Changing Fluvial Environments and Vertebrate Taphonomy in Response to Climatic Drying in a Mid-Triassic Rift Valley Fill: The Omingonde Formation (Karoo Supergroup) of Central Namibia

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The Omingonde Formation of Central Namibia is a redbed succession infilling a half-graben that developed on the upland plateau of southern Gondwana in the early mid-Triassic. Field studies of the rocks and vertebrate fossils of these strata are used to reconstruct the changes that occurred in the rift valley landscapes over approximately 10 My, and show how these changes affected the life habits and preservation of terrestrial reptiles that inhabited the valley at that time.

The early rift basin contained extensive lakes that were filled rapidly with conglomeratic sands deposited on alluvial fans prograding from the active boundary fault. These fans subsequently drained into an axial braided river system. With cessation of downfaulting, the fault scarp retreated and gradients in the basin became gentle enough to convert the braid plain to one or more meandering rivers confined by extensive floodplains. The climate changed from sub-humid at the beginning of rifting, through semi-arid for most of the Omingonde times, to arid at the onset of the overlying Etjo Formation sedimentation. The influx of abundant loessic silt, possibly a peripheral effect of the Triassic "megamonsoon," significantly increased floodplain accretion and the burial potential of surface bones on the Upper Omingonde floodplains.

The major control of fluvial style and floodplain accretion rates in the Omingonde basin was subsidence caused by episodic movements of the boundary fault. However, the association of desiccated and mummified carcasses with thick beds of loessic silt suggests that climatic aridity was the overriding factor controlling the preservation and taphonomic style of vertebrate remains.

INTRODUCTION

In Mid-Triassic (Anisian) times some 241–235 Ma, the supercontinent of Gondwana was still largely intact, although parts of it were showing clear signs of the crustal extension and would later pull it apart (e.g., Stollhofen et al., 1998; Stanistreet and Stollhofen, 1999). The southern margin was being compressed severely by the subduction of the paleopacific plate beneath the Gondwanan plate—the so-called Samfrau active margin. This manifested itself on the surface as a continuous mountain range (the Gondwanides of Du Toit, 1937) with associated foreland depressions (Fig.1). Today, the Cape Fold Belt and Karoo Basin of South Africa are remnants of this compressive phase. Much research has been conducted on the tectonic events within the Cape Fold Belt (Halbich et al., 1983; De Wit et al., 1988; Turner, 1999) and their link to depositional episodes in the Karoo Supergroup (Stear, 1980; Cole, 1992; Smith, 1995). More recently, sequence stratigraphers have attributed the major changes in loci of sedimentation and fluvial style within the main Karoo Basin to migration of the forebulge (Catuneanu et al., 1997).

Vertebrate fossils in the main Karoo Basin are abundant and diverse enough to enable biostratigraphers to define and map nine biozones representing time equivalent sedimentation over the entire basin (Kitching and Raath, 1984; Rubidge, 1995). It is evident that the main Karoo basin contains an almost continuous record of changing terrestrial environments from the Late Carboniferous through to the Early Jurassic (Visser, 1991). The rock units and vertebrate fossils of the main Karoo Basin are used as a stratotype to compare with incomplete and less documented successions in the peripheral basins of southern Gondwana, such as those in Madagascar (Smith, 2000), Zambia (Kemp, 1976), and the Namibian basin described here (Keyser, 1973).

The Early Triassic Karoo basin was positioned around 55 degrees S (Visser, 1991; Fig. 1) and completely landlocked by the incipient Cape Fold mountains to the south, east, and west, and by the vast upland plateau of central Gondwana to the North. The rain-shadow effect of these mountains, combined with a continental interior setting, had an overall drying effect on the climate in the foreland basin. However, sedimentological studies have shown that many of the trunk rivers that flowed into the basin had headwaters in the wet uplands and, therefore, were more perennial than the locally-sourced distributary channels (Hancox, 1998). The climate in southern Gondwana during the early-mid Triassic, based on global modeling (Hallam, 1985), as well as geological (Du Toit, 1948; Smith, 1995) and paleontological data (Grine et al., 1979), was warm to hot, and seasonally arid with mean annual temperatures of between 16–20° C (Smith, 1995).

To the north of the main foreland basin, on the relatively stable interior plateau, a broad belt of linear rift valleys

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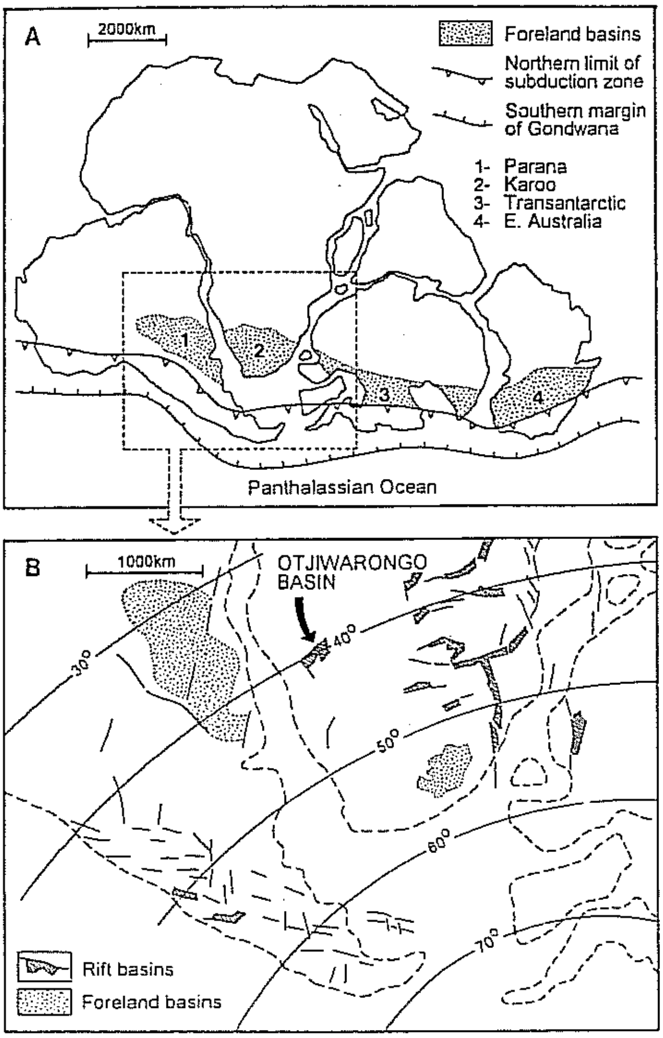

FIGURE 1—Paleoposition of the Omingonde rift in southern Gondwana. (A) the tectonic setting of Gondwana during the late Palaeozoic/early Mesozoic (after Turner, 1999) showing the maximum extent of the foreland basins in relation to the subduction zone to the south. (B) Position of the Omingonde rift in relation to other fault-bounded basins of southern Gondwana that were active during the Early-Mid Triassic, as well as the areas of foreland subsidence at that time. The structural data are from Tankard (pers. commun., 2000) and De Wit et al. (1988), and paleolatitudes after Smith et al. (1981).

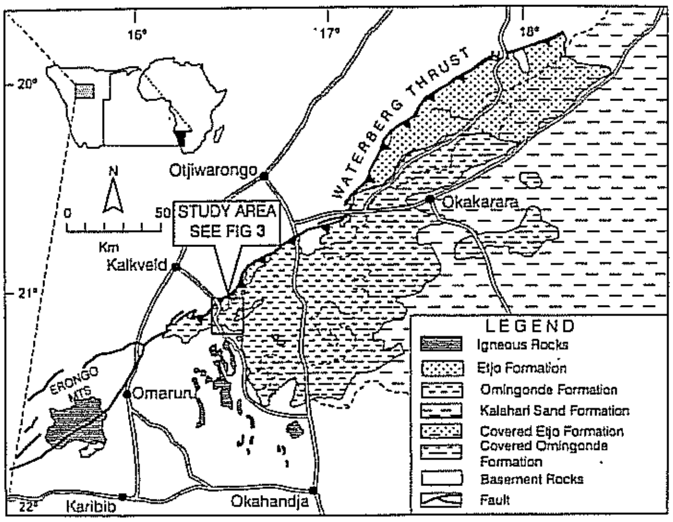

FIGURE 2—The present outcrop area of the Omingonde Formation in Northern Namibia that is strongly influenced by the Early Cretaceous Waterberg thrust fault and the Tertiary Kalahari Sand Formation.

ran roughly NE-SW across southern Gondwana (Fig.1). This structure has been attributed to transtensional forces in the crust that were being released along deep-seated pre-Gondwanan sutures (De Wit et al., 1988). Loffler (1998) interprets this lineament as a "failed rift" that was abandoned after the basin-and-range stage. He invokes mantle upwelling as the cause of crustal upwarping and rifting as a precursor to the early Cretaceous magmatism that accompanied the eventual break-up. During the early-mid Triassic, sediments and fossils of the Omingonde Formation accumulated in one of these rift valleys lying around 40° S at the time. Four parallel half grabens were formed on either side of a pre-existing Neoproterozoic-aged arch. These small basins have been named Otjiwarongo and Erongo on the southern side, and Otjungundu and Goboboseb on the northern edge (South African Committee for Stratigraphy, 1980). The outcrops documented here all lie within the Otjiwarongo Basin (Figs.1 and 2) in the area around Mount Etjo where the Omingonde strata reach their maximum thickness of 700 m (Stollhofen et al., 1998; Holzforster et al., 1999; Fig. 3). These successions, for the most part, lie directly on an uneven, glacially sculpted (Loffler, 1998) surface of Neoproterozoic granites and gneisses. In the northern parts of the Otjiwarongo Basin, the Triassic strata unconformably overlie a thin sequence of diamictites and carbonaceous shales that are lithologically and stratigraphically equivalent to the Permo-Carboniferous Dwyka and Lower Ecca groups at the base of the Karoo Supergroup (Porada et al., 1994; Loffler, 1998).

Vertebrate fossils reportedly were found in Omingonde outcrops in 1926, although their details were never published and the specimens have been lost. In 1971 and 1972, Keyser made collecting trips to Mount Etjo and later published the first preliminary description of the fossil fauna (Keyser, 1973). He concluded that the Omingonde fauna has close affinities to the *Cynognathus* zone in the main Karoo Basin but was slightly more advanced. Thus, he proposed a biostratigraphic correlation with the lower part of the Molteno Formation (Scythian) of the main Karoo basin. The 25 specimens collected by Keyser included a small herbivorous bauriamorph (*Herpetogale*), several specimens of the gomphodont cynodont *Trirachodon*, and a number of medium to large herbivorous dicynodonts (*Kannemeyeria*, *Dolichuranus*, and *Rhopalorhinus*) and cynodonts (*Diademodon* and *Titanogomphodon*). The medium-sized carnivore is represented by *Cynognathus*, and small insectivores by an eriopoid amphibian and an unidentified cynognathid lower jaw. An articulated skeleton of *Erythrosuchus*, a large carnivorous thecodont, was excavated and prepared as part of the current project and is figured in this report. To date, no fossils of fish, plants, or insects have been recovered from the Omingonde Formation.

This study is part of an ongoing project with a working

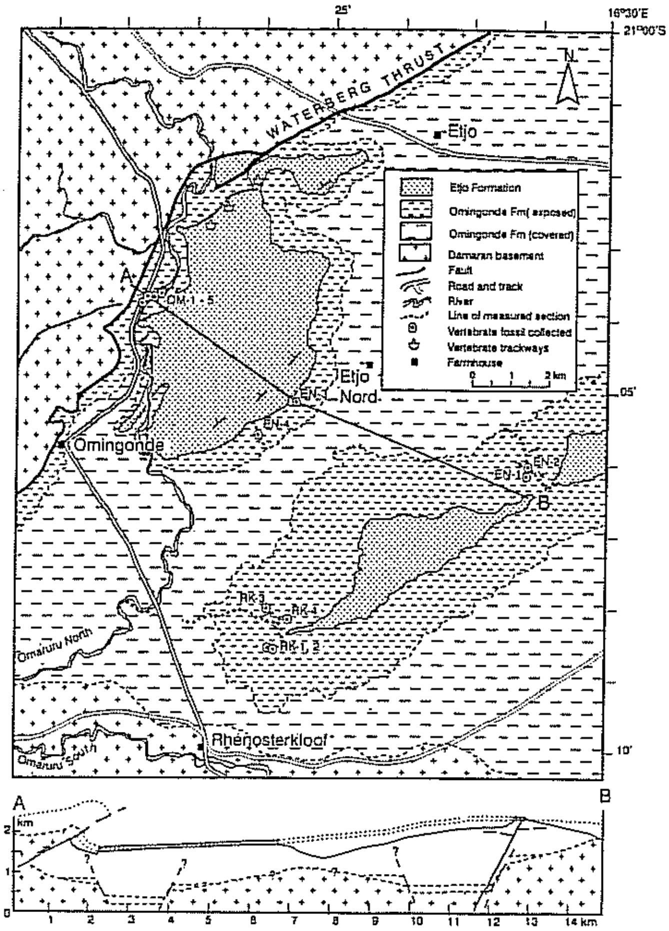

FIGURE 3—Location of measured sections and fossils collected during this study from the Omingonde outcrops on Etjo Mountain. The cross-section shows inferred basement structure and the direction of thrust on the Waterberg fault.

title "Paleoecology of Gondwana," in which sedimentological and paleontological field data are being used to reconstruct the climatic and landscape changes that occurred in southern Gondwana from the Late Permian through to the Early Jurassic. Linking these data to taxonomic and morphological studies of the fossils allows the interpretation of the effect these changes had on the evolution of tetrapods. The Omingonde Formation was selected for study because the few fossils that have been collected indicate a time interval from latest Early Triassic (Scythian) to early Middle Triassic (Anisian; Keyser, 1973), an interval that has an incomplete vertebrate record in the main Karoo Basin (Hancox, 1998). It also provides an opportunity to compare the environmental conditions between a large foreland depression positioned around 55°S, and a small half-graben valley in the elevated more arid inland of southern Gondwana that was lying at about 40°S at the time of infilling (Visser, 1991). Exposures on the slopes of Etjo Mountain offer an almost continuous section through all but the lowermost Omingonde strata (Figs. 2–4). The mountain lies next to a major Neoproterozoic reverse fault, the Waterberg thrust, which was reactivated in the Early Cretaceous. This fault has protected not only the overthrusted strata from erosion, but also provides enough relief to keep the exposures clean and fresh.

FACIES DESCRIPTION

For the stratigraphic sections studied (Fig. 5), five sedimentological facies associations are recognized within the Omingonde succession and two within the overlying Etjo Formation (Fig. 6). The Omingonde facies are envisioned as representing a sequence of changing landscapes through: (1) paludal floodplains with marginal alluvial fans, (2) gravel-bed braided rivers with marginal alluvial fans, (3) loessic plains with saline lakes and ponds, (4) gravel-bed meandering rivers on semi-arid floodplain, and (5) sand-bed meandering streams on semi-arid loessic plains with saline ponds. Above an unconformity and an

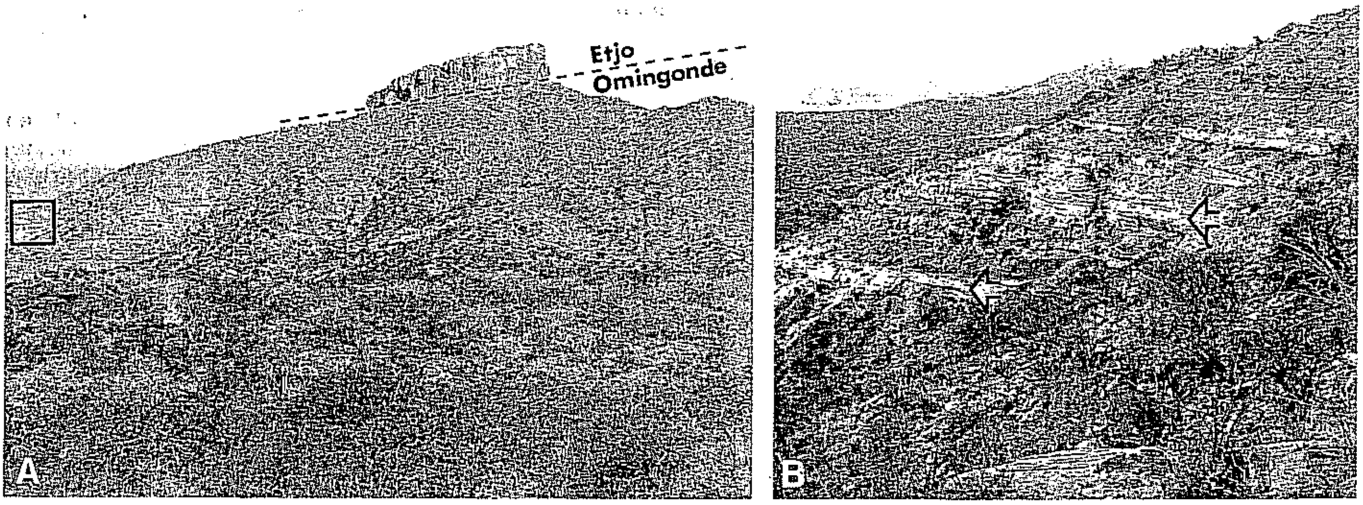

FIGURE 4—Stratigraphy of the Omingonde Formation. (A) General view of Omingonde exposures beneath the capping of Etjo Formation sandstones on the southwestern end of Mount Etjo. (B) Closer view of outcrop framed in (A) showing multistoried conglomeratic sandstones (arrowed) of the Middle Omingonde Formation interpreted as the in-channel deposits of a braided river.

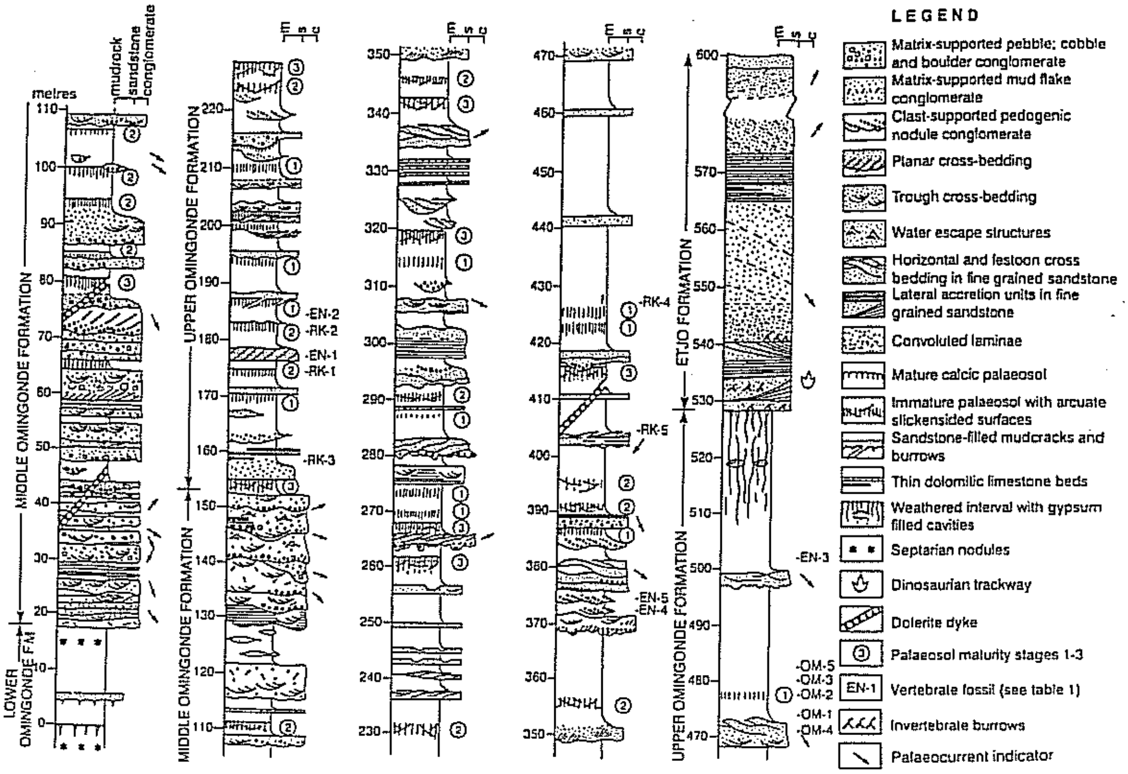

FIGURE 5—Composite sedimentological logs from the Omingonde Formation exposures on the southwestern end of Etjo Mountain, Namibia. Paleocurrent data are averaged from several readings taken mainly from planar and trough cross-bedding. See Figure 3 for transect localities.

apparent hiatus, the Etjo Formation includes (6) "wet desert" wadis and barchanoid dunes, capped by (7) a sand sea of large longitudinal dunes.

Lower Omingonde Paludal Floodplains with Marginal Alluvial Fans

Only the upper 25 m of this facies is exposed in the study area but similar sequences have been documented in nearby boreholes as infilling bedrock valleys (Holzforster et al., 1999). The strata are dominantly dark reddish-brown, fissile, massive siltstone with irregular claystone interlaminations with minor interbedded conglomeratic sandstones. These tabular sandstone bodies are 3–5 m thick and are structured with trough and planar cross-bedding. They are interpreted as crevasse splay sheets emanating from the toe of an alluvial fan (Loffler, 1998).

The monotonous mudrocks contain small vertically orientated rhizocretions associated with clearly defined narrow horizons of cobble-sized, oblate nodules. The nodules are composed of massive gray micrite, each containing a central drusy quartz- lined cavity with radiating shrinkage cracks. In this respect, they can be termed septarian nodules (Brewer, 1964). They vary in shape from biconvex to biconcave in cross-section. Microprobe and X-ray analyses indicate a microcrystalline micrite groundmass, with both fibrous and equant calcite mineralization in the cracks along with stringers of hematite. These nodules possibly were formed from a gelatinous lime mud precipitated on the sediment-water or sediment-air interface that went through a process of chemical desiccation (syneresis), which caused the distinctive radiating shrinkage cracks (Neal, 1974). Astin (1986) proposes an alternative process that does not involve a surface precipitate. He concluded that the cracks are formed in pedogenic calcareous nodules as tensile fractures during rapid burial and compaction of the host mudrocks.

The massive siltstones and laminated claystone are interpreted as formed by suspension settling of muddy fines in standing water of lakes or ponds. The horizons of color mottling, septarian nodules, and root casts within the monotonous mudrocks are interpreted to be hydromorphic soils developed in these palustrine/lacustrine sediments. Such soils are formed on the exposed margins of shallow-sided lakes during lowstand periods (Wright and Platt, 1995). Similar paleosol peloids with sparry calcite filled septarian shrinkage cracks have been described from Late Triassic Maleri Formation of southern India (Sarkar, 1988) and the Late Triassic Dolores Formation of southwestern Colorado (Blodgett, 1988). Their association with rooted horizons is considered to be indicative of seasonal wetland conditions where the water table is close to the surface for much of the year, and actually intersects the surface for some of the year (Sehgal and Stoops, 1972). Thus, the interpreted environment of the lower Omingonde formation is of wet floodplains with ponds and marshes fed by streams issuing from marginal alluvial fans along the fault scarp. No fossils have yet been found in this facies. The paucity of organic remains in the Lower Omingonde mudrocks possibly is due to poor preservation rather than an original scarcity, although the lack of suitable outcrops for finding macrofossils also may be a factor.

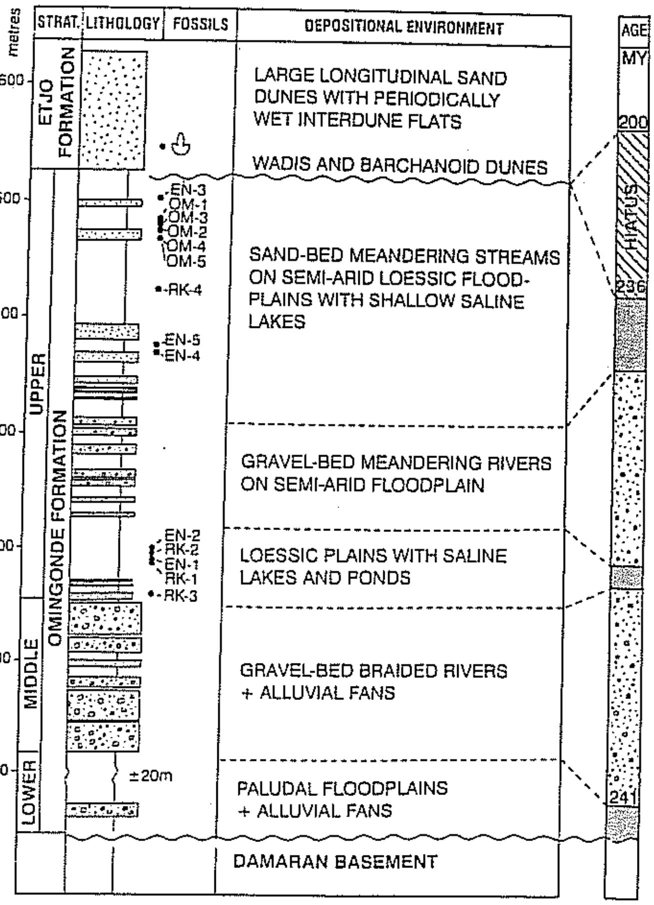

FIGURE 6—Summary of the stratigraphy, depositional environments, and vertebrate fossil localities of the Omingonde Formation. (Tridactyl footprint symbol indicates Early Jurassic dinosaur trackways in the basal Etjo beds).

Middle Omingonde Gravel-Bed Braided Rivers and Marginal Alluvial Fans

The Middle Omingonde at Etjo Mountain comprises at least 80% in-channel deposits consisting of two prominent conglomeratic sandstones separated by a narrow interval of pedogenically modified siltstone beds (see Figs. 5 and 6). These two major 10-to-15 m-thick sandstone bodies are each made up of several (7–10) vertically stacked, tabular, upward-fining units (Fig. 4B) at the study locality.

The lowermost conglomeratic sandstone, near the base of the Middle Omingonde (30–40 m on Fig. 5) is structured with planar and trough cross-bedding and contains an interval of poorly cemented, matrix-supported conglomerate containing rounded cobbles and boulders of vesicular lava (Fig. 7A and B). The chaotic texture and immature lithic arenite matrix of this interbed suggests emplacement by a series of high-density debris flows. Such deposits have been recorded in the proximal and mid-fan regions of alluvial fans in modern arid zone rift valleys (Blair and McPherson, 1994). Paleocurrents measured mainly from planar foresets in the conglomeratic sandstone unit are strongly southeasterly, flowing away from the interpreted active rift margin into the axis of the basin. The paleocurrents and sedimentary facies (Fig. 5, 20–40 m) suggest that the lower of the middle Omingonde sandstones were deposited by several coalescing alluvial fans.

The uppermost prominent sandstone at the top of the Middle Omingonde is made up of several stacked fining upward units (Fig.7C). Each unit is erosively-based and consists of a basal layer of well-sorted, rounded to subrounded, grit- to cobble-sized clasts of granite, marble, chert, and quartz with abundant reworked pedogenic nodules set in a coarse litharenitic matrix (Fig. 7D). These predominantly clast-supported conglomerates contain minor angular green-and-maroon mudrock clasts, rare isolated therapsid limb and jawbones, and rounded bone fragments. In each depositional unit, the basal conglomerates grade upward into trough cross-bedded, whitish-yellow arenite with flame structures. Paleocurrent readings from this sandstone (Fig. 5, 130–150 m) indicate a swing to a more east-southeasterly flow direction away from the interpreted fault and tangentially across the axis of the basin. Deep fissures filled with slumped and partially liquified sands (Fig. 8A), as well as the dewatering flame structures, are interpreted as evidence of synsedimentary seismic activity, possibly linked with nearby volcanism.

This upper ledge-forming sandstone body is interpreted as having accumulated in a single large braided river with a perennial, but fluctuating, discharge regime (Holzforster et al., 1999; Mack and Leeder, 1999). Diagnostic features include (1) lack of large-scale lateral accretion surfaces, (2) episodic scour-and-fill sedimentation, (3) dominance of extrabasinal clasts over reworked bank material, (4) immature coarse sand matrix, (5) low divergence of paleocurrent directions, and (5) absence of slack-water fines that would indicate ephemeral discharge regime. The thickness and lateral continuity of these sandstone sheets suggests that they were part of an axial drainage system (Mack and Leeder, 1999), in which case the original rift axis was orientated E-W with an easterly plunge. This trend is tangential to that of the later Waterberg thrust, suggesting that the resultant vectors of extensional and compressional forces may have been different.

A 25-m-thick interval (75–100 m on Fig. 6) of overbank fines, made up of dark reddish-brown (Munsell 5YR 4/3) horizontally-bedded siltstone with lenses of gritstone and reworked pedogenic glaebules, occurs between the two prominent conglomeratic sandstone bodies. Sand-filled meniscate burrows of the *Taenidium*-type are evident in the rare intervals of reddened siltstones that have not been modified pedogenically. These indicate the burrowing activity of arthropods, probably beetles, into the dry floodplain surface (Smith et al., 1993). To date, no vertebrate fossils have been recovered from this lithofacies. At least 6 moderately mature calcic paleosols occur in this interval. Each paleocaliche consists of a meter-thick horizon containing numerous roughly spherical, small, pebble-sized calcareous nodules (Fig. 8B) that become larger and more closely packed towards the base. The most mature paleosol at meter 80 (Fig.8B) is interpreted to be equivalent to a stage III aridosol (Gile et al., 1965) with vertically disposed rhizocretions (Fig. 8C), rough-surfaced calcareous nodules, and a coalesced Bt/Ca horizon (Fig. 9). A calcretized, siltstone-filled cylinder (Fig. 8D) in this paleosol is possibly a vertebrate burrow cast. Similarly structured calcic aridosols occur in other Triassic rift-valley fills, such

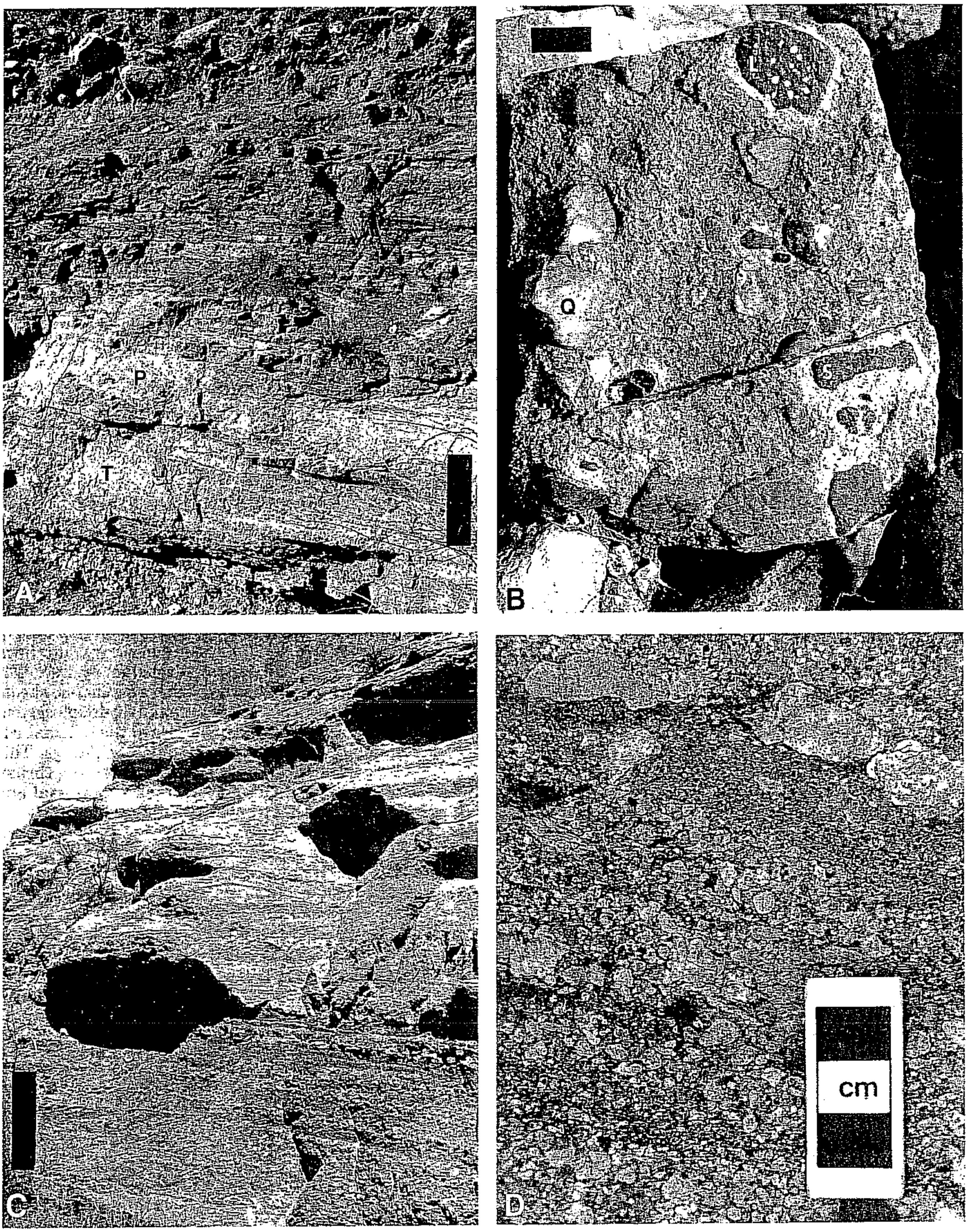

FIGURE 7—Middle Omingonde sedimentary facies: (A) gravel bed braided stream facies showing stacked tabular units of trough (T) and planar (P) cross-bedded conglomeratic sandstones. Scale bar=1 m. (B) Matrix-supported conglomerate facies of the alluvial fan environment.

as the Middle Triassic Otter Sandstone (Purvis and Wright, 1991) and the Late Triassic Owl Rock Formation of the southwestern U.S. (Tanner, 2000). They also occur in the alluvium of abandoned floodplain terraces in semi-arid continental basins, such as the Ayre Basin of Australia (Butler, 1958). Here the mean annual rainfall of <750 mm is highly seasonal, falling largely as cloudbursts in the cooler winter months, and causes surface run-off and overbank floods to locally scour the floodplain surface. Summer conditions are warm to hot and generally dry, with a mean annual temperature of 20° C. A similar climatic regime is envisaged for southern Gondwana during the accumulation of the Middle Omingonde strata, although the wet/dry seasons probably were better defined due to the rain shadow effect of the Gondwanide mountains to the south (Visser, 1991).

Vertebrate fossils in this facies are very rare and too fragmented to be identified. One recognizable cynodont lower jaw was found in a conglomerate lens within the upper thick sandstone body. Centimeter-sized angular bone fragments found among mudrock clasts on some sandstone bedding planes, and a possible burrow fill, are the only other signs that tetrapods were present.

The paleoenvironment of the Middle Omingonde is interpreted as valley-confined southeasterly to eastward flowing (possibly axial) braided rivers with relatively perennial flow, although subject to seasonal fluctuations. Numerous, relatively small high-angle alluvial fans emanated from gulleys in the hanging wall. Some of the scarp-fed fans were supplied with volcaniclastic clasts, suggesting some contemporaneous volcanism. In a few cases, fans prograded far enough into the rift valley to impinge on the edge of the braided system. Floodplain soils formed at the time had clay-rich textural B horizons overlain by moderately mature calcrete, and are clear evidence that, although restricted in area, the abandoned terraces were well-vegetated under a warm, seasonally wet, semi-arid climate.

Upper Omingonde Loessic Plains with Saline Lakes

Immediately above the uppermost prominent sandstone of the Middle Omingonde, the succession takes on the appearance of typical argillaceous redbeds. Thick beds of pale-red, structureless siltstone contain numerous thin conglomerate lenses and thin, laterally-accreted sheet sandstones. A minor but distinctive component of this facies is a 4-m-thick interval containing several thin (10 cm) but laterally continuous (>100 m) beds of micro-laminated limestone. Five vertebrate fossils were collected from this facies during the course of this study (see Fig. 6); four were found in massive siltstone and one in a conglomerate lens.

In contrast to the dark reddish brown color of the Middle Omingonde mudrocks, the siltstone beds of the Upper Omingonde are pale red in color (Munsell color 10R4/4) and more thickly bedded (0.5–3meters thick) with no discernable primary sedimentary structures. They invariably display some evidence of pedogenesis, but horizonation generally is more weakly developed than lower down. Pedogenic features in the stage 1 paleosols include: olive-colored mottling; isolated light-gray calcite-lined root tubules; weakly developed, claystone-lined, vertic ped structures; and a few arcuate planes. Pea-sized calcareous glaebules are scattered throughout the profile. In more mature stage 2 paleosols, the curved planes are better developed and the calcareous nodules become concentrated into a definite BCa horizon (Fig. 9). The paleosols all are interpreted as calcic vertisols based on their vertically-orientated rhizocretions, calcified skew planes, and thick horizons of densely packed, light-gray calcareous nodules (Blodgett, 1985). The lack of primary bedding in the siltstone and relatively immature soil profiles suggest a fairly rapid rate of floodplain aggradation under a warm, seasonally wet climate. The volumetric dominance of structureless siltstone with calcic and argillic horizons is interpreted to reflect the influx of considerable amounts of loessic dust (Gustavson and Holliday, 1999) from an arid (non-glacial) source on the surrounding plateau. Similar non-glacial loess deposits with the same structural and pedogenic features have been described from Middle Triassic rocks of Utah (Chan, 1999).

Numerous, thin (<0.25 m), pebbly, medium-grained tabular sandstones have distinctive sharp, flat basal contacts and display low angle lateral accretion surfaces. Some have a sharp undulating upper contact with mudrock-filled channels, although most have a transitional contact with sandstone stringers that interdigitate with the overlying siltstone. Intraclasts of mudrock are common in the lower part of each sandstone body. Trough cross-bedding is the dominant structure. Based on their overall tabular geometry (sharp but flat bases and gradational tops with lateral accretion topography), these thin sandstones are interpreted as ephemeral crevasse- splay sand sheets and floodplain-distributary channels (Olsen, 1989). By inference, therefore, a trunk channel was still present as a meandering river situated in the axis of the basin that, by this time, had migrated some distance to the southeast.

The conglomerate lenses are clast-supported and composed predominantly of well-sorted, pebble-sized reworked pedogenic nodules, silty mudstone pebbles, and grit-sized quartz clasts. Commonly, these conglomerates fill wide shallow scours in the floodplain siltstones, and some display high-angle sigmoidal crossbeds indicative of lateral accretion on the inner bank of a narrow sinuous channel. Despite clear evidence of high-energy flow conditions, there is no significant sand fraction associated with these conglomerates. Conversely, reworked nodules rarely are found in the sheet sandstones, although they were present in the underlying alluvium at the time that the sand was deposited. It is concluded that the sheet sands and the peloidal gravels were deposited at different times by different processes. The former were deposited

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Note the subrounded clast of boulder quartz (Q) on the left, platy clasts of basement schist (S) at the bottom, and an amygdaloidal lava cobble (L) at the top of the photo. Scale bar= 5cm. (C) Gravel-bed braided channel-fill eroded into pedogenically modified overbank fines. Scale bar=1m. (D) Close-up of reworked pedogenic glaebules in a lag conglomerate at the base of a Middle Omingonde braided channel sandstone.

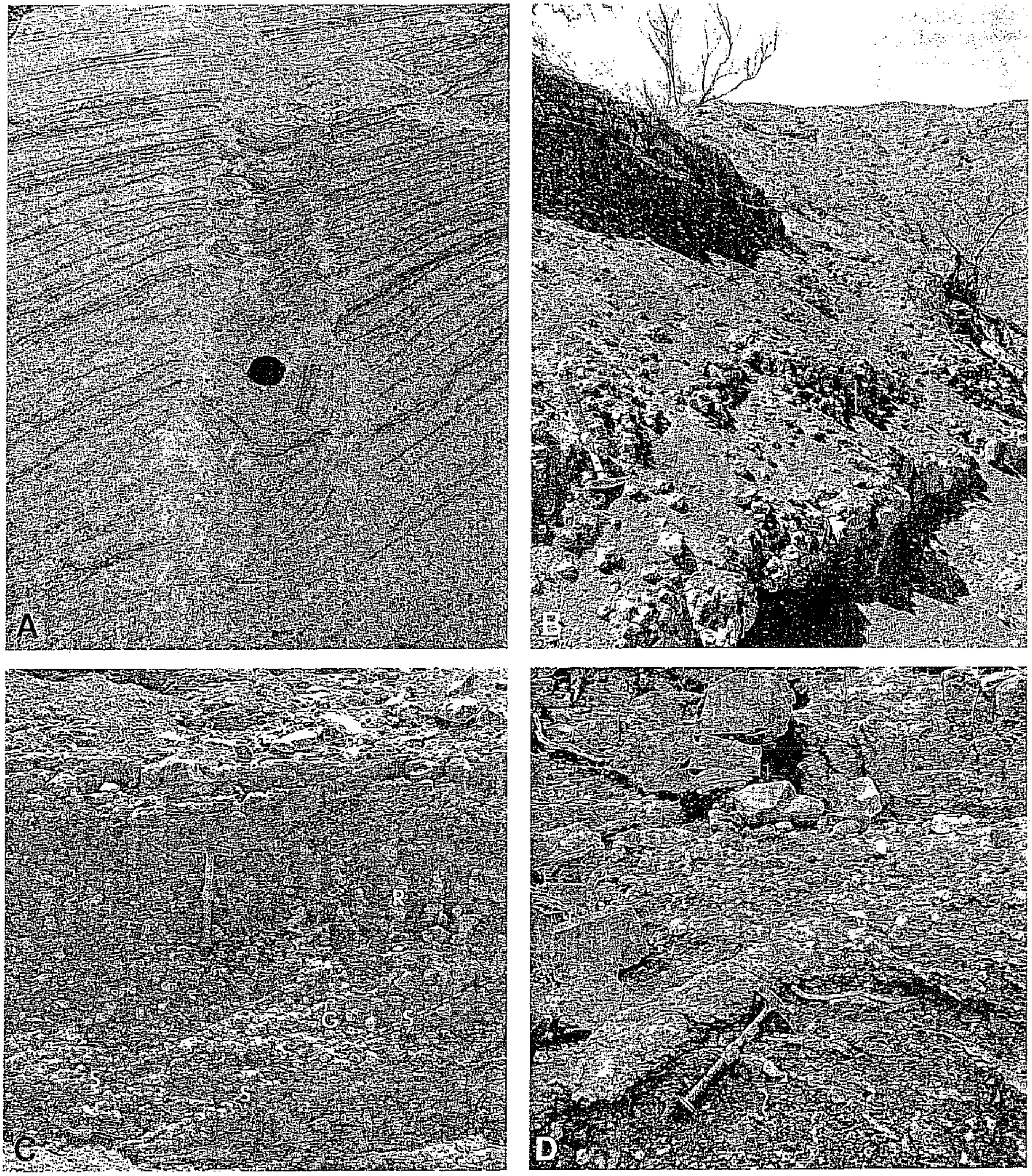

FIGURE 8—Upper Omingonde sediments and paleosols. (A) Soft sediment-deformation structure attributed to seismic activity in trough cross-bedded conglomeratic sandstone of the Upper Omingonde Formation. Lens cover = 5.5 cm diameter. (B) Natural exposure of a mature calcic paleosol (Type III of Fig. 9) in overbank mudrocks. (C) Vertical rhizocretions (R), densely packed glaebules (G), and sub-horizontal skew planes (S) in a mature aridosol. (D) Calcretized cylindrical vertebrate burrow cast in a mature aridosol formed in pale red loessic siltstone.

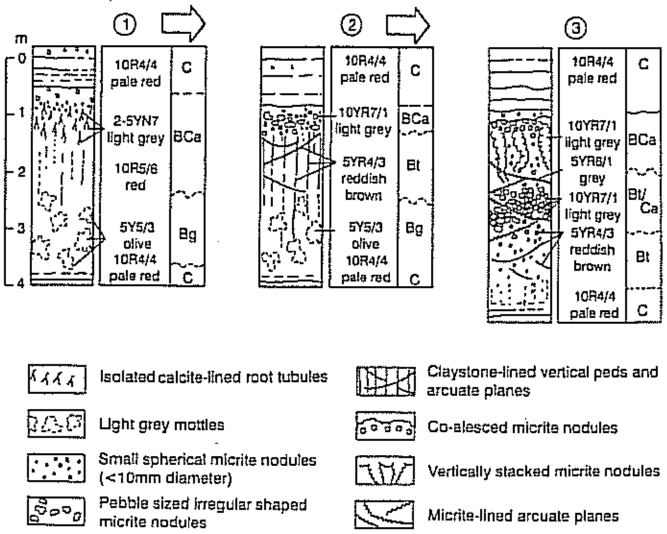

FIGURE 9—Pedogenic features of three successive stages in the maturation of calcic paleosols in the Omingonde Formation mudrocks based on observations from this study.

during overbank flood events emanating from an axial river (Williams, 1971); the latter were deposited by more localized sheet flows on the floodplain during and immediately following rainstorms (Allen and Williams, 1979).

Throughout the study area, three thin (<10 cm), laterally continuous (up to 100 m), white weathering, well-indurated, limestone beds (Fig. 10A, C) crop out at the same stratigraphic level (meter 145–147 of Fig. 5). The limestone sheets line decimeter-scale shallow depressions in the floodplain siltstones. They contain brecciated mudrock clasts that have been generated by penecontemporaneous precipitation of calcium carbonate in the surficial alluvium. The uppermost 2–3 cm of the limestone beds are free of mudrock breccia and composed of microlaminated dark gray micrite with a distinctive knobbly upper surface (Fig. 10C). Basal contacts are less well defined and are transitional to a 25-cm-thick zone of irregular limestone intercalations that pass downwards into a horizon of small calcareous nodules (Fig. 10B) that, in turn, grades into unaltered siltstone. The central portion of the limestone is finely laminated with light/dark millimeter-scale layers of silt-rich and silt-poor carbonate. The laminae have a crenulated appearance in vertical section and a distinctive pustular bedding- plane texture that is interpreted as the impression of algal mats on a carbonate mud surface (Carozzi, 1962). Carbonates with similar textures are formed subaqueously near the margins of playa lakes (Dean and Fouch, 1983). Microlaminated carbonate sheets similar to those of the Omingonde have been described from other ancient floodplain successions. These include the Mercia Mudstone in southern England (Talbot et al., 1994) and Owl Rock Formation of southwestern U.S. (Tanner, 2000), both from the Late Triassic, and the Miocene Intermediate Unit of the Madrid Basin (Sanz et al., 1995).

The basin-shaped geometry of these carbonate lenses and their brecciated basal contacts with overbank mudrocks suggests that they were deposited in small isolated ponds and lakes on semi-arid floodplains. Their restricted stratigraphic range suggests that there was a relatively short period of wetter climate (a pluvial) when the water table seasonally rose to intersect lows in the floodplain of the axial river system, forming a patchwork of saline lakes and ponds.

Vertebrate fossils are relatively common in the massive maroon siltstone beds of the Upper Omingonde (Figs. 5 and 6 and Table 1). They are preserved in three distinct taphonomic assemblages, as either (1) individual skulls or post cranial bones (Fig. 11A-D); (2) partially articulated single skeletons or very rarely multiple skeletons of the same taxon (Fig. 12A); or (3) multitaxa bonebed-type accumulations of isolated bones within pockets of reworked pedogenic nodules (Fig. 12B).

Field observations of some 2500 *in-situ* therapsid fossils in the main Karoo Basin (Smith, 1993) made it possible to identify regularly occurring patterns of skeletal disarticulation that could be grouped into 8 taphonomic classes (A-H of Fig. 13). These classes range from fully articulated curled-up specimens (A) through articulated skeletons with straight or reflexed spinal curvature (B), isolated skulls, with cervical vertebrae (C) and with (D) or without (E) attatched lower jaws, to isolated lower jaws (F) and individual post cranial elements (G) that are rarely concentrated into bonebed-type occurrences (H).

Figure 13 shows the distribution of skeletal disarticulation classes among all the *in situ* fossils found in the study sections. The overall distribution of disarticulation classes in the Omingonde sections shows a dominance of near

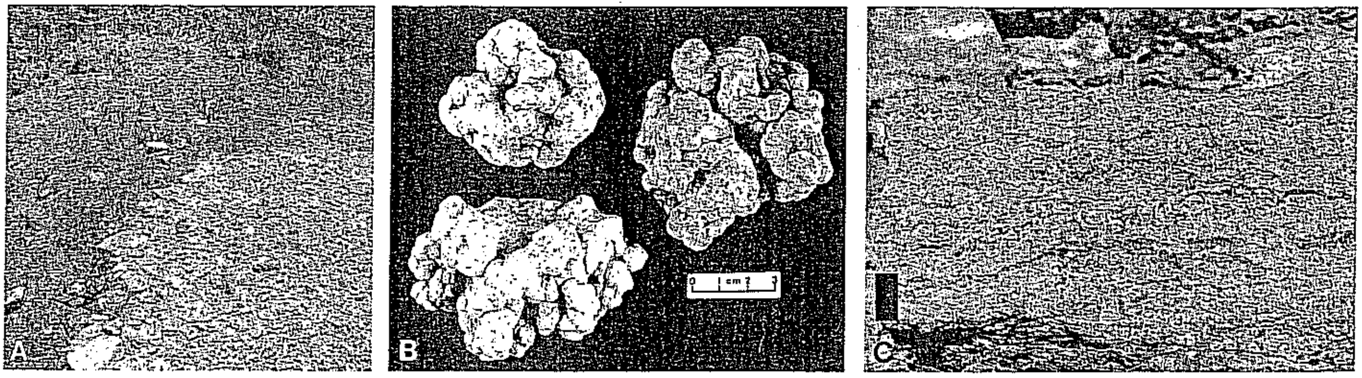

FIGURE 10—Upper Omingonde saline lake facies. (A) Thin bed of playa-type lacustrine carbonate in the Upper Omingonde loessic floodplain mudrocks. (B) Distinctive irregularly shaped calcareous nodules associated with playa carbonates. (C) Close-up of microlaminated carbonate bed shown in 8A. Scale bar= 2 cm.

TABLE 1—Field identification, taphonomic class, and brief description of the vertebrate fossils collected during the course of this study. These specimens are now permanently housed in the Geological Museum, Windhoek, Namibia.

Field no.	Taxon	Taphonomic class (Fig. 13)	Description of fossil
EN-3	*Trirachodon*	E	Skull minus lower jaw
OM-1	*Kannemeyeria*	G	Isolated ulna
OM-3	*Diademodon*	B	Skull plus lower jaw and articulated partial skeleton
OM-2	?*Massetognathus*	E	Skull minus lower jaw
OM-4	*Erythrosuchus*	B	Skull plus lower jaw and articulated partial skeleton
OM-5	*Trirachodon*	D	Skull plus lower jaw
RK-4	*Trirachodon*	B/D	4 skulls associated with partly disarticulated skeletons
EN-5	Kannemeyerid	?B	Eroded posterior portion of articulated skeleton
EN-4	*Cynognathus*	D	Eroded snout with lower jaw
EN-2	Cynodont indet.	G	Isolated femur
RK-2	*Diademodon*	D	Skull plus lower jaw
En-1	Cynodont indet.	?D	Skull within large nodule
RK-1	Kannemeyerid	D	Eroded skull plus lower jaw
RK-3	*Trirachodon*	D	Skull plus lower jaw

complete skeletons missing only their distal elements (class B) and skull-only occurrences (classes D and E). This taphonomic signature is similar to that recorded by Hill (1979) from modern mammal carcasses on semi-arid floodplains in East Africa. He noted that desiccation of the skin covering the carcasses of small savanna mammals causes it to become mummified and hold the disarticulated bones in close association indefinitely. It has been speculated that the therapsids had a leathery skin without scales or hair (Romer, 1966; Chudinov, 1970). Under semi-arid climatic conditions it is proposed that therapsid carcasses lying on the middle and upper Omingonde floodplains would have dried fairly rapidly, such that mummification of the skin may well have played an important role in the preservation of near complete skeletons with straight or reflexed spinal curvature (taphonomic class B).

Another feature of the fossil bones that indicates burial under arid conditions are the pervasive fissures that dissect the bones, some of which display slight vertical displacement (Fig.11D). The fissures clearly were formed after burial and are the result of shrink/swell movements of the surrounding soil peds during wet/dry seasons (Gustavson, 1991). Smaller-scale hairline cracks on the fossil bones initially were formed through exposure to sun drying before burial, although in some specimens they have been widened and lengthened by compaction to give the bone a crazed appearance (Fig.11C). A similar mechanical process was invoked for the post burial fragmentation of kannemeyerid bones excavated from red mudrocks in the Late Triassic Chinle Formation of Eastern Arizona (Fiorillo and Padian, 1993).

This facies is interpreted as an expansive semiarid floodplain subject to long, warm and dry summers and short, wet winters. During the summer, the regional water table dropped and convection-driven dust storms were common. Calcium carbonate was precipitated in algal mats at the sediment-water interface as the floodplain ponds dried-up. Winter months, however, were much wetter; heavy thunderstorms caused sheet run-off that scoured the soils down to the caliche horizons. The nodules and bones were washed locally into depressions in the floodplain by the run-off and, in places, more sustained flow deposited them within sinuous channels. Overbank flooding from the trunk channel periodically inundated this area and, although crevasse splays rarely reached the distal floodplain, the sinuous channels emanating from them did, at times, rejuvenate the end-point playas.

Upper Omingonde Gravel-Bed Meandering Rivers on Semi-Arid Floodplains

Above the massive loessic siltstone interval of the Upper Omingonde, for some 80 meters (220–300 m of Figs. 5 and 6), thin conglomeratic sheet sandstones are more common. Each single-storied channel sandstone is rarely thicker than 3 m and they are separated by somewhat thicker intervals of pedogenically modified maroon mudrocks. The sandstone bodies have distinctively runnelled (Flood, 1983) basal scours with numerous gutter casts, up to 1 m deep, filled with small pebble-sized gravel clasts. Clasts comprise well-rounded and near spherical quartz pebbles and rounded-to-oblate red mudrock clasts. The basal gravel grades upward into trough cross-bedded, coarse-grained sandstone with foresets accentuated by thin gravel stringers. Several irregular internal discontinuity surfaces, each dipping at an angle of around 25 degrees, extend from bottom to top of the sandstone bodies. These discontinuities are interpreted as lateral accretion surfaces, and are defined most clearly in the topsets where each accretion unit tapers and interdigitates with the overlying mudrocks. These tapering sandstone stringers are commonly ripple cross-laminated and bioturbated. Bioturbation is manifested by meniscate *Taenidium* burrows. Isolated mudrock-filled "shoestring" channels, up to 3 m wide and 1 m deep, rarely are preserved in the upper surface of the gravelly sand sheets.

The overbank fines in the lower and upper part of this facies comprise a series of closely stacked paleosols. However, the lower and upper parts are separated by a ±25-m-thick interval of massive siltstone that is almost devoid of pedogenic modification. Vertical calcareous rhizocretions and nodule trains in stage 2 and 3 paleosols are interpreted as tap roots adapted to exploiting highly fluctuating water tables (Purvis and Wright, 1991). Despite the evidence for vegetation in the paleosols, intensive searching of extensive clean outcrops of this facies failed to locate any vertebrate fossils.

The interpreted paleoenvironment of this facies of the Upper Omingonde is that of a wide flat alluvial plain traversed by ephemeral gravel-bed meandering rivers. The gutter casts are a characteristic feature of arid zone sheet-flood deposits (Myrow, 1992) and are caused by spiralling vortices that erode parallel grooves in the floodplain surface (Flood, 1983). The combination of an absence of ground-covering vegetation and cyclonic thunderstorm activity would have led to excessive surface run-off. As flow waned, the grooves filled with gravel bedload to form gutter casts. The floodplain channels were subjected to a se-

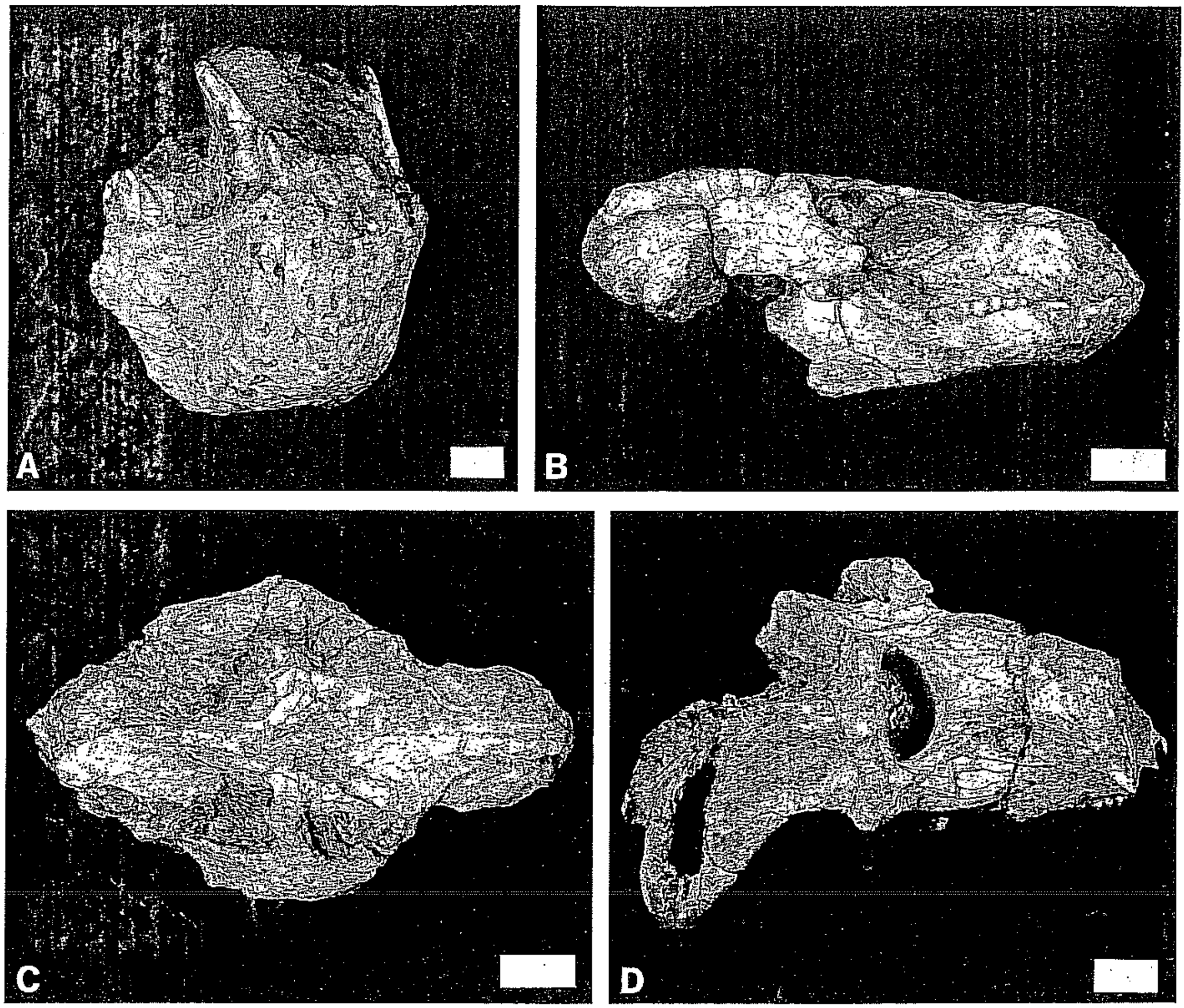

FIGURE 11—Omingonde Formation therapsids. (A) Isolated lower jaw of *Cynognathus*, a carnivorous mammal-like reptile and type fossil of the *Cynognathus* Assemblage Zone (Rubidge, 1995). Scale bar = 1 cm. (B) Lateral view of one of the 4 *Trirachodon* skulls shown in Figure 12A that are interpreted to have been preserved within a burrow. Scale bar = 2 cm. (C) Dorsal view of *Trirachodon* skull EN-3 showing crazed pattern of fissures in the bone caused by the displacive growth of calcite in the K horizon of an Upper Omingonde aridosol. Scale bar = 2 cm. (D) Lateral view of a *Diademodon* skull minus lower-jaw. Note the vertical fissures through the specimen interpreted as post-burial deformation by shrink-swell movements in a calcic vertisol. Scale bar = 2 cm.

ries of flood events separated by long periods of no flow. Each flood event deposited coarse- to medium-grained sand on the inner bank of the channel meanders, thus increasing its sinuosity with each accretion event. Similar sandstone bodies within a redbed sequence have been described from the Lower Jurassic Moenave Formation of Utah (Olsen, 1989).

The paucity of pedogenesis and vertebrate fossils in this facies is difficult to explain. It is possible that boundary fault activity temporarily increased basinal subsidence rates, creating accommodation space in the rift valley. The rivers adjusted by increasing sinuosity and frequent avulsions, resulting in numerous single-storied gravelly sand bodies and a considerable increase in floodplain accretion. The homogeneous, thickly-bedded, light red siltstone beds have a conchoidal fracture and can be traced laterally for several hundred meters. These are some of the diagnostic characteristics of loessites (Chan, 1999; Johnson, 1998). Thus, there appears to have been constant accumulation of eolian silt over the valley floor that did not allow enough time for soil horizonation processes to form mature profiles. The lack of vertebrate remains possibly is due also to rapid floodplain accretion rates where there was too little time between depositional episodes for natural mortality to deliver enough skeletons to be fossilized.

Upper Omingonde Sand-Bed Meandering Rivers on Semi-Arid Floodplains with Shallow Saline Lakes

Continuing higher in the Omingonde succession, the fluvial channel sandstone bodies lose their gravel compo-

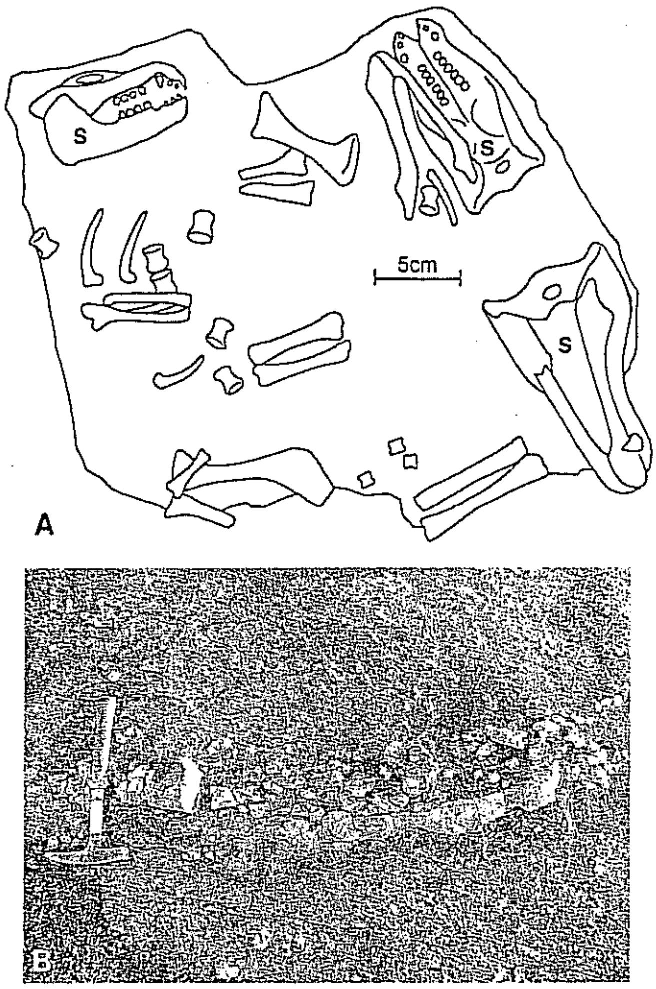

FIGURE 12—Examples of the taphonomic modes of vertebrate burrows and reworked paleosols of the Omingonde Formation. (A) Sketch plan-view of specimen RK-4, an excavated block from an Upper Omingonde loessite with an interpreted *Trirachodon* burrow-fill containing 4 skulls with articulating lower jaws (three are labelled, S, one had eroded out and lay loose, Fig.11B). Two skulls are preserved ventral-up and the third lateral-up, and they are associated with scattered post-cranial elements. (B) Conglomerate of reworked pedogenic nodules in the Upper Omingonde floodplain mudrocks containing concentrations of isolated dicynodont and cynodont post-cranial elements of taphonomic class H.

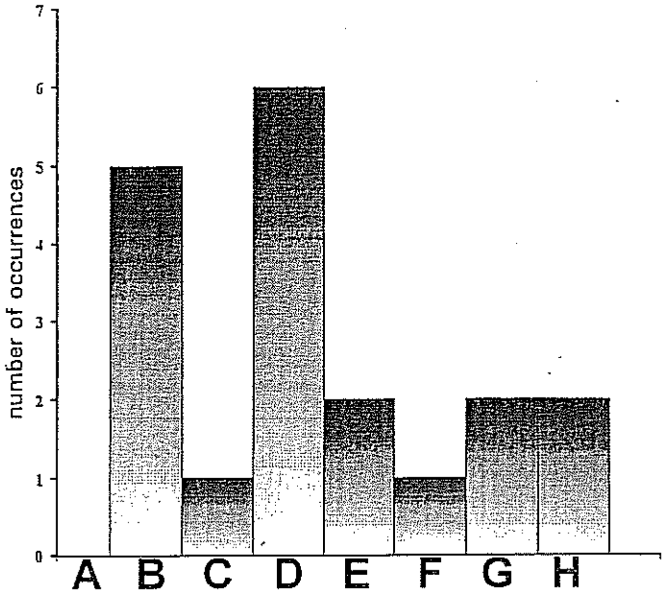

FIGURE 13—Skeletal disarticulation classes of 19 Omingonde vertebrate fossils collected from floodplain deposits of the Upper Omingonde. Although the sample is not large, there are relatively more partially articulated skeletons and bonebed occurrences than would be expected. This taphonomic signature is interpreted to be indicative of desiccation on warm semi-arid floodplains subject to periodic dust storms. A- Fully articulated skeleton, B-Articulated skeleton with some scattering, C- Skull + lower jaw + cervical vertebrae, D- Skull+lower jaw, E- Skull minus lower jaw, F- Isolated lower jaw, G-Isolated post cranial elements, H-"Bonebed" of isolated elements of mixed taxa.

nent yet retain high sinuosity characteristics and, as such, may be described as preserved in-channel deposits of sand-bed meandering rivers. Figure 14 is a panel section of a cliff exposure in this facies at the *Eryrthrosuchus* quarry. It shows two channel sandstones, cut perpendicular to flow, separated by fossiliferous maroon siltstone. The sandstones display ribbon-shaped cross-sectional geometry and lateral accretion surfaces typical of meander-belt point- bar deposits (Friend, 1983). The channel sandstones have runnelled basal scours and comprise trough cross-bedded, coarse-grained sandstone with scattered maroon mudrock pebbles (Fig. 14). Paleocurrents are dominantly easterly, parallel to the inferred fault scarp (see Fig. 5, 470–490 m). The upper portions of these single-storied channel sandstones display a series of inclined lateral accretion units. Each unit comprises an upward-coarsening siltstone capped by a sandstone wedge that tapers into a convex-topped bar form (Fig. 14). The top surfaces of these interpreted scroll-bar sandstones commonly are bioturbated by subhorizontal, unlined meniscate back filled burrows, identified as *Taenidium*. These are attributed to the immediately post-flood scratch digging activity of beetles into a wet substrate (Smith et al., 1993).

The sandstone-to-mudrock ratio decreases from 1:4 at the base of this unit to 1:6 at the top. The overbank fines are dominantly thickly-bedded, pale red, massive siltstone with some horizontally laminated fine-grained sandstone sheets containing minor mudrock flakes. Horizons of calcified arcuate planes (Fig. 15A,B) are common in the massive mudrock, indicating the dominance of type 2 paleosols (see Fig. 9) in this part of the succession. These homogenous siltstone beds with vertic structures are interpreted as loessic in origin, each having been deposited rapidly in a single dust storm (Pye, 1995).

Within the overbank deposits of the Upper Omingonde, lenses of reworked pedogenic carbonate nodules occur in shallow elongate depressions (in plan view, they are ovoid in shape, each measuring on the order of 1.25 x 3 m; Fig.12B). The nodules are suspended in a matrix of maroon siltstone with abundant mudrock flakes and pebbles, along with isolated bones of a variety of vertebrate taxa, including *Kannemeyeria*, *Trirachodon*, and *Cynognathus*. These intraformational floodplain gravels are similar to interfluve gravels described by Allen and Williams (1979) from the Old Red Sandstone of Wales, which they attribute to localized erosion and reworking of floodplain caliche nodules by sheetwash during thunderstorms.

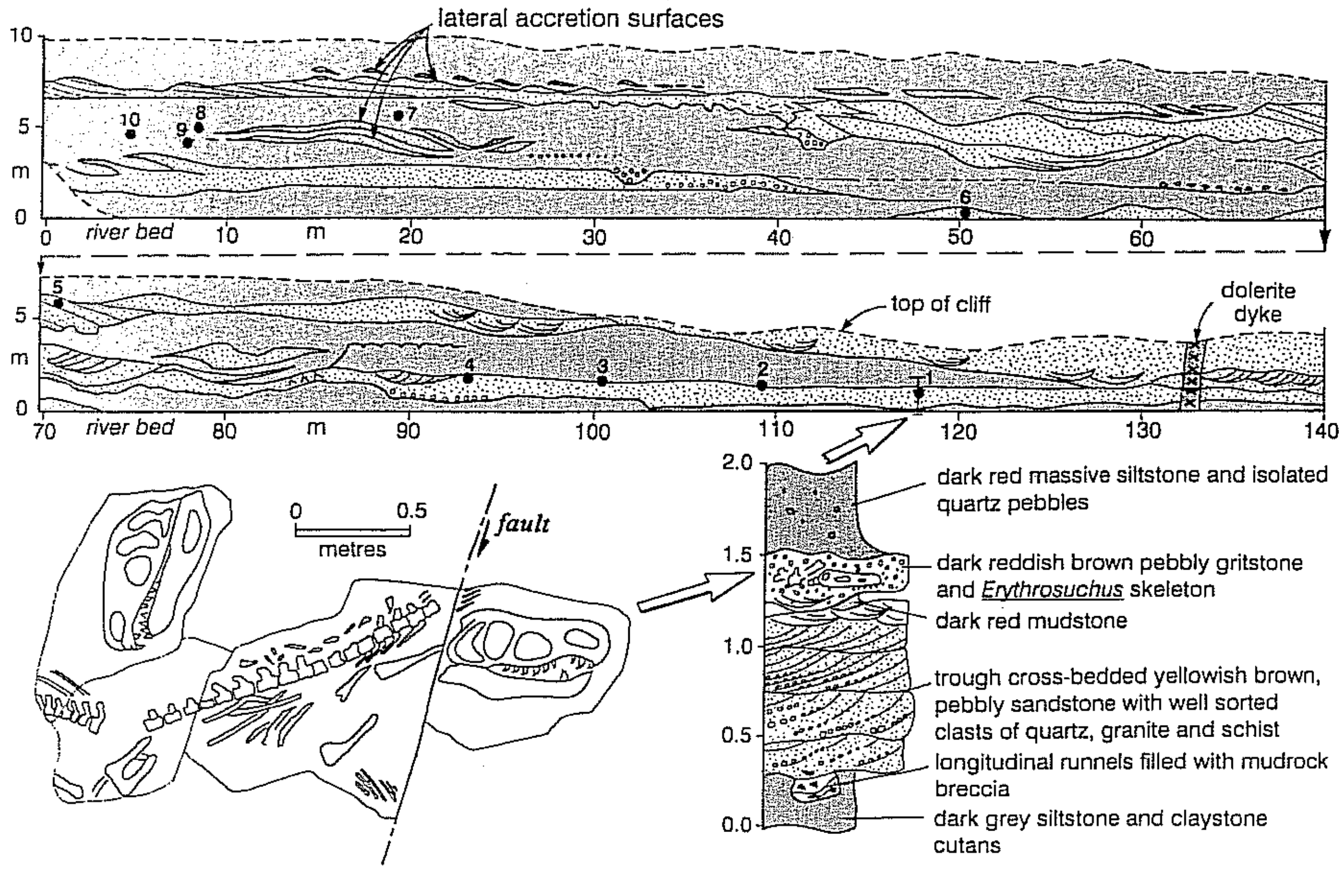

FIGURE 14—Panel section of Upper Omingonde sand-bed meandering river facies showing ribbon-shaped geometry with lateral accretion surfaces. The detailed sedimentological section is at the locality of an articulated *Erythrosuchus* (OM-3) skeleton that was collected in this study (see Fig. 16). Field descriptions of fossil occurrences are as follows: (1) OM-3 *Erythrosuchus* sp. near complete partially articulated skull and skeleton; (2) Isolated small vertebral column with articulated ribs (observed); (3) Isolated small? cynodont tibia; (4) Isolated small? cynodont scapula; (5) *Trirachodon* skull minus lower jaw lying dorsal-up with scattered post-cranial elements; (6) Scattered small ribs and scapula; (7) OM-3 *Diademodon* skull plus lower jaw and articulated partial skeleton; (8) Scattered small post cranial elements; (9) *?Massetognathus* skull minus lower jaw lying dorsal-up; and (10) Isolated dicynodont lower jaw lying ventral-up.

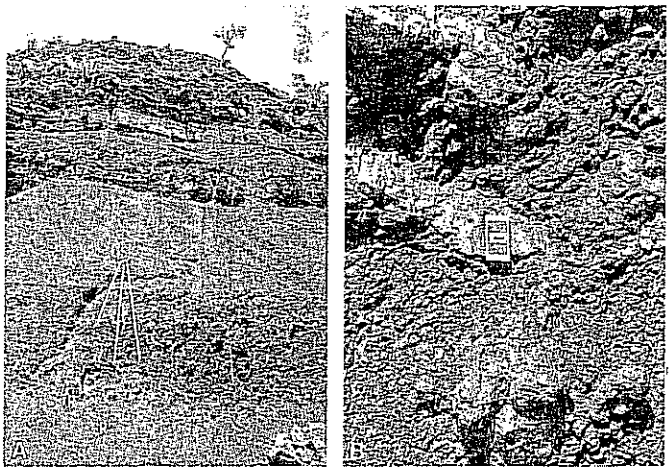

FIGURE 15—Upper Omingonde loessic paleosols. (A) Paleovertisol in loessic siltstone (foreground) overlain by strata of the sand-bed meandering river facies. Note the cross-cutting arcuate skew planes (S) and vertical calcareous rhizocretions (R). Scale bar =1 m. (B) Close-up of the skew planes shown in (A) displaying claystone-veneered and slickensided surfaces.

Exposures of this facies, high on Etjo Mountain, have yielded 2 occurrences of multiple *Trirachodon* skeletons. One occurrence (RK-4) has four skulls and their partially articulated post crania in close association (Fig. 12A). Similar aggregations of *Trirachodon* recently have been described from time-equivalent strata in the main Karoo Basin (Groenewald et al., 2001), and these are associated unequivocally with a network of underground burrow casts that were filled passively with silt and subsequently cemented with pedogenic carbonate. The natural infilling of vertebrate burrows excavated into arid zone floodplains may be influenced by many variables, of which the geometry of the burrow, cementation of host alluvium, flood periodicity, and proximity to areas of eolian sedimentation are possibly the most important. If an abandoned burrow collapses before infilling has begun, its presence in the stratigraphic record will be very difficult to detect. However, impressions of nesting material on a scratch-marked surface, or articulated skeletons in typical hibernation pose, are good evidence for a collapsed burrow (Smith, 1987). The Omingonde cynodont aggregations are interpreted as evidence for their estivation behavior in a shallow underground burrow that remained open for several months after death, allowing scavengers to partially dis-

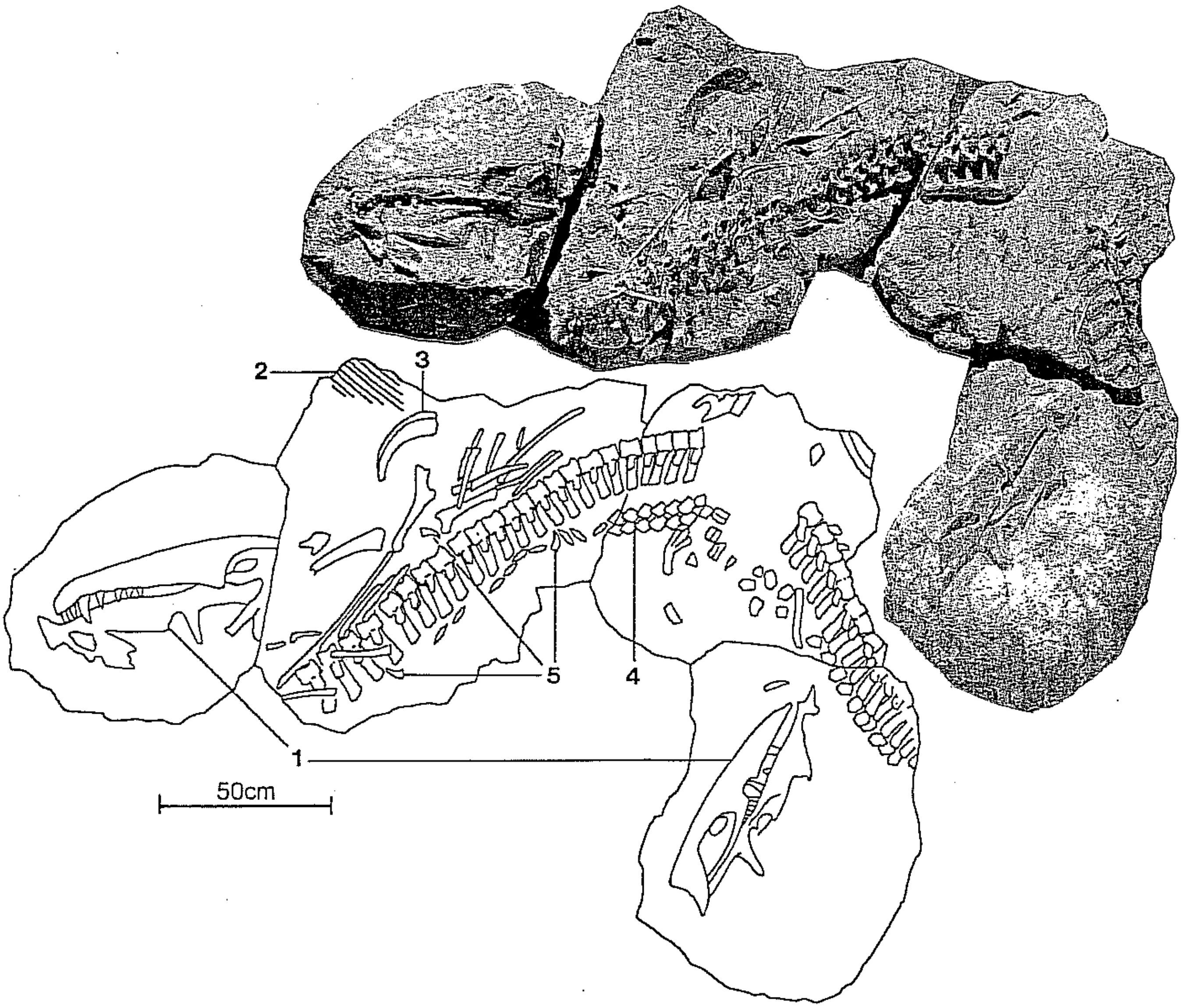

FIGURE 16—Partially disarticulated, but still associated, *Erythrosuchus* skeleton from an Upper Omingonde channel sandstone (taphonomic class B of Fig. 13) showing an unusual taphonomic feature in that the skull has been parted longitudinally along the saggital plane with its lower jaw still in articulation (1). This is interpreted as evidence for the presence of rigid desiccated skin that held the lower jaw in place when the subsequent flood scattered the partly embedded skeleton. (2) Isolated portion of gastralia ribs, (3) distal end of scapula, (4) two rows of dermal armor (osteoderms) in life position probably also held in place by desiccated skin. (5) Isolated incisors that dropped out as the skull was parted.

articulate and scatter the skeletons before the chamber roof collapsed.

Rare vertebrate remains occur in the medium-grained sandstone sheets as mostly isolated and fragmented, but not waterworn, bones and teeth. Exceptionally, a partially articulated skeleton may be found, such as the *Erythrosuchus* skeleton (OM-3, Figs. 14 and 16), which was figured by Pickford (1995) and excavated during the course of this study. The anterior portion of the axial skeleton is intact and remains articulated with the skull. A single break occurred in the thoracic region and the posterior portion was moved slightly and rotated as a whole. The presence of articulated dermal armor and scattered osteoderms surrounding the skeleton indicate that the skin was intact when the carcasse came to rest in the streambed. The animal has all the indications of having died in a dry riverbed. Scavengers, such as *Erythrosuchus* and *Cynognathus*, may have opened up the carcass and dismembered the legs. The disarticulation pattern (Hill and Behrensmeyer, 1984) and the relatively fresh bone weathering stages (Stages II and III of Behrensmeyer, 1978) suggest that the skeleton was left partially embedded for 2–4 years before final burial. Some of the dermal armour plates dropped out as the skin dried, and sections of the rows of gastralia ribs also became detached from the carcass but still remained attached to the skin. A flood subsequently scoured around the half-buried carcass and dislodged the protruding half of the skull, transporting it about 2 meters downstream. The only plausible explanation for the lower jaw remaining in articulation while the skull parted along its length is that it was held firmly in place by rigid desiccated skin (Hill, 1979). Skeletons of reptiles, such as *Erythrosuchus* that died in the dry riverbed, were subjected to scavenging but retained a high degree of articulation due to desiccation of the skin and cartilage. The following flood event entrained the loose small and dense bones with low surface-to-volume ratios (such as phalanges, teeth, scutes, etc.) and buried them a few meters downstream. However, the flow was not competent enough to move the embedded carcass. Thus, the taphonomic style of this channel-hosted *Erythrosuchus* skeleton indicates two short sedimentation events separated by a relatively lengthy period of desiccating subaerial exposure. Such conditions within a stream channel are strongly indicative of ephemeral wadi-type hydrology, and is further evidence for climatic aridity in the Omingonde rift basin.

Out on the floodplains, however, the skeletal remains are more disarticulated. Here, small herds of lumbering kanemmeyerid dicynodonts probably were preyed upon by *Erythrosuchus* and scavenged by *Cynognathus*, neither of which had the ability to break large long bones with their teeth, although they were probably capable of removing complete limbs. Infrequent sheet floods transported the loose post-cranial elements along with reworked pedogenic nodules into elongate depressions in the floodplain surface. The thick loessic silt accumulations appear to have been the favored substrate for cynodonts, such as *Trirachodon*, to dig estivation chambers. There is evidence that several animals died together, their disarticulated skeletons remaining in association possibly in an abandoned burrow system.

Most of the upper Omingonde vertebrate fossils are found in three different facies reflecting different depositional environments of the ancient rift valley (Table 2). Each facies has a distinctive taphonomic style; however, they all have an arid zone signature. Terrestrial reptile bones were buried most commonly within ephemeral stream channels, within loessic silt dumped on the floodplain surface, and within sheetwash gravels reworked from the floodplain surface.

The taphonomic signature of the upper Omingonde arid zone floodplains may be summarized as a combination of: (1) channel sandstone-hosted, partially disarticulated mummified carcasses; (2) loessic siltstone-hosted partially articulated but associated skeletons of one or possibly several individuals of the same taxon; and (3) fully disarticulated, multitaxa accumulations in conglomerates derived by reworking of the floodplain surface.

DISCUSSION

This investigation shows that the depositional environments in the Omingonde rift basin changed over 5 million years in the mid-Triassic between 241 and 236 million years ago. The relatively rapid switching of fluvial style, the abundance of extrabasinal clasts, and proximity to an active fault margin strongly suggest that tectonism controlled the accumulation of sediments in this basin. However, it is also evident that there is a climatic signature of progressive aridity overprinted on the sequence. The basin floor rapidly subsided with each movement of the NE-SW trending bounding fault. These movements were in response to major crustal extension in the pre-south Atlantic rift zone, and they greatly influenced the surface gradients and the volume of sediment that could be accommodated in the basin at the time. The facies sequence from the Lower Omingonde wet floodplain, through loessic floodplains of the middle and upper Omingonde into the sand sea of the Etjo Formation indicates changing climates in this part of central Gondwana from subhumid, through semi-arid, to arid with some short-lived wetter intervals.

Aeolian sedimentation began in middle Omingonde times, becoming more significant during the upper Omingonde with the influx of loess from the surrounding plateau. It is perhaps not just coincidence that loessites are a feature of other Middle Triassic basins in Pangea, especially those located in the equatorial regions (Chan, 1999). This synchronous increase in non-glacial loess deposits has been attributed to increased continentality caused by the coalescence of Pangea and the onset of "megamonsoonal" climatic conditions in the tropics (Dubeil et al., 1991). It is quite possible that the Omingonde rift also was subjected to strong seasonal westerly winds generated by the Pangean megamonsoon, even though it was positioned just south of the tropics at the time. Figure 17 illustrates the changes in fluvial landscape in the Omingonde basin and the following section summarizes the effects that these changes had on the vertebrate communities.

(1) Lower Omingonde sediments accumulated within axial lakes that filled elongate depressions running parallel to the base of the fault. The climate at this time was sub-humid and, despite the generally high watertable, marginal areas of the lake floor were subjected to desiccation and incipient pedogenesis during lowstand intervals. Close to the active margin, cones of colluvium accumulated on the lake floor fed by high-energy streams that were eroding back into the fault scarp. No fossils have yet been recovered from these strata, probably due more to a lack of suitable outcrop rather than preservation failure or an inhospitable environment for vertebrates.

(2) With progressive headward erosion over tens of thousands of years, the marginal colluvial cones developed into mature alluvial fans prograding up to 5 km away from the escarpment into the basin. Here, they merged with a large braided river that flowed northeast down the axis of the rift valley. The middle Omingonde succession reflects this alternation between side-valley and down-valley fluvial systems, the former containing clasts of amygdaloidal basalt that possibly erupted along the boundary fault. The climate at this time is interpreted as semi-arid with strong seasonality indicated by mature calcic BCa horizons in ferruginized overbank alluvium (Goudie, 1983; Khadkikar et al., 2000). Although only a few vertebrate fossils have been recovered from this interval, they indicate that high-energy conditions prevailed over the limited floodplains, with extensive reworking causing destruction of the bones before fossilization.

(3) Upper Omingonde strata reflect a period of tectonic stability during which time the fault escarpment gradually was denuded and deeply incised. In the axial regions of the basin at this time, lower gradients led to an increased proportion of silt and fine sand in the sediment load carried by the side valley tributaries. This change in bedload, combined with a lower down-valley gradient and increas-

TABLE 2—Summary of the lithofacies, interpreted paleoenvironments, and taphonomic processes of the Omingonde Formation.

Lithofacies	Interpreted paleoenvironment	Vertebrate taphonomy	Interpreted taphonomic process
Massive pale red siltstone beds with minor, single-storied, laterally-accreted channel sandstone bodies and limestone sheets	Sand-bed meandering streams on semi-arid loessic floodplains with shallow saline lakes	Fossils relatively common in mudrock facies as: 1. Sandstone-hosted partially disarticulated and locally scattered large *Erythrosuchus* skeleton	1. Death site in an ephemeral streambed, desiccated, scavenged, and buried *in situ* over 2–3 years with at least one flood event
		2. Mudrock-hosted isolated post crania and partially disarticulated but associated skeletons of small and medium-sized cynodonts	2. Death, desiccation and disarticulation on a loessic floodplain. Dispersal and burial within a 1–2 years by sheetfloods
		3. Isolated complete bones of medium-sized dicynodonts and cynodonts within conglomeratic lenses of reworked pedogenic nodules	3. Localized sheetflood scouring of floodplain concentrating exposed and previously buried bones into a shallow depression
Laterally accreted pebbly sandstone bodies with runnelled bases interbedded with maroon mudrocks and calcic paleosols	Gravel-bed meandering rivers on semi-arid floodplain	No vertebrate fossils recovered	
Pale red massive siltstone beds with minor tabular bodies of pebbly sandstone and sheets of microlaminated limestone	Loessic plains with saline lakes and ponds	Fossils relatively common in loessite as: 1. Isolated skulls without lower jaws and isolated postcranial bones	1. Attritional mortality on floodplain with 2–5 years residence before burial with loess
		2. Partially disarticulated but associated single and rarely multiple skeletons of the cynodont *Trirachodon*	2. Death, scavenging and burial by loessic dust within a network of underground burrows
		3. Isolated complete bones of dicynodonts and cynodonts within conglomeratic lenses of reworked pedogenic nodules	3. Localised sheetflood scouring of floodplain concentrating exposed and previously buried bones into a shallow depression
Thick multistoried, planar cross-bedded pebbly sandstones with interbedded matrix-supported cobble conglomerate. Minor mudrock intervals with thick nodule horizons	Gravel-bed braided rivers and alluvial fans	Fossils very rare and channel hosted. A single cynodont lower jaw and angular fragments of bone in basal conglomerate	Bones derived from eroded banks and possibly floating carcasses were transported as bedload and deposited within the thalweg gravels
Laminated maroon mudrock with septarian concretions, minor tabular coarse-pebble conglomerate beds	Paludal floodplains flanked by alluvial fans	No vertebrate fossils recovered	

ingly irregular discharge regime, caused a gradual switch from a single, wide and shallow braided system to a series of narrow meanderbelts separated and confined by extensive floodplains. Horizons of calcified root channels and arcuate shrink/swell slickensided surfaces attest to the fact that the floodplains were well vegetated even though they endured seasonal fluctuations in groundwater level. Flourishing channel-bank vegetation also could have contributed to the switch from braided to meandering channel patterns by increasing bank strength (Schumm and Lichty, 1963). It is possible that floodplain accretion rates were increased by the addition of loessic silt and fine sand. Strong vertic textures in some of the Upper Omingonde paleosols are characteristic of loess-hosted pedogenesis. The episodic accumulation of the massive loessic silt beds provided the ideal burial mechanism for vertebrate skeletons that were lying on the floodplain surface, and today these strata host the bulk of the Omingonde vertebrate fossils. Vertebrate fossils occur in three taphonomic modes reflecting different arid zone processes on the Omingonde floodplains: (1) ephemeral channel-hosted, partially disarticulated mummified carcasses; (2) loessic siltstone-hosted, partially articulated but associated skeletons of one or several individuals of the same taxon possibly in

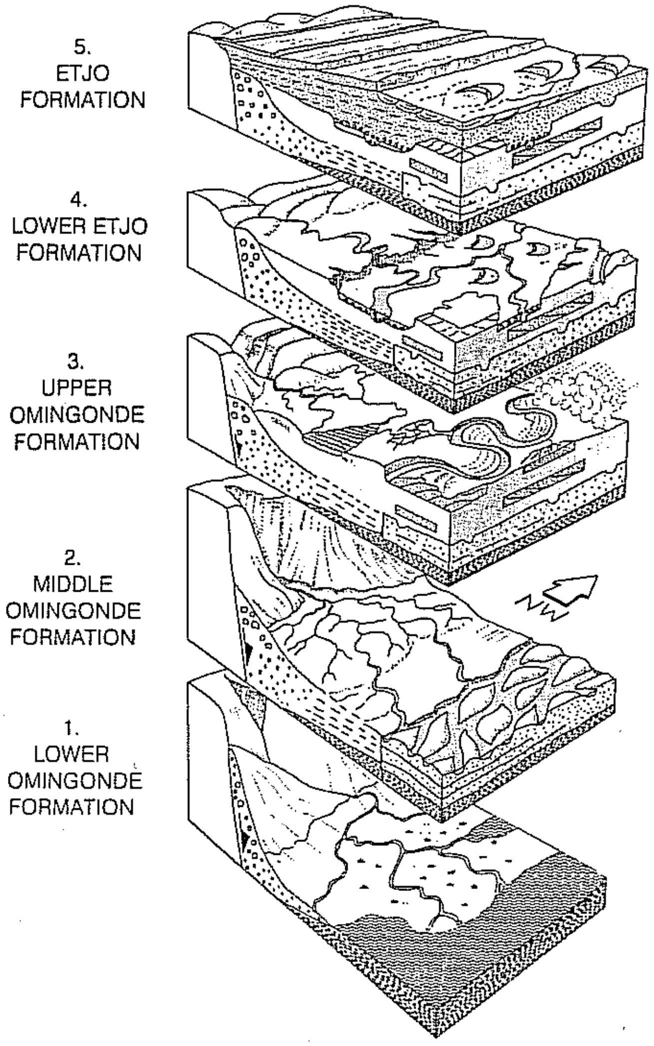

FIGURE 17—Summary of the changing landscapes in the Otjiwarongo Basin from late Early Triassic through to Early Jurassic during the accumulation of the Omingonde and Etjo formations. Diagrams illustrate the interplay of tectonics and progressive climatic drying, and interfingering of fault-scarp and southeasterly flowing axial drainage systems (right to left in diagram). The floodplain accretion rates were increased considerably by the influx of loess in the upper Omingonde Formation.

underground burrows; and (3) fully-disarticulated, multitaxa accumulations in pedogenic glaebule conglomerates derived by reworking of the floodplain surface. Further work on the Omingonde outcrops will concentrate on floodplain processes and a better understanding of the taphonomic pathways so as to fully define the taphonomic signatures of vertebrate fossils in rift-valley settings under increasing climatic aridity.

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