phenocrysts of the basalt are intensively replaced by haematite and various clay minerals. However, the tongue-like shape of the scoriaceous basalt fragments are distinct, and are interpreted as weakly welded scoria-fall deposits derived from small proximal scoria cones.

Fluvio-deltaic to shallow marine deposits of the Permian Tsarabis Formation

The Tsarabis Formation comprises three characteristic facies associations, totalling 125 m in thickness. (1) An amalgamated, sheet-sandbody facies association which is overlain either by (2) an upward-coarsening, tabular cross-stratified sandstone facies association, or (3) a hummocky cross-bedded, bioturbated sandstone facies association. All of these facies elements thin upward and towards the depocentre where they interfinger with fine-grained Huab Formation deposits.

Amalgamated sheet-sandbody facies association

This facies association dominates both the base of the succession and the eastern part of the basin. It grades upwards either into the upward-coarsening tabular cross-stratified sandstone facies or into the hummocky cross-bedded, bioturbated sandstone facies. Characteristic are sheet-like sandbodies, up to 8 m thick, which developed a thinning- and fining-upward architecture. Cross-sections reveal that the sheets comprise zones of trough cross-bedded, channel sandstone bodies which interfinger laterally with tabular cross-bedded strata towards the west (Fig. 4).

The trough cross-bedded zones are made up of numerous channel bodies, 12-40 m wide and up to 4 m thick. Channel bases show incision up to 4 m deep and are locally draped by thin, imbricated pebble layers which grade upward into trough cross-bedded arkosic, medium- to coarse-grained, pebbly sandstones. Pebbles consist of rounded quartz and feldspar and abundant lithoclasts of schist, quarzite and granite as well as mud-chips and reddish mud granules.

Tabular cross-stratified zones are formed by coarse-grained, pebbly sandstone units with low-angle planar foresets and up to 3.5 m thick. Basal contacts are only slightly undulatory with thin gravel layers. Pronounced concentrations of large tree logs (up to 30 m long and 1.5 m in diameter), e.g. at the Petrified Forest National Monument (Fig. 1), occur in the top part of these units.

Sets of both types of cross-bedded strata are separated by parallel laminated and small-ripple bedded sand-

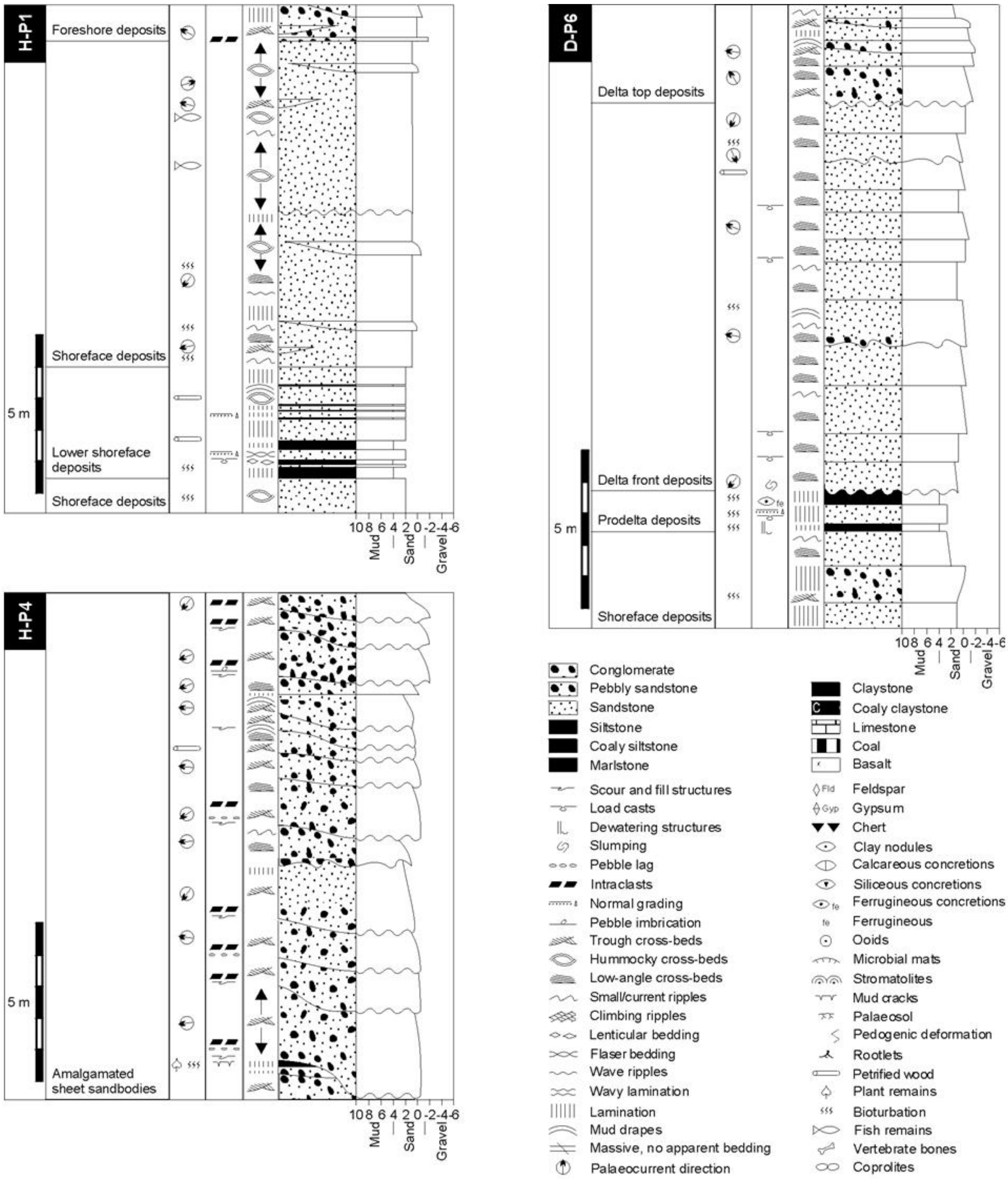

Figure 4: Sections illustrating the facies of the Tsarabis Formation in the central (H-P1) and the eastern Huab area (H-P4 and D-P6). Section 'H-P1' comprises hummocky cross-bedded foreshore and shoreface deposits whereas section 'D-P6' involves shoreface deposits overlain by a prograding delta sequence. The easternmost section 'H-P4' is characterised by braid plain deposits. See Fig. 1 to locate sections.

stone units with small-ripple cross bedding overlain by thin channel-fill siltstones, scour and fill bedded units up to 25 cm thick or only thin mud drapes. Such units locally show accumulated plant debris, bioturbation and mud cracks, indicating soil development.

Channel morphologies, high degrees of channel amalgamation, moderate variations of palaeocurrent measurements (230 - 300°) and the general lack of floodplain deposits, suggest that the sheet sandbody facies was deposited by broad, mobile, braided stream systems. The trough cross-beds are interpreted as sinuous-crested subaqueous dune deposits which formed in relatively deep water (Cant, 1978), whereas planar cross-bedded strata originate from shallow, ripple-topped bar forms (Singh, 1977) deposited under waning-flow conditions. This suggests a braidplain environment, either with areas of persistent flow divided by areas of sandflat character (Nemec, 1992) or with pronounced variations in water discharge.

Upward-coarsening tabular cross-stratified sandstone facies association

Cyclically arranged upward-coarsening units of mudstone to coarse-grained sandstone, up to 20 m thick, with sharp planar bases characterise this facies association. Cycles are introduced by alternations of plane-bedded mudstone and graded medium- to fine-grained sandstone layers which are intensively bioturbated and contain abundant dewatering structures, slump folds and loaded bases. Upwards these grade into well sorted, medium-grained sandstones with foresets 0.2 - 1.5 m thick and of at least 50 m lateral continuity. Foresets usually dip at angles between 20 and 25° but reach dips up to 35° in the eastern part of the basin. The upper parts of the cycles include cosets up to 1.8 m thick of pebbly, medium- to coarse-grained sandstones with small-ripple bedded tops and set boundaries constrained by thin mud drapes. In the eastern Huab area silicified tree logs and impressions of wood bark are present in these sandstones. The top parts of the upward-coarsening cycles are incised by trough cross-bedded, medium- to coarse-grained, pebbly, channel sandstone bodies up to 20 m wide and up to 8 m thick. Palaeocurrent measurements reveal a vector mean towards the west.

Distinct coarsening-upward trends of these units together with the development of classic bottomset, foreset and topset geometries indicate prodelta, deltafront and deltaplain sub-environments of a prograding delta. The remarkable dip of the delta foresets and the abundance of soft-sediment deformation structures indicate relatively steep delta front slopes, typical of Gilbert-type deltas (Corner *et al.*, 1990). In addition, this eastern area is characterised by coarser grain sizes which fit well with the observation of a westward-directed transport of debris by fluvial distributary channels dissecting the deltaplain. Such channel-fill sandstones were deposited in a regime of fluctuating discharge producing gravel lenses during flood peaks and thin mud drapes during periods of largely reduced discharge (Corner *et al.*, 1990).

Hummocky cross-bedded, bioturbated sandstone facies association

This facies association is characterised by upward-coarsening units, up to 15 m thick, consisting of plane-bedded mudstones interbedded with fine-grained, small ripple-, flaser- and lenticular-bedded sandstones grading upward into well sorted coarse-grained sandstones. The latter developed low-angle accretion surfaces and either medium to large-scale hummocky cross-stratification or plane lamination. Hummocky beds are 20 - 80 cm thick with wave lengths ranging between 1.2 and 3.5 m. Basal contacts are either planar or low-angle scoured and several of the upper surface contacts are wave or current-rippled. In places the entire fine-grained parts at the bases of such upward-coarsening units are eroded and the hummocky beds either immediately stack on one another or are separated by thin, erosively based pebble layers which define incised channel bases. Palaeocurrent directions from trough-crossbeds of such channels are variable but reveal a westerly vector mean. The entire succession shows abundant bioturbation dominated by vertical to subvertical dwelling structures, resembling the shallow marine *Skolithos* ichnofacies. Concentrations of fossil wood fragments and fish remains generally occur in the sandy strata towards the top of the units. Towards the west a pronounced interfingering with the Huab Formation is apparent (Fig. 6).

Facies architecture, ichnofossil association and the interrelationships with other facies imply nearshore marine deposits transitional to the facies of the Huab Formation. Individual sequences herein are interpreted as shallowing-upward successions grading from lenticular and flaser-bedded mudstones and sandstones of the highly bioturbated transitional zone into hummocky cross-bedded and plane laminated sands of a shoreface to foreshore setting. The hummocky cross-stratified units in shoreface successions are interpreted as typical storm wave generated deposits (Duke *et al.*, 1991) which are sporadically incised by shallow, pebble-bearing channels. In addition, facies architecture, palaeocurrent measurements and the constant westward-directed low-angle inclination of the laminated sandstone units imply a depocenter situated west of the Huab area in the Paraná domain.

Palaeobiological constraints

The Tsarabis Formation preserves spectacular silicified and calcified tree logs, up to 30 m in length and 1.5 m in diameter, occurring within both the amalgamated sheet sandbody facies and the hummocky cross-bedded, bioturbated sandstone facies. They resemble *Araucaria* sp. (written comm. Bamford, 1998) and seven cordait species (Kräusel, 1956). Moreover, the upward-coarsening cross-stratified sandstone facies yield impressions of *Calamites* sp. and lepidodendroid bark. Fragments of acrolepid and elasmobranchid fish, associated with labyronthodontid amphibians (Ledendecker, 1992) are concentrated in the bioturbated hummocky cross-bedded sandstone facies. The abundance of ichnofossils varies significantly depending on facies. The amalgamated sheet sandbody facies contains *Planolites* isp., *Skolithos* isp., *Palaeophycus tubularis*, and various snail tracks. In the upward-coarsening tabular cross-stratified sandstone facies, traces typical of marine environments *Teichichnus* isp. and *Chondrites* isp. occur with *Planolites* isp. The most dense ichnofauna is developed in the hummocky cross-bedded, bioturbated sandstone facies, comprising *Syphonichnus* isp., *Planolites* isp., *Monocraterion* isp., *Skolithos* isp., *Diplocraterion* isp., *Arenicolites* isp. and *Teichichnus* isp. which support the interpretation of a marine shoreface setting. The Tsarabis Formation as a whole varies gradually in facies from fluvio-deltaic dominated settings in the eastern basin to storm-influenced marine-deltaic settings towards the west.

Marine deposits of the Permian Huab Formation

The dominantly fine-grained, mixed carbonate-clastic deposits of the Huab Formation conformably overlie the Tsarabis Formation in the western Huab area where a cumulative thickness of up to 75 m is preserved. Towards the eastern basin margin, the Huab Formation interfingers with the Tsarabis Formation and preserved thicknesses are widely reduced due to pre-Etendeka erosion (Wanke *et al.*, 2000). The Huab Formation consists of four major facies associations (Fig. 5): (1) a laminated calcareous mudstone and marlstone facies association, which is interbedded with (2) a flat-pebble conglomerate facies. Towards the west both facies are gradually replaced by (3) a stromatolite bioherm facies association grading upward into (4) a laminated mudstone facies association, that progressively onlaps all other facies. The completeness of measured sections strongly depends on their structural position adjacent to syn-depositional faults (Fig. 6).

Laminated calcareous mudstone and marlstone facies association

Interbedded calcareous mudstones and marlstones, as well as minor limestone and pebbly sandstone interbeds, characterise this facies association. Rock units are amalgamated to form successions up to 25 m thick. The facies development is restricted to areas east of the stromatolite bioherm facies association.

Mud- and marlstone beds are usually plane laminated with less abundant wavy and lenticular-bedded or massive beds interlayered. Abundant plant remains and ichnofossils characterise this facies. In the marginal eastern Huab area, abundant clay nodules and calcareous concretions are associated with abundant desiccation and shrinkage cracks, root tubes and remains of the heteromorphous symbiotic microorganism *Microcodium* (cf. Freytet and Plaziat, 1982).

Interbeds of coarse-grained, pebbly sandstones and fine-grained calcareous sandstones, up to 50 cm thick, are characterised by erosional bases and normal grading. The coarse, basal parts of these units are trough cross-bedded and grade upward into plane-laminated or small ripple-bedded horizons with wave-rippled tops. Limestone interbeds, up to 25 cm thick, reveal laminated microbial mat structures; a few isolated domal stromatolites are up to 45 cm high.

The restriction of this facies association behind a coastal barrier landward of the stromatolite bioherms implies quiescent water conditions of a shallow lagoonal area. This favoured the formation of dominantly laminated sediments, as well as growth of microbial mats and isolated domal stromatolites. Storm events are recorded by wavy and lenticular-bedded mud- and marlstone units (McCave, 1970). The graded, erosionally based, pebbly sandstones are viewed as tempestites. *In-situ* brecciation, abundant carbonate nodules and the presence of root tubes besides *Microcodium* suggest subaerial exposure and pedogenic modification of the marginal lagoonal areas along the eastern margin of the Huab area (cf. Freytet and Plaziat, 1982).

Stromatolite bioherm facies association

In the central Huab area abundant stromatolite bioherms occur in a belt 35-50 km wide which defines the westernmost limit of the previous calcareous mudstone and marlstone facies association. The bioherms form

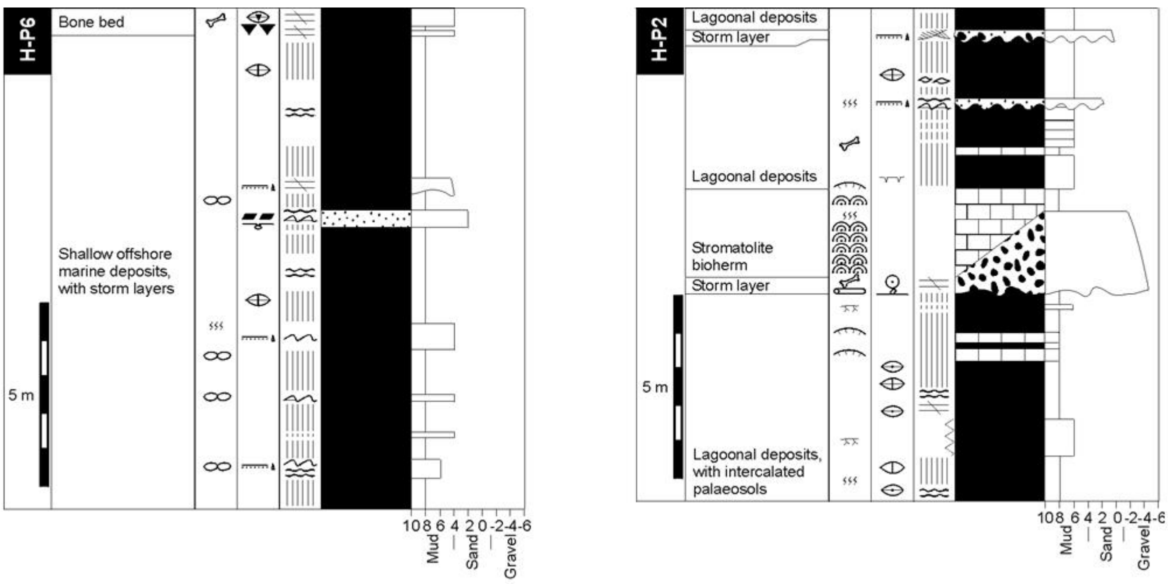

Figure 5: The contrasting build-up of shallow, offshore, marine deposits of the Huab Formation in section 'H-P6' (left) versus the lagoonal facies of section 'H-P2' (right) containing large stromatolite bioherms (legend contained in Fig. 4). Locations of measured sections are given in Fig. 1.

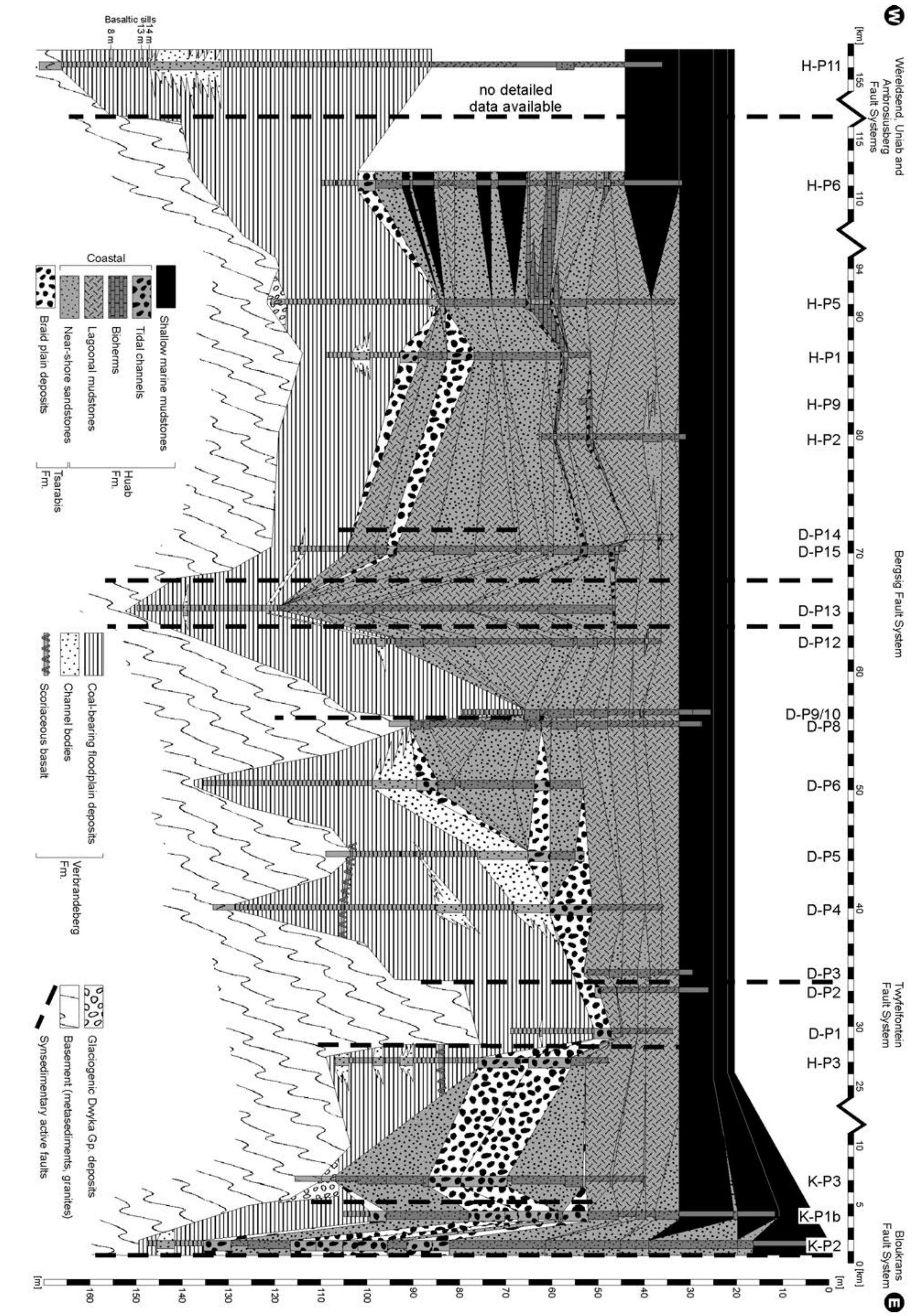

Figure 6: W-E trending cross-section through the Lower Permian Karoo deposits of the Huab area. Changes in facies architecture from west to east reflect the influence of both the marine seaway located in the basin centre towards the west and syn-depositional faulting contemporaneous to transgressive sequence development. Indicated are the codes of measured sections with their locations marked in Fig. 1.

elongate ridges, lens-shaped in cross section, with the largest structure about 50 m long, 22 m wide and 4.6 m high. Most of them are oriented approximately E-W, with the intervening gaps filled by the clast-supported flat pebble conglomerate facies. Towards the west the stromatolites developed widespread sheets up to 5.5 m thick. Both display multiple internal undulating erosion surfaces occasionally marked by subvertical boring structures.

Stromatolite bioherm ridges of this size today form in intertidal (Playford and Cockbain, 1976) to subtidal (Dill *et al.*, 1986) nearshore environments. The sheet-like stromatolite bioherms in the western Huab area record subtidal zones where thick microbial mats form hardgrounds sparsely colonised by boring organisms. In contrast, internal erosion surfaces associated with the bioherm ridges in the eastern Huab area reveal a temporally emerged intertidal environment with bioherm ridges oriented perpendicular to the palaeo-coastline. Playford and Cockbain (1976) related the preferred orientations of modern stromatolite bodies to the backflow of incoming waves. Once established, discrete ridges are believed to have funneled the tidal or storm-induced currents along the inter-ridge swales that connected the offshore with the landward lagoonal environments. Considering this facies architecture and its relationship to associated facies of the Huab Formation, we attribute the stromatolite bioherm facies to shallow barriers between the lagoon and the offshore shelf.

Flat pebble conglomerate facies

Massive flat pebble conglomerates form channelised units up to 2.3 m thick, usually with distinct erosive bases. They are preferentially developed within the inter-ridge depressions but also form tabular sheets 10 - 60 cm thick interlayered with the calcareous laminated mudstone and marlstone facies association. Imbrication of flat pebbles is common. Clast lithologies include marlstones, fine-grained sandstones, mudstones with and without microbial mats, ooliths, stromatolites, silicified tree log fragments, vertebrate remains, and flat pebble conglomerates. These components are embedded in a clast-supported framework comprising an abundant poorly sorted matrix of mud, angular coarse-grained quartz grains, ooids and mud granules.

The clast components strongly resemble the lithologies of the laminated calcareous mudstone and marlstone facies association and the stromatolite bioherm facies association. Such a high degree of softclasts is typical of intraformational conglomerates and usually form by reworking of unlithified cohesive sedimentary strata such as desiccated muds or marls, often under the influence of storm waves (Matter, 1967). The ooids and ooliths, exclusively preserved as reworked material in the flat-pebble conglomerate facies, support this assumption; they originally formed in very shallow, agitated, calcium carbonate saturated waters such as lagoons or tidal flats (Tucker and Wright, 1990).

Laminated mudstone facies association

This facies association consists of a succession, at least 20 m thick, dominated by coprolite-bearing mudstones with a few sandstone beds interlayered. Individual mudstone units, 1.5 - 45 cm thick, developed normal grading and a transition from plane-laminated basal parts to wavy or small-ripple bedded tops. Locally, undulatory based, calcareous mudstone units, 3.5 - 20 cm thick, are developed which show the same transition in bedding.

Interlayered sandstone beds are 5 - 20 cm thick and display sharp, slightly erosive basal contacts associated with abundant sole marks but diffuse planar top contacts. They grade upward from intraclast-bearing, plane-laminated, medium-grained sandstone into fine-grained, low-angle and small-ripple bedded sandstone with wave-rippled tops. In places, disc-shaped calcareous concretions, up to 1.5 m in diameter, developed, as well as significantly smaller (15 - 40 cm), siliceous concretions and thin (2 - 30 mm) and discontinuous undulatory chert beds.

The abundance of plane-lamination associated with this facies suggests that it was formed by fallout of suspension load with periodic disturbance by wave activity as evidenced by graded, erosively based layers (Nelson, 1982; Duke *et al.*, 1991). Considering the bioturbated hummocky cross-bedded sandstone facies of the Tsarabis Formation which interfingers with these beds, we relate this mudstone facies to an offshore environment characterised by deposition below fair-weather base but above storm wave base. Furthermore, the apparent lack in ichnofossils suggests an overall low availability of oxygen in the substrate (Sagemann *et al.*, 1991).

Palaeobiological constraints

Most important for the palaeoenvironmental interpretation of the Huab Formation is its ichnofauna, including *Skolithos* isp., *Siphonichnus* isp. and *Planolites* isp. The occurrence of U-shaped *Rhizocorallium irregulare* in particular, with widths of up to 16 cm, are important as they are known exclusively from marine environments (Fürsich and Mayr, 1981). Ichnofossils are relatively diverse in the laminated calcareous mudstone and marlstone facies, but in the wave influenced mudstone facies only *Planolites* isp. occurs where it is restricted to the more massive layers. The stromatolite bioherms, formed by the biogenic build-up of microbial mats (Riding, 1991), contain various examples of boring traces resembling *Trypanites* isp. Abundant abraded ribs and vertebrae of the amphibious reptile *Mesosaurus tenuidens* (Oelofsen, 1981) are contained in these marine facies. The remains of *Mesosaurus* in particular are concentrated with ellipsoidal and cone-shaped coprolites, 1.0 - 4.5 cm in diameter, within a distinct

0.5 - 10 cm thick bone bed in the laminated mudstone facies association at the top of the Huab Formation. Towards the west this grades into a concretionary horizon characterised by large, disc-shaped calcareous concretions (0.6 - 2.0 m in diameter) yielding large quantities of bone in a central layer. This bone bed documents a marked regression near the end of the Huab Formation and is unconformably overlain (Fig. 2) by fluvio-lacustrine red beds of the Gai-As Formation.

Tectonic and climatic controls on deposition

The Lower Permian sedimentary succession of the Huab area in NW Namibia records the signatures of both tectonic and climatic controls on deposition. Sediment thicknesses and facies of the Tsarabis and Huab Formations vary significantly across the N- and NNW-trending fault zones (Fig. 6) and illustrate their pronounced syn-depositional activity. They are dominantly westward-dipping normal faults which caused an antithetic block rotation (Stollhofen, 1999, Wanke *et al.*, 2000). This explains why thick, almost complete successions are preferentially developed in hangingwall positions west of the faults, whereas largely condensed or even cannibalised sections characterise the uplifted footwall positions towards the east.

On a regional scale, both the Tsarabis and the Huab Formations record nearshore to terrestrial facies associations dominating the eastern Huab area, whereas there is evidence of increasing offshore marine deposition to the west. This trend coincides with dominantly westward-directed palaeocurrents and implies a depocentre west of the Huab outcrop area. Furthermore, a significant backstepping pattern of the terrestrial facies associations is apparent in a W-E cross-section (Fig. 6). Terrestrial environments of the Verbrandeberg Formation were successively replaced by landward-stepping marine facies of the Tsarabis and Huab Formations. The resulting retrogradational stacking pattern is mirrored by time-equivalent, but much thicker Lower Permian successions (Fig. 2) in southern Namibia (Grill, 1997), South Africa (Visser, 1993) and South America (Rohn, 1994), and is believed to be related to a third-order rise in relative sea-level (Vail *et al.*, 1991) which is modified by the regional tectonics of the Huab area (Wanke *et al.*, 2000).

We infer that post-glacial, humid conditions during deposition of the coal-bearing Verbrandeberg Formation were followed by progressively warmer, temperate climates throughout accumulation of the Tsarabis and Huab Formations. During deposition of the Verbrandeberg Formation, lowland meandering river environments with chiefly constant discharges prevailed in the area and developed a dense autochthonous vegetation. Deposition of the Tsarabis Formation presumably took place under more temperate conditions with relatively high, but fluctuating, discharges which suppressed both soil formation and river bank stabilisation by vegetation. The abundance of well preserved tree logs, most of which are characterised by distinct growth rings, indicate seasonal fluctuations in climate. Finally, the Huab Formation accumulated under permanently warm-temperate climatic conditions, supporting ooid formation and organic productivity, the latter including large stromatolite bioherm structures, a rich amphibian fauna and the formation of oil-shales in time equivalent deposits of the Whitehill and Irati Formations (Oelofsen and Araujo, 1983).

The Huab area in a southern Gondwanan context

Both the base and top of the Carboniferous-Lower Permian succession in the Huab area are bounded by unconformities indicating its regional-scale megasequence status within the Karoo Supergroup (Stollhofen, 1999). Overlying the crystalline basement the base of this megasequence is defined by a pronounced hiatus. Its top is outlined by a considerable erosional, and locally angular, unconformity below the overlying red beds of the latest Lower Permian Gai-As Formation (Wanke *et al.*, 2000) which are entirely continental (Stollhofen *et al.* 2000) and constrained by biostratigraphy and radiometric dates (Fig. 2). The Carboniferous-Permian megasequence development can be identified over large areas of southern Gondwana (Zalán *et al.*, 1990; Tankard *et al.*, 1995) and therefore relates to a phase of basin development separate from the megasequences below and above.

The Huab area preserved this Lower Permian megasequence but it is much thinner than in the main Karoo and Paraná Basins. However, the advantage of exposure and the preservation of both marine body and trace fossils provide better insight into its transgressive marine nature. Thickness and facies variations are related to significant E-W-extension accommodated by sets of normal faults parallel to the axis of the early southern South Atlantic rift zone (Stollhofen *et al.*, 2000). The considerable amount of crustal stretching affecting the area is manifested by the eruption of basaltic scoria, comprising one of a few *in-situ* occurrences of Permian volcanics in southern Africa. Starting with the Carboniferous Dwyka Group, the broad intracontinental rift depression was repeatedly affected by marine incursions from the south (Martin, 1975; Bangert *et al.*, 2000) with large Permian delta complexes prograding along the axis of the elongate basin (Gama, 1979; Grill, 1997). Flooding of this intracontinental rift zone culminated in establishment of the 'Whitehill sea' (Oelofsen, 1981), a marine seaway of which isolated deposits are recorded as far north as northern Brazil and Guayana (Oelofsen and Araujo, 1983; Williams, 1995). After repeated phases of incipient extensional basining and the ultimate extrusion of Lower Jurassic and Lower Cretaceous flood basalts, this long-lived zone of crustal extension ended up as a failed rift (Sibuet *et al.*, 1984). Favourable outcrop conditions in Namibia and Brazil preserved the marine-influenced Upper Carboniferous to Lower Permian succession which is an important archive of the very early pre-breakup extensional history in the southern South Atlantic region.

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