# A description of the sedimentology and palaeontology of the Late Triassic–Early Jurassic Elliot Formation in Lesotho

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Sedimentological studies of the Late Triassic to Early Jurassic Elliot Formation (Karoo Supergroup) in Lesotho have proved to be a fundamental element in our research into the development of the main Karoo Basin of southern Africa. Complementing previous research in South Africa, studies of the architecture of the sedimentary units in the Elliot Formation reveal that there are two contrasting types of sandstone body geometries, each resulting from different fluvial depositional styles. In the lower part of the formation, the sandstones resemble multi-storey channel-fills, interpreted as deposits of perennial, moderately meandering fluvial systems. On the other hand, the upper part of the formation is characterized by mostly tabular, multi-storey sheet sandstones which resulted from ephemeral fluvial processes. Based mainly on changes in the fluvial style and palaeocurrent pattern within the formation, the regional lithostratigraphic subdivision applied to the Elliot Formation in South Africa is applicable in Lesotho as well. This study adds detail and therefore refines the stratigraphic subdivision documented for the South African succession, and as such forms an important framework for palaeontological, palaeoecological and biostratigraphic studies in Lesotho.

**Keywords**: Lesotho, facies architecture, palaeocurrents, main Karoo Basin.

## INTRODUCTION

The Late Trassic–Early Traissic is an important time both palaeontologically and geologically, and the excellent exposures in Lesotho have proven to be crucial to our understanding of this period of the geological history of Gondwana, which preceded the break-up of the supercontinent. This paper presents the results of a field-based sedimentological investigation of the Elliot Formation (Karoo Supergroup) in the southern and western half of Lesotho, which forms part of a regional research project focussed on the development of the main Karoo Basin in southern Africa. The investigation of the Elliot Formation in South Africa predated the present study, and its results are described in three papers by the same authors (Bordy *et al.* 2004a,b,c). Although various aspects of this work overlap with the descriptions of the South African succession, this work is warranted because of the high-quality exposures in Lesotho, which have not been described in terms of modern sedimentology and which allow for the intrabasinal correlation of the southern and northern outcrops of the formation within southern Africa. In addition, these exposures often show the elemental architecture better than their South African counterparts, a fact that is especially true for the upper part of the formation. Furthermore, these sedimentological descriptions will aid current palaeontological and biostratigraphic work being undertaken in Lesotho.

Numerous important fossils have been collected from Lesotho including holotypes of cynodonts *Tritylodon* (Owen 1884) and *Scalenodontoides* (Crompton & Ellenberger 1958), mammals *Erythotherium* (Crompton 1964) and *Megazostrodon* (Crompton & Jenkins 1968), as well as numerous well-preserved dinosaur and crocodilomorph specimens. Furthermore, Lesotho has the best exposures of Late Triassic to Middle Jurassic vertebrate trackways in southern Africa (Ellenberger 1970; Olsen & Galton 1984). Previous palaeontological collections were, however, often not stratigraphically well-constrained, many important palaeontological specimens are unprovenanced, and the Lesotho exposures have lacked the extensive methodological sampling of their South African counterparts (e.g. Kitching & Raath 1984). This is changing, however, and there is a renewed interest in the numerous dinosaurs trackway sites, as well as in the Triassic and Jurassic faunas of Lesotho (Smith & Battail, pers. comm.). With many specimens still *in situ,* the Lesotho exposures presently offer some of the last virgin ground for controlled, detailed taphonomic and biostratigraphic collecting. Although the Elliot Formation in Lesotho presents a vast potential for new and biostratigraphically significant findings, without a well-established geological framework the advancement of palaeontological research in Lesotho will be hampered. This paper therefore documents, for the first time, the stratigraphy, detailed sedimentary facies architecture, thickness and palaeocurrent patterns, as well as brief notes on new fossil localities in the Elliot Formation of Lesotho.

### Geological background

The Elliot Formation is part of the Late Carboniferous to Middle Jurassic Karoo Supergroup (Fig. 1) which outcrops in the main Karoo Basin of South Africa and Lesotho, as well as in several other separated outcrop areas in central and southern Africa (Johnson *et al.* 1996; Bordy 2000; Bordy & Catuneanu 2001). The main Karoo Basin is a retro-arc foreland basin which developed in front of the

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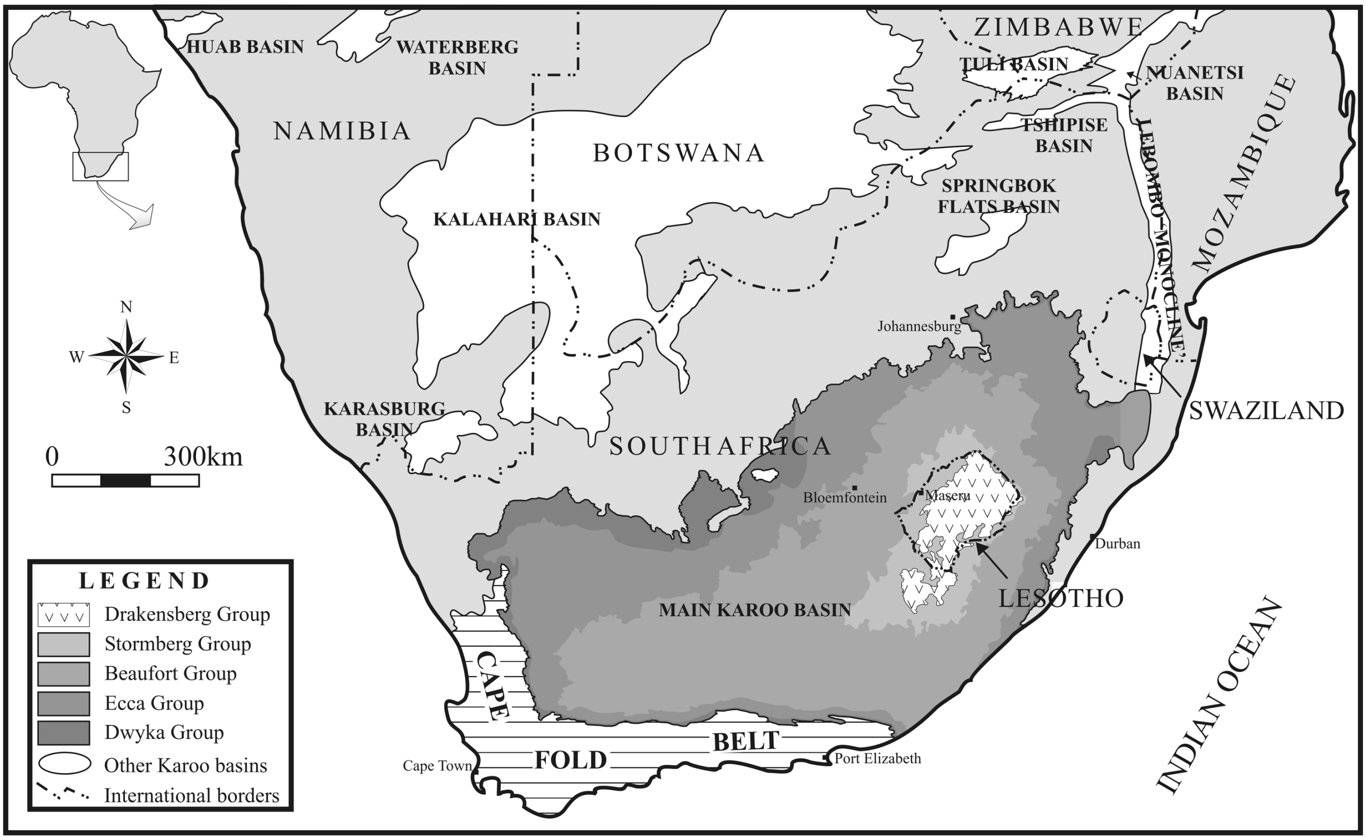


**Figure 1**. Geological map of the Karoo Supergroup in the main Karoo Basin (Lesotho and South Africa), and other outcrop areas with Karoo-age deposits in southern Africa (modified after Johnson *et al.* 1996; Catuneanu *et al.* 1998).

Cape Fold Belt (Fig. 1) in response to the late Palaeozoic–early Mesozoic subduction of the palaeo-Pacific plate beneath the Gondwana plate (e.g. Johnson 1991; Catuneanu *et al.* 1998; Pysklywec & Mitrovica 1999; Catuneanu & Elango 2001). Together with the underlying Molteno and overlying Clarens formations, the preserved succession of the Elliot Formation (Fig. 2) was deposited during the final stages of the basin history, in a foresag setting (Catuneanu *et al.* 1998).

**Previous research**

In spite of the excellent Elliot Formation outcrops in southern Africa, to date, there are only a few field-based geological investigations dealing with the sedimentological relations of the formation. Most of these studies were undertaken in South Africa and have shown the formation to consist of continental red beds of fluvial, lacustrine and aeolian origin (e.g. Botha 1968; Le Roux 1974; Johnson 1976; Visser & Botha 1980; Eriksson 1983 1985; Kitching & Raath 1984; Smith *et al.* 1993; Johnson *et al.* 1996; Johnson *et al.* 1997; Smith & Kitching 1997). The only detailed description of the Elliot Formation of Lesotho is a general geological report complied by Stockley more than fifty-five years ago (Stockley 1947). Although there is a reasonable database of the dinosaur fossils and footprint locations in Lesotho based primarily on work done by P. Ellenberger over two decades from the 1950s to 1970s (Ellenberger 1970), the sedimentology and exact stratigraphic position of a number of the sites are largely unknown. Ellenberger (1970), however, utilized the stratigraphic position of the various trackway sites to establish a subdivision for the Molteno, Elliot and Clarens formations in Lesotho. This nomenclature has not been internationally accepted, and it should be noted that it has also not been rigorously tested.

## DATABASE AND INTERPRETATIONS

**Stratigraphy**

The present study undertaken in Lesotho confirmed most of the findings of the previous South African survey (Bordy *et al.* 2004a,b,c). The most important analogy between the South African and Lesotho records is that the lithostratigraphic distinction between the lower and upper part of the formation documented in South Africa, is possible throughout Lesotho as well (Fig. 3). The formation therefore comprises two units on a basinal scale, which show different and characteristic facies assemblage, isopach and denudation patterns, and are referred to as lower Elliot Formation (lEF) and upper Elliot Formation (uEF), respectively. Apart from the geological differences, the boundary between the two units is also manifested in the geomorphology of the study area, as it forms a regionally traceable plateau. This break of slope is especially well developed in the southern outcrop area, but is also evident in the north (Fig. 3; Mauteng, Maseru District). Considering new fossil finding (Yates, written comm., 2004) it is unclear whether the two units (i.e. the lEF and uEF) correspond with the biostratigraphic units defined by Kitching & Raath (1984) as the *Euskelosaurus* and *Massospondylus* range zones, respectively. However, the tripartite lithostratigraphic subdivision (Lower,

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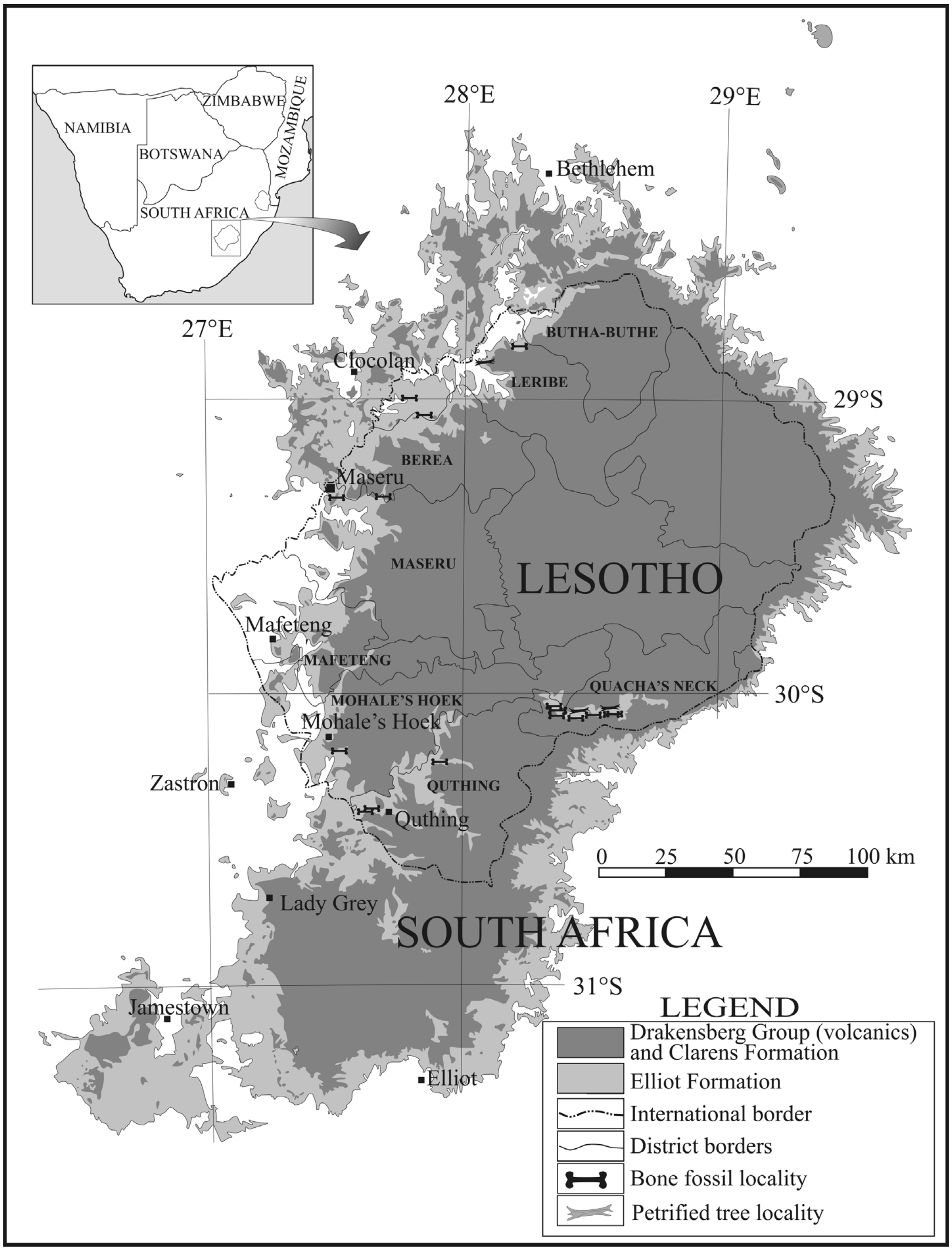


**Figure 2**. Geological map of the Elliot Formation in Lesotho and the Republic of South Africa (modified after the 1:1 000 000 geological map of South Africa, Swaziland and Lesotho, SA Geological Survey (1984) showing new fossil localities. See Table 1 for Global Positioning System (GPS) coordinates.

Middle and Upper Elliot formation) of Kitching & Raath (1984) could not be traced on a regional scale, and in our classification the Middle Elliot formation is included in the uEF. A tentative correlation of the lower and upper Elliot Formations, and the zones developed by Ellenberger (1970) suggests that the lEF comprises zones A4, A5 and A6, while the uEF coincides with zones B1, B2 and B3 of Ellenberger's (1970) terminology.

**Sedimentology**

Three major sedimentary characteristics, namely the colour, grain size and association of sedimentary structures (i.e. facies architecture) of the Elliot Formation are remarkably different in the lower and upper part of the formation in Lesotho. In addition to these characteristics, thin-section analysis of some fifty Elliot Formation sandstone samples from South Africa (Bordy *et al.* 2004c) showed that the petrography of the two units is also distinct with the uEF richer in feldspar than the lEF. The lEF lithologies are represented by various, lighter shades of red, and mottling of olive green, gray, yellow and purple, which contrast with the deep red or maroon, and sporadic light grey mottles of the uEF deposits (i.e. in general terms, lEF ~ light red, uEF ~ deep red). Generally, in a vertical section of the Elliot Formation, the fine- to medium-grained sandstones of the lEF are followed by very fine- to fine-grained sandstones in the lower part of the iEF and fine- to medium-grained sandstones in the


**Figure 3**. Outcrop scale differences between strata of the lower and upper Elliot Formations (lEF and uEF) are clearly visible due to the differential weathering of the dissimilar lithologies (Maseru).

upper part of the uEF. Locally (e.g. in the vicinity of Mount Moorsi, Quthing District), the uppermost uEF sandstones have medium to coarse grain sizes. As for the South African sections (Bordy *et al.* 2004b,c), the lEF sandstones become finer in grain size along a south–north profile, while the uEF sandstones lack lateral grain-size variations. Reference sections for the lEF are in the vicinity of Thabana Morena (southeast of Mafeteng, Mafeteng District), and for the uEF between Qacha's Neck and Sekake (Qacha's Neck District).

*Facies architecture of the lower Elliot Formation*

Architecturally, the lEF in Lesotho is characterized by lenticular, multi-storey, laterally impersistent (max. 100–150 m) sandstone bodies with maximum thicknesses of 20–25 m, and mudstone units of 20–30 m. The frequency of the sandstone bodies is constant within the lEF. Within the individual sandstone bodies, large- or medium-scale lateral accretion surfaces are common (Fig. 4A,B,C), separating slightly upward-fining successions (Lateral Accretion architectural element – LA) which are characterized by trough and planar cross-stratification, massive beds, and less commonly low-angle cross-stratification.

The quality of the lEF mudstone outcrops in Lesotho are inadequate for very detailed sedimentological interpretations, but in general sedimentary structures are rare, and most of the clay- and fine silt-rich mudstones are massive, or very rarely horizontally laminated. Pedogenic over-

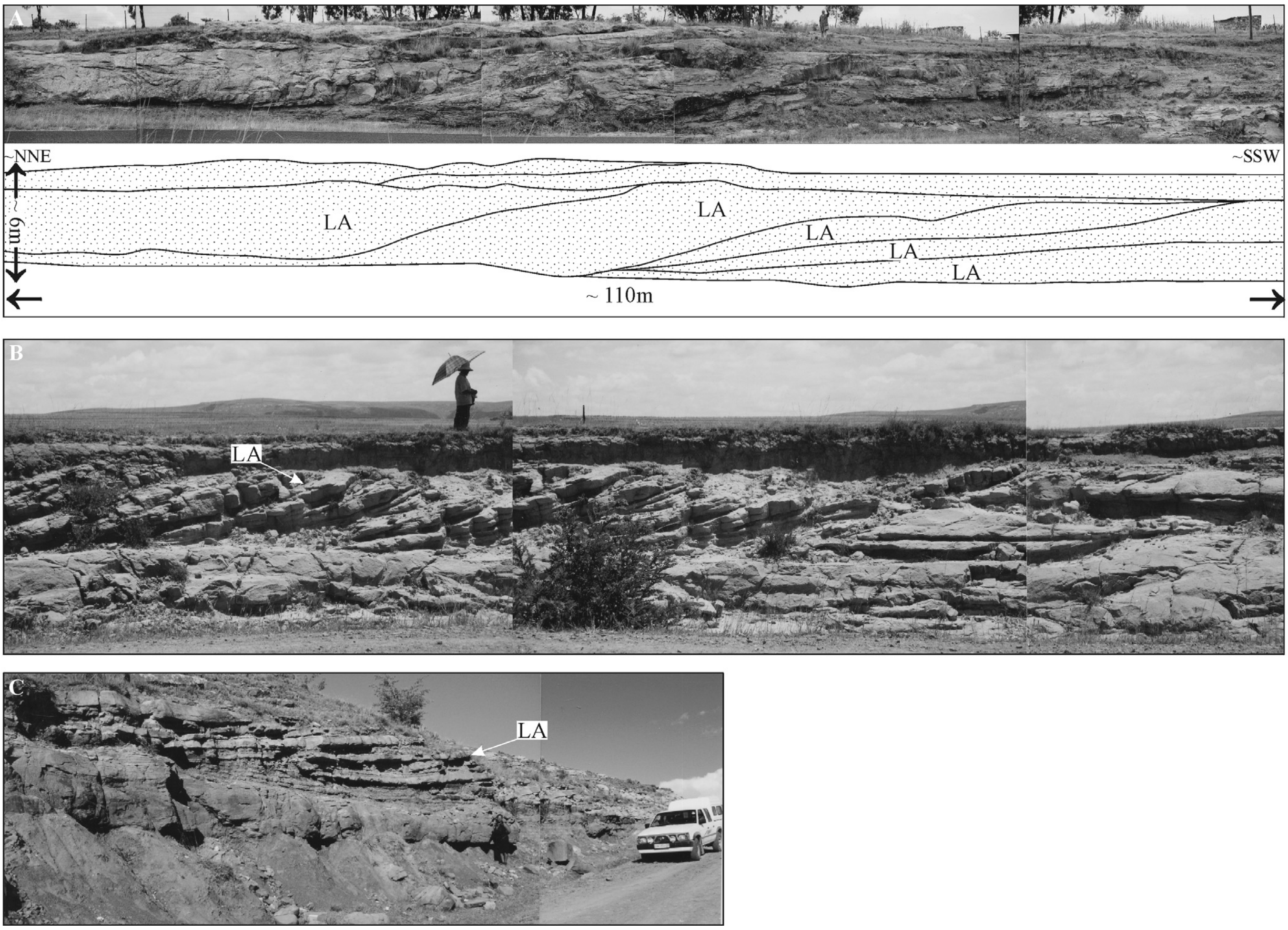


**Figure 4**. Gently inclined, large- (**A**, Hlotse, Leribe District) and medium-scale (**B**, east of Butha-Buthe, Butha-Buthe District; **C**, west of Ha Ntsekele, Leribe District; person for scale) lateral accretion surfaces (LA) in multi-storey sandstone bodies of the lower Elliot Formation. Person for scale.

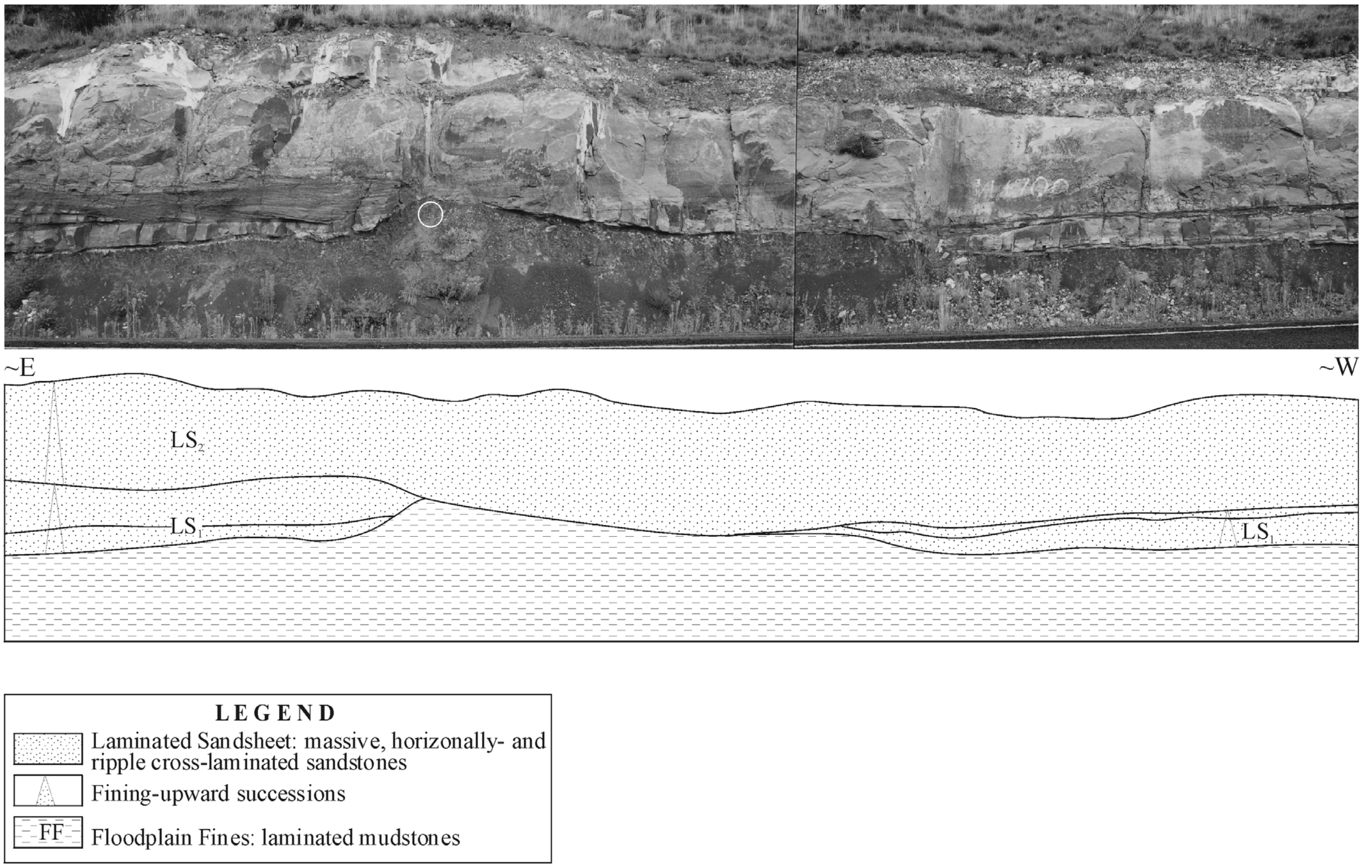


**Figure 5**. Sharp, laterally persistent bounding surfaces in a upper Elliot Formation tabular sandstone body. Note the lack of major irregularities at the base of the two slightly upward-fining successions (between Whitehill and Malimong, Qacha's Neck District). Hammer in white circle for scale = 28 cm.

printing is rare in the south, and even in the north, such alteration remains restricted to irregular mottles, a few dessication cracks, and rare calcareous glaebules. Small (max. 5–6 m thick), asymmetrical channel-shaped successions, and thin (0.2 to 1.2 m), laterally continuous tabular layers or rhythmically bedded units (<0.3 m) of sand- and mudstone are common features of the lEF mudstone units in South Africa (Bordy *et al.* 2004b) but have not been noted in Lesotho. However, their absence may simply be due to the limited number of lEF mudstone outcrops in Lesotho. The above mentioned sedimentary characteristics suggest a palaeoenvironmental interpretation that is identical to the scenario reconstructed for the lEF of South Africa (Bordy *et al.* 2004b), i.e. one of relatively narrow, fairly fixed, and meandering channels, and extensive floodplain areas. In addition, the diversity of large-bodied herbivores in the lEF suggests that the floodplains were well vegetated (Yates, pers. comm.). The reconstructed palaeomilieu is also consistent with the results of the previous researchers on the Elliot Formation (e.g. Botha 1968; Le Roux 1974; Visser & Botha 1980; Eriksson 1983, 1985; Smith *et al.* 1993) which all depicted a meandering river environment with associated floodplain areas for the depositional setting of the lower part of the Elliot Formation.

*Facies architecture of the upper Elliot Formation*

The uEF in Lesotho is characterized by sheet sandstone bodies several tens of metres wide, with maximum thicknesses of between 5 and 6 m, and 0.5 to 10 m thick mudstone units. The frequency of the sandstone bodies increases stratigraphically upwards in the uEF. Most sandstone bodies in the uEF are bound, and internally separated by, semi-horizontal, laterally persistent erosion surfaces, which lack basal irregularities larger than a few tens of centimetres (Fig. 5). In the uppermost part of the Elliot Formation, just below the junction with the Clarens Formation, amalgamated lenses of sandstones with cumulative thicknesses up to 15 m are present at places. These uppermost sandstone bodies are coarser in grain size (up to medium sand) than the other sandstones in the uEF, and at one locality (Levis Neck, Leribe District) gently inclined (shallow) lateral accretion surfaces are present (Fig. 6). The sandstone bodies of the uEF are generally characterized by couplets of horizontal and ripple cross-laminated (Fig. 7), or massive and ripple cross-laminated sandstone layers. Thicker massive beds, rare trough cross-stratification, small-scale water escape structures (Fig. 7), mud-drapes (Fig. 7), dessication cracks (Fig. 8A,B) and various bioturbation features were also observed. In addition, the uEF is characterized by a unique and fairly common lithofacies type which can be used as a regional 'hallmark' of the upper part of the Elliot Formation both in Lesotho and South Africa. In Lesotho, this lithofacies, which is a pedogenic glaebule conglomerate, occurs throughout the outcrop area (e.g. Malimong, Qacha's Neck District; Maphutseng, Mohale's Hoek District; Maseru; Ha Ntsekele, Leribe District), and is generally


**Figure 6**. Localized lateral accretion (LA) surfaces in the uppermost, lenticular sandstone bodies of the upper Elliot Formation (Levis Neck, Leribe District). Person for scale in white circle.

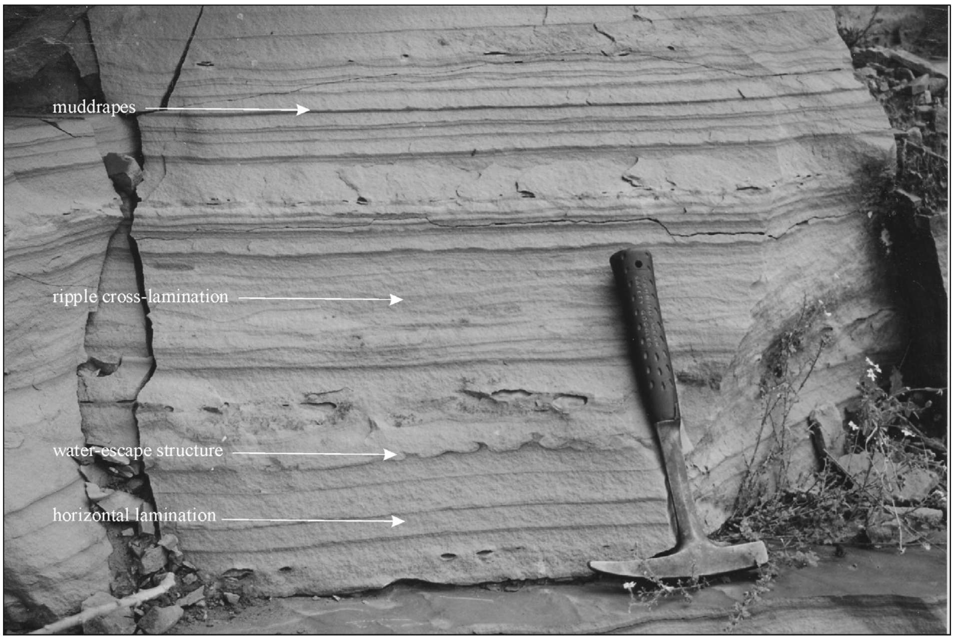


**Figure 7**. Horizontal lamination is commonly associated with ripple-cross lamination in the upper Elliot Formation sandstones. Small-scale water-escape structures and mud-draped surfaces are also present (along the Quthing River, Quthing District). Hammer for scale = 28 cm.

massive; however horizontal (Fig. 9) and cross-stratified beds were also observed. Apart from the granule- to pebble-sized, well-rounded carbonate and septarian nodules, other clasts, in decreasing frequency, include mudstone and sandstone, fossil bones and teeth, and occasional small quartz pebbles. Limited to the uEF, but less common than the pedogenic glaebule conglomerates, are red intraformational sandstone clast breccias and clast-rich sandstones with occasional soft sediment deformations. The angular clasts in these lithofacies are predominantly fine- to very fine-grained sandstones that show occasionally horizontal lamination. In addition, massive, very fine to fine-grained sandstone beds occur in conjunction with them. Examples of these lithofacies were documented in the south near Whitehill (Qacha's Neck District) and in the north near Ha Jonathane (Leribe District). As for the South African outcrops (Bordy *et al.* 2004b), these lithofacies are rarely found in association with the larger uEF sandstone bodies, but occur within uEF mudstone units at many places. Most of the mudstones in the uEF are massive, but horizontal lamination is more common than in the lEF mudstones. Other sedimentary structures encountered in these mudstone units are pedogenic alteration features, and include 0.2–3 m thick, laterally continuous (over 120 m) calcareous surfaces, calcretized root traces, calcareous concretions, large-scale calcretized and clay-lined shrinkage cracks and irregular, light grey mottles

Newly developed road-cuts in southern Lesotho (Qacha's Neck District), between Qacha's Neck and the area west of Sekake, present high-quality exposures of the different subunits within the uEF mudstones. Small, asymmetrical channel-shaped successions with shallow lateral accretion surfaces (Fig. 11) and laterally continuous, tabular sandstone intercalations (Fig. 12) are quite common in the upper part of uEF mudstone units, especially in association with the coarser grained, more channelized sandstone units with lenticular geometries.

The genesis of the sedimentary rocks in the lower and upper parts of the upper Elliot Formation are slightly different. The laterally persistent sheet sandstone bodies in the lower part of the uEF are seen as distal sheetflood deposits (*sensu* Hogg 1982), while the more channelized facies at the top of the uEF are interpreted as single thread, incised channels produced by successive streamfloods (*sensu* Hogg 1982). In both parts of the uEF, mudstones are explained as sediments accumulated in the floodplain environment in standing water bodies and/or abandoned watercourses. The various pedogenic alteration features and desiccation cracks in the mudstones suggest that calcareous palaeosol horizons were common, and that the floodplains were subject to long periods of dessication during the

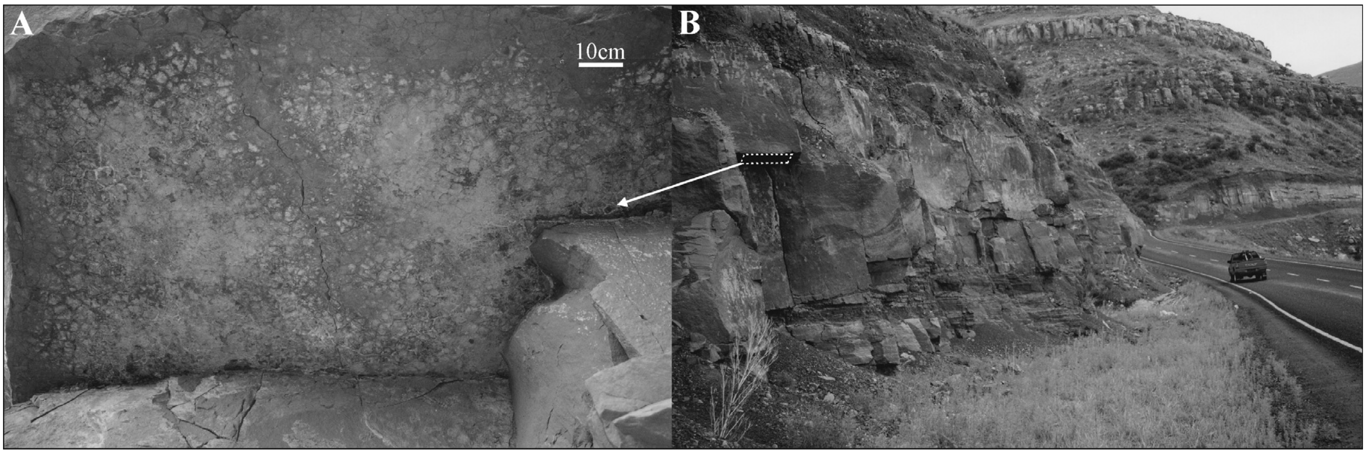


**Figure 8**. Cast of dessication cracks (**A**, lower bedding plane view; bar for scale) in the upper Elliot Formation found within (see arrow) a three metre thick sandstone unit (**B**, vehicle for scale) (between Whitehill and Malimong, Qacha's Neck District).

deposition of the uEF. The other, uniquely uEF lithofacies, the pedogenic glaebule conglomerates, the matrix-supported intraformational sandstone breccias, and the clast-rich sandstones, are interpreted as having been formed through the denudation of the floodplains and other penecontemporaneous strata. During severe storms (suggested by upper flow regime sedimentary structures), the uEF floodwaters were vigorous enough to erode the floodplain, thus removing the pedogenic nodules from the soils as well as parts of other semi-consolidated formations. These were later incorporated as lag material in the uEF sheet sandstone bodies, or became deposited as colluvial fills of smaller, rainstorm-eroded gullies and other irregular depression on the floodplain. The massive, very fine to fine-grained sandstone beds associated with these strata are interpreted as the first manifestations of aeolian processes during the sedimentation of the uEF.

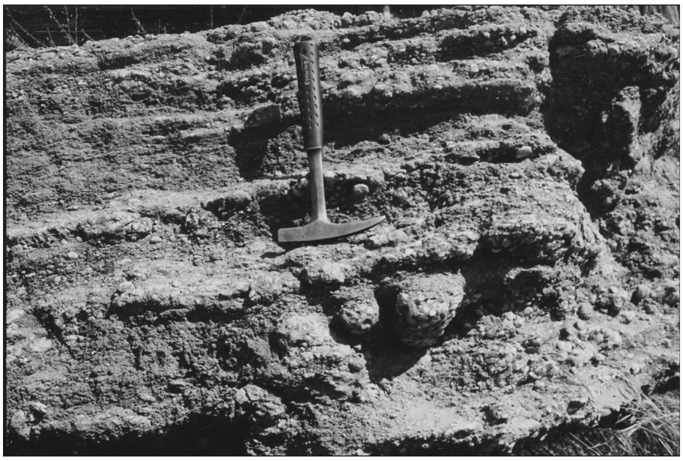

**Figure 9**. Clast-supported pedogenic glaebule conglomerates are unique to the upper Elliot Formation (Maphutseng, Mohale's Hoek District). Hammer for scale = 28 cm.

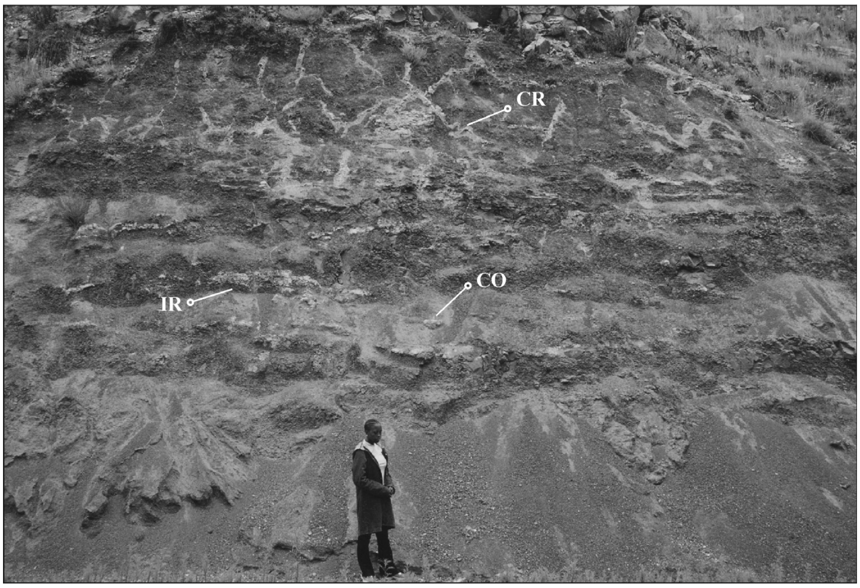


**Figure 10**. Calcareous concretions (CO), irregular mottles (IR), and large-scale calcretized and clay-lined shrinkage cracks (CR) in upper Elliot Formation mudstones (between Whitehill and Malimong, Qacha's Neck District). Person for scale.

Although a similar palaeoenvironmental picture has already been proposed for the uEF in South Africa (Bordy *et al.* 2004b), the present study not only reinforces previous interpretations, but due to the better quality road-cuts also provides a more sophisticated picture of the depositional setting of the uEF, and an improved control of the three dimensional architecture of the succession. For instance, the observed shallow, lateral accretion surfaces in the lenticular sandstone bodies of the uppermost uEF are the only indication that the later streams were slightly meandering. Also, the dessication cracks within the sandstone units characterized by couplets of horizontal (or massive) and ripple cross-laminated beds indicate that short-lived flood events with pulsating discharges were separated by periods of non-deposition and dessication. In addition, the good-quality exposures of the uEF mudstones in the Qacha's Neck District, aid the interpretation of the various sandstone subunits found

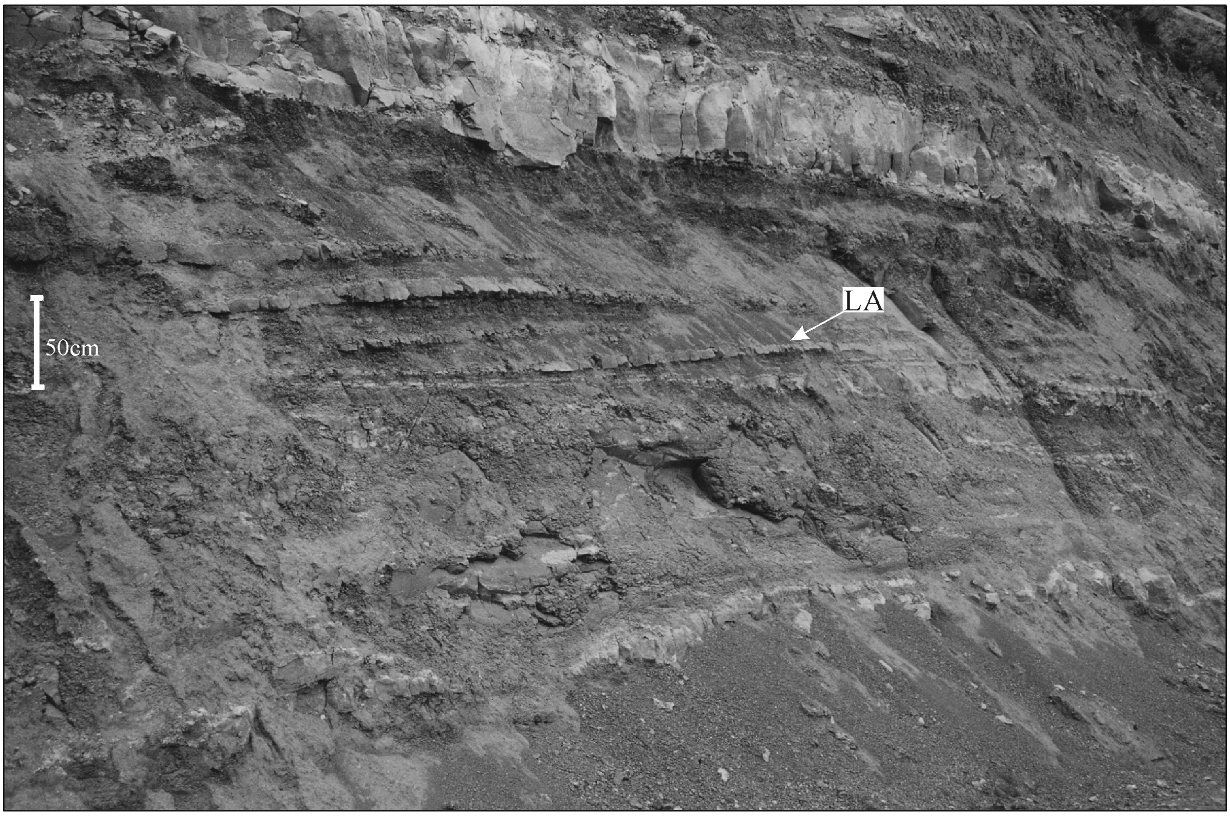


**Figure 11**. Shallow, lateral accretion (LA) surfaces in the channelized sandstone intercalations of the upper part of upper Elliot Formation mudstone units (between Whitehill and Malimong, Qacha's Neck District). Bar for scale.

within the floodplain deposits. In this way, it is clear that the lenticular sandstone bodies of the uppermost uEF were characterized by frequent crevassing, as demonstrated by the sharply bounded, tabular, thin sandstone strata with uneven upper surfaces that are situated in close proximity to the lenticular sandstone bodies (e.g. Fig. 12). Furthermore, the various size of the asymmetrical, channel-shaped deposits, with laterally accreted layers (e.g. Fig. 11) which were identified as secondary, sinuous channels of the floodplain, show that these secondary channels existed in various sizes from rivulets to 2–3 m deep watercourses.

**Thickness variations**

In order to determine the regional thickness pattern of the Elliot Formation, the correct recognition of the lower and upper boundaries of the formation is paramount. The basal contact of the Elliot Formation is easily identified in the western and northern outcrop areas where the underlying Molteno Formation is characterized by grey, gritty

**Figure 12**. Laterally continuous (outcrop scale), tabular sandstone intercalations in the upper part of the upper Elliot Formation mudstone units (between Whitehill and Malimong, Qacha's Neck District). The upper surfaces of these thin sandstone strata are characteristically uneven. Vehicle for scale.

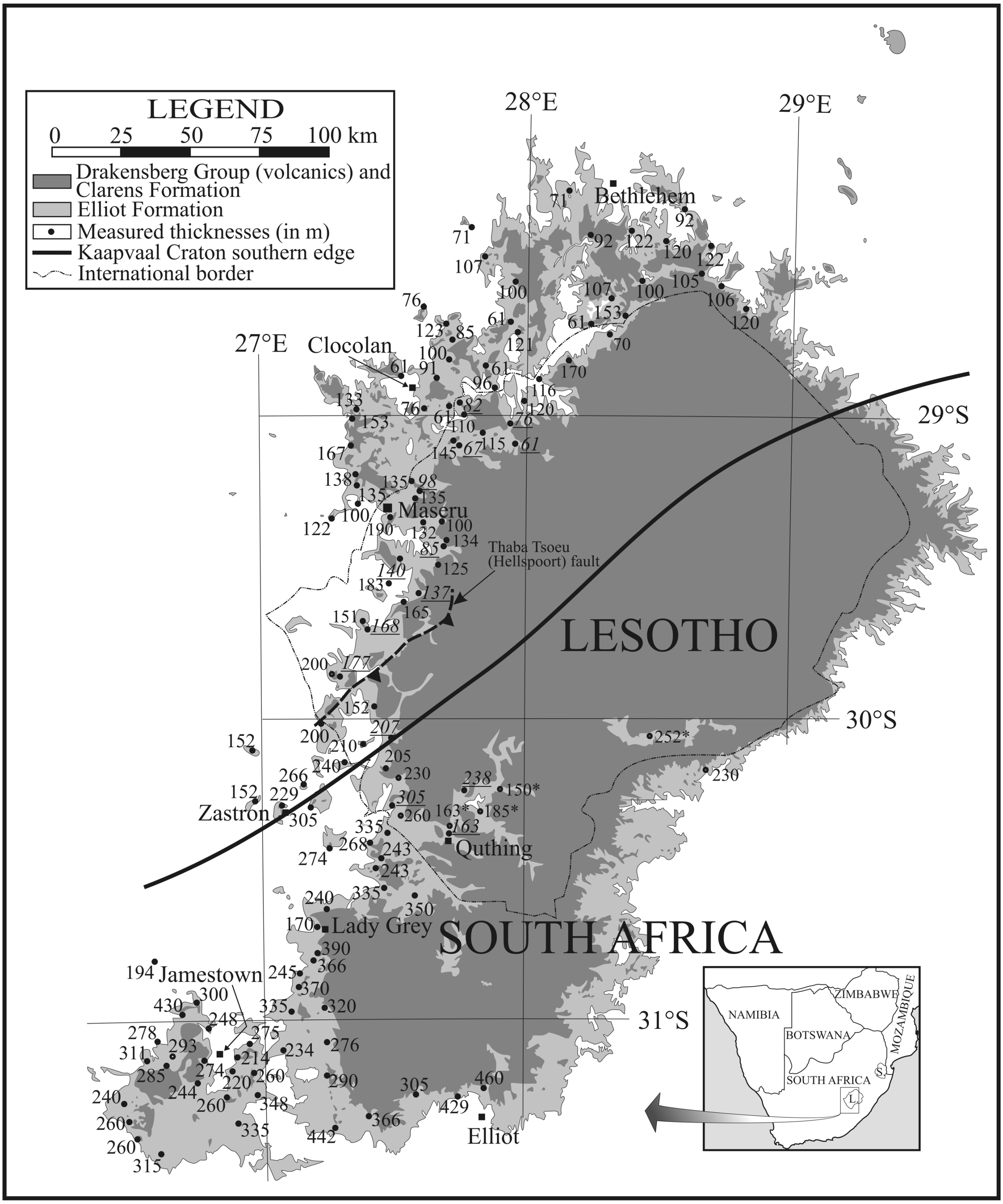


**Figure 13**. Thickness measurements of the Elliot Formation in Lesotho (underlined data in italics based on Stockley (1947); * marks incomplete Elliot Formation thicknesses) and South Africa. South African measurements are from Bordy *et al.* (2004a).

sandstones in contrast to the dusty yellow, medium-grained sandstones of the lEF. Here, as a general rule, the strata of the Molteno Formation form virtually flat plains above which the lEF sequence appears as terraced slopes.

The upper boundary of the Elliot Formation in Lesotho is either gradual (e.g. at Malimong, Qacha's Neck District), where the uEF terminates in sandstones (either fluvial or aeolian) or sharp (e.g. Qualo, Butha-Buthe District), where the uEF terminates in mudstones. In some places (e.g. Qacha's Neck District), there is a transitional zone between the red uEF sandstone and mudstones units, and the yellow-white, massive Clarens Formation sandstones. This zone consists of an inter-bedded succession of deep or light purple, massive, fine- to very fine-sandstones and mudstones, and yellow-white, massive sandstones. The architecture of these beds (e.g. erosion surfaces resulting in channel-shaped sandstones bodies) suggests some of them are fluvial, rather than aeolian in origin, and they were therefore considered as part of the uEF during the thickness measurements.

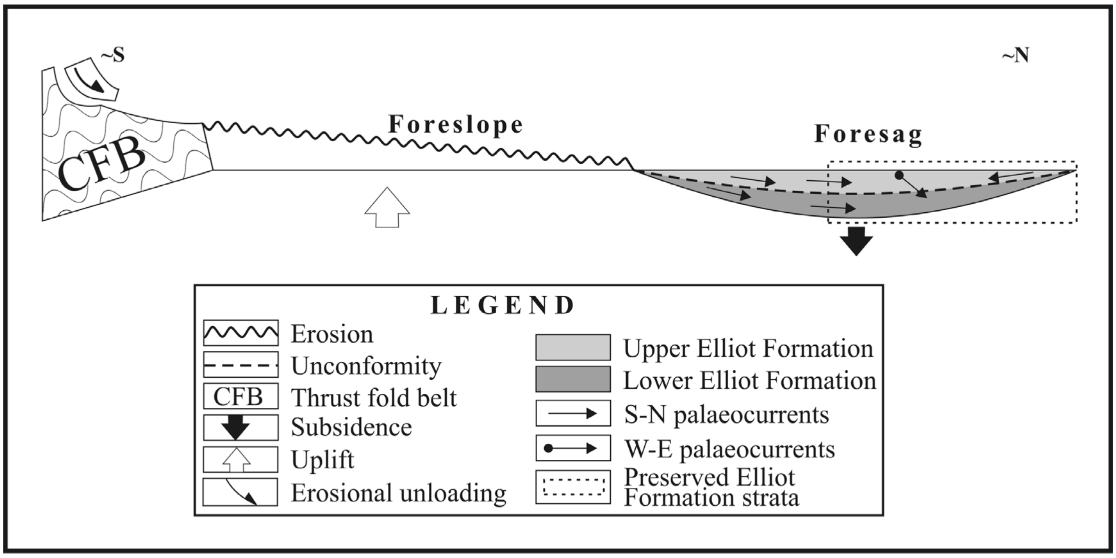


**Figure 14**. Hypothetical cross-section of the Karoo foreland system during the deposition of the Elliot Formation showing the dominant palaeocurrents in both lower and upper Elliot formations (after Catuneanu *et al.* 1998; Catuneanu & Elango 2001).

The well-documented (e.g. Botha 1968; Le Roux 1974; Johnson 1976; Visser & Botha 1980; Kitching & Raath 1984; Eriksson 1985; Smith & Kitching 1997) regional (from south to north) thickness decrease of the Elliot Formation in South Africa, was first demonstrated in Lesotho by Stockley (1947), and the present study has merely confirmed and quantified this finding (Fig. 13). It must be emphasized, however, that in the southern regions, especially along the Senqu River in Quthing and Qacha's Neck Districts, the base of the Elliot Formation is not exposed, and most of the thickness measurements in this area represent only part of the formation (i.e. are minimum values only).

The gradual thickness decrease of the Elliot Formation from south to north was explained by Catuneanu *et al.* (1998) as a consequence of the late stage development of the main Karoo Basin. These authors envisaged that the Elliot Formation, together with the underlying Molteno and overlying Clarens formations (i.e. the old 'Stormberg Group') constituted the foresag fill of the Karoo foreland system (i.e. main Karoo Basin and Cape Fold Belt). These formations with their northward tapering thicknesses thus represent the northern half of the Late Triassic–Early Jurassic foresag (Fig. 14). In the general northward thinning of the formation, there is a marked thickness reduction in the area between Zastron (South Africa) and Mohale's Hoek (Lesotho) which seems to coincide with the southern margin of the Kaapvaal Craton (Fig. 13).

Although the Lesotho data south of this zone are incomplete, measurements south and north of the Kaapvaal Craton southern edge show large discrepancies. North of Kaapvaal Craton southern boundary thicknesses are usually below 200 m both in Lesotho and South Africa, whereas south of this zone the gross thickness is usually considerably more than 200 m. In addition, the few measurements that were carried out south of this zone show large thickness variations within short distances (Fig. 13).

We suggest that the development of the variable thickness patterns in this area was probably controlled by a structural zone related to the margin between the southern edge of the Kaapvaal Craton and the northern edge of the Natal–Namaqua Mobile Belt. It is also noteworthy that the only major, post-Karoo fault in Lesotho, the Thaba Tsoeu fault of Stockley (1947) (also known an the Hellspoort fault) runs parallel to the southern edge of the Kaapvaal Craton (less than about 30 km north of this zone), reinforcing the idea that this area is a long lived, tectonically important region (Fig. 13). In addition, at Mohale's Hoek, a set of two dolerite dykes, each approximately a hundred metre wide, also parallels the aforementioned zone.

**Palaeocurrents**

To reconstruct the palaeodrainage during the Elliot Formation, the dip direction of one hundred and eighty-four foresets of planar cross-stratified sandstones were measured. The data were collected from medium- and large-scale planar cross-stratified units in major sandstone bodies only, because more reliable trough cross-stratified sandstones are rare. It is important to mention that rare trough and larger channel axis orientations were found to be consistent with the main orientation direction of planar cross-bedded sets.

Current indicators show that the major sediment supply directions were from south to north and southwest to northeast in the lEF, and from the south, southwest and west in the uEF (Figs 15, 16 & 17). Differences in the sediment supply patterns are not only traceable between the southern and northern regions (Fig. 15), but also between the lEF and uEF (Figs 16 & 17). Fig. 16A shows that the mean current vector was to the ~N in the lEF, while Fig. 16B indicates that this vector diverted to the ENE during uEF times. Palaeocurrent patterns of the Elliot Formation in Lesotho are strikingly similar to those measured in the South African outcrop areas (Bordy *et al.* 2004c), and the palaeocurrent data suggest that throughout the deposition of the Elliot Formation, sediment was supplied from the south, probably from the Cape Fold Belt. In the uEF, especially in its northern regions, sediments were also derived from a source in the west. Considering the findings of Bordy *et al.* (2004c), this source

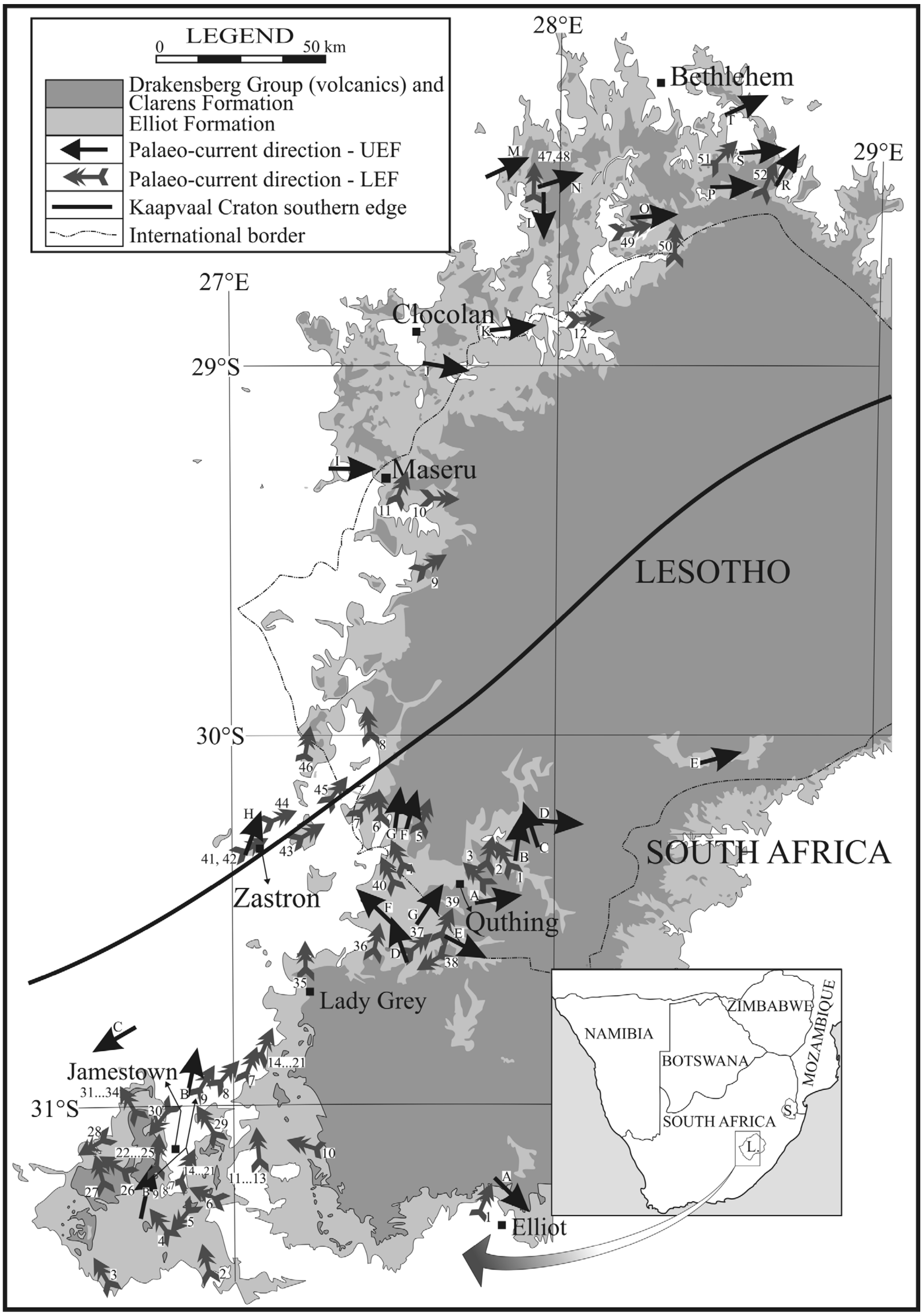


**Figure 15**. Palaeocurrent map of the Elliot Formation (numbers showing lower Elliot Formation measurements; letters showing upper Elliot Formation measurements – see Fig. 17 for more detailed information) in South Africa and Lesotho. South African measurements from Bordy *et al.* (2004c).

in the west may have been partially responsible for the higher feldspar content of the uEF sandstones. On these grounds, it is speculated that a palaeobasement high existed west of the present outcrop area.

**Fossils**

As a result of permit requirements, fossils discovered during this investigation could not be collected, but a few, highly weathered specimens (Table 1) were submitted to the Director of Culture at the Ministry of Tourism, Culture and Environment in Lesotho. The abundance of the material observed, and left *in situ,* in the field has once again highlighted how imperative it is that these fossils be removed and preserved. Cracked, disarticulated and fragmented fossil bones were found in the overbank deposits of both the lEF and uEF (Table 1, Fig. 18A–F). Fossils were not found in channel-fill sandstones; however channel-lags often contain fragmentary fossil bones, mainly in association with carbonate glaebule conglomerates in the uEF (e.g. Maseru, Maputseng). Large dinosaurian bones observed in the uEF at Peka (Leribe District) (Fig. 18A,B) are important in light of the recently documented

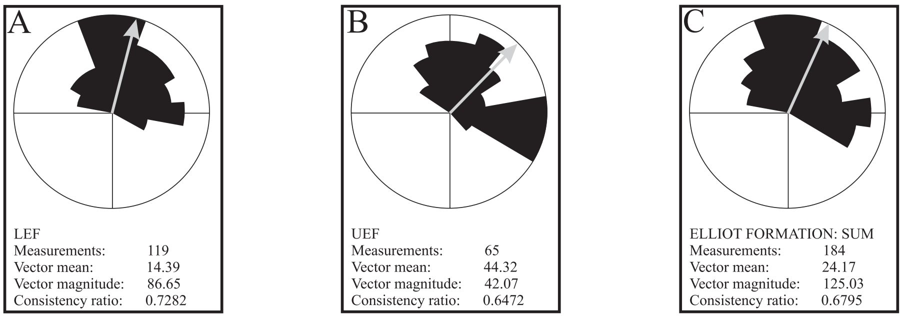


**Figure 16**. Summary palaeocurrent rose diagrams for planar cross-bedded sandstones in the Elliot Formation of Lesotho. **A**, lower Elliot Formation; **B**, upper Elliot Formation; **C**, Elliot Formation (all measurements).

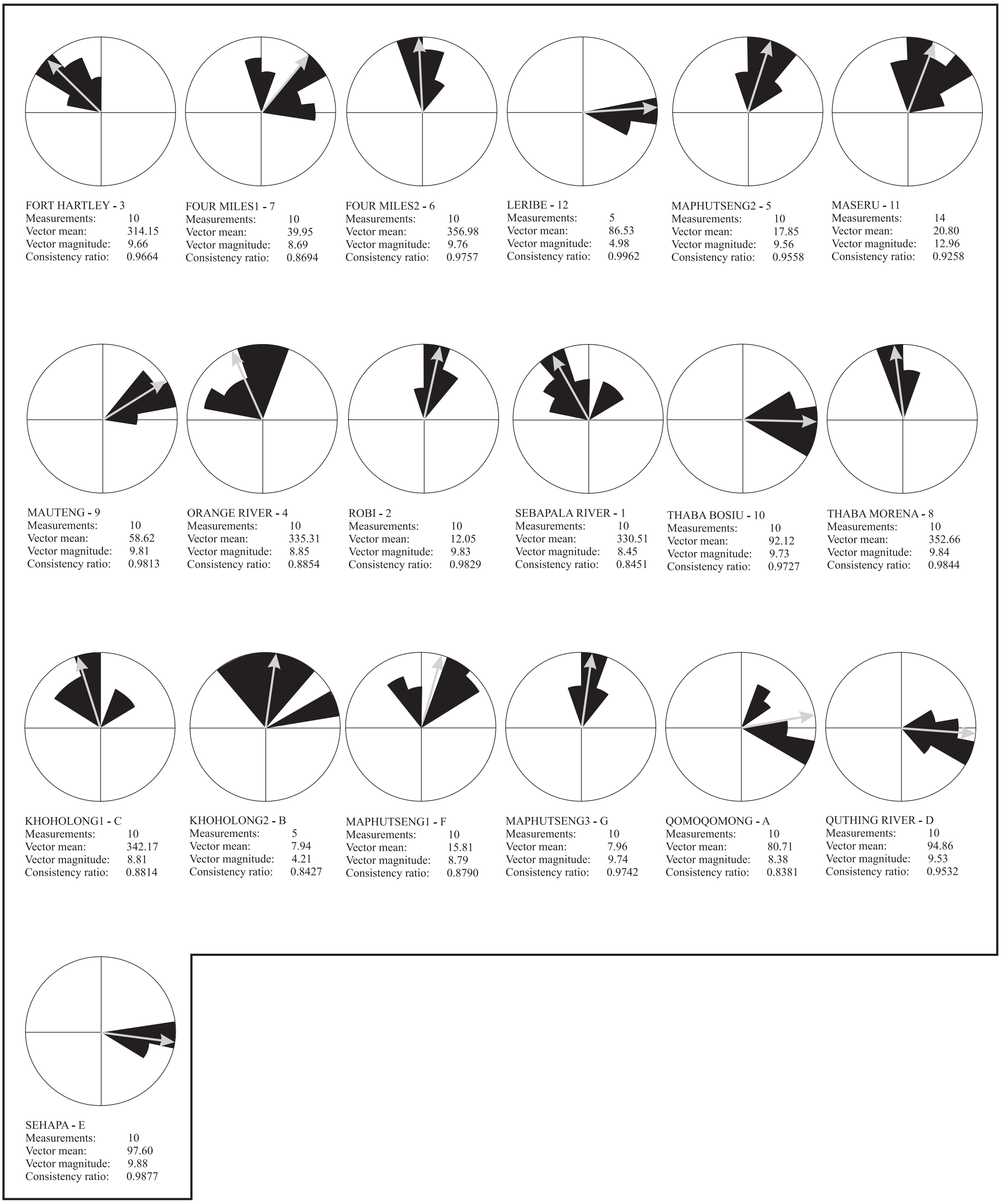


**Figure 17**. Palaeocurrent rose diagrams for planar cross-bedded sandstones in the Elliot Formation (Lesotho). Numbers refer to lower Elliot measurements, letters indicate upper Elliot Formation data. Roses are listed in alphabetic order of the locality names.

**Table 1**. List of fossil bone localities identified during this study (collected specimens are stored at the Lesotho National Museum, Ministry of Tourism, Culture and Environment, Maseru, Lesotho).

| Geographical coordinates in degrees (S/E) | Nearby locality | Altitude in m | Short description | Notes |
|---|---|---|---|---|
| 28°47.405′/28°13.159′ | Ha Rampae | 1770 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected RAM1 |
| 29°19.950′/27°42.5′ | Qiloane | 1670 | Fossil bone fragments | Upper Elliot F. mudstones. No sample collected |
| 29 20.615′/27°29.51′ | Ha Thetsane | 1755 | Fossil bone fragment in pedogenic nodule conglomerate | Upper Elliot F. conglomerates. See sample collected THE1 |
| 28°58.70′/27°45.98′ | Peka | 1578 | Fossil bone fragments (long, toe, etc.) | (?Upper) Elliot F. mudstones. See samples collected PEK1 and PEK2 |
| 29°02.284′/27°48.705′ | Ntsekele | 1639 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected NTS1 |
| 28°51.650′/28°04.133′ | Leribe | 1734 | ?Fossil wood | Upper Elliot F. mudstones. See sample collected SEB1 |
| 30°01.579′/28°19.72′ | Sekake | 1863 | Fossil bone fragments | Upper Elliot F. mudstones. No sample collected |
| 30°04.044′/28°25.363′ | Sekake | 1600 | Fossil wood | Upper Elliot F. mudstones. See sample collected SEK3 |
| 30°03.973′/28°25.648′ | Sekake | 1602 | Fossil wood | Upper Elliot F. mudstones. See sample collected SEK4 |
| 30°03.732′/28°28.432′ | Tebellong | 1628 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected SEK5 |
| 30°04.135′/28°28.937′ | Whitehill | 1683 | Fossil bone fragments | Upper Elliot F. mudstones. No sample collected |
| 30°03.249′/28°29.071′ | Whitehill | 1680 | Fossil bone fragments (+ 1 vertebra) | Upper Elliot F. mudstones. See sample collected SEK7 |
| 30°03.812′/28°31.353′ | Whitehill | 1666 | Fossil bone fragments (+ 1 vertebra) | Upper Elliot F. mudstones. See sample collected SEK8 |
| 30°03.793′/28°31.562′ | Whitehill | 1668 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected SEK9 |
| 30°03.801′/28°31.828′ | Ha Noosi | 1676 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected SEK10 |
| 30°13.548′/27°52.603′ | Orange and Quthing rivers confluence | 1500 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected QUTH2 and QUTH3 |
| 30°23.331′/27°37.013′ | Alwynskop | 1520 | Fossil bone fragments | Upper Elliot F. mudstones. See sample collected ALW2 and ALW3 |

occurrence of a large sauropod (*Sauropoda* indet.) in the uEF of the northern part of the Karoo Basin (Yates *et al.* 2004) as well as the occurrence of large theropod footprints in the rocks of the lower Clarens Formation in South Africa. Fossil wood fragments were collected in two outcrops near Sekake (along the Senqu River), at the base of the uEF sequence.

Most invertebrate trace fossils in the Elliot Formation occur as relatively rare, but strongly bioturbated, shallow bedding plane features. Such trace fossils are virtually absent from the lEF (Fig. 19A), while the uEF ichnofossils are of relatively higher diversity and abundance (Fig. 19B, C–F). Vertebrate tracks, especially dinosaurian footprints, were observed at several localities (e.g. Maputheng, Roma, Quthing) (Fig. 20A,B). However, it has to be emphasized that the vast majority of the fossil footprint localities mentioned by Ellenberger (1970) proved to be very difficult, or impossible to relocate because of the lack of precise site descriptions.

The occurrence pattern (as rare, but strongly bioturbated, shallow bedding plane features) of most of the Elliot Formation invertebrate trace fossils has been documented by Hasiotis (2001) within dryland river deposits as an indicator of rare, but intensive biological activities in dryland alluvial settings dominated by episodic rainfall. The reason for the relatively higher diversity and abundance of trace fossils in the uEF may therefore be explained by the fact that in a depositional environment characterized by punctuated episodic sedimentation, the land-derived organic debris is supplied more sporadically, but more intensively than in a more humid setting (e.g. lEF). Since bioturbation intensity reflects moisture availability, their absence from the floodplain deposits might mean that the overbank areas were moist for only short periods of time during the uEF.

## CONCLUSIONS

Sedimentological and palaeontological studies of the Elliot Formation in Lesotho has provided new and crucial insights to the palaeoenvironmental setting in southwestern Gondwana during Late Triassic to Early Jurassic times. Our understanding of the depositional history of the upper Elliot Formation, in particular the details of the fluvial architectural elements is enhanced by the quality of the uEF exposures in Lesotho, most of which are in the new road-cuts of the Qacha's Neck District. New data on gross thickness of the Elliot Formation emphasize the importance of the southern boundary of the Kaapvaal Craton in basin development studies, and it highlights that it seems to have played a significant role in the development of thickness patterns during the deposition of the Elliot Formation. Palaeocurrent measurements in Lesotho complement those documented in South Africa (Bordy *et al.* 2004c), and indicate that the source of sediments shifted from a predominantly southern (i.e. Cape Fold Belt) to a mainly western source (probable basement high) from lEF to uEF times.

The fact that the transition between the different sedimentation styles corresponds to changes in palaeocurrent trends (and sandstone petrography for the South African

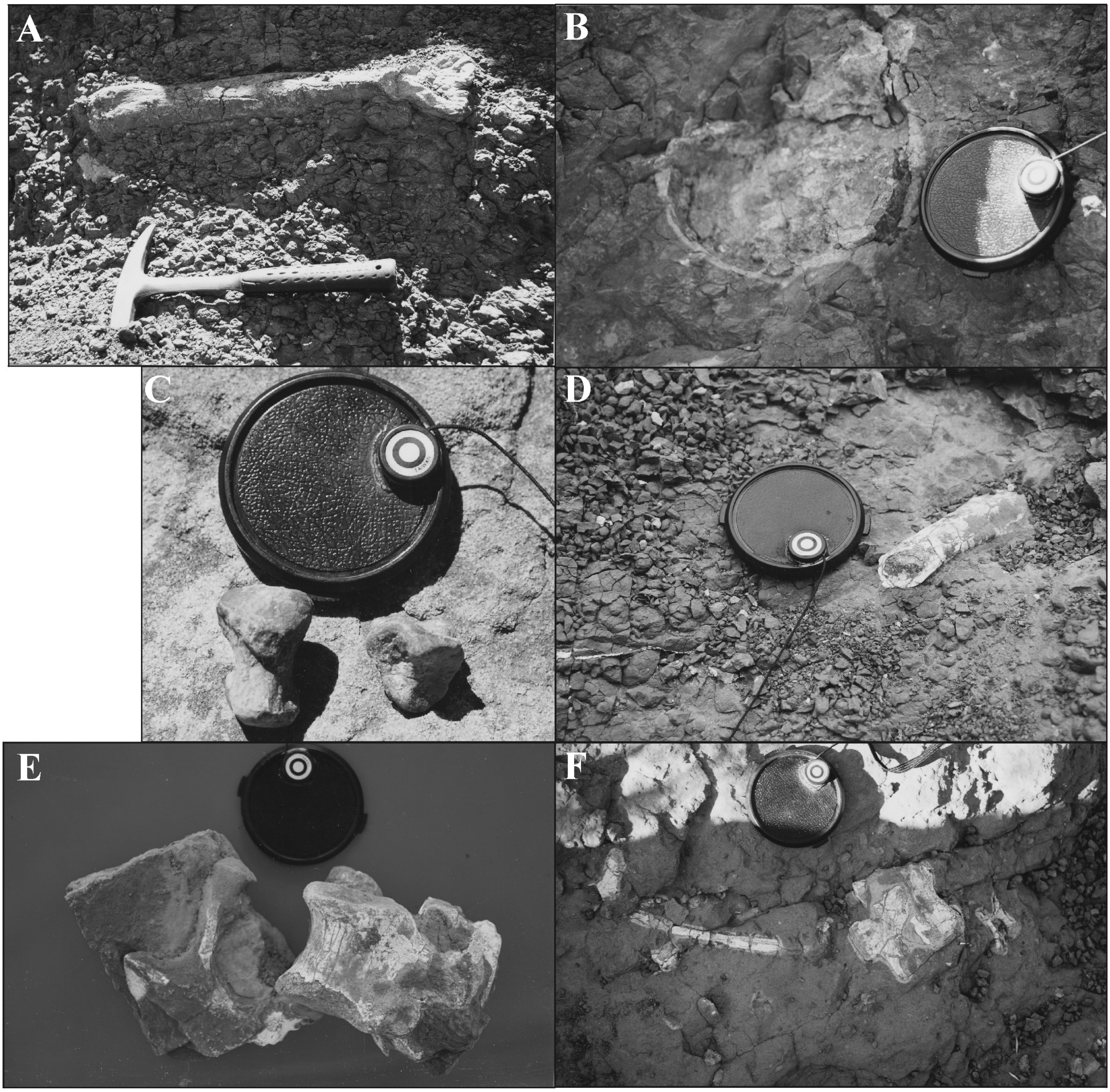

**Figure 18**. Fossil bones from the upper Elliot Formation. (**A, B, C**, Peka, Leribe District; **D**, Ha Noosi, Qacha's Neck District; **E**, Sehapa, Qacha's Neck District; **F**, Sekake, Qacha's Neck District. (Hammer (= 28 cm) and lens cap (= 5.8 cm) for scale.

samples) implies that the changes in the fluvial style in the Elliot Formation are primarily tectonic in nature. In particular, the geometry of the sandstone bodies (laterally impersistent lEF *vs* continuous uEF) and frequency of pedogenic alterations (rare in lEF *vs* common in uEF) indicate that the tectonic subsidence rate became reduced by the time of the uEF deposition. On the other hand, the increasing sandstone body frequency (e.g. amalgamated sandstones at the uEF/Clarens junction) and coarser grain-sizes in the upper part of the uEF suggest periods of slightly higher subsidence rates that were outpaced by even higher sediment supply rates (i.e. accommodation rapidly consumed by the overwhelming clastic input). The coarser grain sizes are explained by the gradual steeping of the foreslope which resulted in higher fluvial energy and thus in the supply of coarser sediments than in the lower part of uEF.

We suggest that in the light of the stratigraphic framework outlined above, the fossil trackway sites of Lesotho should be restudied, since their preservation and abundance may allow for a reinterpretation of Ellenberger's work, and once correctly stratigraphically positioned, would aid in biostratigraphical and palaeoecological studies of this important period of Gondwana's evolutionary history.

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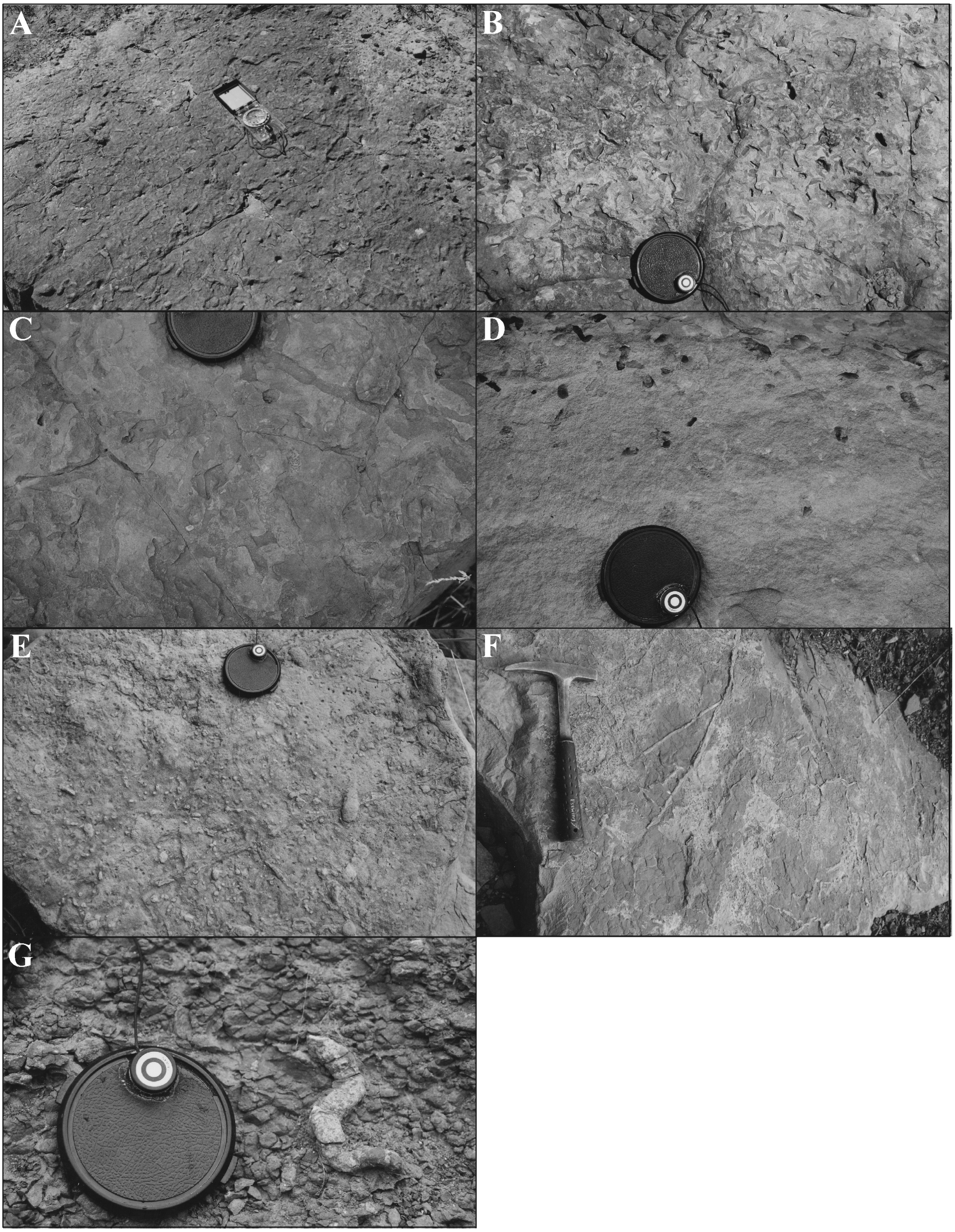


**Figure 19**. Bioturbation on upper bedding planes of sandstones are extremely rare in lower (**A**, Mauteng, Maseru District) and common in the upper Elliot Formation (**B**, Thaba Bosiu, Maseru District; **C, D, E**, Whitehill, Qacha's Neck District; **F**, between Whitehill and Malimong, Qacha's Neck District). Invertebrate trace fossils are also more frequent in upper Elliot Formation (**G**, between Whitehill and Malimong, Qacha's Neck District) mudstones than in the lower Elliot Formation. Open compass (= 14 cm), lens cap (= 5.8 cm) and hammer (= 28 cm) for scale.

regarding the Elliot Formation, and locating ichnofossil sites near Roma. Mrs N. Khitsane (Director of Culture: Ministry of Tourism, Culture and Environment, Lesotho) is acknowledged for her kind permission to undertake this study. The authors also wish to thank the late Prof. J.W. Kitching and Dr M.A. Raath for stimulating discussions regarding the palaeoenvironmental conditions of the Elliot Formation. We thank the two anonymous reviewers for their thoughtful comments on the original manuscript. Also, special thanks to Drs Mike Raath and Marion Bamford for their editorial support.

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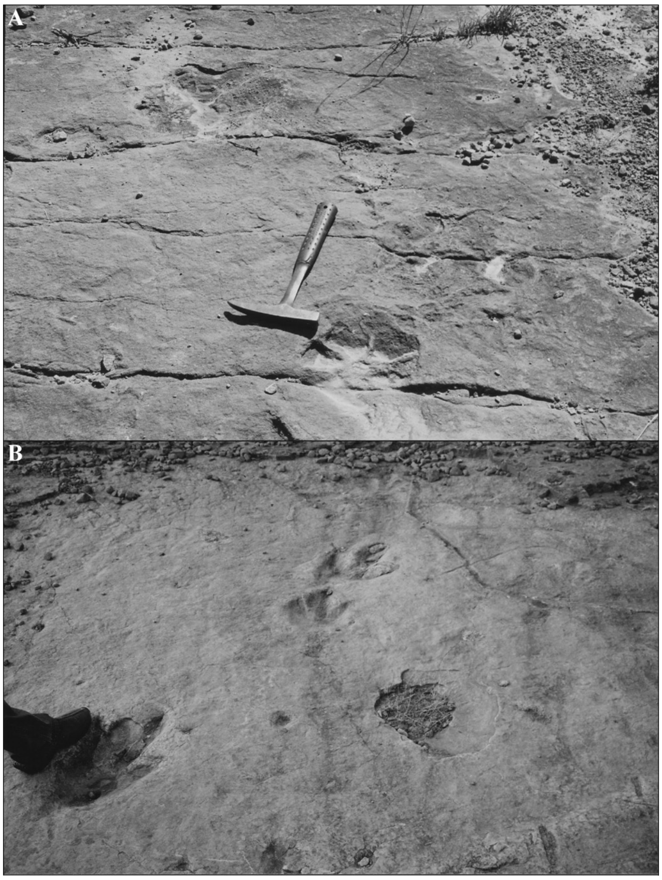


**Figure 20**. Footprints from the Elliot Formation. **A**, Four-toed(?) footprint in the lower Elliot Formation (Maphutseng, Mohale's Hoek District). Hammer for scale = 28 cm; **B**, Three-toed footprint in the uppermost upper Elliot Formation (Roma, Maseru District). Adult human foot for scale.

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