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The stratigraphy and sedimentology of the reservoir interval of the Kudu 9A-2 and 9A-3 boreholes

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The Kudu 9A-2 and 9A-3 boreholes were drilled from 1987 to 1988 as follow-up wells to test the extent of the Barremian gas-bearing sandstones encountered in the Kudu 9A-1 well which was drilled in 1974. The reservoir interval is subdivided into a Lower Non-Marine (Lower Gas Sand) and an Upper Marine Unit (Upper Gas Sand). The former includes the main reservoir in Kudu 9A-3 where it is thickest and comprises a medium-grained anhydritic sandstone which is interbedded with terrestrial basalts and volcaniclastic deposits. The massive nature of the sandstones and the presence of high-angle cross-bedding, anhydrite and well-sorted and well-rounded sand grains, suggest an aeolian origin, perhaps in a coastal dune complex. The vertically and laterally associated basalts and volcaniclastic deposits also show features of subaerial deposition. The volcaniclastic sandstones contain a high proportion of well-rounded and well-sorted sand grains in a red iron oxide-stained matrix and similar sand penetrates cracks in the extensively oxidised tops of the basalts. The thickness variations of the aeolian sandstones may relate to the control exercised on their deposition by the basalt topography. The Upper Marine Unit comprises alternations of very fine- to medium-grained sandstone, conglomerate, calcareous claystone, limestone and siltstone which were deposited in nearshore environments as evidenced by the abundance of shell fragments and the trace fossil Ophiomorpha. In addition, high-energy sedimentary structures together with conglomerates and carbonaceous material suggest periodic fluvial sediment supply to the shoreline. The facies that comprise the Lower and Upper reservoir sandstones both have the potential for extensive lateral development.

Introduction

The Kudu gas field lies off the southern coast of Namibia, 130 km due west of the Orange River mouth (Fig. 1). This paper deals with the stratigraphy and sedimentology of the reservoir target interval of two follow-up boreholes, Kudu 9A-2 and 9A-3, which were drilled from 1987 to 1988 in order to test the extent of the reservoirs intersected by ,he discovery well, Kudu 9A-1, in 1974. Work is based on information contained in unpublished reports by Marot *et al*. (1988) and Wickens and McLachlan (1988), which were commissioned by Swakor (Pty) Ltd, the Namibian petroleum exploration agency. This report also draws on geological and technical information from logs and operational data set out in the well-site data summaries (Soekor Drilling Geology Section, 1988a,b).

A total of 227 m of recovered core was available for study from the two boreholes and sidewall cores and cuttings were used where necessary. Observation and interpretation were significantly aided by the preparation of black and white photographs of the split core on a scale of 1 :4. No geophysical log correlation was attempted but log-shape motifs were used to aid the interpretation of depositional environments and the dipmeter logs proved useful in understanding the nature of the main (Lower Gas Sand) reservoir sandstone. Sedimentary profiles have been constructed and displayed against geophysical logs to illustrate the vertical facies arrangement (Figs 2 and 3).

All depths referred to are drillers' depths given as metres below kelly bushing (mbKB) which refers to a measurement datum on the rig which lies about 26 m above sea level.

Proposed correlation

It is convenient to describe the stratigraphy and sedimentology of the two boreholes by making use of the correlation set out in Fig. 1. The correlation is simplistic in that it serves to relate the sequence of lithologies in the studied wells without reference to the Kudu 9 A-I well which lies 7.5 km south of Kudu 9A-2 and 4km to the north of Kudu 9A-3. This has been necessary because little sample material is available from Kudu 9A-1 and it was therefore not included as part of the original unpublished technical studies.

The lithological correlation might represent, to an extent, a chronostratigraphic correlation, as the Kudu wells lie along depositional strike. The main transgressive event above the top of the highest lava in each well may hence be synchronous.

The studied intervals of the boreholes can be divided into two major parts (Fig. 1):

- a Lower Non-Marine Unit incorporating the whole of the Lower Gas Sand of Kudu 9A-3 and possibly part of the Lower Gas Sand of Kudu 9A-2. This unit includes basalt, anhydritic aeolian sandstone and volcaniclastic sandstone;
- an Upper Marine Unit incorporating the Upper Gas Sand of both wells and possibly part of the Lower Gas Sand of Kudu 9A-2. It also includes limestones and volcaniclastic sandstones.

Shelly material indicative of shallow-marine conditions is not present below 4413.00 m in Kudu 9A-2 and 4348.50 m in Kudu 9A-3, with the minor exception of a thin shelly unit at the base of correlation unit B. The non-marine/marine sedimentation boundary marks a significant change in depositional environment and may well be associated with an unconformity at, or close to, the top of the highest lava in each borehole.

Distinctive sedimentary facies (including the basalts) have been recognised and interpreted in terms of their depositional environments and history, possible geometry and lateral extent.

Sediments containing clasts of volcanic rocks are

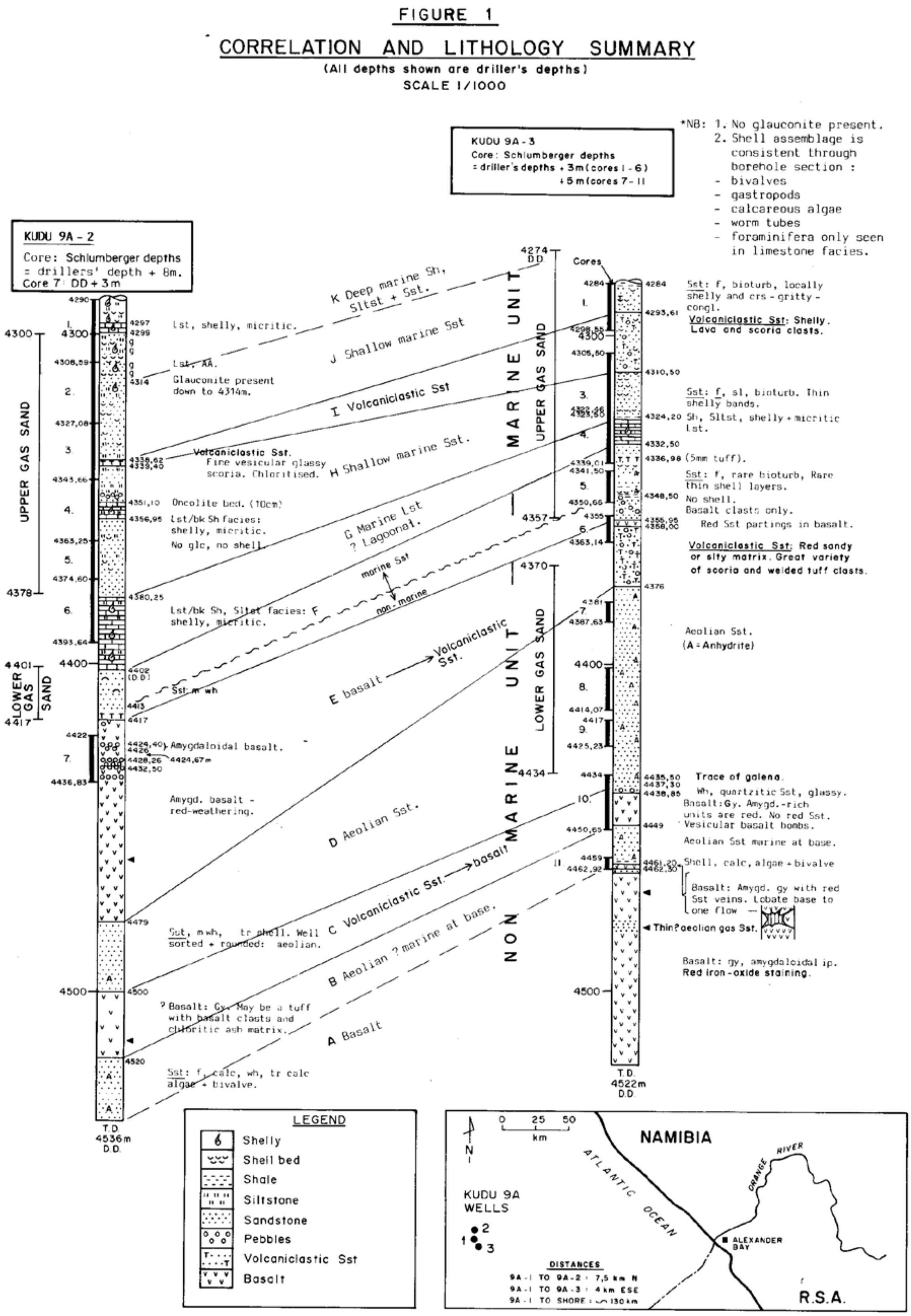

Fig. 1: Locality map, proposed correlation and lithological summary.

SEDIMENTARY PROFILE : KUDU 9A-2

FIG. 2

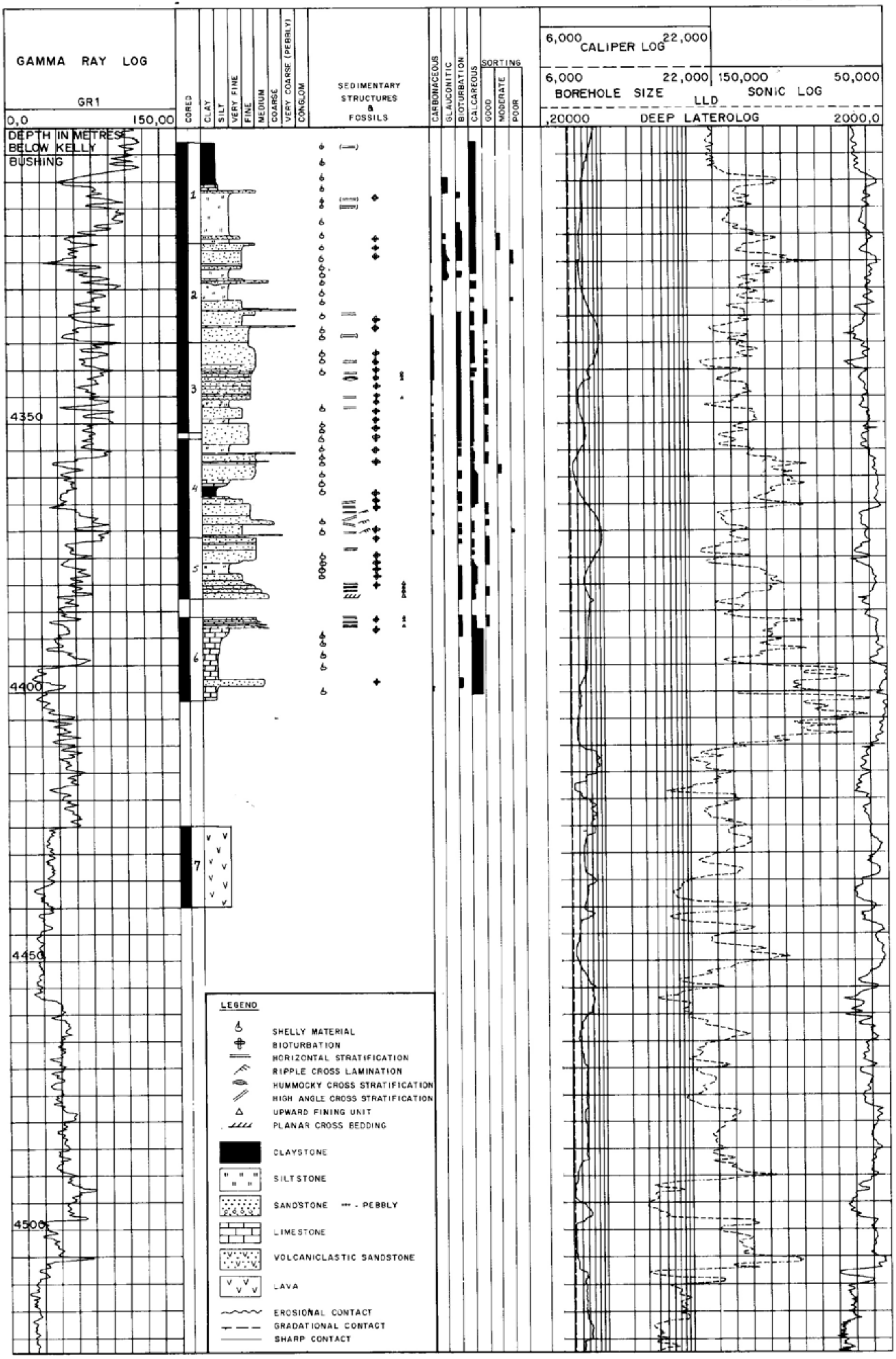

Fig. 2: Sedimentary profile, Kudu 9A-2.

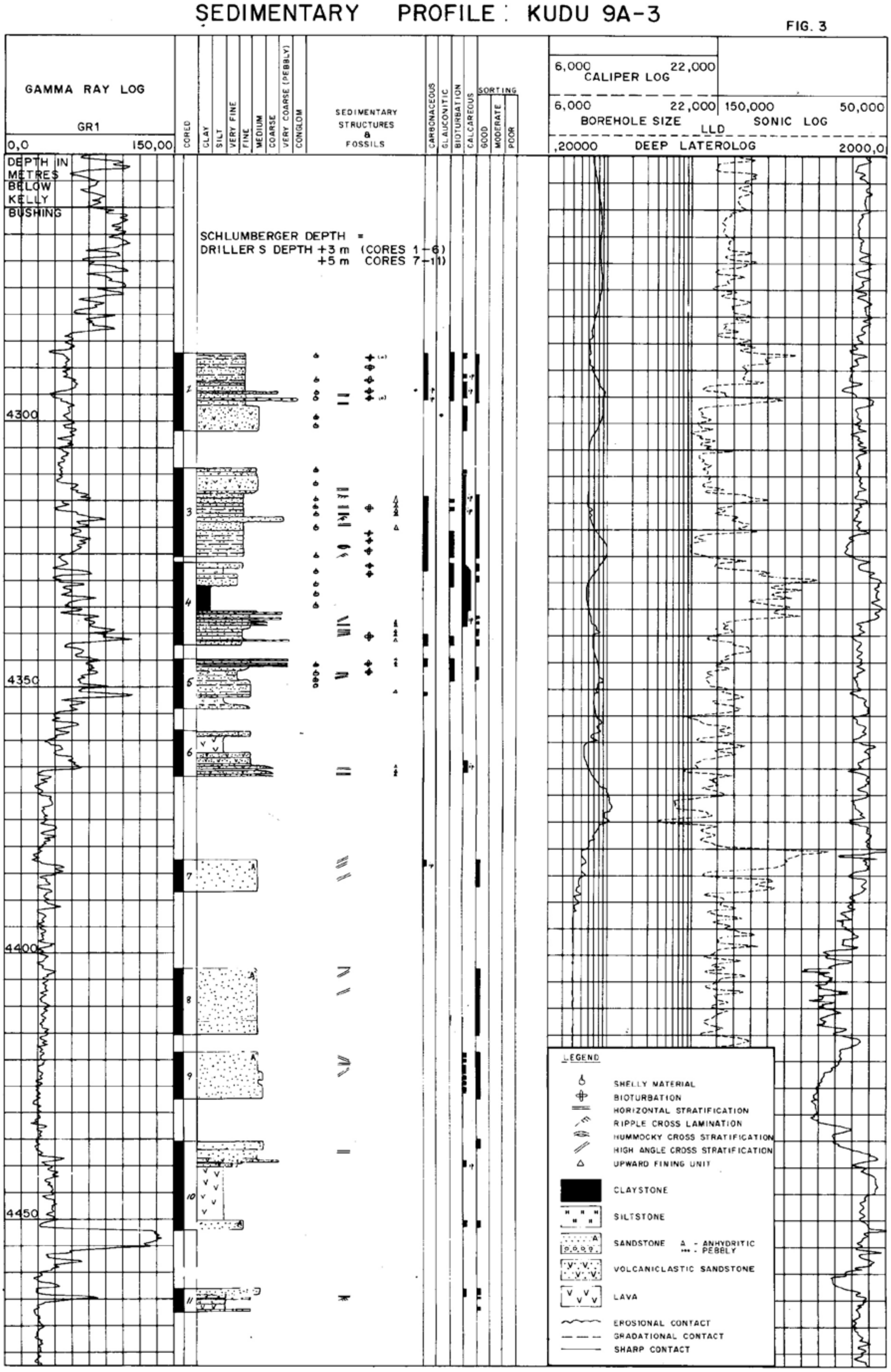

Fig. 3: Sedimentary profile, Kudu 9A-3.

common in the reservoir target intervals of the Kudu wells. They fall naturally into two groups: the first includes sandstones containing rounded clasts of volcanic rocks as a distinctive but typically minor component and the second group includes sediments which are typically dark in colour due to an abundance of angular vesicular volcanic clasts, which resemble pyroclasts, as well as eroded clasts of basalt. The latter could be referred to as tuffs or tuffaceous sandstones but, as they have not been examined in detail, it is considered best at this stage to refer to them by the non-genetic term "volcaniclastic sandstone" (cf. Cas and Wright, 1987). Their nature and possible mode of origin will be discussed further in the report.

Stratigraphic description and interpretation

The facies recognised are (see Fig. 1):

Facies 1: Basalt (correlation units A, C, E).

Facies 2: Volcaniclastic sandstone (correlation units C, E, I).

Facies 3: Anhydritic (aeolian) sandstone (correlation units B, D).

Facies 4: Very fine- to medium-grained sandstone (correlation units F, H, J, K).

Facies 5: Coarse/pebbly to conglomeratic sandstone (correlation units F, H, J).

Facies 6: Calcareous claystone (calcilutite) (correlation units G, H, K).

Facies 7: Shelly and micritic limestone (correlation units G, H, K).

Facies 8: Siltstone (correlation unit K).

Facies 1: Basalt (correlation units A, C, E)

The basalts are confined to the Lower Non-Marine Unit. A total of 72 m was intersected in Kudu 9A-3 and 62 m in Kudu 9A-2 and it is probable that a significant additional thickness exists below the total depths of the boreholes. The correlation shown in Fig. 1 suggests that a number of different basalt flows are present and that laterally they not only vary significantly in thickness but that they also correlate with volcaniclastic sandstones. The latter, because they have a high proportion of basalt and/or glassy basaltic clasts, can easily be mistaken for lava, especially in drill cuttings. All of the lavas appear visually very similar. Major element analyses conducted on cores from Kudu 9A-1 in 1979 by Berkstrom and Bakker (Pty) Ltd, for Soekor (Soekor unpubl. data) show the lava to be a high-magnesium alkali basalt which differs in composition from those described from onshore in southern Africa (Duncan *et al.*, 1984). Both amygdaloidal and massive basalt are present. The amygdales typically consist of zeolite, calcite, quartz, jasper, chlorite and, less commonly, epidote. Despite the fresh appearance of the lavas, ferromagnesian minerals and volcanic glass are commonly extensively chloritised and alteration to red iron oxide is also widespread.

The cored intersections were carefully examined for signs of subaqueous emplacement but no convincing supportive evidence was found. It is concluded for the following reasons that the basalts were essentially subaerially emplaced:

- the adjacent sediments were predominantly subaerially deposited (see later);
- the lavas show no evidence of the extensive spalling and hyaloclastic brecciation or glass shard formation that would be expected in subaqueous flows (Cas and Wright, 1987; Fisher and Schmincke, 1984);
- red iron oxide alteration typical of terrestrial weathering is ubiquitous in the lava (Cas and Wright, 1987);
- rounded structures in Kudu 9A-2, core 7 (e.g. ca. 4430-4431 m), which could be construed as pillows, are not associated with hyaloclastic shards and are believed to be lava bombs instead.

It seems likely that an erosional unconformity separates the highest basalt (at least in Kudu 9 A - 3) from the overlying beds of the Upper Marine Unit. The top of the lava in core 6 is bored and pitted and resembles a marine hard-ground surface.

Facies 2: Volcaniclastic sandstone (correlation units C,E,I)

This facies (Fig. 4) is complex as it includes a variety of clasts of different origins. Its overall characteristic is the presence of a high proportion of volcanic clasts including eroded basalt clasts, basalt clasts with chilled margins, and basaltic glass in the form of scoria or eroded clasts or shards, all in sizes ranging from ash through lapilli to bombs. The glassy material is typically chloritised. Sand- and silt-size grains of quartz are present in variable proportions as dispersed material and the facies lacks clear evidence of traction structures and appears massive except for crude upward-fining cycles, e.g. core 6 of Kudu 9A-3 (Fig. 4).

The volcaniclastic facies occurs at three different levels which are discussed in turn:

Correlation unit C

The volcaniclastic sandstone facies is present only in Kudu 9A-2 where no cores were cut and its recognition is based on stereomicroscope and thin section study of cuttings and a single sidewall core. It consists of rounded clasts of amygdaloidal basalt set in a chloritised glassy matrix.

Correlation unit E

This facies is best developed in Kudu 9A-3 but is represented also by a thin unit (<5 m thick) at the top of the uncored section of basalt above core 7 in Kudu 9A-2.

In Kudu 9A-3 core 6, where this facies is capped by a thin basalt, it varies in colour from greenish grey to pink depending on the ratio of green chloritised basalt or scoria clasts to pink iron oxide-stained sand grains.

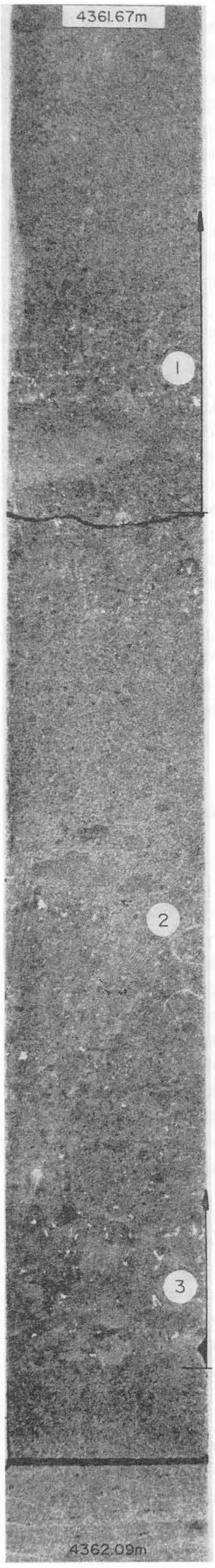

Fig. 4: Core 6, Kudu 9A-3. Upward-fining cycles in volcaniclastic sandstone;
1. base of upward-fining unit;
2. eroded basalt clasts set in green chloritic matrix;
3. base of upward-fining unit.

These sand grains are strikingly well rounded and well sorted. The volcanic clasts vary in size from ash to lapilli. The ash-sized grains are typically angular and vesicular glassy clasts that resemble pyroclasts. In some cases they have been compressed and resemble welded tuffs. The coarser clasts are typically vesicular basalt.

Correlation unit I

This volcaniclastic facies is similar to that of correlation unit E but red iron oxide weathering is less apparent. It contains up to 50% sandy material in places and pebble- and sand-size clasts of shelly micritic limestone similar to that of correlation unit G. Fragments of marine bivalves are present throughout.

Interpretation

The consistent presence of volcanic scoria together with the proximity of lavas of the same composition suggests that some of the sediments included in this facies originated from pyroclastic surge or air-fall processes. However, because of the widespread presence of non-volcanic sediment grains, it seems wise to follow Cas and Wright's (1987) use of the non-genetic term "volcaniclastic" where the origin of the facies is uncertain.

There is a clear association of the volcaniclastic sandstones with the basalts in the Lower Non-Marine Unit and it is possible that the facies resulted from the remobilisation and mass-flow redistribution of unstable accumulations of sedimentary and pyroclastic deposits on the flanks of the eruption centres. This could have taken place in a continental environment, as appears to be the case in correlation units C and E, since there is no palaeontological evidence of a marine depositional environment. In the case of unit E, the well-rounded and well-sorted sand grains present in the volcaniclastic sandstones are considered to have been introduced by aeolian transport. In correlation unit 1, the presence of marine shell and the shallow-marine nature of the adjacent sediments indicate deposition in a shallowmarine environment. The high proportion of scoria in some of the thin bands suggests, however, that some of these may have been deposited directly as pyroclastic air-fall deposits resulting from contemporaneous igneous activity.

Facies 3: Anhydritic (aeolian) sandstone (correlation units B, D)

This facies is confined to the Lower Non-Marine Unit of the boreholes (Fig. I) and constitutes the bulk of the Lower Gas Sand of Kudu 9A-3. The total thickness of the anhydritic facies in this borehole is 73 m and there are, in addition, thin sandstones of similar appearance within the underlying basalt (e.g. the thin gas-bearing sandstone at 4478 m to 4482.50 m in Kudu 9A-3). It correlates with uncored anhydritic sandstones in Kudu

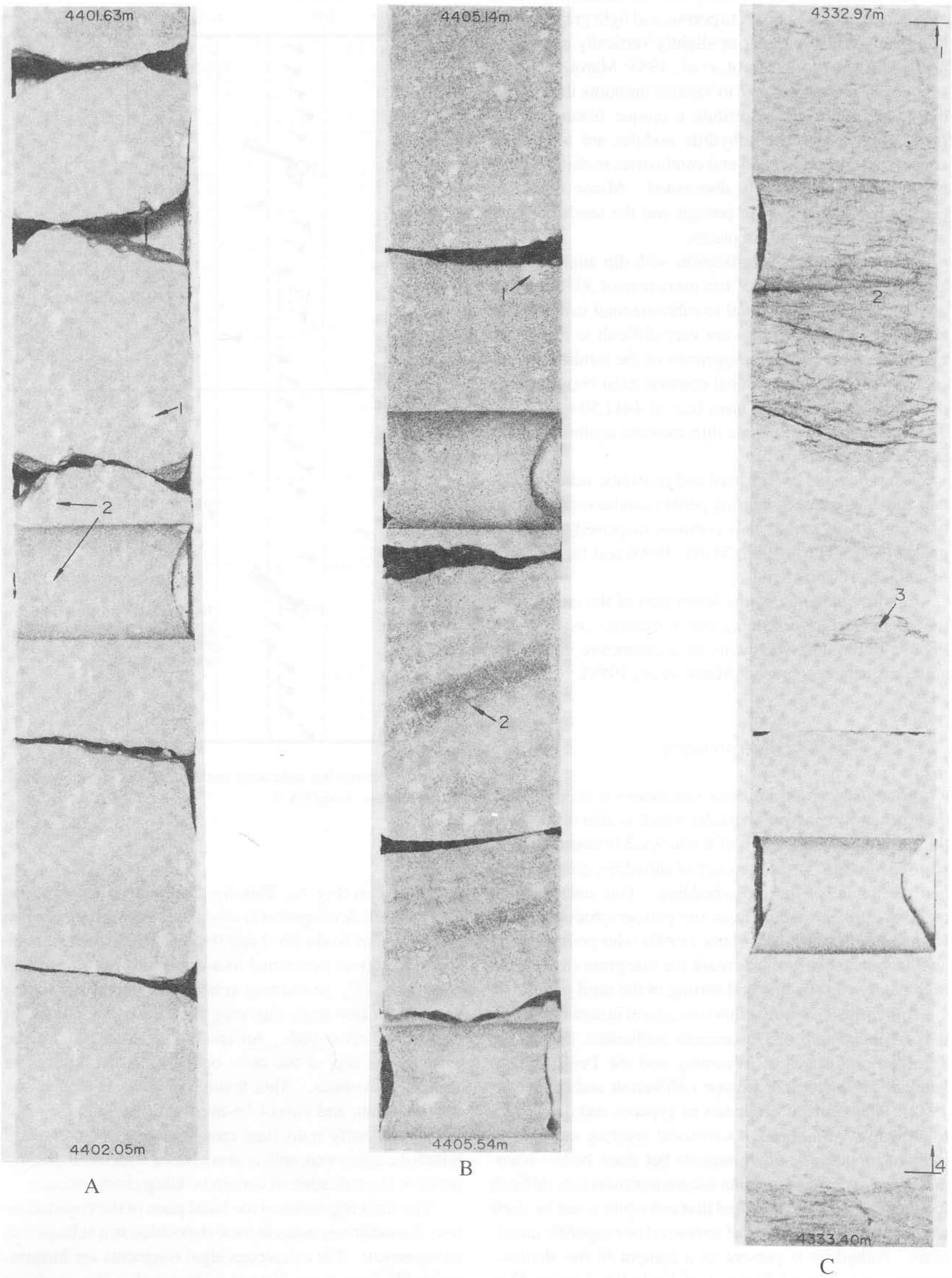

Fig. 5A: Anhydritic sandstone facies; 1 and 2 - circular and elongated anhydrite nodules.
B: Anhydritic sandstone facies; 1 - anhydrite nodule; 2 - cross-stratification.
C: Very fine- to medium-grained sandstone facies; 1 - top of bed; 2 - bioturbated zone; 3 - *Ophiomorpha nodosa* burrow; 4 - erosional base of bed.

9A-2 which total 37 m in thickness.

The sandstones are typically fine- to medium-grained, well sorted, slightly porous to porous and light grey to white in colour. White, circular or slightly vertically elongated, nodules of anhydrite (Marot, *et al.*, 1988; Marot, 1990) up to 1 cm in diameter occur in various amounts throughout these sandstones and constitute a unique feature of this facies (Fig. 5A). The anhydrite nodules are sometimes concentrated in clusters several centimetres in diameter, but generally occur randomly distributed. Minor specks of carbonaceous material are present and the sandstones are very slightly calcareous in places.

Large-scale cross-stratification with dip angles generally in the order of 20 to 25° to a maximum of 30° alternates with massive and horizontal to subhorizontal stratification (Fig. 5B). Bedding planes are very difficult to recognise, mainly because of the homogeneity of the sandstones, except where irregular erosional contacts exist between beds of slightly different grain sizes (e.g. at 4411.50 m in Kudu 9A-3) and where high-angle dips truncate against horizontally bedded layers.

The sandstone is very hard and quartzitic near the contact with a basalt clast-bearing pebbly sandstone in core 10 of Kudu 9A-3, which also contains dispersed specks of galena (Marot *et al.*, 1988; Marot, 1990) and fine laminae of carbonaceous material.

In both boreholes, in the lower part of the correlation unit-B anhydritic sandstone, shelly material consisting of bivalve debris and fragments of a distinctive calcareous algae has been recognised (Marot, *et al.*, 1988).

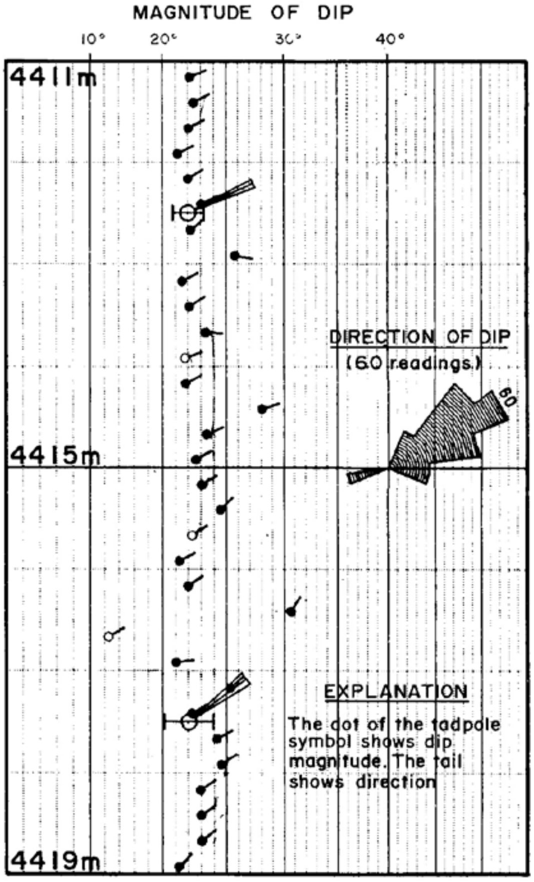

Fig. 6: Dipmeter log indicating uniform dip direction of aeolian sandstone, Kudu 9A-3.

Interpretation

An aeolian origin for these sandstones is supported by their generally massive character which is also reflected in the gamma-ray-log pattern of Kudu 9 A- 3 between 4365 m and 4435 m (Fig. 3), the presence of anhydrite, good sorting, and the nature of the cross-bedding. This interpretation receives further support from the petrographic studies of Marot *et al.*, (1988) and Marot (1990) who point out that angular quartz overgrowths mask the true grain size and the high degree of rounding and sorting of the sand grains.

Anhydrite is the most common cement in aeolianites and it is frequently present in ancient aeolianites, e.g. in the Tensleep sandstones of Wyoming and the Permian Rotleigendes Formation of Europe (Ahlbrandt and Fryberger, 1982). This mineral originates as gypsum and dehydrates to anhydrite with burial. Occasional layering may reflect interdune evaporitic environments but since bedset boundaries are very vague, aeolian sub-environments are difficult to identify. It should be noted that anhydrite is not by itself an unambiguous indicator of terrestrial or evaporitic conditions. Anhydrite is present as a cement in the shallowmarine sandstones of Facies 4 of Kudu 9A-3 up to 20 m above the top of the Lower Non-Marine Unit (Marot, 1990).

The dipmeter log over the interval 4410 m to 4420 m in Kudu 9A-3 indicates a very uniform dip direction which suggests a wind transport direction towards the east to east-northeast (Fig. 6). This dipmeter pattern and direction is not as well developed or is absent elsewhere in the aeolian sandstones of Kudu 9A-2 and 9A-3. The dip angles in the cores vary from horizontal to a maximum of 30° with an average of 25°. In addition to horizontal stratification, the presence of low-angle dips may represent avalanche toeset beds of the cross-beds. An upward increase in dip angle towards the top of the cross-bed set is characteristic of aeolian cross-beds. This feature is not reflected in the dipmeter data and cannot be used with confidence in the cores to identify individual cross-bed sets. The angle at which the cores were split is also a factor which complicates positive identification of certain bedding characteristics.

The shell fragments in the basal parts of the correlation-unit-B sandstones indicate local deposition in a subaqueous environment. The calcareous algal fragments are indistinguishable from those that are widespread in the overlying shallow-marine sediments and further suggest a similar shallow-marine environment. It seems likely that the aoelian sandstones were deposited in a coastal environment as part of a dune complex.

Facies 4: Very fine- to medium-grained sandstone (correlation units F, H, J, K)

This facies is confined to the Upper Marine Unit of the two boreholes. It is characterised by the general presence of shell fragments, carbonaceous claystone laminae with mica flakes, intensive bioturbation (Fig. 5C), upward-fining cycles and small-scale tractional structures. The sandstones are mostly tight, fine- to very fine-grained, light grey to dark grey, moderately to well sorted and calcareous to very calcareous in places where closely associated with abundant shell fragments. The shell fragments are often concentrated in the basal part of beds with erosional lower contacts (Fig. 5C) and vary from large fragments of thick-shelled bivalves, to comminuted thin-shelled bivalves, gastropods and calcareous algae. Scattered grains of glauconite, sometimes in association with scattered well-rounded quartz grains, only occur (above 4315.60 m) in cores 1 and 2 of Kudu 9A-2 (Fig. 2). Fig. 1 suggests that glauconite is absent from Kudu 9A-3 cores because coring started at a lower stratigraphic level. The lower extent of glauconite in Kudu 9A-2 coincides with the lower limit of planktonic foraminifera and radiolaria as recorded by McMillan (1988). Fine carbonaceous material and occasional coalified wood fragments, mostly pyritised, are also present.

Bedding-plane contacts are easily recognised where upward-fining units with erosional contacts occur and where this facies alternates with claystone, siltstone, conglomeratic sandstone and volcaniclastic deposits. At certain levels bedding planes are totally destroyed by intensive bioturbation. Bed thickness varies from a few centimetres to more than 1 metre. Well-developed upward-fining units, sometimes cyclically arranged, occur, for example, in core 3 of Kudu 9A-3 and core 5 of Kudu 9A-2 with thicknesses of 20 to 76 cm (Fig. 5C). These units often have an accumulation of shell fragments and/or medium to gritty sand as basal lag deposits. Pebble lags, mainly of lava, are also present. In Kudu 9 A - 3, this facies contains varying amounts of volcanic material, e.g. immediately above the contact with the volcaniclastic sandstone in core 1 and above the erosional contact with the lava in core 6.

Eroded pebble-size clasts of basalt are present in the lower part of core 5 in Kudu 9A-3 (4349 m to 4350.60 m) and have been included in this facies for convenience although this unit really represents a subfacies. It lacks shelly material and is strongly calcified in places and doubtless represents a different depositional environment.

Primary sedimentary structures include parallel lamination, ripple cross-lamination, planar cross-stratification (Fig. 7 A), small-scale trough cross-stratification and possible hummocky cross-stratification. The latter two types are not easily identifiable in cores because they are relatively large structures and the angle at which the fore set laminae are observed can lead to misinterpretation. High-angle cross-stratification, possibly related to the migration of medium- to large-scale ripples in a channel, occurs in beds with thicknesses up to 1 m in Kudu 9A-2 (Fig. 7A). Slightly curved stratification at 4334 m in Kudu 9A-2 may represent hummocky cross-stratification. Upward-fining units are normally characterised by parallel lamination, followed by ripple cross-lamination. Where intense bioturbation occurs, the sandstones have a massive appearance, e.g. in the upper part of core 1 of Kudu 9A-3.

Bioturbation is common throughout this facies in both wells and the most prominent burrows are of horizontal to subvertical *Ophiomorpha nodosa* (Fig. 7B). The walls of these burrows, which vary in diameter from 0.5 to 2 cm, are lined with dark carbonaceous claystone pellets and compare with those made by modem callianassid shrimps (Curren, 1985, p. 266).

Other trace fossils include burrows which resemble *Macaronichnus segregatis* (Curren, 1985; burrow walls lined with a concentration of micaceous material that forms a distinct rim which is darker than the burrow fill and the surrounding matrix), *Helminthoida* (Crimes, 1975; 0.5 mm diameter horizontal winding traces) and *Thallasanoides* (Crimes, 1975), especially in cores 4 and 5 of Kudu 9A-2.

Interpretation

The abundance of shell fragments and the dominant presence of the trace fossil *Ophiomorpha* are the first indications of deposition in shallow, shoreline-restricted environments for the bulk of this facies. The presence of carbonaceous material and carbonaceous claystone laminae, occasional coalified wood fragments and the association of this facies with thin, gritty to conglomeratic layers (Facies 5), indicate terrestrial sediment supply to a shallowmarine environment where it has been reworked under moderate-energy conditions. *Ophiomorpha* generally seems to be restricted to the littoral or shallow littoral zone and normally occurs in neither fresh nor deeper marine water (Crimes, 1975). Its association with the other types of trace fossils mentioned above is quite common in lower to upper shoreface deposits (Howard, 1972; Leckie and Walker, 1982; Curren, 1985; Balseley, 1986). The cyclic deposition of upward-fining units with lower erosional contacts, concentration of shell fragments and pebbly lags in places, and the occurrence of possible hummocky cross-stratification, but mostly parallel lamination, may represent reworking of sediments by moderate storms in a lower shoreface environment. The lower energy sedimentary structures such as wave- and current-ripple cross-lamination mark the resumption of fair weather conditions, but are rarely preserved as a result of intense bioturbation. Slow sedimentation between episodes of sand deposition creates optimal living conditions for filter feeders such as callianassid shrimps and polychaete worms (considered responsible for the trace fossils *Ophiomor-*

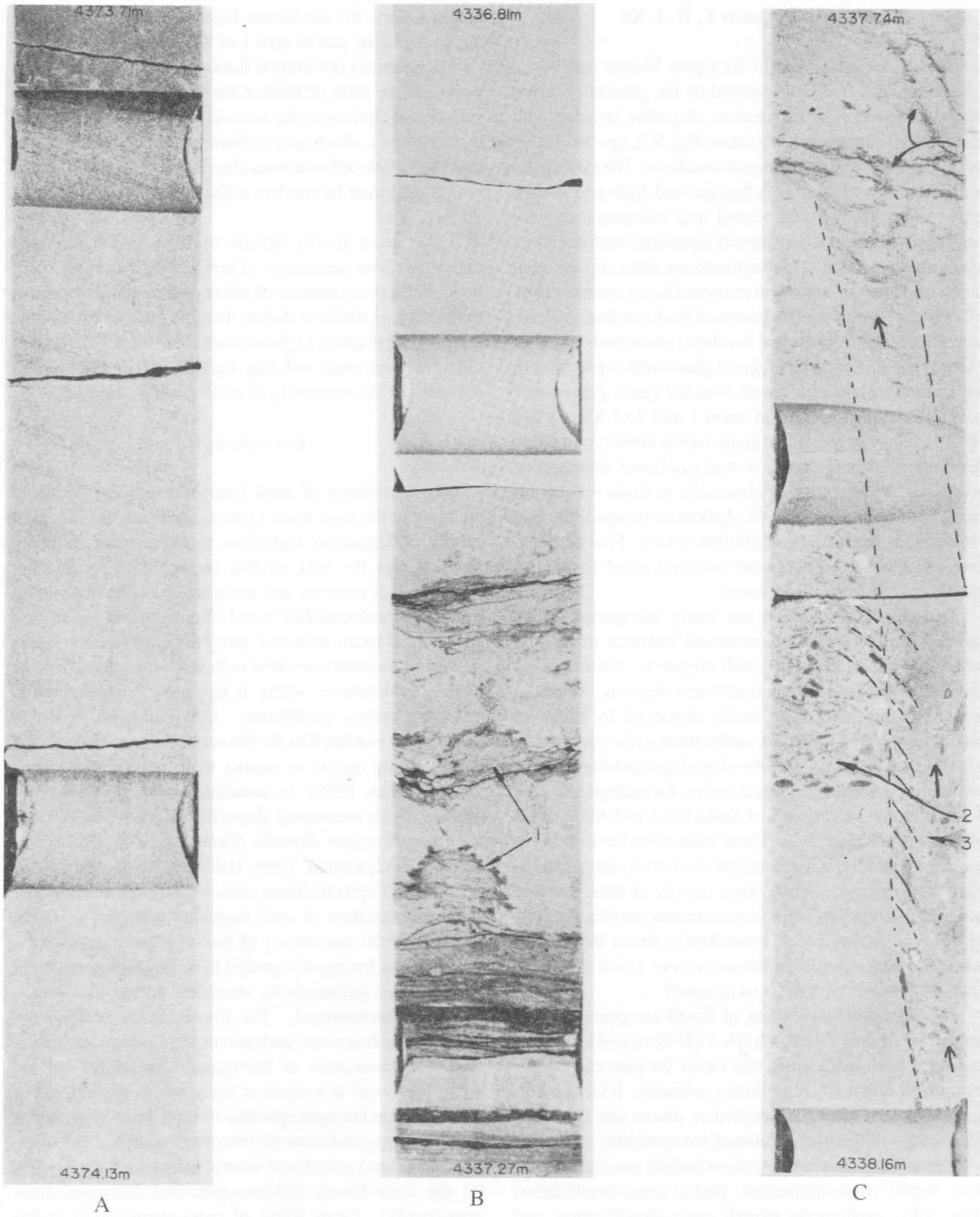

Fig.7A: Facies 4 sandstone showing planar cross-stratification (bed approximately 1 m thick).
B: Facies 4 sandstone with horizontal *Ophiomorpha* burrows; 1. faecal pellets lining the walls of burrows.
C: Facies 5 sandstone. Escape burrow with conglomeratic material as backfill; 1. bifurcating traces of *Ophiomorpha*; 2. conglomeratic layer showing downward drag of grains; 3. centre of burrow filled with sand overlying the conglomerate bed.

pha and *Macaronichnus*, respectively). Other forms of cross-stratification in this facies (e.g. planar-tabular cross-beds) could have resulted from the migration of sandbars in various parts of the shoreface environment during deposition from storm-generated unidirectional currents.

The various sub-environments of deposition in the shore zone are difficult to define from cores and it is believed that some of the sandstone beds that do not show typical features of shoreface deposition were deposited in closely related environments, such as tidal-inlet channels, ebb- and floodtidal deltas, spit-bars and washover fans.

Facies 5: Coarse/pebbly to conglomeratic sandstone (correlation units F, H, J)

This facies is confined to the Upper Marine Unit and individual upward-fining sandstone beds have medium-grained to pebbly lags near their bases (Fig. 8A). It is also associated with erosional contacts and sometimes with high-energy traction structures. Good examples of this facies are associated with cyclic deposition, viz. cores 4 and 5 of Kudu 9A-3. An 8 cm thick burrowed conglomeratic layer (Fig. 7C) occurs at 4338.02 m in Kudu 9A-3, where it forms the basal lag of an upward-fining sandstone bed. The clasts are mainly well-rounded volcanic pebbles. Possible reverse grading, which may indicate gravity-flow deposition, has also been observed.

Thin conglomeratic layers consisting of clasts of volcanic rock, quartz and shell fragments occur above the volcaniclastic sandstone in core 2 of Kudu 9A-3.

The volcaniclastic sandstones also have coarse pebbly material, mainly well-rounded basalt clasts, at the bases of upward-fining cycles. A conglomeratic unit with eroded basalt clasts in a sandy matrix occurs just above the basalt contact in core II of Kudu 9A-3.

Interpretation

The coarse to pebbly clastics are mainly associated with Facies 4 sandstones. Their presence in the depositional environments inferred for Facies 4 can be explained by the proximity of rivers as a source for coarse clastics and storm-generated gradient currents as the transporting agents for these sediments to the lower-shoreface environment, where subsequent reworking as lag deposits occurred. Where long vertical escape burrows and large-scale cross-stratification occur, deposition was probably very rapid, from bed-load transport in subtidal channels or from storm-generated density currents. In modem oceans, the only known processes are storm-generated bottom-rip or density currents. A similar mode of transport was proposed for the conglomerate bodies in the Cretaceous Gates Formation, British Columbia (Leckie and Walker, 1988).

The thin pebbly lag deposit at the base of a siltstone layer in core 3 of Kudu 9A-2 may represent remnant deposits on an erosional surface following a transgression.

The abundance of lava pebbles suggests that at least some of the coarse clastics were derived locally from the underlying basalt and/or from the underlying or interbedded volcaniclastic sandstones.

Facies 6: Calcareous claystone (calcilutite) (correlation units K, H, G)

This facies is confined to the Upper Marine Unit. It occurs in cores I and 4 of Kudu 9A-2 and in core 4 of Kudu 9 A- 3. It is closely associated with limestone and calcareous siltstone in the Upper Marine Unit and has gradational upper and lower boundaries. In colour it is dark grey to dark brown with lighter shades corresponding to more calcareous intervals (Fig. 8B). Comminuted and large shell fragments (replaced by pyrite) occur throughout. The claystone is very calcareous and grades into limestone where large concentrations of shell fragments occur. Pyrite commonly replaces carbonaceous material and sometimes forms thin laminae. Oncolites are present at 4332.53 m in Kudu 9A-3 (Fig. 9). They show a characteristic cellular texture in thin section which allows very fine grains in sandstones to be recognised as having originated from fragmented oncolites. This algal material is referred to as “calcareous algae” in the text and figures.

Interpretation

The presence of abundant and diverse shell fragments and the association of this facies with shelly limestone and shallow -marine sandstone (Facies 4) indicates deposition in a quiet, low-energy marine environment. Siesser (1972a) suggested that algal nodules (such as the oncolites noted above) formed optimally in shallow water between low -tide level and 10m but that there was evidence to suggest growth in water as deep as 100 m. It is also possible that the oncolites were reworked into the facies 6 sediments from a shallower environment as evidenced by the septarian fractures (Fig. 9) which suggest subaerial exposure. These conditions could occur in a very shallow and protected environment behind a beach-barrier complex, as in the case of a nearshore lagoon, or they could also occur in a relatively deep-water environment below effective wave base.

The close association of this facies with calcareous siltstone, shelly limestone, glauconite, radiolaria and planktonic foraminifera in core I of Kudu 9 A-2 suggests, for this interval only, a relatively deeper environment in the offshore, well below effective wave base. The occurrence at 4354 m (core 4) in Kudu 9A-2 is underlain by an assemblage of facies which differ from the typical sand deposits in the lower-shoreface environment, as suggested for Facies 4. The relatively non-bioturbated, low-angle stratified sandstone could be representative of deposition in a foreshore or tide related subenvironment prior to the development of lagoonal conditions. In Kudu 9A-3, this facies is associated with non-shelly, less bioturbated sandstones with basal gritty lag deposits. This probably reflects a shifting regressive shoreline situation which is ideal for the development of lagoonal conditions, perhaps in an interdistributary bay setting. The overlying bioturbated shelly sandstone may represent the progressive change to shallow-marine conditions.

Facies 7: Shelly limestone (correlation units G, H, K)

This facies is best developed in core 6 of Kudu 9A-2. Minor limestone development occurs in close association with Facies 6 in cores I and 4. Similar limestone occurs in core 4 of Kudu 9A-3.

The limestone in core 6 of Kudu 9A-2 is dark grey to dark brown due to the presence of clay and organic material. It is typically micritic and contains variable amounts of intact and comminuted thin-walled bivalve fragments and pyrite. Stylolite development has resulted in a characteristic texture of interlocking, irregular and lenticular limestone lenses separated from each other by stylolitic contacts along which shale and organic material are concentrated (Fig. 8C). A well-sorted, fine- to medium-grained sandstone with relatively sharp upper and lower contacts occurs interbedded with the limestone between 4389.66 m and 4391.03 m. The upper half contains *Ophiomorpha* while the lower half shows near-horizontal stratification.

The fossil assemblage consists of bivalves, gastropods, whole and fragmented oncolites, possible ostracodes and rare benthonic foraminifera. The irregular lumps of cellular shelly material at 4393.3 m in Kudu 9A-2, core 6, that resemble coral or bryozoa are colonial calcareous worm tubes. Coalified wood fragments are frequently present.

The calcareous claystone in core I of Kudu 9 A-2 is very shelly below 4297.54 m and can be regarded as a limestone. The limestone has a lenticular texture as a result of dissolution and stylolite formation. Shell fragments, mainly bivalves, are concentrated at the base of upward-fining cycles (Fig. 8C). Glauconite and secondary pyrite are present in variable amounts. The limestone occurrence in core 4 is similar to that in core 1 but lacks the glauconite, planktonic foraminifera and radiolaria.

Interpretation

The limestones are typically associated with dark grey claystone and siltstone with abundant shell fragments. The fossil assemblage is consistent with the interpretation of a shallow-marine or lagoonal environment. Oncolites are typical of shallow water which is periodically sufficiently agitated to overturn them (Siesser, 1972a). Deep-marine fossils are conspicuously absent. The presence of overlying Facies 4-type sandstones in core 6, which also continues upwards in core 5 of Kudu 9A-2, suggests an offshore environment of deposition which follows a lagoonal environment. The correlation of this lower limestone facies in Kudu 9A-2 with the calcilutite facies in core 4 of Kudu 9A-3 is speculative because of the different positions with regard to the underlying lithologies. This again stresses the complexity of shoreline related sub-environments and the difficulty in making direct correlations.

The micritic limestones are typical of shallow environments such as lagoonal mud flats but there is no reason why the shelly material could not have been transported to the offshore part of a subsided lagoon. The limestone in core 1 of Kudu 9A-2 is associated with glauconite, planktonic foraminifera and radiolaria-bearing claystone and siltstone and represents a deeper offshore environment. The large concentrations of bivalve shell fragments at the bases of thin, upward-fining cycles may also represent hurricane-type storm-derived and reworked material in an otherwise quiet offshore environment.

Facies 8: Siltstone (correlation unit K)

A homogeneous calcareous siltstone unit occurs between 4299.32 m and 4307.5 m in core I of Kudu 9A-2.

Between 4312.72 m and 4319.0 m in core 2 of Kudu 9A-2, it contains thin interbedded sandstone beds, one with a coarse-grained basal lag deposit.

The siltstone of core I and 2 of Kudu 9A-2 is dark grey, calcareous in part, and contains shell fragments, pyrite streaks, carbonaceous claystone laminae and various amounts of glauconite and quartz grains. A 14 cm thick zone of concentrated shelly material with an erosional base occurs at 4302.81 m in Kudu 9A-2. Faint horizontal bedding marked by carbonaceous claystone laminae occurs throughout. The paler intervals are more shelly and calcareous. Minor pyritised wood is also present. Abundant articulated thin-shelled bivalves occur between 4346.07 m and 4347.52 m in Kudu 9A-2. Large quartz grains up to 4 mm in diameter float in a dark grey silty matrix above a pebbly lag at 4347.70 m in Kudu 9A-2, the latter forming a sharp contact with underlying Facies 4-type sandstones. A white to yellowish opaque mineral (weathered feldspar?) occasionally occurs together with calcite and pyrite as circular concentrations 0.5 mm in diameter. These resemble worm burrows with the yellowish mineral concentrated more to the outer rim of the burrow. Other burrows, sometimes filled with clean sand, are up to 7 mm in diameter.

Interpretation

The siltstone units regularly occur interbedded with

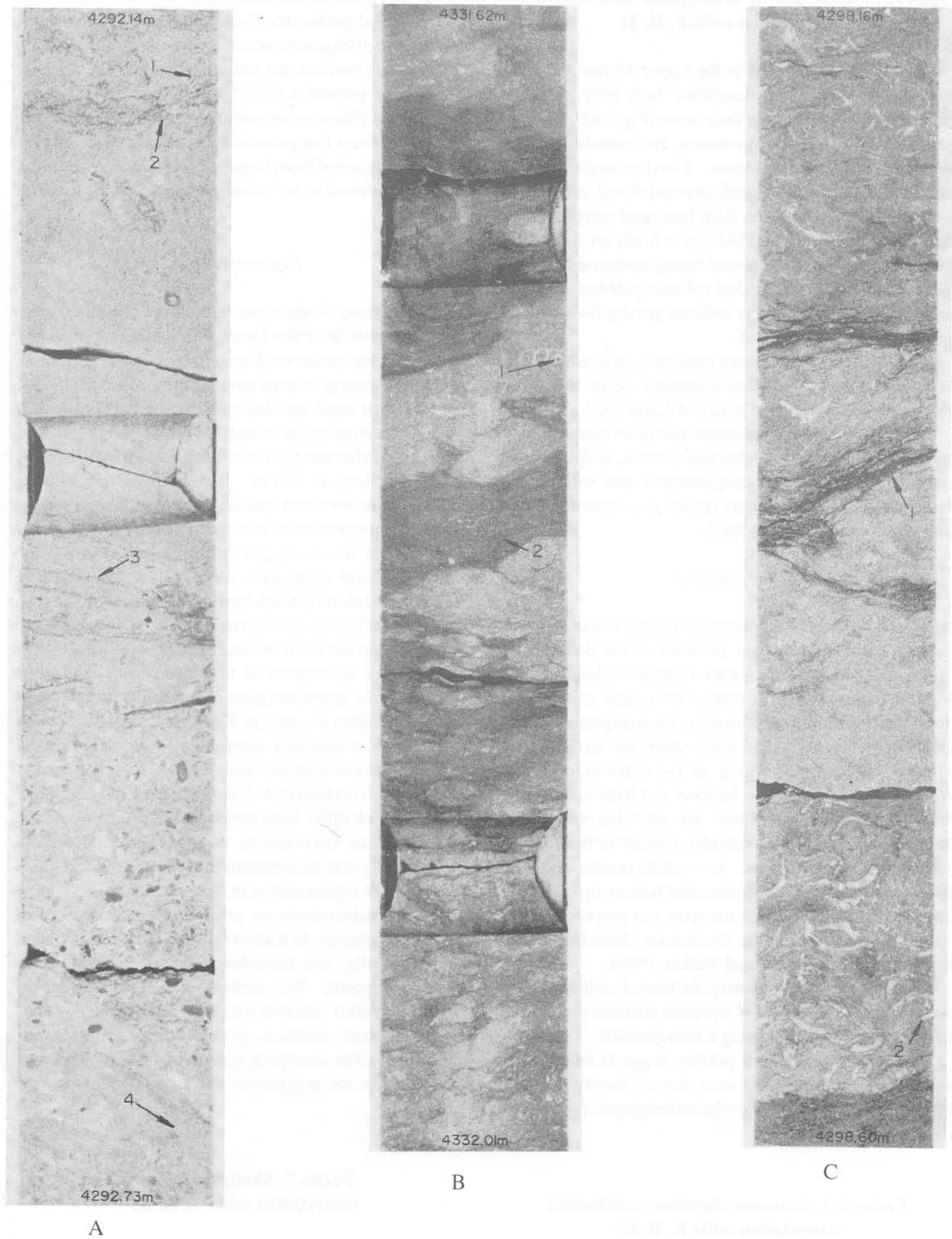

Fig. 8A: Facies 5. Matrix-supported conglomerate layer containing shell fragments, quartz and basalt clasts; 1. bioturbated carbonaceous zone, shell fragments, coarse angular lithic grains in calcitic matrix; 2. gradational contact; 3. graded layers; 4. deformed calcareous sandstone intraclast.

B: Facies 6. Calcilutite; 1. gastropod; 2. pale patches are shelly micritic limestone.

C: Facies 7. Shelly limestone; 1. claystone partings; 2. high concentration of bivalve fragments above erosional base.

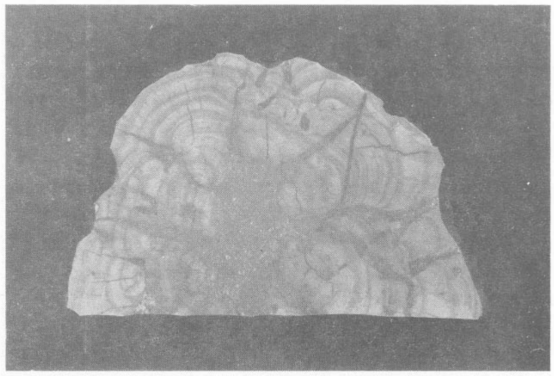

Fig. 9: Polished cross-section of an oncolite. Note the septarian fractures. (Kudu 9A-3, 4351.23 m). Life size.

Facies 4 (sandstone) and are mainly associated with Facies 6 and 7 (calcareous claystone and shelly limestone), which suggests a lower-shoreface to offshore environment of deposition. The abundance of shelly material, faint horizontal bedding, occasional wood debris and the presence of glauconite in cores 1 and 2 indicate a quiet and protected marine environment.

Conclusions

(i) The vertical association of the various sedimentary facies, sedimentary structures, trace fossil and fossil assemblages, together with the presence of basaltic lavas and volcaniclastic deposits, reflect deposition in a low-lying, tectonically active coastal environment.

(ii) The main reservoir target interval of the Kudu 9A-2 and 9A-3 boreholes can be divided into a Lower Non-Marine Unit and an Upper Marine Unit.

(iii) The Lower Unit includes terrestrial basalts, volcaniclastic sediments and aeolian sandstones, while the Upper Unit includes fine- to medium-grained shallow-marine sandstones with minor limestone, calcilutite, carbonaceous shales and volcaniclastic sediments.

(iv) The main producing reservoir (Lower Gas Sand) of Kudu 9A-3 is an aeolian sandstone, whereas the Upper and Lower Gas Sands of Kudu 9A-2 and the Upper Gas Sand of Kudu 9A-3 are shallow-marine sandstones. The lack, in the latter, of echinoderm debris (typical of a normal-salinity-range marine environment) may be an indication that the depositional environment of the Upper Marine Unit (below 4314 m in Kudu 9A-2) was of lower than normal salinity either as a result of some restriction in circulation to the open sea or as a result of a large influx of freshwater (cf. Siesser, 1972b, p. 88).

(v) The transition between non-marine and marine sediments is probably associated with an erosional unconformity.

(vi) The lateral extent of the reservoir sandstones is difficult to predict from the data available at the time of writing, but it is suggested that:

- the Upper Gas Sands of both wells probably have a wide lateral extent, especially along strike, and may become coarser in a landward direction;
- the Lower Gas Sands of Kudu 9A-3 may be more limited in extent as it is clear that over the 11.5 km strike distance between the wells, there is a significantly thinned equivalent in Kudu 9A-2. The potential for lateral continuity of aeolian sands over large areas is nonetheless good. The thickness variations evident may relate to the control exercised on the aeolian sand distribution by lava topography as has been suggested recently by S. Lawrence of ECL Consultants (pers. comm., 1989). The interpreted wind transport direction from the south and west suggests that the sand bodies may be elongated in a north-south to southwest-northeast direction.

(vii) On a broader regional scale, it appears from the regional geology (E. Jungslager, pers. comm. 1989) that the Lüderitz ridge to the north and the unnamed ridge to the south, approximately on the Namibia/South Africa boundary, will limit the distribution of the sandstones.

(viii) The volcaniclastic sandstones are considered to largely represent mass-flow redistributed volcanic and sedimentary material. In the case of core 6 of Kudu 9A-3, the process occurred predominantly in a terrestrial aeolian sand-dominated environment, while the volcaniclastics of correlation unit I in both wells clearly accumulated in a shallow-marine environment. The abundance of vesicular scoria and their concentration in thin laminae and beds within the volcaniclastic sandstones suggest that some of these clasts or units may have been deposited directly by aerial or pyroclastic mass-flow mechanisms.

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