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The Gai-As Lake System, Northern Namibia and Brazil

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INTRODUCTION

The separation of South America from Africa during the Early Cretaceous isolated equivalent stratigraphic sequences on both continents. This is well established for rock sequences, including flood basalts, which were deposited prior to oceanic onset; however, earlier extensional events are also recorded by the resulting intracontinental basins. Of these, the depositional area containing the Late Permian–earliest Triassic Gai-As Lake is a prime example.

The aims of this paper are (1) to record facies generated within and outside the lake body and (2) to compare them with correlative bodies on the other side of the present-day South Atlantic Ocean, and (3) to record the controls of fault structures on facies architecture and lake margins. The advantages of good exposures produced by river dissection of the continental margin in northern Namibia allows good access for identifying synsedimentary fault controls on the Gai-As Lake. We suggest that these can be extrapolated to correlative sequences at the conjugate South American side where exposure and thus the potential for recognition of synsedimentary structural activity is limited; consequently, the Paraná “basin,” commonly dealt with as an intracratonic sag basin, may be underlain by a complex of stacked rift and thermal subsidence-controlled depositional centers.

GEOLOGIC CONTEXT

In northern Namibia, sections of the Gai-As and overlying Doros formations are well exposed in the Huab area (Figure 1B, C), located next to the present Atlantic coastline some 400 km northwest of Namibia’s capital city, Windhoek. The structural setup of this area in central Gondwana is characterized by northerly trending sets of westerly dipping extensional faults, interpreted as synthetic to a more major westerly dipping detachment system (Stollhofen, 1999). Synsedimentary extensional activity associated with these faults expresses one of several successive periods of intracontinental rifting during the early extensional history of the pre-southern South Atlantic rift zone (Figure 2A).

The Gai-As and Doros lake sediments are correlatives of the Beaufort Group (Karoo supergroup), a stratigraphic unit widespread in whose equivalents are various Late Carboniferous–Early Jurassic depositional areas over a large portion of the Gondwana supercontinent (Figure 1A). Of these depositional centers, two major basin types are represented: (1) those such as the main Karoo basin of South Africa, which developed as a flexurally deformed foredeep in front of the northerly overthrusting Cape fold belt (Veevers et al., 1994a) and (2) the more elongate graben and half-graben basins, known from Namibia (Stollhofen et al., 1998, 1999),
Botswana (Smith, 1984), Zimbabwe, Zambia, Malawi (Ring, 1995), Tanzania (Wopfner, 1991), and Madagascar (Hankel, 1994), which define intracontinental rift systems affected by repeated phases of extensional faulting (cf. Lambiase, 1989; Tankard et al., 1995).

**GAI-AS AND DOROS FORMATIONS**

The Gai-As Formation is up to 170 m thick and breaks naturally into two subunits that are informally termed the lower and upper Gai-As Formation (Figure 2B). This lacustrine succession is separated by an unpronounced hiatal unconformity (Figure 2B) from the underlying, mesosaurid-bearing marine deposits of the Huab Formation, an equivalent of the Lower Permian (Artinskian) Whitehill Formation of South Africa and the Irati Formation of Brazil (Anderson, 1981; Oelofsen, 1987). In the Huab area, the top of the Gai-As Formation is most commonly defined by a widespread erosional unconformity below the overlying eolian dune deposits of the Lower Cretaceous Twyfelfontein Formation (Stanistreet and Stollhofen, 1999). Adjacent to the pronounced northerly trending faults, however, a more continuous deposition is recorded in local hanging-wall traps by semi-conformable contacts of
Figure 2—The Gai-As and Doros Formations of northwestern Namibia (A) placed within the regional tectonostratigraphic framework, which is modified from Light et al. (1993), originally based on the stratigraphies inferred from seismic sections in the Namibian offshore area. (B) Correlation of Gai-As and Doros Formations with equivalent strata in South Africa and Brazil by using radiometric and biostratigraphic age constraints.

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the mudstone-dominated lacustrine Gai-As to the overlying sandstone and gravel-dominated (<30 m) Doros Formation (Stanistreet and Stollhofen, 1999). A time-stratigraphic gap above the Gai-As and Doros units is caused by a Late Jurassic to Early Cretaceous unconformity. The time gap is reduced toward the east to south-southeast of the central Huab area, where an intervening Triassic to Lower Jurassic sequence is preserved, involving the Omingonde and Etjo Formations (Figure 2B) in the Goboboseb, Brandberg, Erongo-Karibib, and Waterberg areas (Figure 1B). The Jurassic/Cretaceous unconformity is conspicuously offset by faults and further accentuated by the development of paleosols and subvertical eolian sandstone-filled fissures up to 20 cm wide and reaching up to 15 m deep into the uppermost Gai-As, Doros, and Omingonde successions, respectively.

EXTENT AND AGE OF THE GAI-AS LAKE

The geometry and extent of the Gai-As and Doros Formations are controlled by earlier basin geometries, in particular those that hosted Lower Permian sequences. In this regard, equivalents of the Lower Permian Whitehill Formation are widespread in southern Africa and South America and form a prominent marker horizon (Oelofsen and Araujo, 1983), which records the latest major marine transgression into southern west Gondwana during the Permian. We use this marker horizon to set up a stratigraphic framework for the comparison of the overlying lacustrine sequence in various parts of the pre-southern South Atlantic rift zone and the neighboring foreland.
basin of South Africa. Because outcrop areas are in two areas on either side of the Atlantic, great care was taken in comparing lake sediments in Namibia with lake sediments in Brazil by using radiometric and biostratigraphic constraints.

Based on its conspicuous red coloring, the discovery of an isolated cynodont tooth (von Huene, 1925) and supposed dinosaur vertebra (Keyser, 1973), the Namibian Gai-As Formation had originally been assigned a Late Triassic age. Later, Horstemke (1992) and Ledendecker (1992) correlated the Gai-As Formation both with the Brazilian Serra Alta, Teresina, and Lower Rio do Rasto Formations and the South African Collingham to Waterford Formations (cf. Figure 2B) by using endemic bivalve associations, which suggest a Late Permian age. Only recently, the Late Triassic age constraints of von Huene (1925) and Keyser (1973) were shown to be based on misinterpretations of the fossil fauna (B. S. Rubidge, 1997, personal communication).

New radiometric dating of zircon separates from tuff beds interlayered with the top part of the Gai-As succession (cf. Figure 2B) revealed U/Pb ages of 265±2.5 Ma. This would principally confirm the stratigraphic positioning of Horstemke (1992) and Ledendecker (1992) and place this part of the Gai-As Formation as uppermost Lower Permian according to the time scale of Harland et al. (1990). This datum is close to U/Pb zircon ages of 261 M (de Wit, 1998, personal communication) derived from tuffs of the Cistcephalus assemblage zone sensu Rubidge et al. (1995) of the Upper Permian Teekloof Formation (Beaufort Group) in the western Cape region of South Africa. In contrast with the Gai-As Formation in Namibia, this stratigraphic unit is placed more than 2000 m above the Huab-equivalent Whitehill Formation.

As the entire Namibian Gai-As Formation only contains endemic bivalves of the Terrara altissima biozone, characterized by Leinzia similis (cf. Figure 2B), it can be confidently correlated with the Upper Permian Serrinha Member of the Rio do Rasto Formation in the Brazilian Paraná basin. Comparable to the stratigraphic relationships in South Africa, this unit is located about 500 m above the Whitehill/Huab equivalent Irati Formation. Remains of the dicynodont Endothiodon occur at the base of the Upper Permian Morro Pelado Member of the Rio do Rasto Formation, immediately above the Serrinha Member (Barberena et al., 1991). This suggests a faunal affinity to the biostratigraphically well-constrained Pristerognathus, Tropidostoma, and Cistcephalus assemblage zones sensu Rubidge et al. (1995), located in the Upper Permian Teekloof Formation (Beaufort Group) of the main Karoo basin in South Africa. Such a biostratigraphic relationship coincides perfectly with the previously discussed correlation of the tuff beds between South Africa and Namibia; however, age assumptions based on amphibian remains (including vertebrae) and wood fragments, both from the top of the upper part of the Namibian Gai-As and Doros Formations still remain problematic. The vertebrae were determined to derive from Triassic mastodonsaurid or matoposaurid amphibians, but teeth occurring at the same stratigraphic level are more rhinesuchid in shape, suggesting an Upper Permian age (B. S. Rubidge, 1998, personal communication). These stratigraphic relationships might imply a discrepancy between the traditional biostratigraphy and radiometric ages, which is also obvious from log fragments of silicified Podocarpoxylon wood occurring in the Doros Formation. In South Africa and elsewhere, the latter is only known from Early Triassic and younger strata (Bamford, 1998); consequently, it appears that the Gai-As/Doros succession contains some faunal and floral elements that are apparently biostratigraphically younger than their numerical correlatives in South Africa.

In summary, radiometric and biostratigraphic age constraints suggest a Late Permian–earliest Triassic age for the Namibian Gai-As and Doros Formations. Correlative beds are the upper Abrahamskraal and lower Teekloof Formations in South Africa and the Serrinha Member of the Rio do Rasto Formation in Brazil. Additional equivalents of these units might be represented in Argentina, Paraguay, and Uruguay, and in the Kaokoland area of northwest Namibia (cf. Figure 1A, B). This implies that equivalent beds of the entire post-Whitehill Ecca Group (Collingham to Waterford Formations) in South Africa and of the Serra Alta and Teresina Formations in Brazil are poorly or not preserved in northern Namibia; however, in southern Namibia, they may be partly represented by the up to 740-m-thick Aussenkjer and Amibberg formations of the Karasburg area (cf. Miller, 1992).

LAKE DEVELOPMENT

The trans-Atlantic correlation between the Gai-As and Rio do Rasto formations would imply the existence of an elongated inland water body extending over more than 1.5 million km² along an overall northwest–southeast trend (Porada et al., 1996) during the Late Permian–Early Triassic. Other extensive lakes existed at the same time in eastern central Africa (Yemane and Kelts, 1990), and some were probably strung along comparable rift networks with intervening fluvial deposits or basement highs. Considering the global paleogeographic reconstructions of Scotese and McKerrow (1990), Scotese and Barrett (1990), and Lottes and Rowley (1990), the Gai-As lake area was situated at a latitude of about 40° south during the Permian. Such a paleogeographic and paleolatitudinal setting would be susceptible to intense mid-latitude winter cyclones as reviewed by Duke (1985). Climates in southern Gondwana have been inferred as cool-temperate and seasonal on the basis of isotope geochemistry, clay mineral assemblages, and palynoflora of Late Permian sequences in northern Malawi (Yemane et al., 1996; Yemane and Kelts, 1996). With the paleolatitudinal setting of Malawi about 15° south of Namibia, warm-temperate to subhumid/semiarid climates can be predicted for the area occupied by the Gai-As paleolake.

The Gai-As and Doros Formations together record an overall shallowing- and coarsening-upward trend
(Figure 3): (1) the lower Gai-As Formation characterized by laminated claystones and mudstones, (2) the upper Gai-As Formation comprising dominantly mudstones with interbedded limestones, sandstones, and fallout tuffs, and (3) the Doros Formation dominated by sandstones and gravels with minor interbeds of mudstones and limestones. The base of the Doros is normally unconformable with the underlying Gai-As Formation, but shows an angular unconformity due to the activity of synsedimentary faults; however, the Doros Formation is integral to Gai-As Lake development and therefore will be included in our study.

Facies architecture of the lithologic units outlined varies laterally and was affected by contemporaneous activity of extensional fault systems. The spectrum of environments is generally best represented in the central part of the Huab area, whereas toward the east (Verbrandeberg region), a condensed sequence development is recorded, and toward the west (Atlantic coastline and Paraná basin), enhanced sequence developments are encountered; therefore, the lithologic sequence of the Gai-As Formation is described on the basis of the central Huab area type sections (Figure 3), well exposed in cliffs at localities Klein Gai-As, Three-ways, and north of Doros (cf. Figure 1C). We will examine their lateral variation eastward toward the lake margin and then westward toward the basin center. Finally, we relate lake development to the contemporaneous geodynamic evolution of the pre-southern South Atlantic rift zone.

Lower Gai-As Formation: Offshore Lacustrine Setting

Early lake history is recorded by a 35-m-thick succession (Figure 3) of reddish to violet, mostly laminated mudrocks containing thin (1–3 cm) tabular interbeds of normally graded, fine- to medium-grained sandstone layers and a few laminated limestone beds, 10–50 cm thick. At least two widespread shale horizons (Figure 3A) are associated with conspicuous concentrations of articulated and disarticulated shells of the *Leinzia* molluscan fauna. Concentrations occur in several layers, up to 4 cm thick, with a dominance of concave-down shells reflecting the influence of traction.

Thick shaly units were deposited dominantly from suspension fallout in a quiet offshore lacustrine hemipelagic setting. We interpret the limestone beds as deposited by storm-initiated flows transporting clastic carbonate grains into the offshore region. Sand was only sparsely delivered to the offshore to form tempestites and turbidites, the majority of which contain abraded fish bones, teeth, scales, and fin spines. Such thin, sandy units acted as nuclei for early diageneric formation of abundant disc-shape dolomitic concretions measuring up to 3 m in diameter (Horsithemke, 1992). Wave activity was counteracted by the stabilizing effects of microbial mats at the lake margin. Major storms seem to have rarely affected this part of the sequence. Concentrations of bivalve shells reveal a low diversity of population, which could happen in an ecologically stressed setting such as a saline lake where lake overturns due to thermal density instabilities or storms may cause mass mortality of bivalves, later to be reworked by gravity flows.

Upper Gai-As Formation: Upward-Shallowing Lake with Tempestites

This succession is about 20 m thick and comprises red violet mudstones containing minor tabular sandstone interbeds, laminated or small-scale cross-bedded limestone, and laminated rhyolitic to dacitic fallout tuff (Figure 3B). The fine- to medium-grained sandstones, 1–10 cm thick, are normally graded and show rare basal load casts and wave-rippled tops. Commonly, such beds contain concentrations of fish bones, scales, and teeth in a single layer at their top surface, which reflects density grading of biogenic particles. They are interpreted as tempestite or turbidite beds arranged in a thickening- and coarsening-upward architecture, the latter suggesting a gradual overall shallowing of the lake toward the top of the middle unit.

Lenticular to tabular limestone beds up to 35 cm thick are found particularly in the lower half of the unit. Both laminated stromatolitic limestone beds and micritic limestone/sandstone interlaminated beds are developed, the latter showing rhythmic wavy and lenticular bedding with isolated current and wave ripples made of sand. Such bedding is well known from intertidal and shallow subtidal areas (Reineck and Wunderlich, 1968; Reineck and Singh, 1980), but has also been described from non-tidal deltaic settings (e.g., Coleman, 1966). We agree with McCave (1970) that processes associated with storm and calm conditions are generally the primary cause of wavy and lenticular bedding. One of the interlaminated limestone/sandstone beds is characterized by conspicuous concentrations of articulated and disarticulated shells of the *Leinzia similis* molluscan fauna in a single layer 2–5 cm thick. A biological picture of what was happening in the lake is provided by disarticulated skeletal fragments of large mastodonsaurid or matoposaurid amphibians and abundant fragmentary fish remains of *Namaichthys* and *Atherstonia*. Such large organisms required the lake to be permanent to develop well-established food chains. Also required were low and stable salinities and temperatures as well as an oxygen-rich environment.

The unit further comprises up to five tuff beds, each 2–5 cm thick, showing a poorly developed normal grading. Tabular geometry of the tuff beds and their conspicuously bright color makes them important chronostratigraphic markers with the lowermost and uppermost tuff beds coinciding broadly with base and top of the upper Gai-As Formation. According to XRD (x-ray diffraction) analyses, the tuff beds usually consist of quartz, albite, orthoclase, sanidine, clinopyroxene, and illite-montmorillonite mixed-layer minerals with some tuff beds containing analcime, calcite, dolomite, and ankerite. Thin sections reveal a microcrystalline groundmass of recrystallized quartz and
Figure 3—Sedimentologic log of the Gai-As and Doros Formations compiled from sections measured at the Klein Gai-As and the north of Doros type localities (see Figure 1C for locations) in the central Huab area. Outcrop photographs of the three subunits illustrate the typical field appearances of (A) laminated mudstones of the Lower Gai-As Formation, (B) mudstones interbedded with thin, normally graded fine-grained sandstones (tempestites or turbidites) and thin fallout tuff beds (arrows) of the upper Gai-As Formation, and (C) mudstones overlain by stromatolitic limestones interbedded with the otherwise fluvially dominated Doros Formation. See Figure 4 for legend of symbols.
analcime with a few juvenile crystals of biotite and sanidine. Heavy mineral separates of the tuffs comprise hornblende, monazite, titanite, zircon, and apatite that fit well with the rhyolitic to dacitic composition determined by XRF (x-ray fluorescence). Overall grain size and sorting characteristics of the tuff beds show that they comprise multiple pyroclastic fallout units in areas distal from the volcanic source region.

The upper Gai-As Formation records a pronounced shallowing of a paleolake, with deposition dominantly at water depths below fair weather, but above storm wave base. This setting resulted in an increasing number of siliciclastic and mixed carbonate/siliciclastic tempestite/turbidite interbeds bearing shallow-water features, such as wavy and lenticular bedding and wave-rippled surfaces. Consistent thicknesses of the thin limestone/sandstone laminae suggest seasonally controlled deposition of siliciclastics and carbonates, including lenses of small-scale cross-bedded clastic carbonate. Longer time intervals of warm climate and low precipitation suppressing siliciclastic input, but favoring microbial activity, are then indicated by tabular, stromatolite-textured limestone beds, up to several decimeters thick. Considering the tectonic framework of the Gai-As Lake, carbonate productivity could have been further influenced by groundwater-controlled input of Ca-rich waters along fault and fracture zones (cf. Gierlowski-Kordesch, 1998).

**Doros Formation: Nearshore Fluvial Setting with Ephemer saline Lake Intervals**

This formation is up to 30 m thick with an abundance of 60–80% sheet-like sandstone beds, up to 2 m thick, dominating the succession. The medium- to coarse-grained sandstones show either planar or low-angle scoured basal contacts and may contain low-angle accretion surfaces, small-scale hummocky cross-stratification, or plane-bedding. Hummocky beds are 5–25 cm thick with wave lengths ranging between 20 and 130 cm. Several of the upper surface contacts are wave-rippled with the majority of ripple crests striking 50–60°. In places extensive bioturbation is preserved with burrows of Planolites ichnosp., Skolithos ichnosp., Beacontes ichnosp., Palaeophycus tubularis, and Rosselia ichnosp., in addition to larval and nematode traces. Also observed are plant debris, imprints of rootlets, and rare layers with concentrations of disarticulated bivalve shells. A thin (max. 4 cm) but widespread marker bed about 8 m above the dated tuff bed contains extraordinarily abundant fish remains, including scales and teeth.

A few channelized, massive or faintly plane-beded sandstone units preserve imprints of rootlets and small fragments and trunks (max. 1.5 m length and 10 cm diameter) of silicified wood, identified as Araucarioxyylon sp.1 and Podocarpoxylon i sp. (Bamford, 1998). The latter suggests an age comparable with that of the upper Beaufort (Bamford, 1998), which would place the Doros Formation in the Lower Triassic. Mudstones are only rarely interlayered in this part of the succession and contain abundant mudcracks and carbonate concretions.

Limestone beds at this stratigraphic level (Figure 3C) are characterized by domal stromatolites (up to 25 cm high) with interdinal areas infiltrated by ooliths and oncolites. Horsthemke (1992) measured in bulk samples 18O values of 3.01–5.62 in the stromatolitic beds. This suggests that considerable salinities developed through evaporation, which would be particularly favored in a hydrologically closed lake system during periods of low rainfall (cf. Cerling et al., 1977). Locally, the stromatolitic limestones contain v-shaped grooves and erosional surfaces that are mantled by thin, normally graded calcareous sandstone layers of laterally uniform thickness. These features are interpreted as storm deposits, interrupting biogenetic growth and mobilizing material in the shoreline area of the lake. Particularly above the stromatolitic limestone units, intercalations of laminated micritic dolomite beds are found, averaging between 0.4 and 1.5 cm thick, but can be up to 18 cm thick. Their sharp planar bases define either vertical amalgamation or a rhythmic alternation with erosionally based, small-scale, cross-bedded fine-grained sandstone layers. Silification is common in the micritic beds, and halite and gypsum pseudomorphs are rarely preserved in the top parts of the layers. We agree with Horsthemke (1992) in interpreting the micritic limestones as evaporitic deposits that formed in alkaline saline lake environments.

Sandstone units are interpreted as regressive sheet-sands (cf. Heward, 1981) and poorly channelized fluvial sheetflood deposits. These were emplaced in a shallow, wave-dominated lake margin/shoreline environment that favored minor lag concentrates of fossil material with interlayered mudstones, preserving abundant subaerial exposure features. Pseudomorphs of evaporite minerals and the 818O values of stromatolitic limestones record periods of enhanced salinity of the lake with more alkaline conditions dissolving silica. Freshwater flushing led to chert precipitation comparing with processes described by Knauth (1994). Development of subaerial exposure features and erosional surfaces suggests that lake level was, in general, significantly lowered during deposition, and the regularity of limestone/sandstone alternations may account for a lower order climatic variation controlling lake level fluctuations, involving evaporation and influx.

**CONTRASTING MARGIN AND BASINAL SETTINGS OF THE GAI-AS LAKE IN NAMIBIA**

Lateral variability of Gai-As and Doros Formation thicknesses occurs across the study area. Maximum thicknesses attain 180 m in the western Huab area, close to the present Atlantic coastline, 70 m in the central Huab type section area (Klein Gai-As), and only 15 m down to total pinch-out around Verbrandeberg in the eastern Huab area. Condensed sequence development in the eastern Huab area particularly contrasts to thicknesses of more than 700 m attained for
the Gai-As/Doros equivalent Rio do Rasto Formation in the southeastern Paraná basin of Brazil, but is mirrored by a complete pin-out in the northeastern part of the Paraná basin. Such thickness variations coincide with pronounced facies changes along southwest-northeast trends both in the Huab and Paraná area, as well as in areas close to contemporaneously active extensional fault systems.

**Transitional Offshore Lake Facies of the Western Huab Area**

To the west of the Gai-As type section, the Gai-As sequences rapidly increase in thickness with considerable facies changes at a distance of 20 km east of the present coastline. Figure 4 (section Ambrosius Berg) shows the threefold subdivision of the Gai-As and Doros Formations can still be identified at this locality in the thick, shale-dominated succession, but limestone, sandstone, and tuff interbeds are much less abundant compared to the sequences containing the marginal facies farther east. Thin, normally graded interbeds of massive, fine-grained sandstones occur exclusively in the middle unit and have been interpreted as turbidite deposits (Horsthemke, 1992). Carbonates occur as calcareous concretionary horizons and thin lenticular unfossiliferous beds. The topmost 30 m of the section is dominated by plane-bedded or hummocky cross-bedded sandstones. No subaerial exposure features are present.

Hummocky cross-stratification is commonly viewed as forming under storm conditions, where waves interact with bottom currents (Harms et al., 1982; Cheel and Leckie, 1993); however, contrasting views exist whether hummocky cross-stratification may be best preserved below fair-weather base (Walker, 1984), in very shallow lacustrine environments (Duke, 1985), or the surf zone of lakes (Greenwood and Sherman, 1986). Compared to the type section, the facies association measured at the Ambrosius Berg locality (Figure 1C) nevertheless records deposition in an offshore basinal setting. These deeper water units are succeeded by a weakly bioturbated shoreface facies comprising sedimentary structures that indicate the influence of considerable wave activity associated with low-frequency storms.

**Marginal Facies of the Verbrandeberg Area**

The section measured at Gudaus hill (Figure 4), about 9 km southwest of the more easily accessible Verbrandeberg locality (Figure 1C), is taken as representative of facies patterns in the eastern Huab area with a total formation thickness attaining 15 m on average. The Gai-As Formation comprises interbedded reddish massive mudstones, fine-grained sandstones, and abundant nodular carbonate with the whole succession heavily affected by a network of desiccation and shrinkage cracks along with voids, many of which are filled by chert. The Doros Formation is represented by an erosionally based, trough cross-bedded, pebbly medium- to coarse-grained sandstone unit that contains Planolites ichnosp. and Phycodeus curvipes ichnosp burrows at its base and larval and nematode traces at the top. Trough cross-beds reveal a low to moderate variation of paleocurrent directions toward the southwest (210–280°), and flat lens-shape channel geometries indicate rivers characterized by relatively high width/depth ratios. Considering the scarcity of mudstone interbeds, the restricted variation of paleocurrent data, and the channel morphologies, this unit is interpreted as an amalgamated braided fluvial channel sandstone complex that formed at the subaerially exposed lake margin in a setting relatively proximal to the clastic source. In situ breccia formation observed in the lower part of the section is a process particularly abundant in palustrine lacustrine carbonates (Freytet and Plaziat, 1982). There, lake level fluctuations may have caused alternating periods of subaerial exposure and flooding of lake-fringing marshes. Carbonate nodules within the section comprise fibrous, micritic, and spartic types, as well as ferruginous calcitic nodules (Horsthemke, 1992), with the latter preferentially forming in the vadose zone under the influence of groundwater level fluctuations (cf. Sehgal and Stoops, 1972). Replacement chert nodules and layers up to 60 cm thick are concentrated in the carbonate-poor host-lithologies. The silica source required for their formation is believed to result not solely from dissolved detrital quartz grains, but also from surface weathering of highly reactive dacitic volcanic glass shards. Enhanced silica concentrations would have been formed by the high pH of saline, alkaline lake waters coinciding with the fallout of volcanic ash. Dissolved silica then would precipitate after lowering of pH due to enhanced freshwater discharge or in sub-lacustrine sediment from groundwaters rich in dissolved sodium carbonate/bicarbonate (cf. Parnell, 1988).

The lower part of the Gudaus hill section is interpreted as hydromorphic calcareous soils that developed contemporaneously with the formation of stromatolitic limestones in the more basinward lake areas. These soils can be viewed as pedogenically modified mudflats of a moderately steep lake margin that is influenced by considerable fluctuations in lake and groundwater levels. Abundant root casts and rhizocretions (cf. Klappa, 1980) indicate that the mudflats of these marginal lake areas were locally vegetated. This fits well with the observation of upright in situ embedded tree trunks and logs, 0.3–0.6 m in diameter, at Bloukrans farm area, about 30 km northeast of Gudaus hill locality (Figure 1C) (Bruhn and Jäger, 1991).

In fact, the facies architecture of the Verbrandeberg area is rather complex because it appears to be controlled not only by contrasting basin-marginal aspects, but also to a considerable degree by the complex structural framework of the eastern Huab area. Due to the
Figure 4—Measured sections of the Gai-As and Doros Formations illustrating the threefold subdivision of the fluvio-lacustrine succession and lateral and vertical changes in facies architecture. See Figure 1C for location of sections.
overlap of major north-northwest-trending structures, such as the Twyfelfontein fault zone and synchronously active east-northeast-trending faults from reactivated neo-Proterozoic Damara basement structures, a mosaic framework of footwall and hanging-wall blocks developed contemporaneous with Gai-As deposition. This is reflected by rapid changes in facies and thickness, with maximum thicknesses on the order of 70 m in hanging-wall block positions and total formation pinch-out associated with footwall blocks. Development of condensed sequences in association with footwall block positions, however, was not all restricted to the Verbrandeberg area but was identified at various other localities, namely the Albin Ridge, Sanianab, and Brandberg localities (Figure 1C).

Fault-Controlled Marginal Fan-Deltas

The section (Figure 4) measured at Brandberg locality (cf. Figure 1C) illustrates another important aspect of Gai-As Lake deposition. The lower part of the Brandberg section correlates with the lower Gai-As Formation at its Klein Gai-As and north of Doros type locations. A thickness of 15 m and a pronounced pedogenetic overprinting of the upper part of the Brandberg section compare to the condensed sequences of the lake margin facies described from the Verbrandeberg area. The overlying Doros Formation comprises a 25-m-thick coarsening-upward succession of trough cross-bedded, pebbly, medium- to coarse-grained sandstones (Figure 4). These are characterized by enhanced feldspar and tourmaline contents and by abundant lithoclasts eroded from both the underlying Gai-As units and the Huab Formation. The sandstones represent deposits of proximal mouth bars and of braided fluvial channels with paleocurrents to the northeast (180°-296°) from measured trough cross-beds. A comparable coarse-grained siliciclastic facies, 2-15 m thick, has been observed at the Doros Crater, Bloukrans farm, Sanianab, Albin Ridge, and Gudaus hill localities (Figure 1C), with the latter two showing a similar association to an underlying pedogenically modified marginal lake facies. On a regional scale, this coarse-grained siliciclastic facies grades basinward into the previously described sheetlike, plane-bedded, or hummocky cross-bedded sandstone units that are interpreted as regressive sheet sands and fluvial sheet-flood deposits of a lake-margin/shoreline setting at the Gai-As type localities.

Considering the structural setting of the localities described, it is significant that all of them are situated on the hanging-wall sides of large-scale northerly trending faults in association with their east-northeast–trending conjugates. The faults were identifiably active from Lower Permian Tsarabis Formation deposition onward (Stollhofen, 1999). The influence of faulting on facies architecture is particularly well recorded at the north of Doros locality (Figure 1C), 8 km north of Doros Crater where a roll-over anticline developed adjacent to the hanging-wall west side of the Twyfelfontein fault zone (Figure 7). The Doros Formation, forming the coarse-grained top unit, is separated from the underlying sequence by an angular unconformity of up to 4° and contains strata that wedge out conspicuously against the developing rollover. By analogy, the coarse-grained facies at Sanianab locality in the western Huab area (Figure 1C) is associated with the major Ambrosius Berg fault zone subparalleling the present coastline. In contrast, the Doros Formation and in places the entire Huab, Gai-As, and Doros successions are eroded at the footwall immediately east of the Bergsig fault.

A picture emerges of a wave-dominated Gai-As lake margin that is fringed by coarse siliciclastic alluvial braided fan-deltas of the Doros Formation prograding off emerging fault scarps. Progradation of such fan-delta wedges would be particularly favored during lake level lowstands, with a proximal fan facies triggered by newly generated fault scarps. The fact that the Huab and Gai-As Formations are partly eroded in footwall positions and the Doros Formation is preferentially preserved in hanging-wall blocks emphasizes that active tectonism occurred contemporaneously with Gai-As lake deposition.

THE CONTINUATION OF THE GAI-AS LAKE INTO BRAZIL

Sections measured in the Brazilian portion of the Paraná basin (Figure 5C) include the entire Passa Dois Group (Figure 6), which attains thicknesses of more than 1300 m (Mühlmann, 1983) and subdivides into the Irati, Serra Alta, Teresina (or Estrada Nova), and Rio do Rasto Formations. Only the Serrinha Member of the basal Rio do Rasto Formation can be correlated to the Namibian Gai-As and Doros Formations on the basis of the *Terraia altissima* biozone (Rohn, 1994), characterized by *Leinzia similis*; however, for the understanding of Gai-As Lake initiation and development as a whole, it is important to study the underlying sequence development as well because this records the paleoecologically well-constrained transition from the marine-influenced mesosaurid-bearing Irati Formation (Whitehill/Huab Formation equivalents) to the lacustrine Gai-As Formation equivalents.

Transition from Marine Irati to Lacustrine Rio Do Rasto

The Irati Formation is conformably overlain by the 10-150-m-thick Serra Alta Formation (Figures 2, 6), which is dominated by dark shales and siltstones containing abundant fish scales. Endemic bivalves of the *Barbosaia angulata* assemblage especially occur in the northeastern part of the basin, near the base of the formation. Several authors interpret this unit as marine (e.g., Gama, 1979; França et al., 1995), despite the fact that no unequivocal marine fossils are known and paleogeographic data point to a basin isolated from the world ocean; therefore, we attribute the depositional environment to a relatively deep, large lake with occurrences of wavy lamination, wave ripples, and bioturbation features in the upper part of
Figure 5—Maps showing (A) simplified geology of the Paraná basin in eastern South America (compiled from Bossi et al., 1975; Schobbenhaus et al., 1984; Zalán et al., 1990, and Fulfaro et al., 1995), (B) the isopach map of the Passa Dois Group (redrawn from Mühlmann, 1983), which also includes stratigraphic units below the lake beds of the Rio do Rasto Formation, with (C) outcrops of the Passa Dois Group in detail. For comparison of structural trends with Namibia, a counter-clockwise rotation of 58.2° (Powell and Li, 1994) has to be performed. Outcrop and isopach maps of the Passa Dois Group include the Irati Formation (Whitehill/Huab Formation equivalent), which is only a few tens of meters thick and therefore does not modify an interpretation based on the illustration.
Figure 6—Composite lithologic logs (from road cuts and borehole cores) of the Gai-As equivalent sequence in east Brazil, comprising the Rio do Rasto Formation (subdivided into the Serrinha and Morro Pelado Members) based on Rohn (1994). Also included are logs of the Serra Alta and Teresina Formations, which are not well represented in Namibia. Only fossil occurrences that are important for correlation purposes are included. See Figure 4 for explanation of additional lithologic symbols and Figure 5C for location of sections. Examples of the signatures used to distinguish the sedimentologic interpretation of individual depositional units are given in the left column. Distances between logs indicated on Figure 5C.
the succession recording a gradual shallowing trend and deposition above wave base.

The overlying Teresina Formation, 150–350 m thick, is almost entirely composed of interbedded gray mudstones and minor, very fine-grained sandstones showing wavy, lenticular, and flaser bedding. In places, the nearshore mudstones contain mudcracks and shallow burrows and trails of a yet unnamed ichnofacies, including Planolites ichnosp. Thicker sandstone units (up to 0.4 m) concentrate in the northeast Paraná basin and are characterized by wave-ripple cross-bedding or hummocky cross-bedding with the latter attributed to a storm wave origin. Few massive, gray siltstones bear freshwater shark remains and fossil plants of the Glossopteris flora, including lycopod stems and leaves as typical representatives. Intercalations (<3 m) of bivalve-bearing, oolitic grainstones exist at many levels throughout the more silty parts of the succession. Several intervals that are particularly rich in limestone intercalations are well marked in geophysical borehole logs and can be correlated across the basin. The oolitic grainstones commonly show wavy bedding and are interpreted as tempestites. We suggest that the ooids formed along the high-energy lake shoreline and then became redistributed toward the basin center during storms. Conditions for carbonate precipitation, such as lake water saturation, temperature, pH, and salinity, were probably favored during more arid climatic intervals or periods of enhanced calcium-rich groundwater input. The bivalves, endemic to the basin, belong to the Pinzonella illuso and Pinzonella neotropica assemblages; the latter of which can be traced as far as eastern Paraguay. This indicates a closed basin cut off from the sea with a relatively uniform lateral facies development (cf. Rohn et al., 1995); however, in the southernmost exposures of the Paraná basin, the Teresina Formation and equivalent Yaguari Formation in Uruguay consist almost entirely of shales (França et al., 1995). This contrasts with the facies development toward the northern parts of the basin (São Paulo state), where the Teresina Formation is gradually replaced by the more marginal facies association of the Corumbataí Formation. This trend is indicated by dominantly red siltstones containing some interbeds of domal stromatolites and ostracod-rich calcilutites, both up to a few decimeters thick. Geochemical analyses of the limestones suggest high salinities, but charophytes indicating freshwater conditions were also found at several levels and may register alternating humid and arid periods with higher salinities resulting from periodically enhanced evaporation. Previously, the Teresina Formation had been interpreted to record a coastal marine environment (e.g., França et al., 1995), a tidal flat, lagoon, and prodelta setting (Gama, 1979), or a storm-dominated sea-lake (e.g., Rohn, 1994); however, as with the Serra Alta Formation, no definitive marine fossils have yet been found, and sedimentary structures, such as hummocky cross-bedding, are not restricted to marine environments (cf. Greenwood and Sherman, 1986).

The Gai-As Lake in Brazil

The Rio do Rasto Formation is subdivided into the Serrinha and Morro Pelado Members (Figure 6). The Serrinha Member, 150–250 m thick, displays a wide facies variability. Greenish, mudcracked muddy siltstones dominate the section, with (<1 m) tabular interbeds of fine-grained sandstone increasing in density into the upper part of the succession. Some are arranged within fining-and thinning-upward cycles, each 4–8 m thick, consisting of massive to hummocky cross-bedded fine-grained sandstone increasing in density into the upper part of the succession. Such successions are attributed to proximal to distal tempestites, but sandstones deposited by turbidites, lobate mouth bars, and rare small eolian dunes are also present in the sections. Fluvial facies are almost absent and only a few, thin massive limestones occur. The biogenic record of the Serrinha Member is quite different from that of the underlying Teresina Formation (cf. Figure 6). Such a pronounced environmental change perhaps relates to a paraconformity between the two stratigraphic units as discussed by Rohn (1994). The bivalves of the Leinzia similis assemblage are endemic and associated with conchostracans, indicating freshwater conditions. Abundant fossil plants include
Glossopteris. Lycopods disappear with the onset of the Serrinha Member, and the sphenophyte Sphenophyl-
num becomes one of the typical fossil plants. As inferred from the abundance of plant remains, the
paleoclimate in general appears to have been more humid than during deposition of the Teresina Forma-
tion, with interludes of aridity evidenced by development of eolian dune sandstones toward the top of the
unit (Rohn, 1994).

The 250–600 (?) m thick Morro Pelado Member (Figure 6) is characterized by red mudstones, local rhyth-
mites, and a higher density of 1–4-m-thick lenticular fine-grained sandstones. The latter are interpreted as
eolian dune deposits that are intercalated with shallow lacustrine and floodplain deposits. Typical fluvial sed-
iment structures are only rarely preserved, probably due to wind abrasion. Fluvial deposits, however, are
particularly well documented in the area around Ponta Grossa arch (cf. Figure 5A), which was probably
affected by uplift at that time (cf. Gama et al., 1982;
Williams, 1995). Fossil bivalves and macrophytic remains are rare (Palaemutela? platinensis assem-
blage), whereas conchostracans are relatively abun-
dant and diverse (including the genus Leaia). The sphenophyte Schizoneura gondwanensis is an important
widely distributed element in many other contemporaneous Gondwanan deposits. These plants are representa-
tives of a marginal hygrophilous vegetation (Rohn, 1994),
with aquatic fauna becoming increasingly localized upsection to floodplain lakes and interdune ponds;
however, basal parts of the Morro Pelado Member contain bones of the endemic amphibians Rastosuchus and
Australerpeton, which are associated with occurrences of the first known terrestrial tetrapods of the
basin. The reptile Endothiodon from the base of the Morro Pelado Member indicates an affinity to the
Beaufort Group Pristerognathus, Tropidostoma, and Cis-
teccephalus biozones sensu Rubidge et al. (1995) of the
main Karoo basin. Fossil plants and the leauid conchos-
stracans also support a Late Permian age of the Rio do
Rasto Formation.

Gama (1979) suggested a large deltaic system sourced from the west and prograding toward the southeast as a sedimentologic model for the Passa Dois Group. Compared to the paleogeographic setting of the Paraná basin (Figure 1A), this delta prograda-
tion would be subparallel to the northwest-southeast and north-northwest–south-southeast–trending axis of the pre-southern South Atlantic rift that initially trended predominantly through the Paraná basin area (Figure 1A). The overall lateral continuity of facies, development of considerable thicknesses, and higher preservation potential of strata compared to their Namibian correlatives suggest a more basal setting for the Paraná area associated with enhanced subsidence within the central parts of the rift zone. Because of this enhanced subsidence, signatures of contempo-
raneous fault activity are generally less pronounced in the Paraná basin when compared to the more mar-
ginal Namibian settings; however, the influence of several important structural elements is still registered by the basin fill. Activity of the Asunción Arch in

Paraguay (Figure 5A), for instance, is evidenced by both the asymmetric isopach pattern of the Passa Dois Group (Figure 5B) and a wedge of coarse sediments paralleling the western basin margin (cf. Gama, 1979). The Ponta Grossa arch (Figure 5A) became uplifted during deposition of the upper parts of the Passa Dois Group, when fluvial intraformational boulders became deposited in the Reserva-Cândido de Abreu region, southwest of the arch (Rohn, 1994).

TECTORIC EVOLUTION OF THE
LAKE SYSTEM

Stollhofen (1999) postulates that the area of rifting prior to the opening of the South Atlantic experienced a series of extensional rift events since the Late Carboniferous, interspersed by relatively quiescent peri-
ods. The ensuing extrusion of voluminous Jurassic and Cretaceous flood basalts in southern Africa and South America (Baksi and Archibald, 1997) thus represent only the peaks of a long-term extensional history cul-
mminating in oceanic opening during the Early Creta-
ceous. The area that was to become the present Namibian continental margin was controlled by a long-lived north-northwest–trending tectonic zonation comprising from west to east: (1) a rift valley depression later bisected to initiate the continental shelf, (2) an adjacent rift shoulder that underwent maximum thermal uplift, (3) an extensionally faulted zone floored by a breakaway detachment, and, farther inland, (4) the relatively stable cratonic continental interior. During the Permian, this tectonic zonation had not achieved its maximum expression; however, the north-northwest–trending rift shoulder and the adjacent rift basin were already defined. In addition, the width of this linear intracontinental extensional zone was not constant throughout its long-lived evolution, but focused toward the center of the rift during its more advanced stages of evolution.

Prior to the establishment of the Gai-As Lake, the intracontinental rift valley was repeatedly affected by northwardly directed marine incursions following the Carboniferous–Permian Dwyka interglacial sea level highstands (Martin, 1975; Horsthemke et al., 1990; Visser, 1997; Stollhofen et al., in press). Comparable intermittent episodes of marine flooding are well
known along other intracontinental rift zones such as the Oligocene Upper Rhine graben in Germany (Schreiner, 1977). Causes of marine incursions may relate to phases of enhanced subsidence or global sea-
level rise. Low or no subsidence or renewed activity of tectonic barriers are potential causes for isolation from the marine, in turn resulting in a closed inland lake and establishment of freshwater conditions. During the Early Permian, the rift valley depression finally extended from the western part of South Africa as far north as northern Brazil to accommodate the Irati–Whitehill sea (Oelofsen, 1987; Williams, 1995). Following this marine incursion and deposition of thick bituminous shales of the Irati/Whitehill Formation and its equivalents, the sedimentary environment
Figure 8—(A) Generalized architectural model of the rift zone, as visualized in Namibia, compartmentalized by orthogonal transfer faults. (B) The distribution of the Gai-As unit illustrates confinement of the lake largely to the rift valley itself, whereas above the rift shoulder (Albin Ridge) the Gai-As and Doros Formations are poorly preserved, with the sequence only starting later in the Late Permian–earliest Triassic.

within the rift valley depression changed gradually into a freshwater lake. This cut-off from the marine realm was perhaps a consequence of large-scale uplift and structural inversion of the Argentinian Puna highlands associated with the Cape-Ventana and San Rafael orogenies (cf. Veevers et al., 1994b; Porada et al., 1996). The depositional sequence recording the marine-nonmarine transition is only fully preserved in the Karoo foreland basin and the Paraná basin, the latter including the more central parts of the rift valley. Thinner and sand-dominated deltaic units of the Corumbatai Formation in the northeastern Paraná basin document the more marginal facies of the rift, which prograded southward, along the rift axis. In northwestern Namibia, however, a hiatus, probably caused by early thermal uplift of the rift shoulder along with the entire rift zone, separates the marine Whitehill equivalents (Huab Formation) from the overlying nonmarine Gai-As Lake deposits.

Comparison of the lateral extent of the Gai-As equivalent deposits to the framework of the outlined structural zonation (Figures 8B, 9) shows the elongation of the extensive lake basin coincides with the axis of the early, north-northwest–striking branch of
the pre-southern South Atlantic rift zone (Figure 1A). Timing and the considerable amount of Permian–Carboniferous tectonic subsidence, followed by thermal cooling, is clearly displayed by the backstripped subsidence curve from a well in the Paraná basin area (cf. Zalán et al., 1990). An important aspect during the period of mechanical subsidence is the tectonic reactivation of basement structures both along the Namibian faulted margin (Clemson et al., 1997; Stollhofen, 1999) and along the conjugate South American side (Brito Neves et al., 1984); however, Permian faulting in the Paraná area appears to have developed more diffusely, spread over a relatively wide area when compared to the Namibian counterparts. Linear gravity lows paralleling the Asunción arch along with the indications of crustal thinning suggest that remnants of one rift basin system lie along the west-central Paraná province (Vidotti et al., 1995). Following Early Cretaceous flood basal extrusion and oceanic onset along a north-south trend, the rift branch penetrating the Paraná area was finally aborted and resulted in a failed rift (cf. Sibuet et al., 1984). In comparison with equivalent successions in Africa (Stanistreet and Stollhofen, 1999), the fill of the Paraná basin area is subdivided into (1) a Permian–Carboniferous, (2) a Triassic–Jurassic, and (3) a Cretaceous megasequence, each separated by time-stratigraphic gaps. Zalán et al. (1990) viewed the Paraná area not as a single basin in the strict sense, but as a combination of tectonically different types of basins with varying outlines stacked on top of one another developing a cumulative geometry, which is commonly referred to as the Paraná “basin.” Some of the evolutionary steps of the Paraná (cf. Klein, 1995) compare well with the development of African Karoo rifts involving sequential stages of extensional faulting, heating, and mechanical fault-controlled subsidence succeeded by subsidence related to periodic thermal cooling and contraction. A comparative example is the North Sea basin, recognized by Sclater and Christie (1980) from backstripped subsidence curves to involve two phases of rifting and thermal cooling superimposed on top of one another. The present North Sea “basin” geometry is superficially that of the last phase of thermal cooling and subsidence.
Lateral extent and the coincidence of thickness and facies variations of the Gai-As and Doros Formations with regional structural elements in Namibia (Figures 1C, 7, 9) illustrate the structural control on Gai-As Lake deposition. By considering the pronounced northwest-southeast to north-northwest-south-southeast elongation and facies architectural pattern of the lake deposits (Figure 9), the huge Gai-As Lake was essentially confined to a rift valley depression, but frequently onlapped onto its shoulders. The Gai-As Lake hosted pelecypods, fishes, and amphibians, the latter growing to considerable size, and would compare well to modern permanent rift valley lakes such as Lakes Tanganyika and Malawi in East Africa (cf. Crossley, 1984; Tiercelin, 1991; Baltzer, 1991). The Gai-As and Doros Formations are not preserved from sections above the rift shoulder where much of the Triassic-Jurassic successions are also missing due to enhanced thermal uplift. Alluvial fans of the Doros Formation prograded into the lake off marginal faults and the rift shoulder, which emphasizes that at least locally considerable relief existed in the lake margin areas. With the establishment of less humid climatic conditions and associated lake retreat, the lake shorelines increasingly fell dry and were modified by pedogenic processes as recorded by the Gai-As Formation at the Gudaus Hill locality (Figure 4). In Brazil, the more sandy parts of the shoreline and fluvial tributaries became significantly affected by wind reworking, resulting in the eolian dune deposits of the upper Serrinha Member and, in particular, the Morro Pelado Member (Figure 6). The development of eolian processes toward the northern end of Lake Gai-As compares well to modern Lake Malawi where southerly winds generate eolian sands from beach ridges, particularly behind southerly facing beaches (Crossley, 1984). As Lake Gai-As most probably experienced predominantly southerly winds (cf. Kutzbach and Ziegler, 1994), the northern end of the lake should be the one potentially most affected by such winds.

In Brazil, stratigraphic sections combined with an isopach map (Figures 5B, 6) of the Passa Dois Group suggest the influence of rifting on depositional patterns there, as well. The area of maximum subsidence, indicated by contours of maximum thickness development (Figure 5B) and offshore facies associations (Figure 6, sections 1, 2, and 3) are localized in the states of Santa Catarina and Paraná. Toward the northeastern Paraná area (Figure 6, sections 4 and 5), the whole Passa Dois Group developed a more marginal facies with a reduced thickness. In addition, its upper part became partially eroded prior to the onset of deposition of the Upper Triassic Pirambóia Formation. Pinch-out of composite sections seems equivalent to the variation on the Namibian basin edge from Klein Gai-As and north of Doros locations eastward to Twyelfontein and from Brandberg eastward to the continental interior. Facies and thickness development in the northeastern Paraná area is mirrored across the depositional area but, according to the slightly asymmetric isopach pattern (Figure 5B), more pronounced towards its southwestern and western margin. The north-south-trending Asunción arch forms the predominant structural element. Although the arch is not exposed in Argentina, its southward extent can be inferred from the almost complete pinch-out of the Teresina Formation and the Serrinha Member in southern Brazil and adjacent Uruguay. Within the Brazilian portion of the pre-southern South Atlantic rift zone, the Asunció structural arch reflects a western rift shoulder, whereas a less pronounced eastern rift shoulder can be expected in eastern Brazil to be associated with the Ipiáçu-Campina Verde depocenter axis (cf. Zalán et al., 1990).

Facies development within the elongate Gai-As lake basin was neither uniform nor was it consistently parallel with the rift axis, either in the main basin area or in the area transitional with the main Karoo foreland basin. As described by Stollhofen (1999) and Holzförster et al. (in press), transfer fault zones sensu Gibbs (1990) compartmentalized the rift zone into a chain of individual depocenters (Figure 8A), which were linked only during times of highstands. Fulfaró et al. (1982), Zalán et al. (1990), and Light et al. (1993) illustrate how “arches” influence the sediment thickness distribution in the Paraná basin area and the rift valley fill buried in the present Namibian offshore area. Examples of such structures are represented by the Goáñia/Alto Parnaíba, the Ponta Grossa, the Rio Grande, and Lüderitz and Kudu arches (cf. Figures 5A, 9), all of which are arranged perpendicular to the main rift trend. They record dominantly strike-slip and oblique-slip deformation (Zalán et al., 1990). The arches became particularly active during the Triassic and developed along strike with both transpressional effects causing linear zones of uplift and erosion and transtensional effects initiating rapidly subsiding half-grabens and pull-apart basin geometries.

The Gai-As lake area was probably cut off from the more southerly parts of the rift zone because of the intervening Kudu and Lüderitz arches. The latter, recognized by Dingle (1992/1993), was operative during the Jurassic, but seems to have already initiated in preceding tectonic events (cf. Light et al., 1993). For instance, on the basis of paleogeographic and facies reconstructions (Figures 8, 9), the Lüderitz arch may divide post-Whitehill/Irati facies associations in the north (Gai-As Formation and Passa Dois Group), from those in the south (Collingham to Teekloof formations) (Figure 9). The area north of the Lüderitz and Kudu arches then became a separate rift valley lake center extending northward into the Paraná area.

Transfer zones in rifts are known to contain complex structural geometries that make them suitable locations for structural hydrocarbon traps (cf. Morley et al., 1990). In terms of the Gai-As Lake, zones of uplift associated with the transfer faults had considerable influence on the development of thickness and facies patterns within the basin. Bituminous black shales of the Whitehill/Irati Formation equivalents, just below the Gai-As Lake deposits, form the major hydrocarbon source rock in the South Atlantic region, and oil-impregnated sandstones of the Pirambóia Formation occur immediately above the Gai-As Lake correlative
beds in Brazil (cf. França et al., 1995). Lopatin-type calculations for the Paraná basin indicate that the Per- mian and older rocks entered the oil window during the Late Jurassic–Early Cretaceous phase of subsi- dence (Zalán et al., 1990), which was ultimately followed by the onset of drift and continental break-up (Figure 2A). Thus, knowledge of structural elements that were active during the Permain–Triassic is fundamental for understanding hydrocarbon wandering paths and future exploration strategies.

**DISCUSSION AND CONCLUSIONS**

The Gai-As Lake formed during an early stage of the long-term extensional history of the pre-southern South Atlantic rift zone and recorded one of a series of early extensional episodes (Figure 2A) that ultimately led to an Early Cretaceous ocean basin (Dingle, 1992/1993). Permian–Carboniferous rifting was succeded by a widespread phase of non-deposition and erosion. Along the central parts of the rift zone, early thermal uplift phases caused a time-stratigraphic gap comprising the Upper Permian–Upper Triassic, prior to extensive Early Jurassic flood basalt extrusions (Stanistreet and Stollhofen, 1999; Stollhofen et al., this volume).

Such an early stage of rifting compares for example to Paleocene–Eocene rift basin developments in the Bohai region of northeast China (Chen Changming et al., 1981) with red beds and evaporitic limestones being deposited within elongate lakes flanked by alluvial fan deltas. Because the marginal rift shoulders in Namibia were tilted away from the rift axis during initial Gai-As Lake deposition, the majority of drainage systems were in turn directed away from the central rift depression. Ingress of coarse detritus into the early rift valley therefore is relatively restricted. Discharge and preservation of clastic detritus is limited to areas neighboring fault scarps and elevated footwall blocks within the rift. Crossley (1984) showed that faults transecting the margins of the modern, central African Malawi rift valley lake were crucial in causing fans to prograde almost directly into the lake. In terms of ancient Lake Gai-As, such a scenario is particularly well recorded in the Brandberg section where the abundance of lithoclasts derived from lithologies stratigraphically below the Gai-As reveals partial erosion of nearby footwall blocks and hanging-wall–confined braided river channels sourcing alluvial fan deltas. In contrast, the Gudaus hill, Sanianab, and Albin Ridge localities (Figure 1C) record condensed sequences associated with areas of reduced tectonic subsidence, characterized by paleosol development. It is remark- able that increases in clastic sediment supply at the base of both the upper Gai-As and Doros Formations coincided with the deposition of pyroclastic fallout material (Figure 3).

A good analogy of the sedimentologic relationships between the Doros and Gai-As Formations is provided by the example of Pliocene–Pleistocene fans prograding into a rift valley setting recorded by Vondra and Burggraf (1978) from Lake Turkana, Kenya. There, widespread fluvial deposition began shortly after deposition of pyroclastic material and localized subsi- dence led to the relative elevation of basin margins with subsequent initiation of erosion in that area. A concurrent climatic change toward less humid conditions was inferred from oxygen-isotope studies of car- bonates, and an apparent increase in alkalinity of paleo-Lake Turkana was recorded by molluscan extinction and changes in authigenic mineral contents of both pyroclastic and siliciclastic sediments. Adjacent to the basin margins, broad alluvial fans accumulated wedge-shaped gravel units. Shifts from low- to high-energy fluvial systems resulted in the erosion of underlying lithologies, downcutting of up to 11 m.

Much of the sediment within Lake Gai-As was probably redistributed by longshore currents, which is common in modern lakes (Cohen et al., 1986; Renault and Owen, 1991) and has been inferred in a variety of ancient lakes (e.g., Allen, 1981; Martel and Gibling, 1991). The longshore currents themselves may have been induced by strong southerly winds (cf. Kutzbach and Ziegler, 1994) that became locally funneled along the north-northwest– to northwest–trending depres- sion traced by the lake axis. In addition, bottom cur- rents comparable to those recorded by Crossley (1984) from modern Lake Malawi may have caused mixing within a thermally stratified lake resulting in mass mortalities of fish and bivalves, both preserved as signif- icant accumulation horizons in the Gai-As sedimentologic record.

Due to its paleogeographic setting at about 40°S, Lake Gai-As would have been influenced by intense winter storms (cf. Duke, 1985) and high rates of evapo- ration during the summer. Such a paleolatitudinal set- ting would compare well to the modern Caspian Sea. The low diversity of fish and bivalve populations indi- cates ecologic stress exacerbated by temporarily saline lake waters established during periods of low precipi- tation and enhanced evaporation. The presence of amphibians and lake-fringing mudflats vegetated by trees suggest, however, that low-salinity lake waters prevailed and were only interrupted by such high- salinity interludes.

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