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Incised valley fill stratigraphy of the Upper Cretaceous succession, proximal Orange Basin, Atlantic margin of southern Africa

I. R. STEVENSON & I. K. MCMILLAN
De Beers Marine, P.O. Box 87, Cape Town 8000, South Africa (e-mail: ian.stevenson@debeersgroup.com)

Abstract: Seismic stratigraphic analysis of a grid of 7860 km of shallow seismic Sleevegun data, plus lithological and biostratigraphic (foraminifera) data interpreted from core and sea-bed samples have been integrated into a detailed geological model for the Upper Cretaceous succession of the proximal Orange Basin. Emphasis has been placed on the palaeoenvironmental interpretation of incised valley fill sequences of this succession. Seismic reflection geometries for the Middle Albian to Lower Cenomanian interval show that the entire coast was dominated by aggradational fluvial braid-plain facies. The Lower Turonian to Upper Coniacian succession marks the appearance of repeated major incision into the exposed coastal plain by large fluvial drainage networks. This succession is characterized by fourth-order, fluvial-to-marine sequences, with valley incision up to 25 km wide and 70 m deep. Detailed palaeoenvironmental analysis indicates periodically waterlogged, highly reducing fluvial floodplain environments with valley systems that were flooded to create wave-dominated estuaries. Major fluvial activity during the Turonian was in an area that lies offshore of the present-day Swartlintjies to Groen River mouths in the southern part of the Orange Basin. During the Coniacian the site of fluvial activity changed to the central Orange Basin, offshore of the present-day Buffels River. These observations contradict previously published views that a dominant Orange River drainage system existed since the Albian, at a position coincident with the present-day mouth.

Keywords: South Africa, Upper Cretaceous, seismic stratigraphy, biostratigraphy, incised valleys.

In recent years, submerged diamondiferous deposits, of mostly latest Quaternary age, lying on the continental shelf off the West Coast of southern Africa have attracted a great deal of economic and geological interest. In the expansive diamond concessions the target areas are typically very small. Locating them requires accurate mapping of the top 6 m of sea bed, which is achieved using high-resolution geophysical surveys (Russell-Cargill 1996). Despite the high level of exploration activity, very little information has been published on the detailed sea-floor geology to date (e.g. Murray *et al.* 1970; O'Shea 1971; Rogers 1977; Kuhns 1995). The rock succession encountered across most of the inner–middle shelf offshore from the Olifants River in South Africa to Bogenfels in southern Namibia (Fig. 1), consists of Middle to Upper Cretaceous rocks, overlain by diamond-bearing Uppermost Pleistocene gravels, which are in turn overlain by a transgressive, Holocene succession that fines upward from gravel to mud.

As part of a continuing diamond exploration programme conducted by De Beers Marine, *c.* 7860 km of shallow seismic data were acquired over the proximal Orange Basin (Fig. 1). These data have been interpreted within a seismic stratigraphic framework, and have been integrated with 1090 km^2 of geologically calibrated sidescan sonar interpretations. Calibration was from stratigraphic and sedimentological studies of over 300 vibracore and rockdrill samples, plus data from over 70 000 airlifted sea-bed samples. These data were all combined to produce a detailed geological model for the proximal part of the Upper Cretaceous succession, particularly the Lower Turonian to Upper Coniacian interval.

A detailed fluvial architecture has been constructed from the seismic data. This has been used to identify stacked incised valleys and document the drainage history development of this area during the Late Cretaceous. Detailed analysis of a single incised valley fill (the Swartlintjies Incised Valley Fill, Fig. 1) has been undertaken. Integration of the seismic interpretations with lithological and biostratigraphic (foraminifera) data obtained from the core and sea-bed samples has allowed the depositional environments of the Cretaceous succession to be constrained. As age-diagnostic foraminifera (especially planktonic foraminifera) are generally lacking in the proximal Orange Basin succession, dating has been achieved by correlating from the shallow seismic, through the deep seismic to reliably dated oil-exploration borehole sections. A depositional model is proposed for the Swartlintjies Incised Valley Fill, which describes the palaeoenvironmental controls influencing incised valley evolution and preservation.

Data

Location

The study area is situated over the middle shelf of the West Coast of southern Africa, between approximate latitudes 27°25′ to 31°43′S, longitudes 15°20′ to 18°10′E, between 70 and 160 m.b.s.l. (metres below sea level). It lies roughly between the Olifants River in the south and Bogenfels in the north (Fig. 1).

Deep seismic data

A regional petroleum industry deep seismic composite profile from a dataset obtained from SOEKOR (Southern Oil Exploration Corporation; now Petroleum Agency SA), is used to illustrate the resolution limits of the shallow seismic data within the context of the entire Orange Basin vertical succession (see Fig. 1 for location, and Fig. 2). The profile extends from 10 km to 210 km offshore Hondeklip Bay, past the present-day continental shelf break, with a section depth of 5 s two-way travel-time (TWT). Major Cretaceous unconformities were mapped from the deep seismic data and correlated to SOEKOR boreholes K-A2 and A-D1, situated WSW and west of Hondeklip Bay, respectively (Fig. 1), using synthetic seismic and biostratigraphic logs. Extrapolation of deep seismic

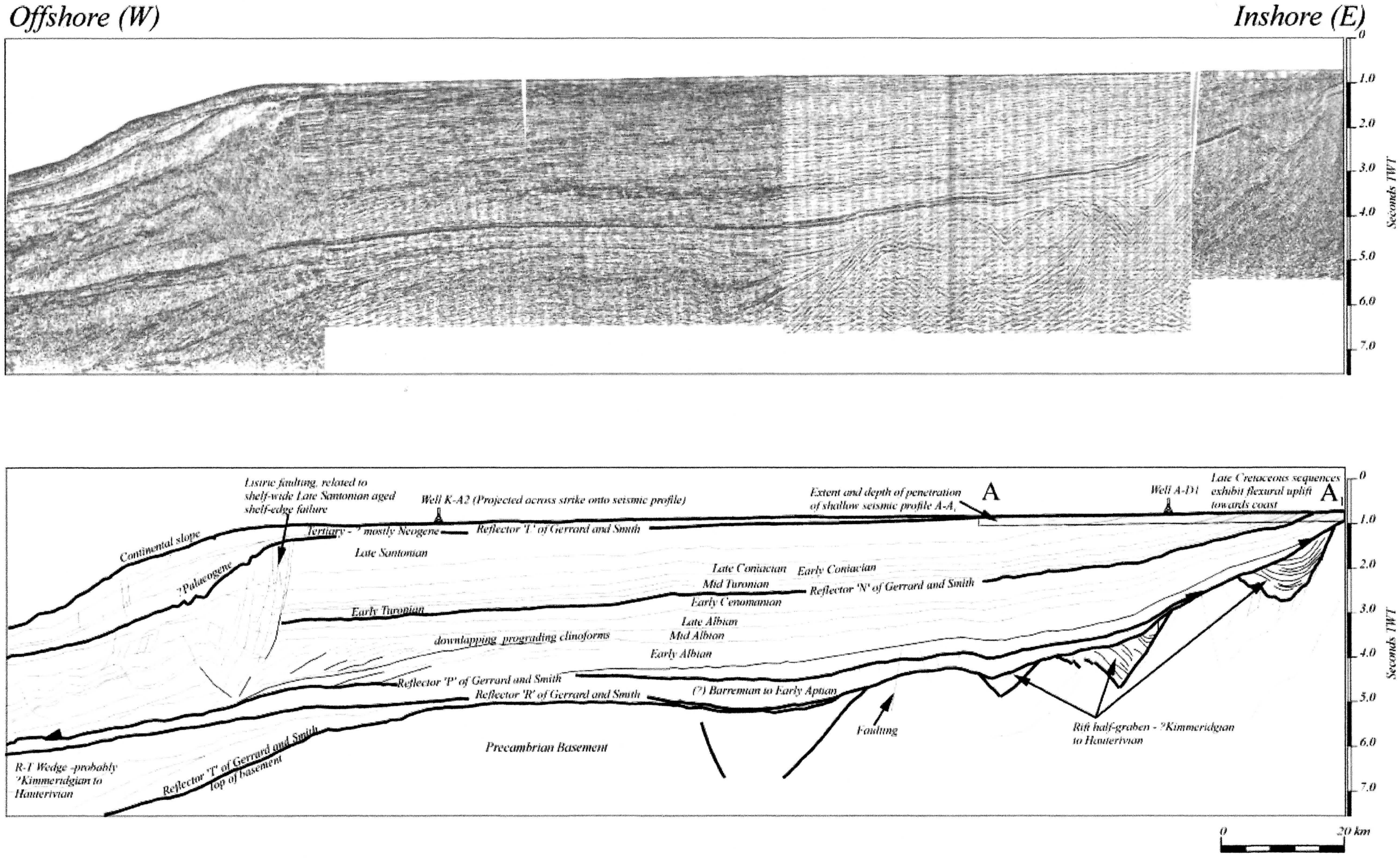


Fig. 2. Deep seismic profile (SOEKOR data), also showing major regional unconformities off Hondeklip Bay of the Orange Basin succession and the extent and depth of penetration of shallow seismic data, in relation to the overall basin stratigraphy (see Fig. 1 for location).

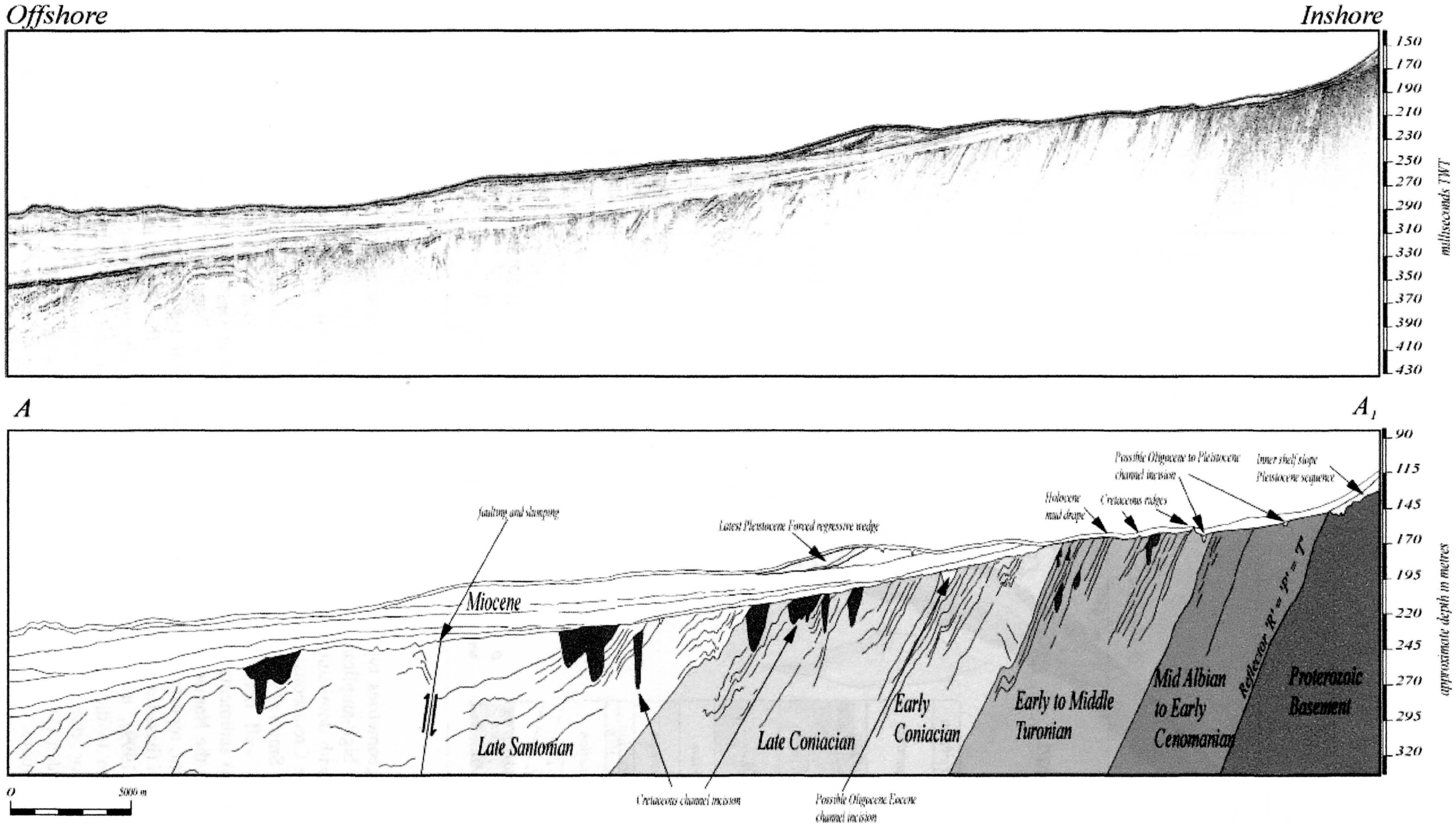


Fig. 3. Shallow seismic dip profile A–A1, uninterpreted and interpreted, showing characteristics of the Cretaceous succession and incised valley fills, and the Cenozoic succession, situated off Hondeklip Bay (see Fig. 1 for location). The section is vertically exaggerated; true Cretaceous reflector dips are *c.* 1.5°.

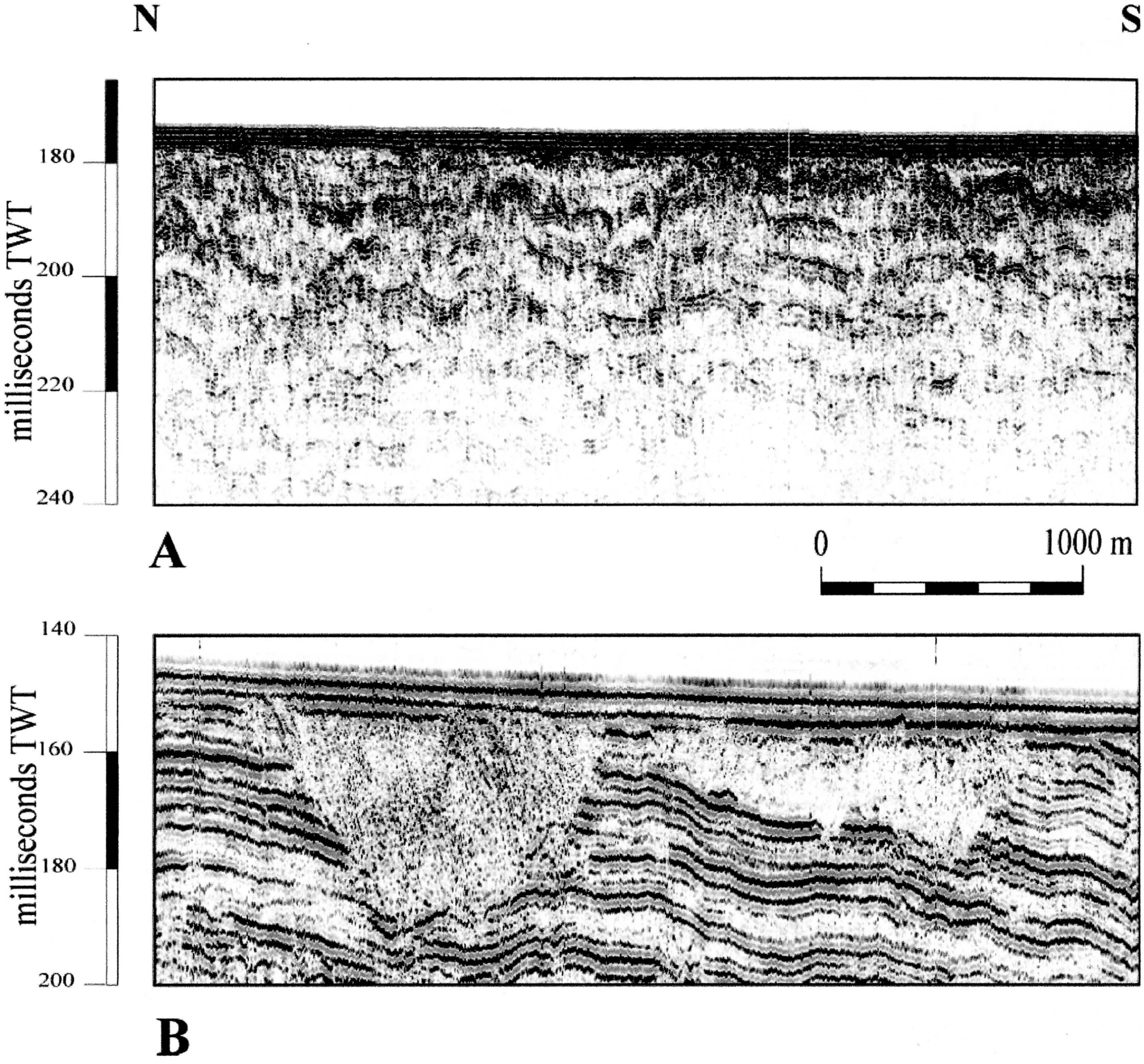


Fig. 5. (**a**) Seismic profile strike section showing high-amplitude, chaotic and hummocky internal reflection patterns typical of the Albian and Cenomanian successions. Channel fills shown here are no greater than 1 km wide and less than 10 m in depth. (**b**) Seismic profile strike section showing continuous high-amplitude reflectors incised by large, well-defined incised valley fill geometries, typical of the Turonian and Coniacian successions. The largest incised valley fill in this example is some 30 m in depth.

distinguished by thick fluvial clays (usually white, pale grey, pink, brown or red), with thin estuarine or hyposaline dark grey clays. These successions contain a wide variety of microfossils from terrestrial plants to hyposaline ostracodes and agglutinated benthonic foraminifera.

Upper Santonian sequence (86–83 Ma)

Santonian-aged sediments are present further offshore, forming the most westward Cretaceous succession that crops out in the study area. Santonian sediments generally subcrop beneath Tertiary sediments, with the exception of a window into the Santonian rocks cut through the Miocene cover in the central part of the Orange Basin, and also off Chameis Bay in the north (Fig. 4). The Santonian sequence is also characterized by incised valley fill formation, with hard brown waxy claystones and rare sandy claystones, containing land-plant microfossils (megaspores, seeds, *Microcarpolithes hexagonalis*) but no foraminifera, and is consequently interpreted as having accumulated in an exclusively fluvial environment. Agglutinated and calcareous benthonic foraminifera, oyster fragments, ostracodes and *Inoceramus* prisms occur in the Upper Santonian soft brown clays off Chameis Bay, Namibia.

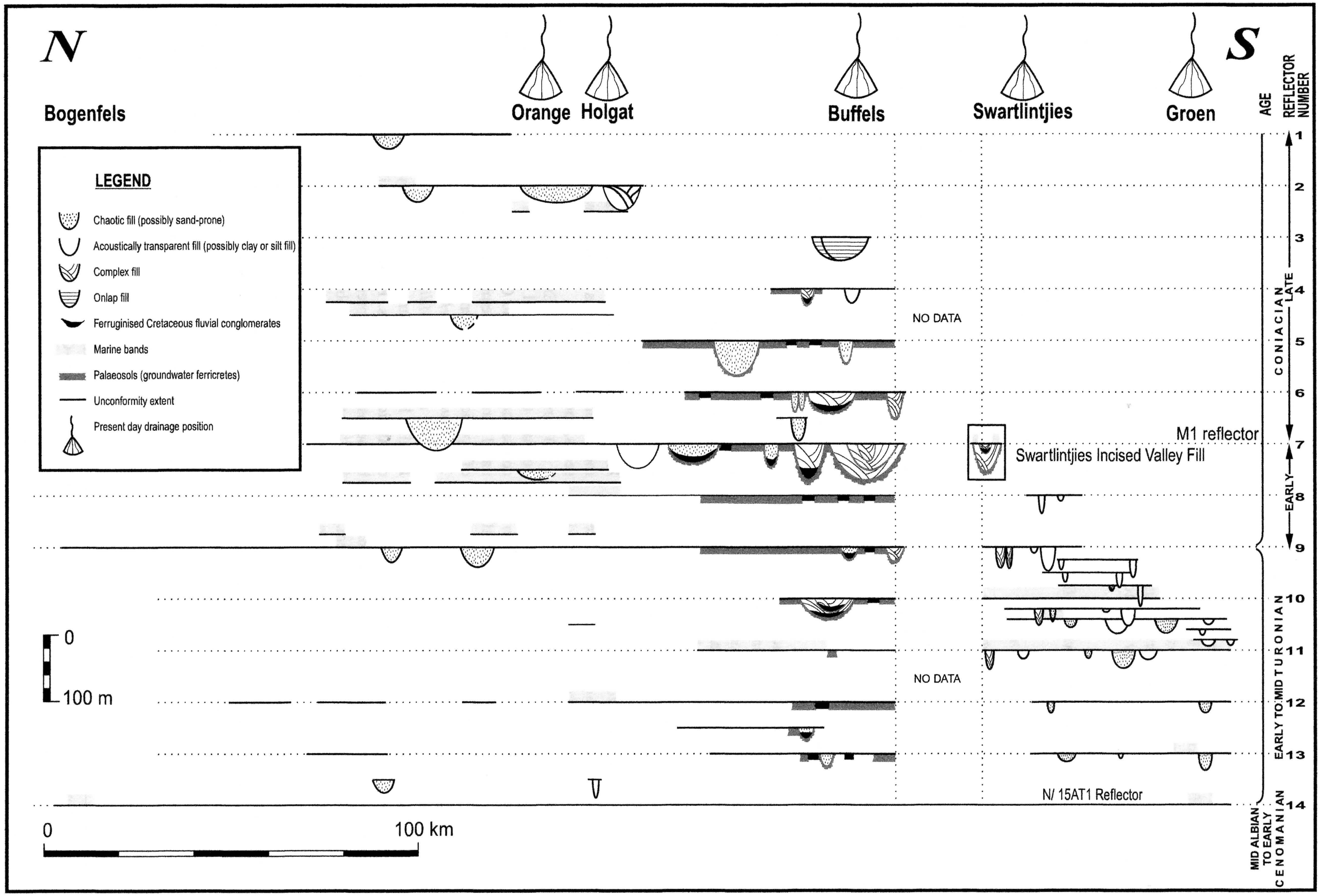
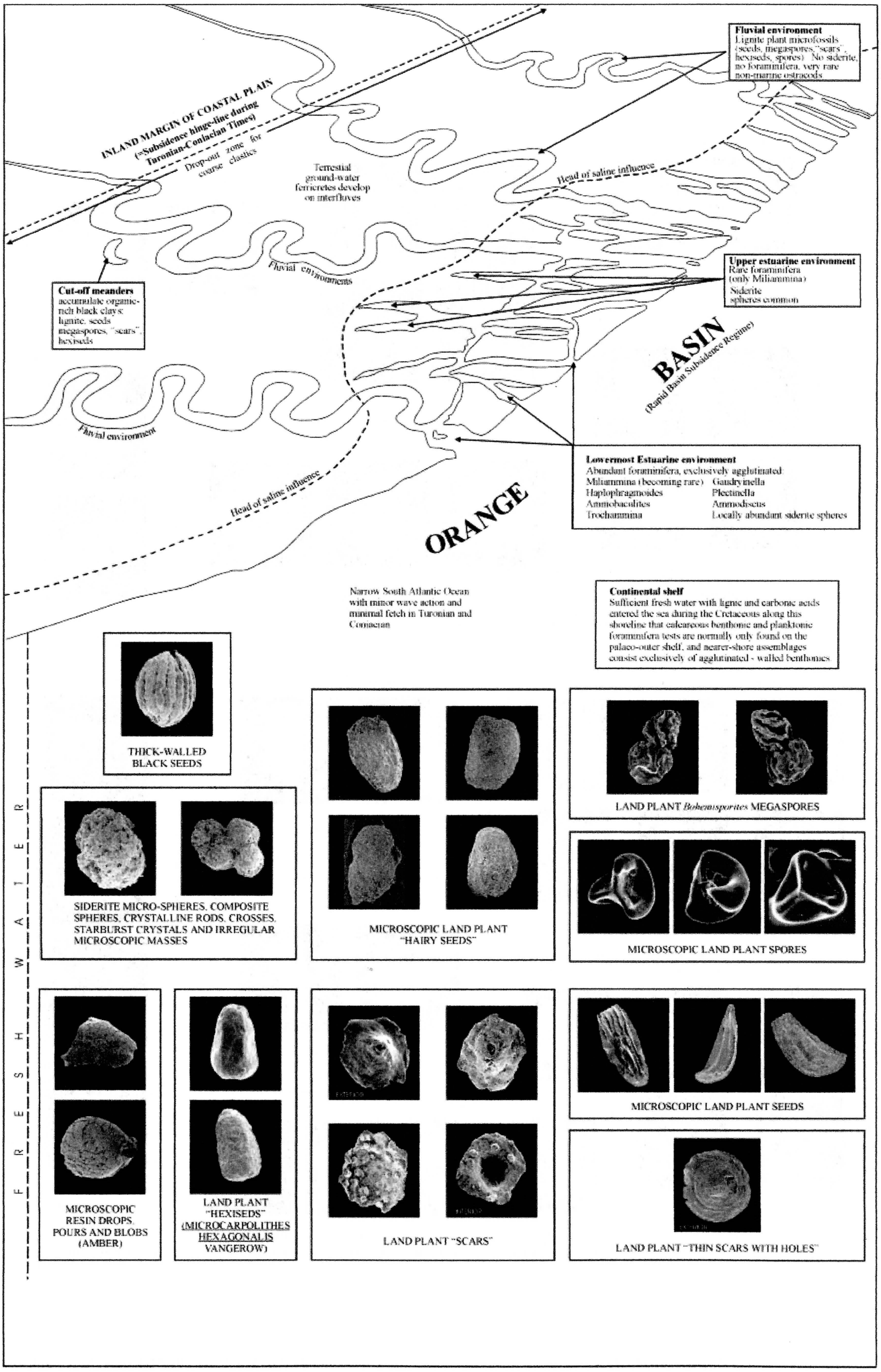


Fig. 7. Fluvial architecture and chronostratigraphy of the Orange Basin for the subcropping Upper Cretaceous (Turonian to Coniacian) succession, from offshore the Groen River, Namaqualand, to offshore Bogenfels, Namibia (see Fig. 1 for location). Diagram shows widths, depths, seismic fill facies and spatial distribution of subcropping valley fill systems, derived from shallow seismic interpretations. The vertical separation between major regional unconformities is arbitrary and serves merely to show their relative chronology.



Fluvial environment
Lignite plant microfossils (seeds, megaspores, "scars", hexiseds, spores). No siderite, no foraminifera, very rare non-marine ostracods

Cut-off meanders
accumulate organic-rich black clays: lignite, seeds megaspores, "scars", hexiseds

Upper estuarine environment
Rare foraminifera (only Miliammina)
Siderite spheres common

Lowermost Estuarine environment
Abundant foraminifera, exclusively agglutinated:

Miliammina (becoming rare)	Gaudryinella
Haplophragmoides	Plectinella
Ammobaculites	Ammodiscus
Trochammina	Locally abundant siderite spheres

Narrow South Atlantic Ocean with minor wave action and minimal fetch in Turonian and Coniacian

Continental shelf
Sufficient fresh water with lignic and carbonic acids entered the sea during the Cretaceous along this shoreline that calcareous benthonic and planktonic foraminifera tests are normally only found on the palaeo-outer shelf, and nearer-shore assemblages consist exclusively of agglutinated - walled benthonics

Seismic architecture, lithofacies and palaeoenvironments of the 'Swartlintjies River' incised valley fill

This complex incised valley fill is *c.* 6 km wide and 70 m deep at its maximum point. It comprises seven major seismic intervals, SWT 1–7 (Fig. 9 and Table 1). Six rockdrill cores and two vibracores were recovered across this incised valley fill, with the maximum depth of penetration recovered being just over 4 m (Figs 10 and 11). From these data it was possible to directly ground-truth five of the major seismic intervals (Fig. 10). Seismic intervals SWT 3 and SWT 6 have not been ground-truthed by coring. Environments and lithofacies are tentatively inferred from their seismic reflection characteristics (amplitude, reflector continuity and internal reflection geometries; see Sangree & Widmier 1977).

Descriptions of the seismic facies, associated lithologies and palaeoenvironmental interpretations are presented in Table 1. Relationships between cores, lithologies and palaeoenvironments are further represented in Figure 12.

Palaeoenvironmental significance of ferricretes and associated relict paleosols

Ferruginized sandstones and siltstones (Fig. 13a and b) are typically associated with sediments external to the palaeochannel fill successions, through which they incise (e.g. cores 01, 02, 04, 05 and 08), whereas ferruginized conglomerates (Fig. 13c and d) are typically associated with the base of some of the palaeochannel fills. Core 03 (Figs 10–12) intersects one of these ferruginized channel-base conglomerates. The conglomerate contains exotic pebble-sized clasts of quartz, jasper, agate, chert and chalcedony, and is most commonly found in Upper Coniacian incised valley fills on the central Namaqualand shelf, offshore of the present-day Buffels River, north of the Swartlintjies River (see Fig. 7). The matrix material of ferruginized sediments outside and within the palaeochannel successions is predominantly goethite, where iron has replaced the clay in the intergranular voids.

On the basis of hand specimens and thin-section analysis of these sediments, the ferruginization is interpreted to represent shallow burial alteration of sediments by ground waters to form ground-water ferricretes (see Wright *et al.* 1992; Wright 1994). Sandstones and siltstones (Fig. 13a and b) are interpreted as part of alluvial floodplain facies, which have been ferruginized through a process of rapid iron accumulation via ground-water mobilization. As floodplain aggradation occurs, the floodplain surface and water table will rise, causing the floodplain sediments to become waterlogged (Allen & Wright 1989). Ground water mobilizes iron under reducing, acidic conditions, which is then fixed by oxidation during falls in the water table to precipitate goethite. Given the nature of the high-frequency cyclicity of the Upper Cretaceous succession, it is likely that these falls in ground-water table are related to relative sea-level falls (uplift).

Ferruginization of basal channel conglomerates is interpreted to occur via ground-water recharging of channel systems through effluent seepage (Ward 1975). Iron is transferred via ground water from topographically higher areas and precipitation occurs at valley base, where the land surface intersects the water table (McFarlane 1983). Therefore, the ferruginization of the basal channel conglomerates is seen as coeval with ground-water ferricrete formation in the interfluves. Ferruginized clasts are also present within these conglomerates, and are probably derived from erosion and reworking of pre-existing ferricretes related to older incised valley fill and fluvial floodplain systems deeper in the succession.

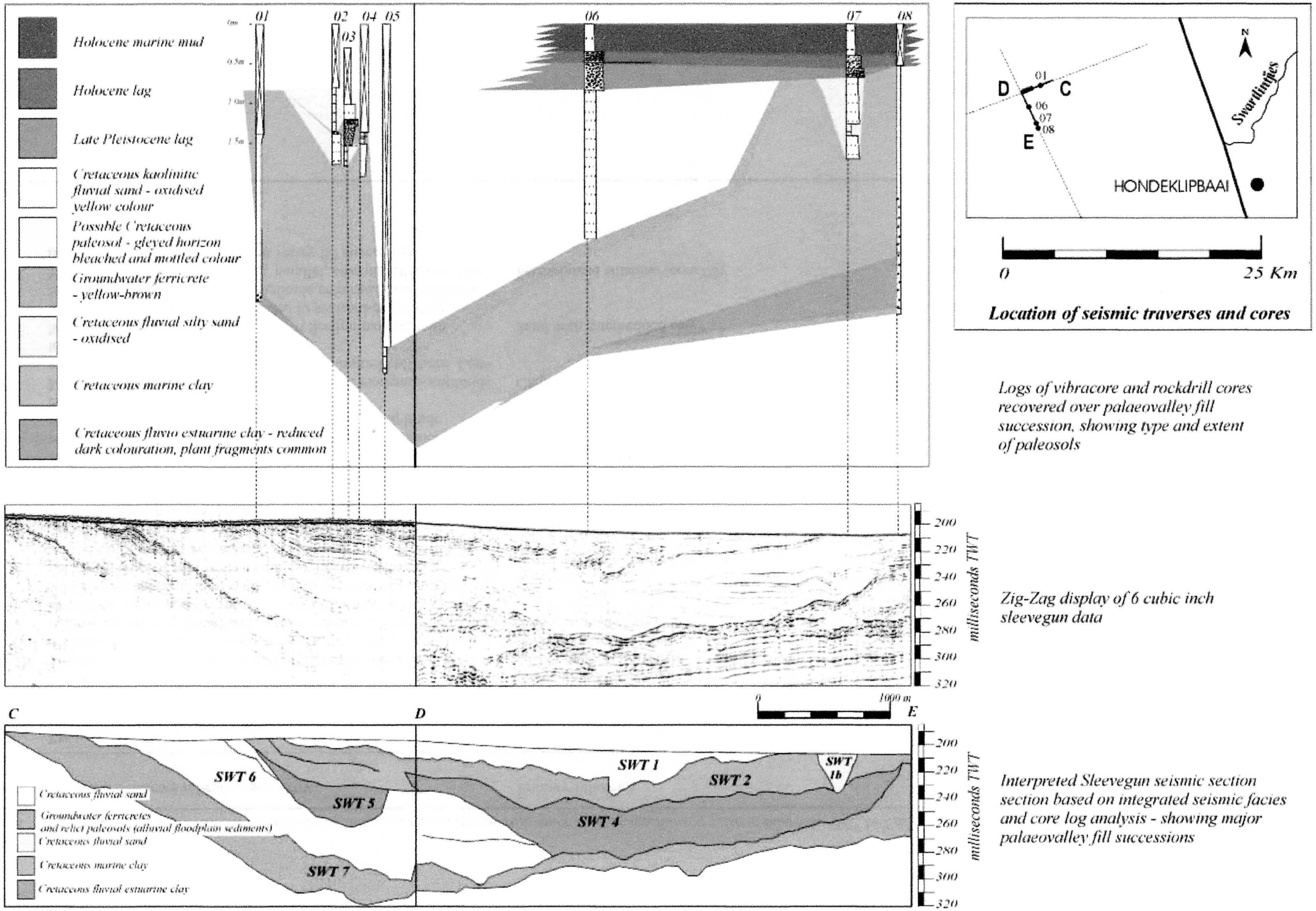
The ferruginized intervals are today exposed on the sea floor as extensive coast-parallel ridges (Fig. 6), as a result of Late Cretaceous to Early Tertiary uplift of the Upper Cretaceous succession and subsequent preferential erosion of these uptilted beds during Cenozoic sea-level movements across the shelf. The present-day distribution of ferricretes is directly linked to the areas where the most dominant ground-water drainage gradients would have operated during the Late Cretaceous, in the areas of most prolific incised valley development during this time. Thickest interval preservation (hence maximum present-day sea-floor relief, *c.* 5 m) occurs offshore of the present-day Buffels River system (see Fig. 1). This corresponds to the area of most repeated fluvial incision over time within the Upper Cretaceous succession.

Discussion

Depositional model for the Swartlintjies River incised valley fill

This section outlines a proposed depositional history for the Swartlintjies incised valley fill succession, which yields valuable insight into the palaeoenvironmental and palaeogeographical settings of the exposed Upper Cretaceous coastal–alluvial plain succession (Fig. 14).

The incised valley fill succession begins with the formation of the valley base during a relative sea-level lowering and incision of fluvial drainage systems onto an exposed Late Cretaceous (Early Coniacian) shelf. During this time ground-water ferricretes develop in response to a lowering of the ground-water table and oxidation of sediments above the water table, as a result of relative sea-level fall and shoreline migration seawards. During the end of this relative sea-level lowering cycle, perhaps during stillstand and turnaround to slow, renewed transgression, fluvial sands and sometimes clay-rich silts cover the valley floor and coarse-grained fluvial gravels. In this incised valley fill succession, the sandy fill (seismic interval SWT 6) possibly overlying a basal gravel unit (inferred from seismic data) can be distinctly divided into two units, based on a regionally extensive reflector observed within the valley fill succession (see Figs 9 and 10). The significance of this unconformity is unclear, but it may represent the proximal end of a transgressive–regressive surface, where the valley perhaps experienced a slight renewed transgressive episode, with marine sediments preserved much further offshore in the succession. Clay-dominated sediments (seismic interval SWT 5) overlie the fluvial sandy succession, and are separated by the transgressive surface, which divides lowstand deposits from transgressive deposits. These sediments reflect a fluvio-estuarine to uppermost estuarine environment, and probably represent bayhead delta or tidal flat deposits. Although not associated with typical sandy barrier and tidal inlet deposits, a tidal ravinement surface (in its broadest sense) is inferred for the base of the clayey silt succession (Fig. 14), with the ravinement surface forming erosional scours down into the underlying fluvial successions (see Figs 9 and 10). The estuarine clays of seismic interval SWT 5 are erosionally truncated by an unconformity overlain by marine clays (seismic interval SWT 2), recording a rise in relative sea level and a movement from upper to lower estuarine environment, with a gradational change to lowermost estuarine–innermost shelf as the succession is followed further offshore. The lower to lowermost estuarine sediments are perhaps analogous to the central basin deposits of Dalrymple *et al.* (1992,



Location of seismic traverses and cores

Logs of vibracore and rockdrill cores recovered over palaeovalley fill succession, showing type and extent of paleosols

Zig-Zag display of 6 cubic inch sleevegun data

Interpreted Sleevegun seismic section section based on integrated seismic facies and core log analysis - showing major palaeovalley fill successions

Fig. 10. Integrated core and seismic interpretations depicting the lithological facies of the Coniacian Swartlintjies River incised valley fill succession and showing positions of cores relative to seismic intervals.

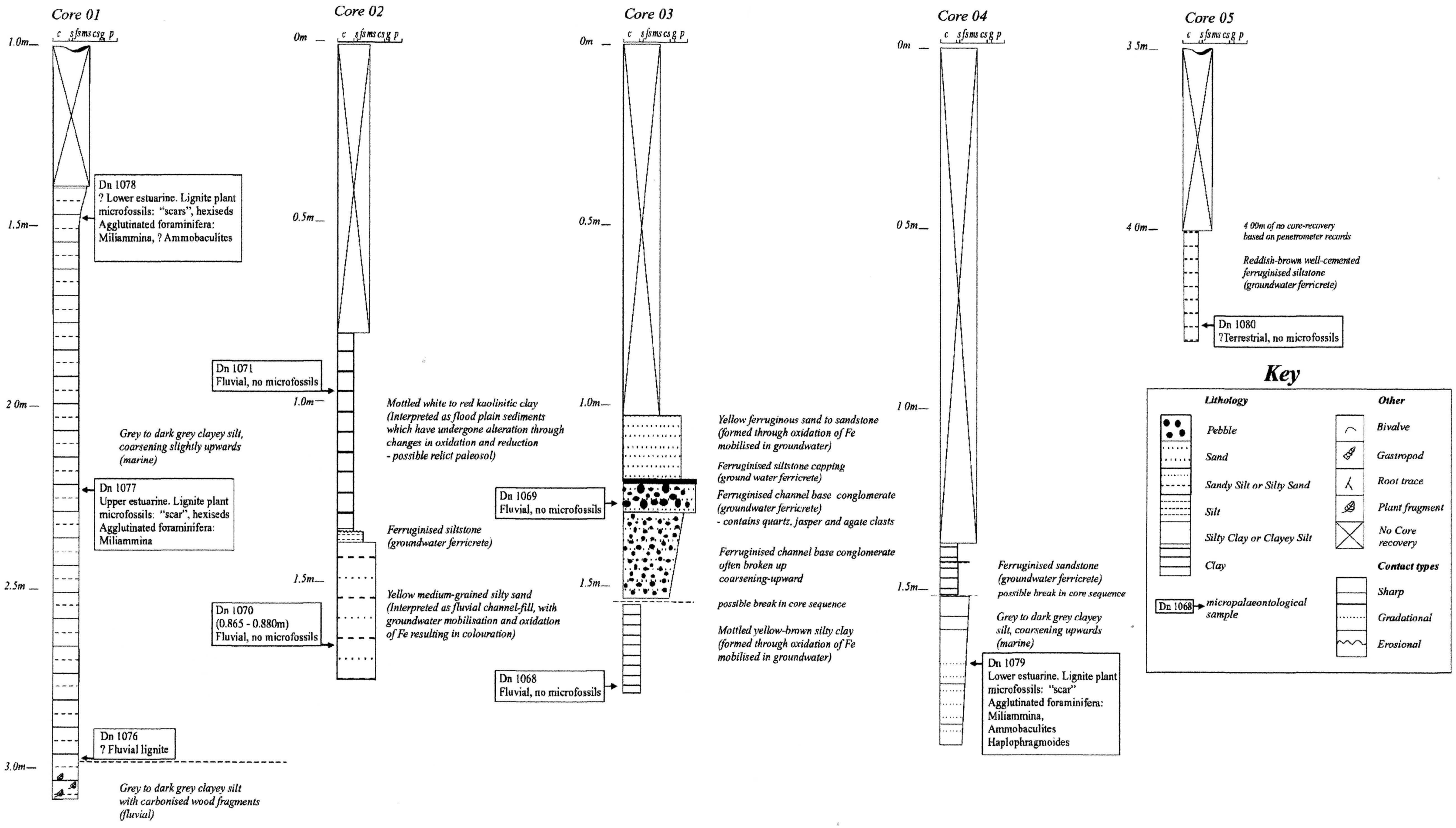


Fig. 11. Lithological logs based on rockdrill and vibracore samples intersecting the Coniacian Swartlintjies River incised valley fill succession.

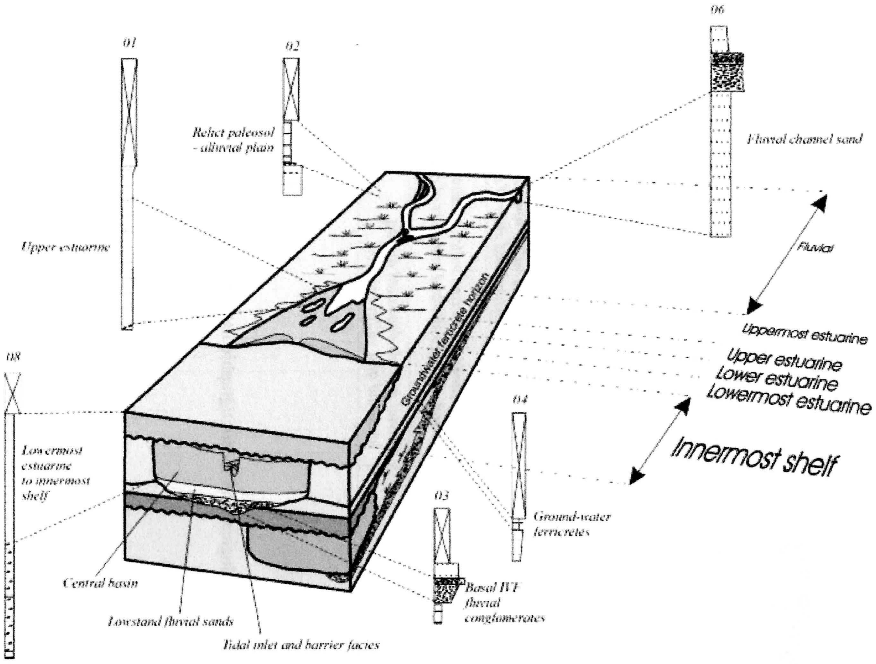


Fig. 12. Schematic diagram of Upper Cretaceous estuarine valley fill sequence with associated facies as indicated by vibracore and rockdrill samples, showing environments of deposition derived from micropalaeontological analysis of sediments. IVF, incised valley fill.

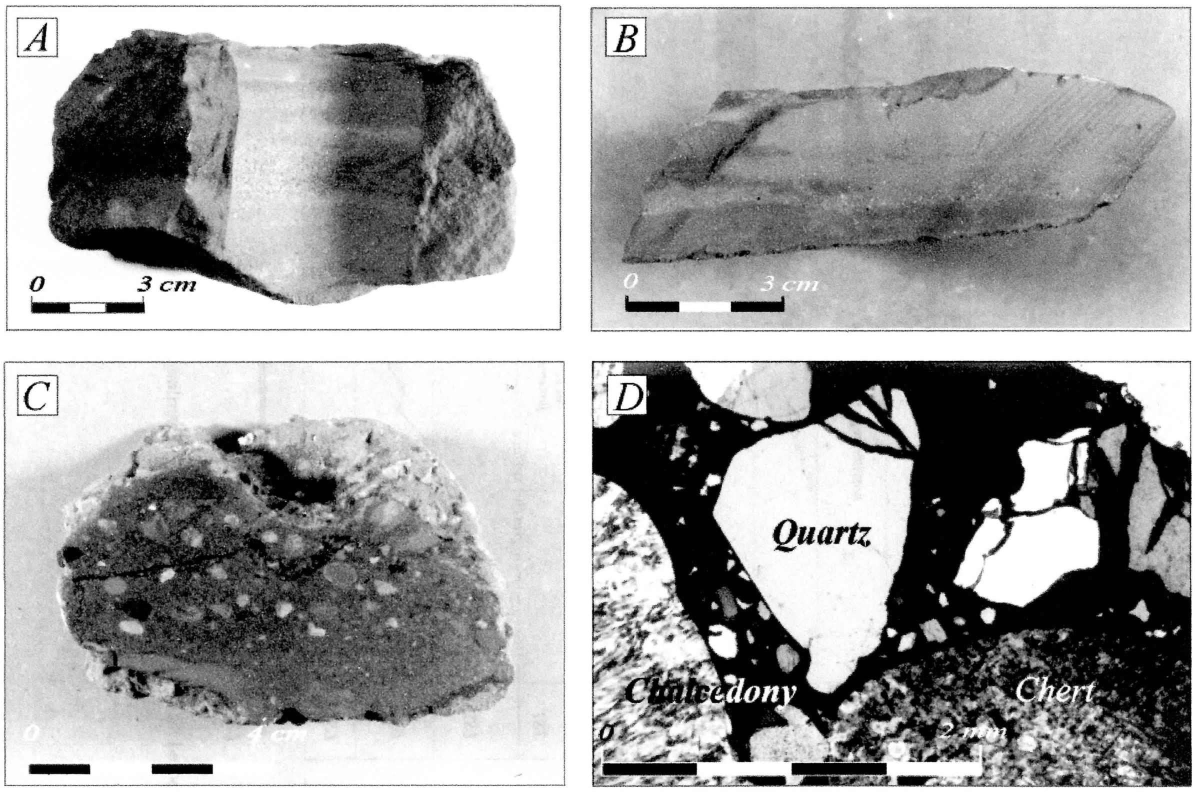


Fig. 13. (**a**) Ferruginized quartz sandstone in hand specimen. (**b**) Ferruginized quartz siltstone in hand specimen. (**c**) Ferruginized matrix-supported channel-base conglomerate in hand specimen, showing exotic clast assemblage, including quartz, jasper agate and chalcedony. Clast-supported conglomerates also occur. (**d**) Photomicrograph of ferruginized channel-base conglomerate, showing subrounded quartz and well-rounded chalcedony and chert clasts. Photomicrograph taken under polarized light.

1994), Allen & Posamentier (1993, 1994) and Zaitlin *et al.* (1994). The overlying interval (SWT 4) is again dominated by clays belonging to a fluvial to uppermost estuarine environment, and therefore signifies a drop in relative sea level. These deposits again probably represent bayhead delta or tidal flat deposit, and also show a marked erosional base to the fill, which is interpreted as a tidal ravinement surface in its broadest sense. The interval is characterized by well-defined clinoforms, which prograde seaward and downlap onto the southern side of the fill unconformity in strike section (Fig. 9). Synsedimentary deformation is suggested by the presence of small-scale faults seemingly restricted to this interval only (Fig. 9), and perhaps reflects channel margin rotational slippage along peaty beds (see Allen & Fulford 1996). These deposits are again truncated by an unconformity, overlain by marine facies, interpreted as having accumulated mainly in a lowermost estuarine–innermost shelf environment, probably representing central basin to marine deposition, and suggest a renewed relative sea-level rise. These sediments belong to seismic interval SWT 2, which interfingers between deposits of seismic intervals SWT 3–5 (Fig. 10). Subsequent relative sea-level fall is suggested by the presence of seismic interval SWT 3, interpreted as sand-prone deposition of possible fluvial or estuarine nature. This interval is erosionally truncated by an unconformity overlain by marine clay (seismic interval SWT 2) of a lower estuarine environment, suggesting a renewed relative sea-level rise. After the filling up of the estuary with marine sediments, which eventually extend out over the valley interfluve (Fig. 9), thus signifying a complete drowning and filling of the valley, a major regression is noted. This is represented by seismic interval SWT 1, which consists of basal fluvial floodplain deposits (ground-water ferricretes), together with associated fluvial channel base conglomerates. The base of this interval marks a second sequence boundary and the start of a second fourth-order relative sea-level cycle (Fig. 14). The ensuing sea-level stillstand and possible start of gentle rise at the end of lowstand deposition resulted in the filling of the rejuvenated valley with fluvial sands. The presence of gleyed soil horizons within this succession suggests a continued relative sea-level rise. This final preserved sequence in the incised valley fill is truncated at the sea-floor surface and unconformably overlain by a veneer of Quaternary marine sediments.

Implications for the drainage evolution of the Late Cretaceous Orange Basin

Figure 15 shows a series of palaeogeographical reconstruction maps for the Orange Basin from Mid-Albian to Late Coniacian time detailing the distribution of fluvial–coastal plain sedimentary facies and major fluvial input points over time. The distribution of fluvial–coastal plain sediments is based on palaeoenvironmental analysis of vibracore and sea-bed samples from this study. In addition, palaeoenvironmental analysis of 32 oil exploration borehole sections (McMillan 2004) provides information on the distribution and occurrence of fluvial–coastal plain facies situated at depth within the Cretaceous succession, beyond the resolution limits of the shallow seismic and vibracore–sea-bed sampling data used in this study, together with data that extend to the southern limit of the Orange Basin. Major fluvial input points shown in these maps are derived from identification of incised valley fills from shallow seismic data (see also Fig. 7).

For the Albian to Cenomanian succession (Fig. 15a and d) fluvial–coastal plain sediments are distributed across the shelf, from Saldanha in the south to Bogenfels in the north. The shallow seismic architecture of these sediments suggests a fluvial braid-plain environment for this deposition, and this style extends with no noticeable changes along the entire length of the shelf. Two localized occurrences of outer shelf massive sandstones, situated offshore of Hondeklipbaai and St. Helena Bay, offshore of Saldanha, suggest a more dominant fluvial input for these localities. The fluvial architecture presented shows the major area of fluvial incision migrating northwards over time, from Early Turonian to Late Coniacian time (Figs 7 and 15). The base of the Early Turonian sequence (Fig. 15c) marks the start of dominant incised valley formation, with incision dominating an area from offshore the present-day Buffels River to offshore the present-day Groen River. An area of outer shelf sandstones is situated further offshore of this fluvial input zone, together with a smaller distribution, located further south, which may also indicate possible major fluvial input from sources between the present-day Olifants River and just north of Saldanha (Fig. 15c). Minor, sporadic fluvial incision is also observed offshore just north of the present-day Holgat River, and offshore Namibia, between the present-day Orange River and Bogenfels. During mid-Turonian time, fluvial incision on the palaeo-coastal plain is concentrated in an area from offshore the present-day Swartlintjies River to offshore the present-day Groen River (Fig. 15d), and the number of incised valley fills has increased (see also Fig. 7). These are higher-order marine-to-fluvial cycles (greater than fourth order) than normally encountered for the Upper Cretaceous succession in this area, and may possibly be attributed to geomorphological processes as fluvial systems readjusted to base-level change through localized stream pattern and channel geometry modification (Wescott 1993; Miall 1996).

Isolated incisions are observed offshore the present-day Buffels River and offshore north of the present-day Orange River. During the Early Coniacian, the area of dominant fluvial incision migrated northwards and was prominent in the area offshore the present-day Swartlintjies River in the south to offshore the present-day Holgat River in the north (Fig. 15e). This time period is also associated with the incised valley fill formation with the greatest depths and widths preserved on the shelf. Minor, sporadic incision can be seen further north of the main incision area, to the north of the present-day Orange River. During the Late Coniacian major fluvial incision was constrained to an area from offshore the present-day Buffels River in the south to offshore the present-day Holgat River in the north (Fig. 15f). The area of coarsest fluvially derived sediments, present as conglomeratic basal channel fills, also coincides with the area of dominant fluvial incision for the Early to Late Coniacian period (Fig. 7). Minor incision can be seen further north of the main incision area, to the north of the present-day Orange River.

The palaeodrainage history presented in this study differs markedly from previously published views on drainage development in the Orange Basin for the Late Cretaceous period. Brown *et al.* (1995) suggested that the ancestral Orange River did not capture drainage until after the Albian (103 Ma). We demonstrate that a change in fluvial style occurs after the Cenomanian, where fluvial incision is dominant offshore central Namaqualand.

On the basis of an analysis of isopach and borehole data, Rust & Summerfield (1990) postulated that the Orange River was the major source of sediment to the shelf during the Coniacian, at a position coincident with the present-day mouth. They attributed a several-fold increase in sediment accumulation during the Late Cretaceous, recorded in the Kudu 9-A2 borehole, situated *c.* 180 km off the present-day Orange River exit, as signifying major sediment deposition to the shelf via the Palaeo-Orange River. However, seismic reflection data reveal that Kudu 9-A2 is the comparison with the work of Brown *et al.* (1995), our data show that incised fluvial systems are most dominant offshore central Namaqualand.

Instead, we suggest that the dominant exit point to the shelf through time is situated offshore the present-day Groen to Buffels rivers. De Wit (1993) suggested that by Late Cretaceous–Early Tertiary time the lower 'Kalahari' system had captured the upper part of the 'Karoo' river. During the Latest Cretaceous period, the offshore record suggests dominant fluvial activity in an area offshore central Namaqualand during the Late Santonian (McMillan 2004). Lower Campanian and Upper Maastrichtian sediments are limited to small wedges beneath the present continental shelf edge, and the latter reflects a change to outer shelf carbonate sedimentary deposition.

Conclusions

This study shows how detailed high-resolution seismic stratigraphy, coupled with biostratigraphic and palaeoenvironmental analysis of an extensive suite of sea-bed samples can be used to improve upon the current understanding of the depositional history and palaeodrainage evolution of the Upper Cretaceous succession of the Orange Basin.

The Lower Turonian to Upper Coniacian succession marks the emergence of dominant fluvial incision onto an extensive coastal plain. Fluvial flood plain facies reflect a waterlogged, highly reducing environment, which favoured the formation of groundwater ferricretes. Repeated fourth-order uplift and subsidence during this period resulted in repeated stacking of fluvial-to-marine facies, reflected by progressive drowning of valley systems and the onset of wave-dominated estuarine incised valley fill. Palaeogeographical reconstruction of the proximal Orange Basin succession shows a complex drainage evolution over time, with multiple fluvial exit points emerging along the palaeocoastline, showing a gradual northwards migration during Early Turonian to Late Coniacian time.

Shallow seismic interpretations presented herein offer significant improvement in resolution over standard petroleum industry seismic data, and are more suited to the identification of incised valley fill systems. The analysis and integration of 736 sea-bed samples from the outcropping Cretaceous succession within a shallow seismic framework also offers improved coverage of the basin to complement historical, widely spaced petroleum borehole control.

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