The Fossilised Desert: recent developments in our understanding of the Lower Cretaceous deposits in the Huab Basin, NW Namibia

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The Lower Cretaceous deposits in the Huab Basin, NW Namibia, comprise fluvial and aeolian sandstones, lava flows and associated intrusions of the Etendeka Group. The sandstones formed part of a major aeolian sand sea (erg) system that was active across large tracts of the Paraná-Huab Basin during Lower Cretaceous times (133-132 Ma). This erg system was progressively engulfed and subsequently preserved beneath and between lava flows of the Paraná-Etendeka Flood Basalt Province. Burial of this erg by flood basalts has resulted in the preservation of a variety of intact aeolian bed forms. Preserved bed forms vary in type and scale from 1 km wavelength compound transverse draa to isolated barchan dunes with downwind wavelengths of < 100 m. Due to the present-day preferential erosion of the lava flows, preserved aeolian dunes are now exposed in 3-D in the position in which they were migrating ~133 Ma ago. A relatively non-destructive eruption style of inflated pahoehoe flows preserved the bed form geomorphology. These first pahoehoe flow fields, comprising olivine-phyric Tafelkop lavas, define a shallow shield-like volcanic feature. This volcanic feature centres around the Doros igneous centre marking this as the likely source for the lavas. Early lava flows followed low topography between dune build-ups, ponding in the interdune areas. Striations left on the sand surface by the lavas indicate the localised flow directions of the lava. Numerous sediment interlayers, preserved between the lava flows, record a change in palaeowind direction during volcanism. This change in climate may have been driven by the ongoing break-up of the West-Gondwana supercontinent or may be a direct result of the widespread volcanism.

Introduction

Large parts of Central and Northern Namibia have been occupied by aeolian sand-seas (ergs) since Jurassic times. Major sand seas of this region include the Jurassic Etjo Formation in the Waterberg region (Holzförster *et al.*, 1999), the Cretaceous Etjo Formation in the Huab Basin (Mountney *et al.*, 1998; Jerram *et al.*, 1999a) also termed the Twyfelfontein Formation (Stanistreet and Stollhofen, 1999), the Tsondab Sandstone Formation (Ward, 1988), and the Quaternary (recent) sediments and active erg system of the Namib Desert (Lancaster, 1995). During the Jurassic-Cretaceous, the African continent rifted with, and then separated from, the South American content. This rifting process and the concomitant impact of the Tristan Hot-Spot resulted in the massive outpouring of flood basalts of the Paraná -Etendeka Flood Basalt Province immediately prior to and during the early stages of continental separation. The Paraná -Etendeka Flood Basalt Province is one of the largest of the continental igneous provinces with a present-day preserved volume in excess of 1 x 10^6 km^3 (Cordani and Vandoros, 1967), with most of the volcanic activity occurring between 135-130 Ma (Renne *et al.*, 1996; Turner *et al.*, 1994; Milner *et al.*, 1995a). Often overlooked is the fact that flood basalts erupt over large areas of land where a variety of active continental environments occur. Due to their high effusion rates, such lava flows have the potential to 'fossilise' and preserve important information concerning these continental environments by encasing sediment and vegetation that would otherwise have a low long-term preservation potential. In the case of the Paraná-Etendeka Flood Basalts, eruption has preserved arid climate continental aeolian deposits that reveal important information concerning the environmental conditions that prevailed in this part of West Gondwana during Early Cretaceous times.

Korn and Martin (1954) and Reuning and Martin (1957) provided some of the earliest geological references to the Karoo and Etendeka stratigraphy and the sediments and intrusions in NW Namibia. This contribution to the Henno Martin Commemorative Volume outlines and summarises the recent developments in our understanding of the Lower Cretaceous deposits in the Huab Basin, NW Namibia. It reports on an ancient sand sea which was engulfed by, and interacted with, the basal Etendeka flood basalts in NW Namibia 133-132 Ma ago, in a process that preserved much of the original dune morphology.

Geological setting and lithostratigraphic development of the Etendeka Group in the Huab Basin

The Etendeka Igneous Province forms the most eastern extent of the much larger Paraná-Etendeka Flood Basalt Province (Fig. 1A). The main outcrops and subcrops of Karoo sediments and Mesozoic flood basalts in Namibia are shown in Fig. 1B, with the location of the Huab Basin highlighted. In the Huab Basin, good 3-D exposure of the Etendeka Group units can be found in the Huab Outliers region and immediately to the north of the Huab River (Fig. 2A). The term 'Huab Basin' was introduced by Horsthemke *et al.* (1990) who identified a variety of stratigraphic units (that are now assigned to the Karoo Supergroup and Etendeka Group) within a basinal feature centred around the present-day Huab River valley (Fig. 2A). The stratigraphy within the Huab Basin records the evolution of this region from Damaran times (500-600 Ma) through to the Early Cretaceous break-up of Gondwana (130-133 Ma). The succession can be divided into three major stratigraphic units (Fig 2A): 1) Damara basement - deformed metasediments and granites, 2) Karoo Supergroup sediments - continental fluvio-lacustrine sediments with marine

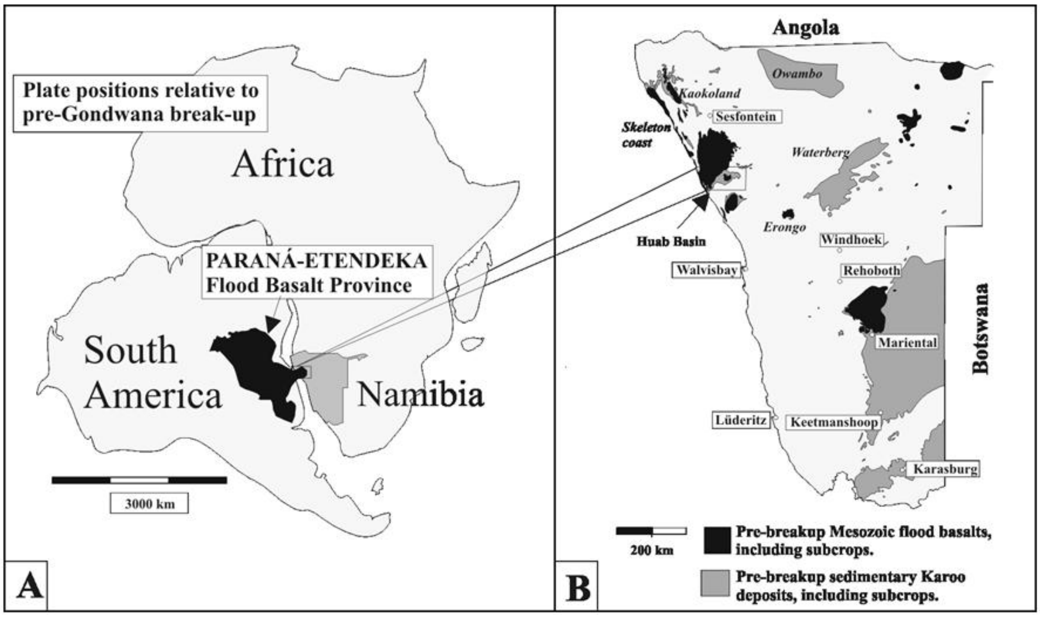

Figure 1: Location maps: A) Location of the Paraná-Etendeka flood basalt province with plates in pre-Gondwana break-up position. B) Map of Namibia showing the distribution of Karoo sedimentary basins and Mesozoic flood basalt cover with location of Huab Basin highlighted.

intercalations, and 3) Etendeka Group - fluvial-aeolian sediments and volcanics.

The stratigraphic nomenclature for the Lower Cretaceous deposits in the Huab Basin has changed significantly since the early works of Reuning and Martin (1957) and Hodgson (1970). For clarity, Figure 3 summarises the development of the nomenclature and outlines its stratigraphic context.

The Karoo stratigraphy in the Huab Basin records episodes of Palaeozoic extension that resulted in deposition of early intra-continental rift-fill successions (Stollhofen *et al.*, 2000; Jerram *et al.*, 1999a). The accumulation of the Karoo Supergroup sedimentary succession was followed by a considerable time gap, possibly up to 120 Ma, prior to the onset of Etendeka Group deposition (Jerram *et al.*, 1999a; Stollhofen, 1999). During this period, a combination of pre-Etendeka rifting, restricted extrabasinal sediment supply, and erosion of existing sediments, generated a large amount of accommodation space in and around the area of the present-day Huab River (Mountney *et al.*, 1998; Mountney *et al.*, 1999a). This depositional hiatus is marked by a basin-wide unconformity that separates Karoo strata from the overlying deposits of the Etendeka Group.

Below we outline the sedimentary and volcanic deposits that characterise the basal units of the Etendeka Group (summarised in figures 2 and 3). The reader is referred to Mountney *et al.* (1998) for detailed descriptions of the fluvial/aeolian deposits, and Jerram *et al.* (1999a) for detailed descriptions of the volcanic deposits in the Huab Basin.

Krone Member

The lowermost deposits that overlie the eroded Karoo surface make up the basal 10-15 m of the Etendeka Group deposits. This unit, termed the Krone Member (Horsthemke *et al.* (1990), is characterised by predominantly cross-bedded, mainly clast-supported, pebble and cobble fluvial conglomerates that were deposited into river valleys cut down into the underlying Karoo sediments and through exposed highs of Damaran basement. The clasts within the conglomerate are largely derived from Damaran meta-sediments exposed at the basin margins. The main drainage direction for these fluvial systems is interpreted to have been from NE to SW (Mountney *et al.*, 1998), similar to that of the present-day Huab River.

Mixed Aeolian Unit

The Krone Member is overlain by up to 30 m of mixed fluvial and aeolian sandstones that represent a transition from a fluvial-dominated to an aeolian-dominated sedimentary environment. Ephemeral stream deposits truncate horizontally laminated sandsheet and cross-bedded dune sand deposits. These are indicative of a semi-arid environment where conditions suitable for aeolian bed form generation were frequently interrupted by episodes of fluvial activity, possibly on a seasonal basis (Mountney *et al.*, 1998). The extent of the mixed aeolian unit is incomplete throughout the basin and its upper limits are truncated by a bounding, basin-wide super-surface (Mountney *et al.*, 1999a). Palaeocurrent analysis of the well sorted, cross stratified sands within the Mixed Aeolian Unit indicate transport directions towards the south-west in the vicinity of the present-day Huab River and towards the south-east in the southerly part of the basin (Mountney *et al.*, 1998).

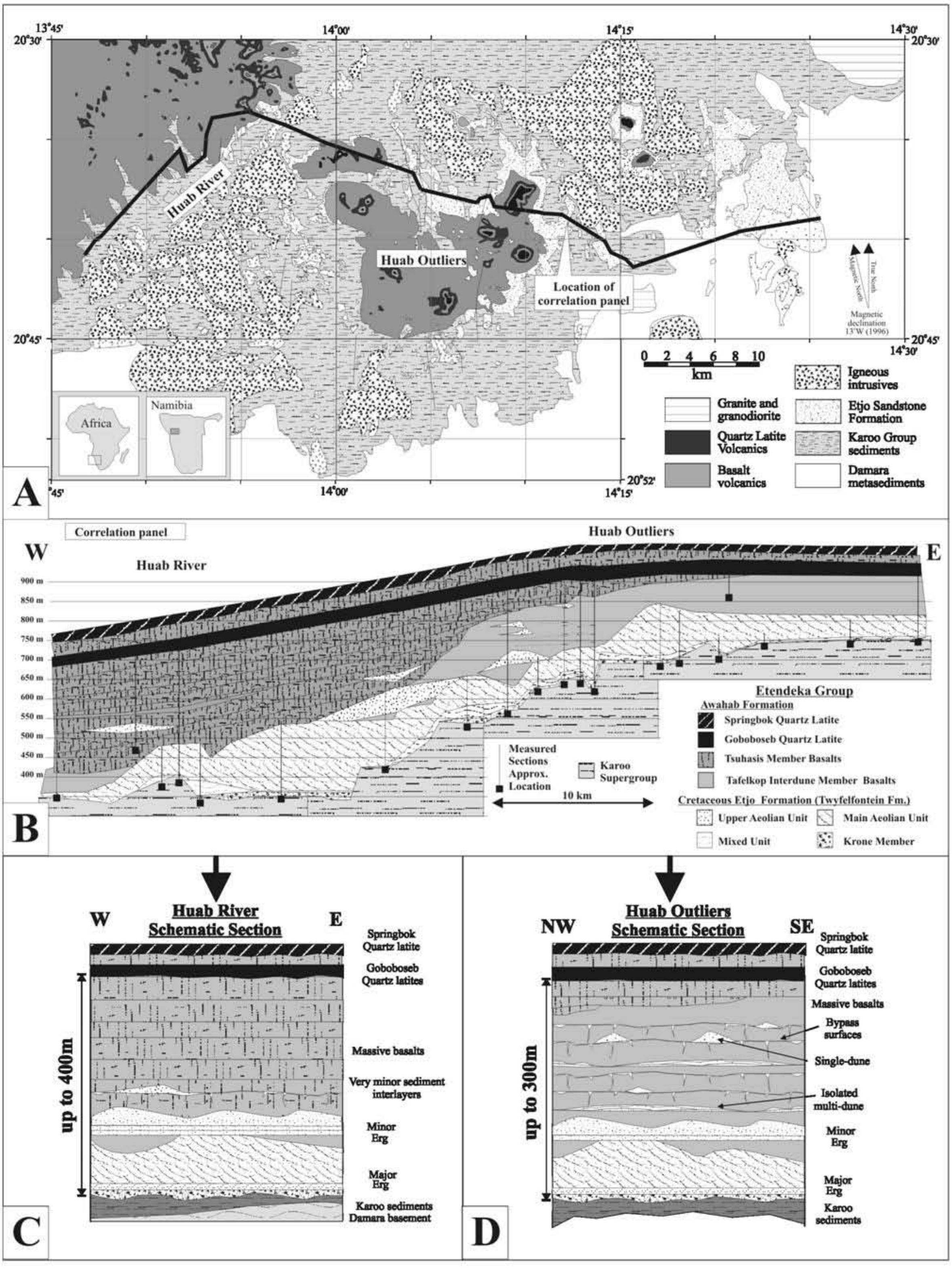

Figure 2: Geology and stratigraphy in the Huab Basin, NW Namibia (adapted from Jerram *et al.*,1999a; Jerram *et al.*, 1999b; Mountney *et al.*, 1999a). A) Detailed geological map of the Huab Basin outlining location of correlation panel. B) Correlation panel running approximately E-W across basin. C) Typical section found in the Huab River area. D) Typical section from the Huab Outliers.

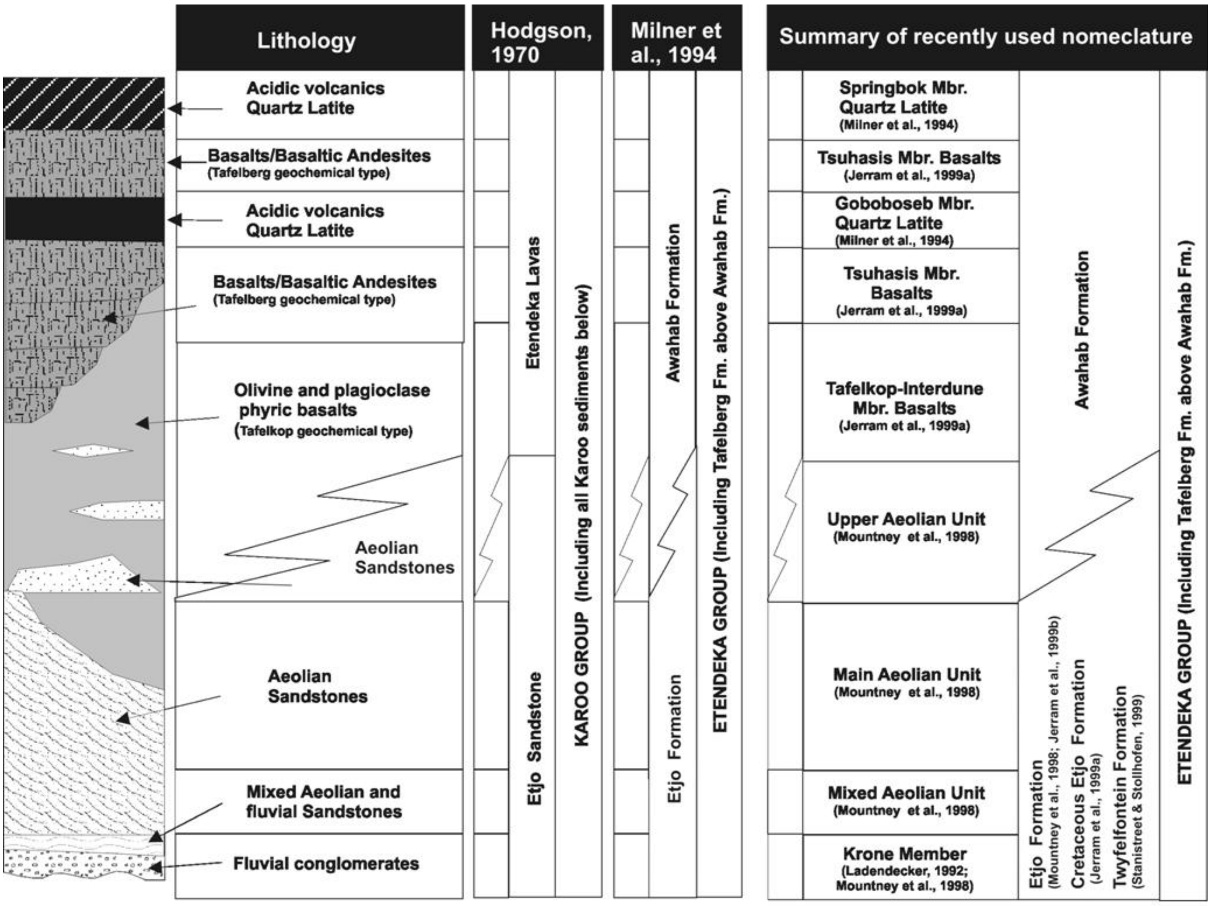

Figure 3: Summary of stratigraphic terms used for the Lower Cretaceous deposits in the Huab Basin.

Main Aeolian Unit

Above the Mixed Aeolian Unit, there is an abrupt transition to large-scale cross-bedded sandstones that attain a maximum thickness of 150 m. These deposits consist exclusively of fine- to medium-grained, red-yellow to white aeolian sandstone units that are arranged into sets of cross-strata that vary in thickness from 1-50 m. Foresets consist of grainflow and grainfall cross-strata, with wind ripple laminated sand deposits preserved in the basal parts of sets (Mountney *et al.*, 1998). Palaeocurrent data reveal an average foreset dip of 24° towards 040°. These deposits are interpreted to represent large-scale aeolian dune bed forms that migrated into the basin under the influence of a south-westerly prevailing wind direction (Mountney *et al.*, 1999a). The deposition of the Main Aeolian Unit was interrupted by eruption of Etendeka flood basalts.

Upper Aeolian Unit

The Upper Aeolian Unit consists of several aeolian sediment interlayers that are interbedded with the basal Etendeka flood basalts. Individual layers within this unit can attain up to 60 m in thickness. The base of the Upper Aeolian Unit may lie either directly on the lowermost basalts or on deposits of the Main Aeolian Unit. In the latter case, the two successions are separated by a laterally extensive bounding surface. Overlying sediment interlayers progressively decrease in thickness and lateral extent upwards. The last of the aeolian sediment units is recorded below the Goboboseb quartz latite flow, a widespread marker horizon within the Etendeka igneous succession. The sediment interlayers are a remarkable example of the interaction between aeolian sands and basalt lava flows and are discussed in detail later.

Tafelkop Interdune Basalts

The term Tafelkop Interdune Basalts was introduced by Jerram *et al.* (1999a) to distinguish the Tafelkop 'Type' basalts in the Huab Basin, which are characteristically interbedded with dune deposits, from those in the Goboboseb Mountains further south which are not. The Tafelkop Interdune Basalts were the first lava flows to enter the basin. These basalts erupted as olivine phyric pahoehoe flows onto the active aeolian sand sea of the Main Aeolian Unit approximately 133 Ma ago (Jerram *et al.*, 1999a). These lava flows were erupted from the Doros igneous complex to the south-east of the Huab Basin, and are thickest around the Huab Outliers region (Fig. 2). Reuning and Martin (1957) first noted the temporal and spatial connection between these olivine phyric lava flows and the Doros igneous complex, invoking the complex as the source for the lava flows. Recent mapping of the thickness variation of the Tafelkop Interdune Basalt member (Jerram *et al.*, 1999a), the identification of feeder dykes close to the Doros igneous centre (Jerram *et al.*, 1999a) and the discovery of a geochemical relationship between the Doros complex and the Tafelkop lavas (Marsh *et al.*, 2000) have further confirmed the genetic link between the Doros igneous centre and the Tafelkop lava flows. It is within the Tafelkop Interdune Basalts that most of the sediment interlayers are preserved.

Tsuhasis Member Basalts and associated quartz latites

Overlying the Tafelkop Interdune Basalts are the Tsuhasis Member Basalts (Figs. 2 and 3). These basalts derive their name from Tsuhasis Mountain in the western part of the Huab Outliers, as recorded on from the geological map of Reuning and Martin (1957) (Jerram *et al.*, 1999a). These basalts are mainly basaltic andesite in composition and are of Tafelberg-type geochemistry but are distinguished from the Tafelberg basalts to the north by a stratigraphic disconformity (Milner *et al.*, 1994; Jerram *et al.*, 1999a). Towards the top of the preserved stratigraphy in the Huab Basin, a large volume of acidic volcanic flows of the Goboboseb and Springbok quartz latites are found. These are interbedded with the Tsuhasis Member Basalts and form good marker horizons throughout the basin. The quartz latite flows have very distinctive geochemistry and have been used to correlate the lava sequence in the Etendeka Group to that in the Paraná Basin (Milner *et al.*, 1995b).

Sediment/lava interaction

Some unusual aspects of the Etendeka Group stratigraphy are the examples of sediment-lava interaction that are preserved in the basal lava flow units, mainly within the Tafelkop Interdune Basalts. Examples of some of the preserved dune features is given in Figure 4. These features indicate that the sand system was active during the onset of flood volcanism and also give some additional controls on the evolution of the system through time (Jerram *et al.*, 1999a & b).

Large amounts of the original erg topography are preserved under the initial lava flows (Fig. 4A), in places up to 100 m of dune topography. This provides important constraints on the maximum dune sizes and dune types of the original erg. Jerram *et al.* (2000) used this preserved topography and large-scale sediment interlayers up to 60 m thick directly above the first lavas to derive an estimate for maximum aeolian dune height in excess of 160 m in the basin prior to the volcanism.

Preserved bed forms with amplitudes in excess of 100 m and wavelengths of 1.3 km (Mountney *et al.*, 1999b) thus provide a rare opportunity to accurately reconstruct the three-dimensional geometry of an ancient aeolian system. Furthermore, erosion has revealed the internal architecture of large, draa-scale bed forms such that the internal architecture of the preserved bed forms can be related to their external morphology. This is important because generally less that 10% of the original bed forms get preserved in ancient aeolian deposits (Rubin and Hunter, 1982). Mountney *et al.* (1999b) noted that both simple and complex bed forms are found in the large compound dunes in the Huab Basin. This is important as it requires caution in the interpretation of simple and/or complex bed forms in partially preserved ancient deposits. Also, the presence of complete dune forms, frozen in-situ by the lava flows, and the partially preserved bed sets within the lower deposits provides the ideal opportunity to test the theory of the relationship between preserved set thickness and original bed-form height (Brookfield, 1977; Rubin and Hunter, 1982). In the Huab Basin it was demonstrated that only the lowermost 10 m of 90 m high bed forms are preserved in the lower deposits (Mountney *et al.*, 1999b).

Smaller dune forms are preserved in their entirety where they have been completely engulfed by basalt flows. Figure 4C shows a section through a superimposed dune that was preserved migrating up the stoss slope of a larger draa form when it was buried by lava. Some of the most exciting finds are perfectly preserved barchan dunes (Fig. 4D) which normally have little long-term preservation potential in the normal aeolian system (Jerram *et al.*, 2000). The best examples are located in the Huab Outliers region where the enveloping lava flows have weathered away to reveal well exposed sandstones that are resistant to weathering. These isolated dunes migrated over a basalt surface between periods of volcanism and were 'overwhelmed' by a subsequent basalt flow. The dunes show a similar geometry and size to modern barchan dunes observed on the present-day Skeleton Coast. The dunes show little signs of modification during burial and must have been delicately encased within the basalt. This is important as it gives independent information about the style of volcanism and emplacement of the basalt flows.

At the contact between the sand and lava a great amount of information is preserved. Examples of some of the preserved features are presented in Figure 5. On the underside of thin sediment interlayers, moulds of pahoehoe features are preserved (Fig. 5A). These represent negative copies of the top of a lava flow and are found only on the base of relatively thin (~2 m) sediment interlayers that have been indurated by the overlying lava flow (Jerram, 2000). On the top surface of the sandstone interlayers, aeolian ripples and lava striations are often found (Fig. 5B). The preservation of ripples again indicates the non-destructive emplacement of the basalt flows. The striations give an indication of the flow direction of the lavas (Jerram *et al.*, 1999b).

A more dynamic sediment-lava interaction is indicated by breccia horizons (Fig. 5C). In most cases these

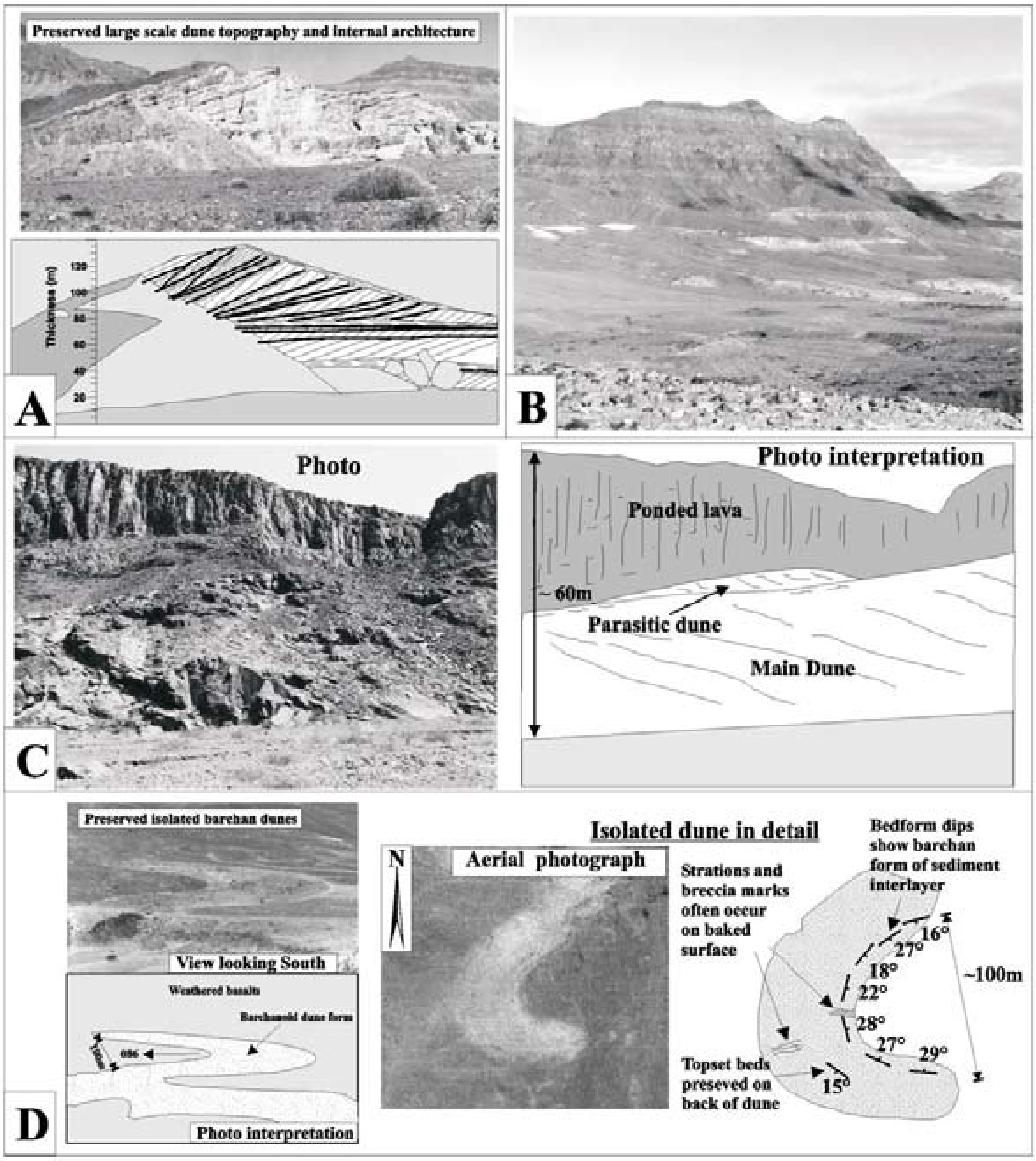

Figure 4: Examples of dune forms preserved by the Etendeka lavas (adapted from Mountney *et al*., 1999b and Jerram *et al*., 2000). A) Dune topography on major erg, lava ponding within interdune lows. Shows evidence for actively migrating sand sea (erg) system. Allows the estimation of maximum dune size. B) Up to ~300 m of stratigraphy showing aeolian sediment interlayers within the flood basalts. C) Parasitic dunes - small dunes preserved migrating up the stoss side of larger dune features; very rarely preserved. Shows a variety of dune types and complex dune relationships typical of modern deserts. D) Complete isolated barchan dune forms present. Normal preservation potential for such feature is zero. Preservation enabled due to burial under lava. Indicates non-destructive emplacement of lavas and provides useful information on the internal geometry of barchan dunes.

horizons are less than 1.5 m thick and represent the interaction of the lava with the sand as the lava flows down the steep slopes of a dune. Other examples of sand-lava mixtures may arise where sand has filtered through a rubbly lava top surface, or where sand actively migrated during the extended emplacement of a flow.

Lava dome inflation and syn-volcanic tectonism during the evolution of the lavas is evident from the preservation of sand filled fissures (Fig. 5D). In some cases these features represent fissures developed on a single flow surface as the cool crust has been expanded due to lava injection and the fissures have later been filled with sand. Other examples include fissures that cut down through more than one flow and must have a tectonic origin (Jerram *et al.*, 1999b).

The examples of sediment-lava interaction preserved in the basal 300 m of the Etendeka stratigraphy provide what is so far the best documented example of the preservation of an ancient aeolian dune system. Additionally, it also provides one of the few examples of sediment-lava interaction in a predominantly arid setting.

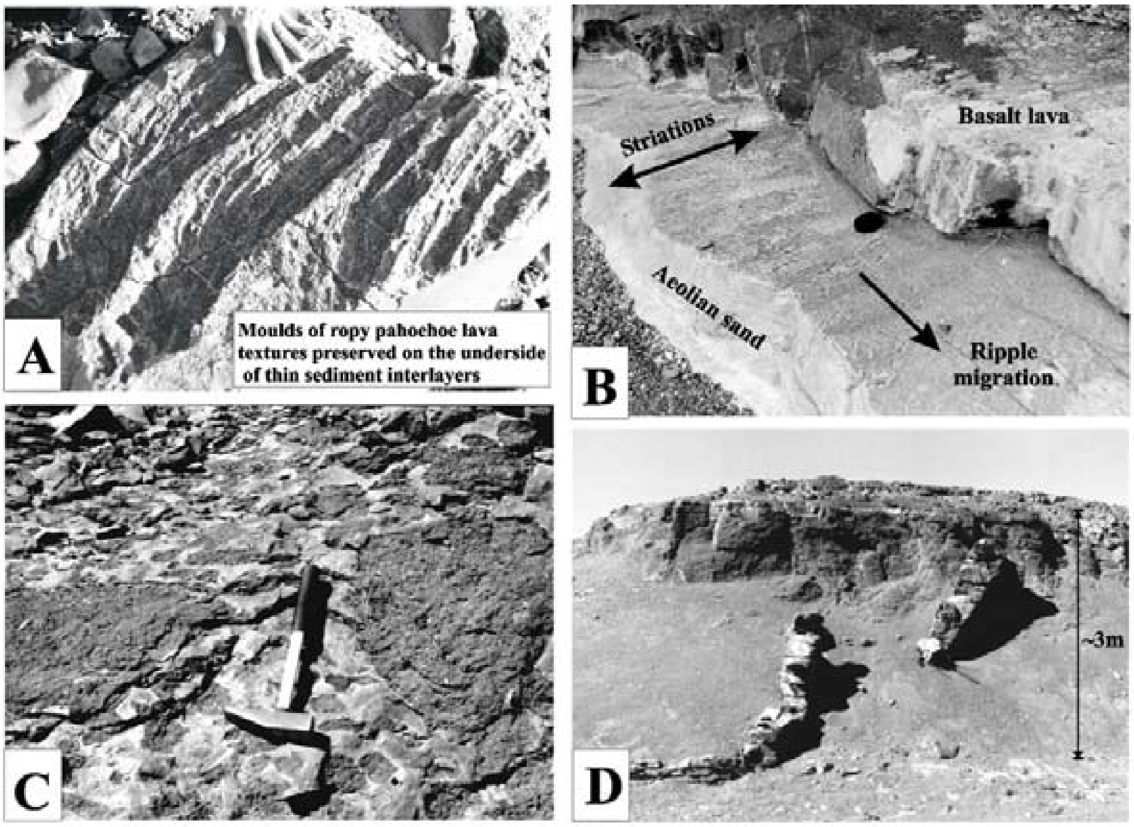

Figure 5: A) Sand moulds of pahoehoe lava textures; important in determining lava flow type, that of passively emplaced inflating pahoehoe lava sheets. B) Topset beds and ripples on sand surface. Striations and imprint marks left on sand surface by lava (adapted from Jerram *et al.*, 1999b). Very rarely preserved in ancient aeolian deposits. Preservation of ripples indicate non-destructive emplacement of lava flows. C) Sediment-lava breccias. Dynamic interaction between the lavas and aeolian sediments. Evidence that sand was unconsolidated when lava erupted. D) Cracks and fissures on the top of lava flows filled with aeolian sand; indicates tectonic activity during lava pile build-up.

Of related interest is the application of the stratigraphic architecture in the Huab Basin as an onshore analogue for the Kudu gas province, offshore southern Namibia. The Kudu province contains aeolian gas-bearing sandstones interbedded with basaltic lava flows (Wickens and MacLachlan, 1990; Jerram *et al.*, 1999b).

Development of the system through time

The basal Etendeka stratigraphy provides important information about the spatial and temporal development of an aeolian-lava system through time, the potential geometry of sand bodies that may be preserved and the nature of the contact relationships between the sediments and the lavas (Jerram *et al.*, 1999b). Figure 6 schematically outlines the development of the stratigraphy in the Huab Basin from the deposition of the Mixed Aeolian Unit until the emplacement of the first quartz latite flows in the basin.

Prior to the onset of deposition of sediments of the Etendeka Group, the basin had undergone a period of non-deposition and/or erosion of up to ~120 Ma in duration (Jerram *et al.*, 1999a; Mountney *et al.*, 1998; Stollhofen *et al.*, 2000). The Karoo stratigraphy records continuing episodes of extension providing early intracontinental rift-fill successions. Rift orientations are predominantly NW-SE to NNW-SSE with occasional N-S structures (Stollhofen, 1999). Deposits of the Krone Member that occupy low points within the basin signify the onset of deposition of the Etendeka Group. These strata contain palaeocurrent data that indicate a drainage pattern from the NE to the SW along the course of the present-day Huab River, with subsidiary valleys draining from the NW and SE (Mountney *et al.*, 1998). The mixed sand sheet and minor dune deposits of the overlying Mixed Aeolian Unit signify an increase in climatic aridity as the fluvial systems shut down and were reworked (Fig. 6A). During this period, aeolian dunes were migrating to the SSW and ESE, with local migration directions being controlled by NE-SW and NW-SE oriented palaeovalleys (Mountney *et al.*, 1998; Mountney *et al.*, 1999a; Fig. 6A). Restricted extrabasinal sediment supply at this time resulted in the basin being under filled with respect to the available accommodation space (Jerram *et al.*, 1999a; Mountney *et al.*, 1999a).

A change in the prominent palaeowind direction from north-westerly to south-westerly occurred at the transition from the Mixed Aeolian Unit to the Main Aeolian Unit. This change in wind pattern tapped the large sand reserves of the Botacatu sand sea that was active in the Paraná Basin to the south-west. The basin then rapidly

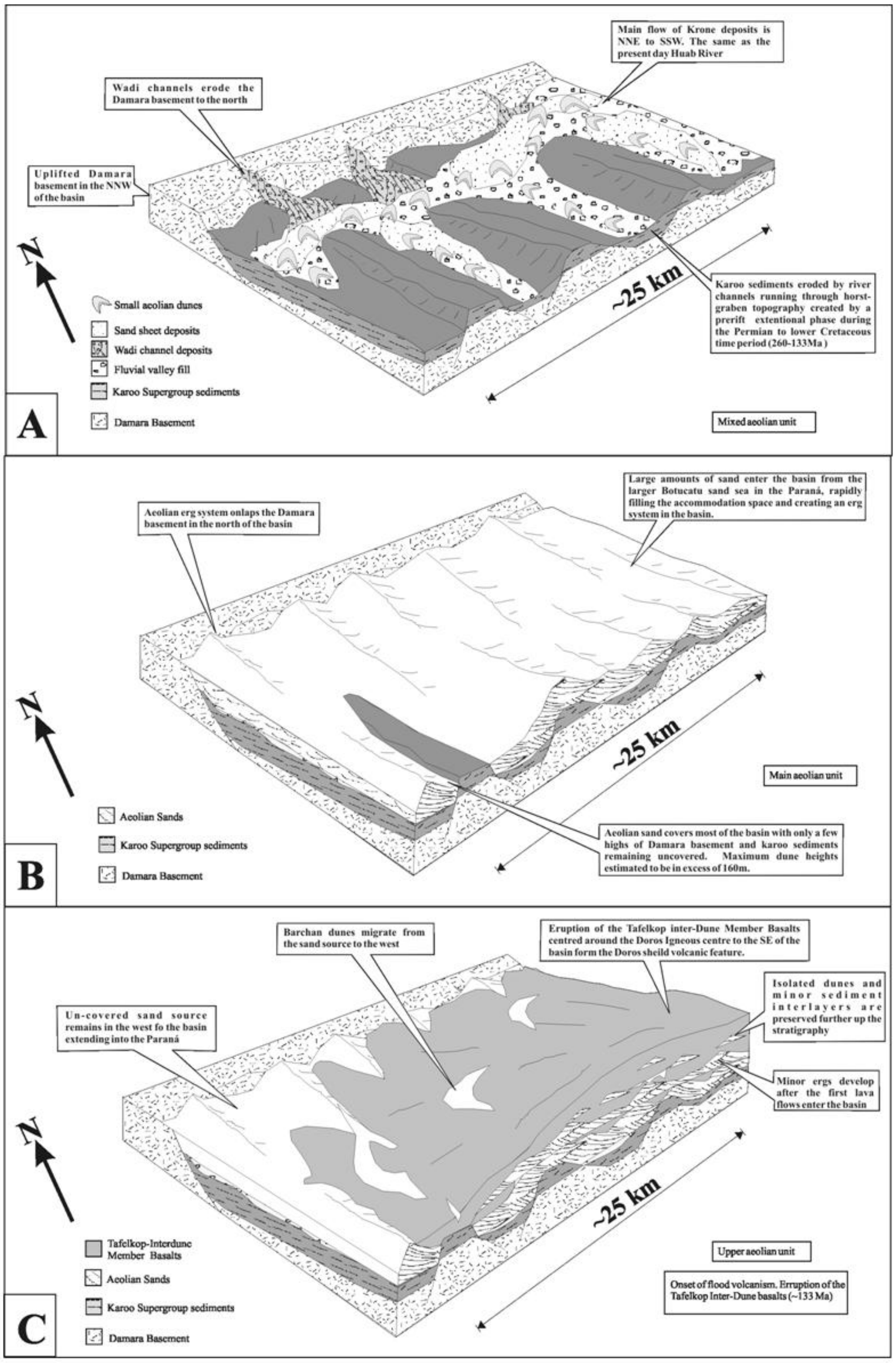

Figure 6: Schematic reconstructed development of the Huab Basin. A) Huab Basin during the Mixed Aeolian Unit. B) Main Aeolian Unit. C) Development of the Doros shield volcanic feature, Upper Aeolian Unit.

filled as large transverse draa bed forms migrated into the region. Older Karoo Supergroup sediments and Damaran Basement rocks were largely covered by the aeolian deposits, although basement rocks in some parts of the basin may have remained exposed (Fig. 6B). The largest aeolian bed forms are estimated to have been up to 160 m high from trough to crest (Jerram *et al.*, 2000).

The onset of flood volcanism was initially restricted to the area around the present-day Huab Outliers in the SE of the basin. Low volume, olivine phyric, pahoehoe lava flows (of Tafelkop geochemical type), sourced from the Doros igneous complex, flowed into the aeolian dune system (Jerram *et al.*, 1999a; Marsh *et al.*, 2000). These lavas first flowed into the topographically low interdune regions in between the large draa bed forms. The first flows were not voluminous enough to fully engulf the major erg system and sand from the higher parts of the erg system remained exposed to be reworked over the first lava surface. This resulted in

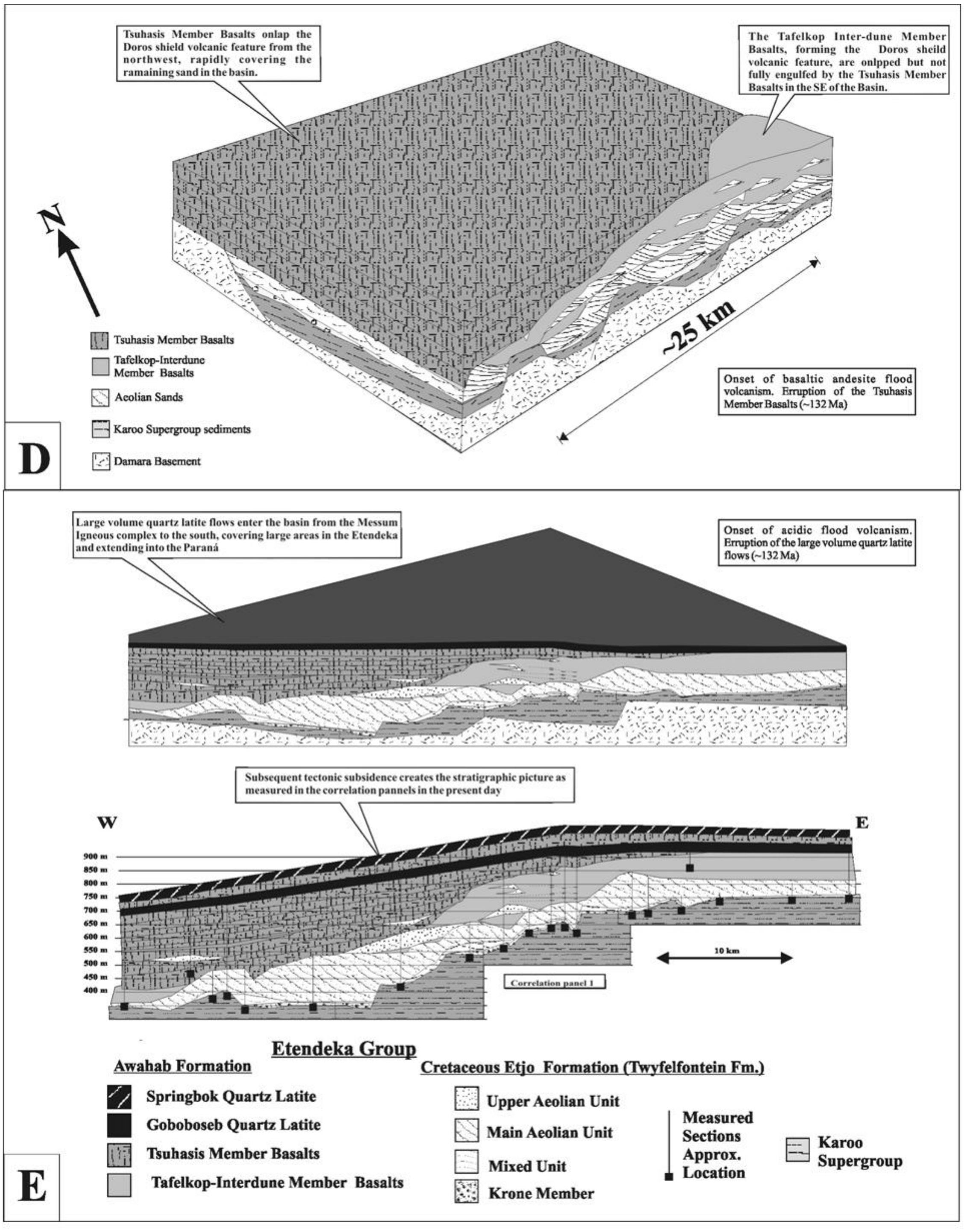

Figure 6 (cont.): D) Deposition of the Tsuhasis Member Basalts on-lapping the shield volcano and rapidly burying the basin. E) Eruption of large volume quartz latite flows. Subsequent tectonic subsidence leads to the distribution observed in the present-day correlation panel.

moderately large sediment interlayers, termed ‘minor ergs’, being redeposited directly over the first lavas (Jerram *et al.*, 1999b) (highlighted in Fig. 6C). Further eruptions built up the lava pile whilst pauses in volcanism were marked by the migration of progressively smaller aeolian bed forms onto the lava surface. These bed forms were buried by subsequent lava flows and now form discrete sediment interlayers. During this period, the Doros shield volcanic feature, centred around the Doros igneous complex, built up through time (Fig. 6C). Reuning and Martin (1957) first suggested the genetic link between the basal Etendeka flows in the Huab area and the Doros igneous complex. Jerram *et al.* (1999a) reported on a feeder dyke from the south-eastern part of the Huab Outliers trending towards the Doros igneous centre, suggesting that the lavas were fed by fissure eruptions in this region. Marsh *et al.* (2000) further confirmed the geochemical link of the Tafelkop

Interdune Basalts with the Doros igneous centre.

The source and style of volcanism then changed with much more voluminous lava flows, of mainly basaltic-andesite composition, erupting from an extra-basinal source, and onlapping the Doros shield volcanic feature (Fig 6D). These basalts, termed the Tsuhasis Member Basalts, appear to have rapidly terminated the already dwindling supply of aeolian sand in the basin. These basalts engulfed the sediments and basement exposed in the WNW of the basin and covered a large part of the Doros volcano prior to the eruption of the Goboboseb quartz latite.

The final stages of volcanism to affect the basin involved the large volume silicic quartz latite flows, of which the Goboboseb flow was the first. These fully blanketed the basin and extended into the Paraná (Milner *et al.*, 1995b). These flows provide a good datum marker throughout the basin (Jerram *et al.*, 1999b) and have been successfully correlated with the Paraná stratigraphy (Milner *et al.*, 1995b).

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