THE BIOSTRATIGRAPHY AND FOSSILS OF THE WHITEHILL AND IRATI SHALE FORMATIONS OF THE KAROO AND PARANÁ BASINS

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Abstract. A comparison is drawn between the biostratigraphy of the Whitehill Shale Formation of the Karoo basin and that of the Irati Shale Formation of the Paraná basin. Facies changes within the formations are compared, and the influence of regressive-transgressive episodes is discussed. Evidence for stratification of the Whitehill-Irati sea and for the presence of highly anoxic bottom brines is discussed. The evidence is drawn from the presence of gypsum and halite crystals in the sediments and also from the nature of the fauna, e.g., the absence of benthic forms. Based on the striking similarity in the biostratigraphy of the two formations, and the presence of specimens of the same species of vertebrates in both basins, the conclusion is drawn that the two formations may represent a transcontinental isochronous unit. It is argued that the two formations were deposited in contemporaneous embayments onto the two continents, extending from a central sea arm that occupied a position between the Karoo and Paraná basins.

Introduction

The Whitehill and Irati are black shale formations covering immense areas in the Karoo basins of southern Africa and in the Paraná basin of South America, respectively. It has long been known that the two formations are remarkably similar, being of about the same thickness and containing similar fossils. The presence of mesosaurid reptiles in both formations was used as one of the first paleontological arguments in favor of the theory of continental drift, for example, by du Toit [1937].

The common occurrence of Mesosaurus in the two formations has long been known. A mesosaurid from the Karoo was described as early as 1864 [Gervais, 1864] and from the Irati in 1886 [Cope, 1886]. Very little, however, was known of these formations or their fossils in spite of Romer's [1970, p. 2] statement that "of contemporary tetrapod life in Gondwanaland we know almost nothing with one notable exception." This exception was supposed to be Mesosaurus. The truth, however, was that at that stage, virtually nothing was known about mesosaurids. A comparison of mesosaurid material from the two continents is only now being made, and the cranial morphology of the southern African material was only recently studied [Oelofsen, 1981].

Of the rest of the fossils of the Irati and Whitehill formations, even less was known. A basinwide biostratigraphical study of the Whitehill formation was only recently done [Oelofsen, 1981]. No such data are available for the Irati, in spite of the need for such a study having been stressed by Mezzalira [1971]. For comparative purposes, information available on single localities in the Irati Formation has to be taken from the literature.

The biostratigraphy of the Whitehill Formation showed it to be a chronostratigraphic unit [Oelofsen, 1981] and the formation was formerly widely used in correlations as such [e.g., Martin, 1961; Heath, 1966; Van Eeden, 1973; Schreuder and Genis, 1973-1974]. Its former use, however, was based on intuition rather than fact, and the validity of the axiom was questioned by Anderson and McLachlan [1979]. The biostratigraphic study by Oelofsen [1981] showed that a number of biozones, consistent throughout the different Karoo basins of southern Africa, are present in the Whitehill Shale Formation. It was furthermore illustrated that the Whitehill Shale Formation, or any one of a number of fossil zones in the shales, can be used as chronostratigraphic units.

The Lithostratigraphy of the Whitehill and Irati Shale Formations

The Whitehill and Irati shales almost exclusively occur as paper-thin laminae. Like the Irati, the Whitehill Shale Formation is generally referred to as a white-weathering black carbonaceous shale [e.g. Schwarz, 1903; Rogers and du Toit, 1909; du Toit, 1927, 1954; Haughton and Frommurze, 1927; Engelbrecht, 1961; Potgieter, 1973; McLaren, 1974; McLachlan and Anderson, 1973, 1977a, b; Van der Westhuizen, 1979]. The formation, formerly known as the White Band, was also defined as such when the current name, Whitehill Shale Formation, was proposed (R. M. Johnson et al., unpublished report, 1975). Unlike the oil shales of the Irati, the shales of the Whitehill are not remarkably carbon rich. According to Anderson and McLachlan [1979] the 12-14% organic matter quoted by du Toit [1954] probably refers to samples from the vicinity of Hopetown, where Cunningham-Craig [1914] and P. R. Botha (unpublished report, 1940) investigated the oil shale potential of the formation. The values, reiterated, for example, by Engelbrecht [1961], and the 6-12% values from the southern Karoo [Haughton et al., 1953] seem to represent maximum values. Subsequent data from fresh borehole samples in areas selected for potentially high oil shale qualities yielded maximum values of 10% and a mean of 4.3% (n = 37) (D. Cole, unpublished report, 1978). X ray diffraction analysis of samples from outcrops in the Great Karoo basin give silica oxide (72-78%), aluminum oxide (11-18%), and small quantities of oxides of potassium, sodium, and phosphorus. The shale therefore is not "highly carbonaceous," as was stated by Anderson and McLachlan [1979, p. 83] in the most recent work on the oil shale potential of the formation. The black shale facies of the Irati Formation, however, is extremely rich in carbon and constitutes the second largest oil shale reserves in the world [Anderson and McLachlan, 1979].

In the middle of the Whitehill Shale Formation a silty shale unit occurs. This shale also occurs in the Kalahari Karoo and the Karasburg Karoo basins and resembles the silty shales immediately below and above the Whitehill Shale Formation (Figure 1).

Dolomitic limestone lenses and layers occur in the eastern outcrops of the Great Karoo basin. Some of the black dolomite lenses show stromatolite-like slump structures, and in them, a yet undescribed crustacean, which I consider to be identical to Liocaris of the Irati Shale Formation, is present.

In the Irati Shale Formation a limestone facies considered to be of shallow water origin is developed in the northern part of the Paraná basin [Oelofsen and Araujo, 1983]. In the middle of this facies of the Irati Shale Formation a gray siltstone is present (Figure 2). In the southern part of the Paraná basin (Passo de São Borja) this gray siltstone in the middle of the formation is replaced by calcareous layers interposed between two layers of black oil shale. In these calcareous layers the shallow water mesosaurids Stereosternum and Brazilosaurus are present [Oelofsen and Araujo, 1983] (Figure 3). At São Mateus, in the central area of the basin, the gray siltstone and limestones are replaced by impure limestones in the middle of the formation. In the Whitehill Shale Formation the trace fossil zone, the only trace of the presence of a benthic fauna, coincides with the intercalated silty shales. The silty shales, limestones, and impure limestones in the middle of both formations are interpreted as registering a eustatically induced regressive episode. The resultant shallowing of the basins led to higher-energy conditions and the shifting of shallow water facies into more centrally situated areas of the basins (e.g., at Passo do São Borja), causing shallow water forms and facies to be sandwiched between deeper-water black shales (Figure 2).

Range Zones in the Whitehill and Irati Shale Formations

The following range zones could be identified in the Whitehill Shale Formation: the trace fossil range zone, the fish range zone, the mesosaurid range zone, and the Notocaris tapscotti range zone. Of the four, only the trace fossil range zone is connected to a specific lithological unit, and it is also the only zone that was originally not developed basinwide. The different zones of the Whitehill Shale Formation will now be discussed in more detail and will, where appropriate, be compared with similar zones of the Irati.

Trace fossil range zone. This zone in the Whitehill Shale Formation coincides with the intercalated silty shale unit in the middle of the formation (Figure 1). This ichnozone is characterized by the presence of Zoophycos feeding trails, and especially Scolicia-type trails. Umfolosia-type trails of the "Diplichnites" group may also be present. This zone marks the lower borders of the fish and Mesosaurus range zones in the Whitehill Shale Formation. Of the presence and distribution of trace fossils in the Irati, nothing is known.

The fish range zone. This zone starts near the middle of the formation, either in the upper part of the intercalated silty shale member (where developed) or in the middle of the black shales, and goes up all the way to the top of the formation (Figure 1). An acme zone in the lowermost portion of the range zone is very conspicuous in the western outcrops of the Great Karoo basin. The thin acme zone (of the order of 100 mm) contains large numbers of fish. The fish in the Whitehill Shale Formation are little known and are in urgent need of study. The Irati fish, of which even less is known, seem to appear just below the intercalated gray siltstone in the São Paulo area [Mezzalira, 1971] and are present in the middle of the formation at São Mateus in the state of Paraná [Araujo, 1976] (Figure 2).

The Notocaris tapscotti range zone. The pygocephalomorphic crustacean Notocaris tapscotti occurs in vast numbers in a very restricted range zone, about 1 m thick and ending about 1 m from the top of the formation (Figure 1). In view of the vast numbers of fossils and the extremely restricted range, the entire range zone could be referred to as an acme zone.

The thickness and position of this zone with respect to the top of the formation are remarkably constant and remain constant over the vast outcrop area of the basin. An important feature of this zone (it proved to be the case in the other zones too) is that its thickness and distance from the top of the formation are directly proportional to the total thickness of the formation itself. In those areas where the formation reaches its maximum thickness of 65 m, the range zone increases from a mean of 1 m to 2.5 m, and the 1 m between the top of the formation and the top of the Notocaris zone likewise increases to 2.5 m (Figure 1).

In the Paraná basin a pygocephalid crustacean Pygaspis braziliensis is present in the top sec-

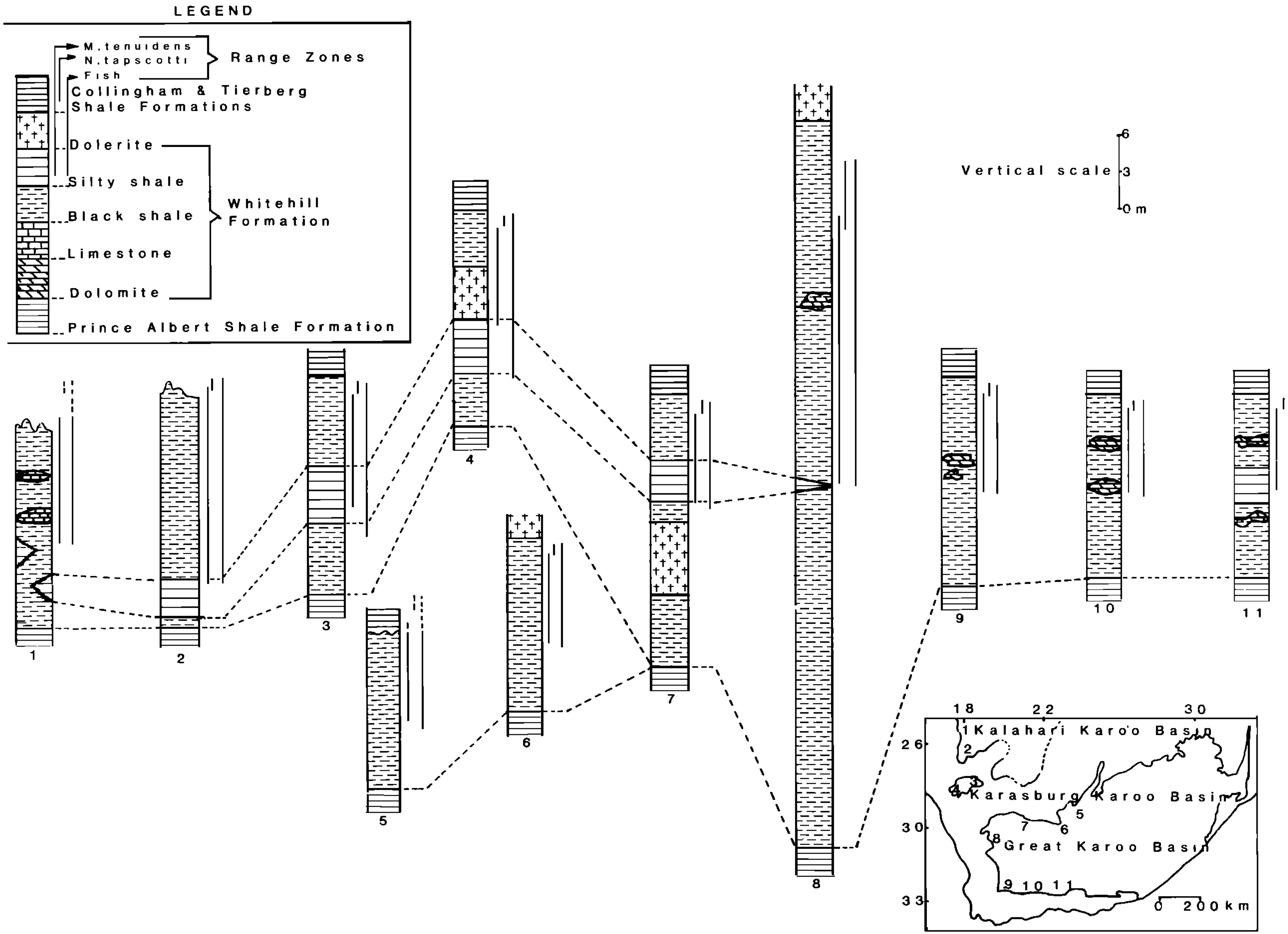

Fig. 1. Whitehill Formation, sections from different localities in the Karoo basins. Numbers refer to localities on inset map. Note distribution of silty shale and range zones of fossils.

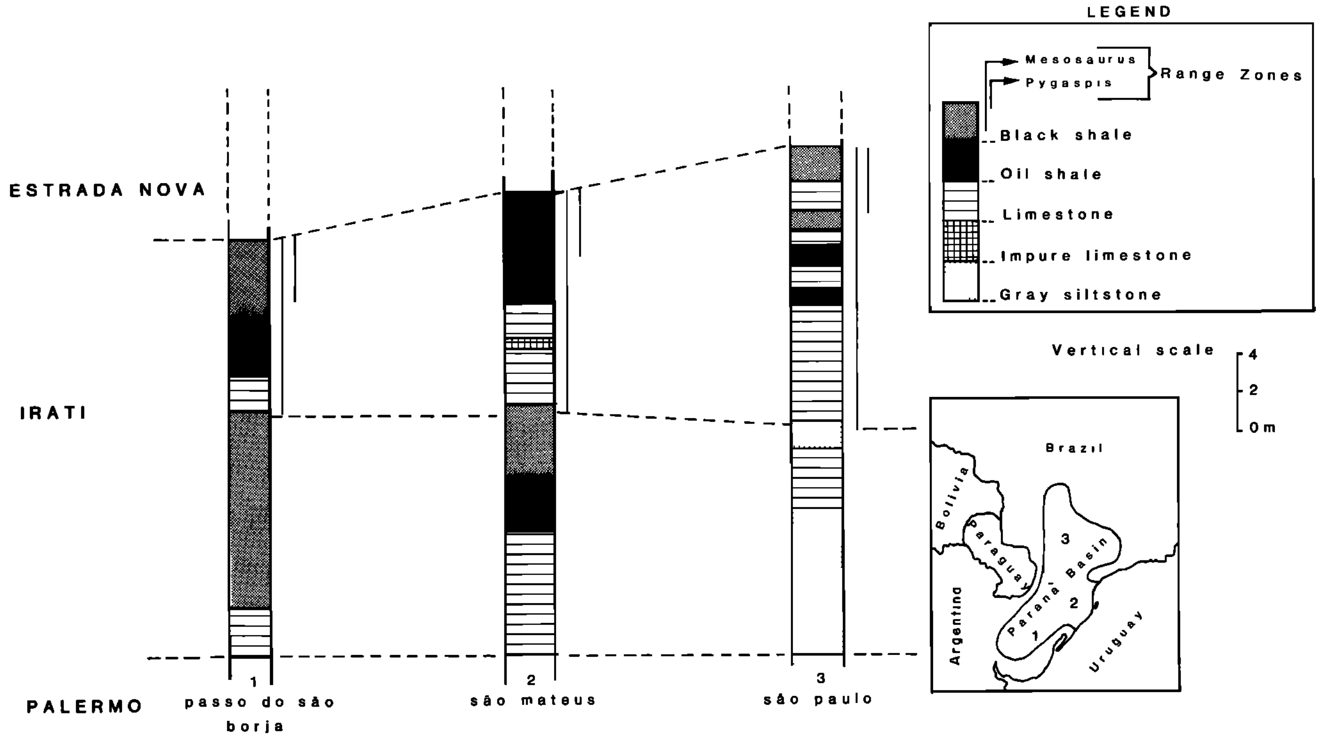

Fig. 2. Irati Formation, general sections from three localities in the Paraná basin. Note the presence of siltstone and the range zones of fossils comparable to conditions in Whitehill.

tion of the Irati Shale Formation, occupying a position similar to that occupied by *N. tapscotti* in the Whitehill Shale Formation (Figures 1 and 2). The two closely related crustaceans seem to have utilized similar niches in the two basins.

The Mesosaurid range zone. In both basins this range zone starts off in the middle of the formation and terminates in the lower part of the pygocephalid crustacean zone (*N. tapscotti* in the Whitehill and *P. braziliensis* in the Irati). In the Whitehill Shale Formation the mesosaurids show no acme zone. In the Irati, however, Araujo [1976] reports an acme zone near the top of the formation in the central basin area (outcrop at São Mateus (Figure 2). Mezzalira [1971] reports *Stereosternum* appearing slightly below the gray siltstone in the São Paulo outcrops. This makes it stratigraphically the first, and, I believe, the earliest appearance of mesosaurids anywhere.

Comparison of the Biostratigraphy of the Two Basins

It is clear from the biostratigraphy of the two formations that comparable biozones are present in the black shale formations of the Karoo and Paraná basins. The presence of two mesosaurid species in both basins, *Mesosaurus tenuidens* and *Stereosternum tumidum* (B. W. Oelofsen and D. C. Araujo, unpublished manuscript, 1986), occurring in identical range zones, is of special importance. The fact that the mesosaurids appear more or less in the middle of the formation shows that the basins were colonized by the mesosaurids approximately halfway through the existence of the Irati and Whitehill "seas" (Figures 1, 2, and 3). The mesosaurids are believed to have evolved in the northern part of the Paraná basin, where they appear lowest down in the stratigraphy. The presence in this area of an unspecialized, plesiomorphic, third species (*Brazilosaurus sanpauloensis*) that shows none of the special adaptations for aquatic life of the other two is taken as further proof of this assumption. *B. sanpauloensis*, moreover, seems to have lacked the ability to reach the African basins, as it has not been discovered in these basins in spite of extensive collecting. It should furthermore be noted that although *Stereosternum* appears slightly earlier in the São Paulo area, the rest of the Paraná and Karoo basins seem to have been colonized in a very short time span. The mesosaurids in the major part of the immense outcrop area of the Whitehill and Irati shale formations appear at the same stratigraphic level, paralleling the eustatic event and therefore possibly constituting an isochron ranging over both basins.

An independent isochron strikingly parallel to the mesosaurid range zone is the eustatically induced regressive event registered in the middle of the formation. The intercalated silty shales and calcareous, dolomitic, and impure limestone layers in the middle of the formations bear evidence of shallowing and an increase in the energy level of the water [Oelofsen, 1981; Oelofsen and Araujo, 1983]. The calcareous and silty layers in what is thought to be nearshore areas (e.g., Passo do São Borja, Figure 2, section 1), contain disar-

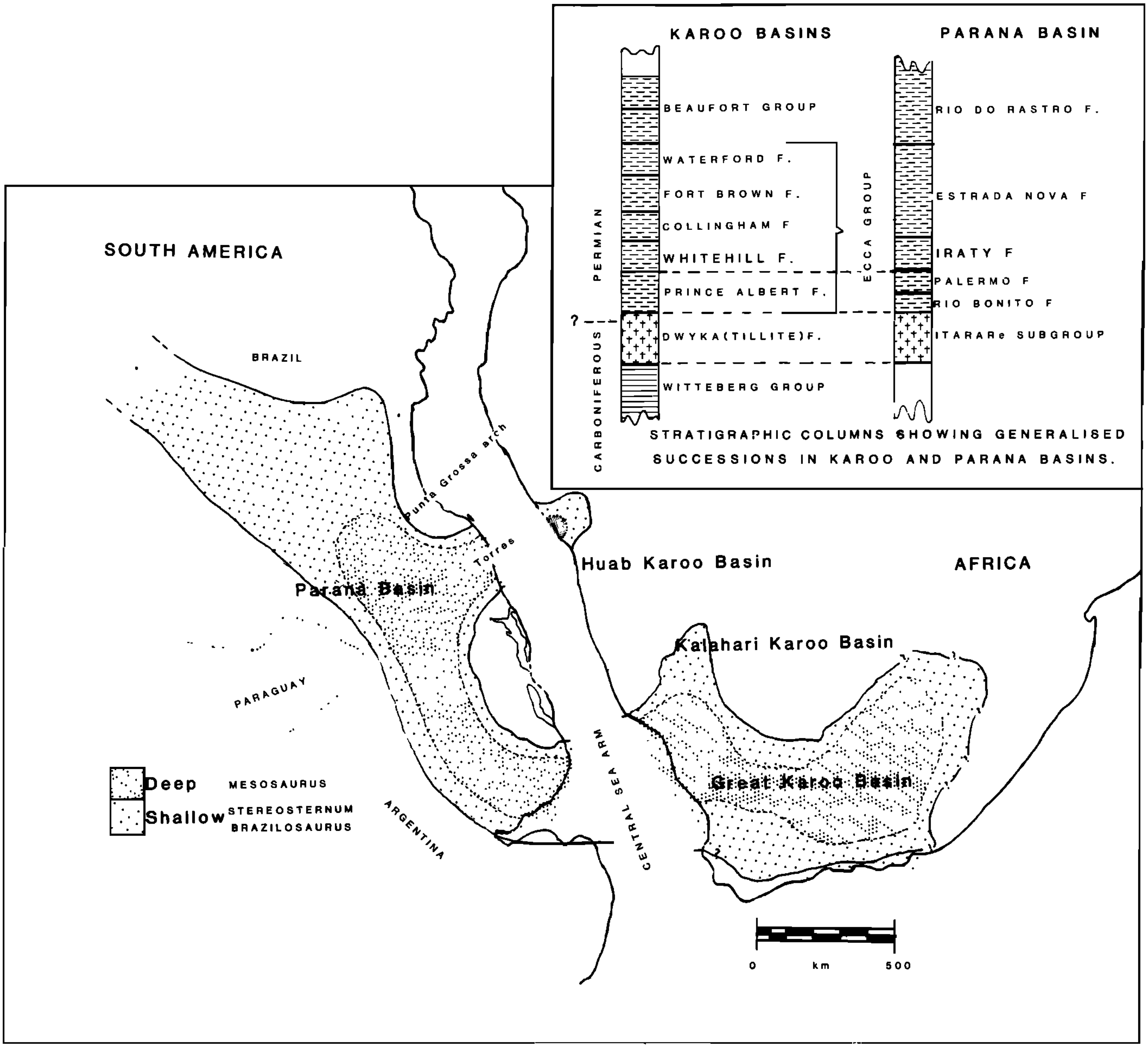

Fig. 3. Reconstruction of Karoo and Paraná basins showing Whitehill and Irati embayments onto Africa and South America from proposed central sea arm between continents. Note possible connection with oceans toward the position occupied by Antarctica.

ticulated and rolled skeletal fragments of Stereosternum and duplicate general conditions in the São Paulo area. At this time, in the São Paulo area, shallow water limestone deposition was replaced by the deposition of gray siltstone, while the deep-water black shale of the central basin area was replaced by the deposition of impure limestones (Figure 2). This phenomenon is repeated in the Karoo basins, and the general shallowing is interpreted as a regression, caused by a general, but short-lived, eustatic event. The striking parallelism, for example, the crustacean and mesosaurid zones in the two formations to the eustatic event is regarded as proof that the two formations in the Karoo and Paraná basins are chronostratigraphic units.

Sedimentation Model for the Whitehill and Irati Shale Formations

From the extremely fine nature of the sediments of both the Whitehill and the Irati, it follows that the river systems that flowed into the basins must have been exceptionally clear, carrying almost all of their load in solution. An important sediment fraction probably entered the basins as airborne particles, and at least part of the material is derived as ashfall from distant volcanic sources [McLachlan and Anderson, 1977a]. With the dust particles, insect wings were also blown into the basins, as a few specimens were recovered from widely separated localities. Subaerial and shallow water emergent features as well as vectorial primary structures are absent from the Whitehill Shale Formation [McLachlan and Anderson, 1977a; Oelofsen, 1981] and also from the Irati.

Casts of syngenetic gypsum crystals occur in the dolomitic limestone lenses of the southern outcrops [McLachlan and Anderson, 1977a]. Casts of single, blade-like gypsum crystals and small rosettes were found in the shales of the western outcrops (Figure 1, section 8). In the northern part of the basin, casts of halite crystals are present in the shales [Van der Westhuizen et al., 1981] (Figure 1, section 7). Seemingly isolated occurrences of gypsum and halite crystal casts are interpreted as indicating greatly increased salinities (brines). These occur in the same range of environments that produce evaporites [Heckel, 1972]. It has long been known that modern gypsum rosettes grow in situ in subsurface clays and sand and precipitate from highly saline brines which sink into the underlying sediments [Masson, 1955]. The presence of such saline bottom brines prevented benthic organisms from entering the basins and establishing themselves. It was only during the deposition of the silty shale layer that the anoxic conditions were temporarily upset. This allowed benthic and burrowing organisms to enter the basins, and the trace fossil range zone is therefore associated with this layer.

For the Irati Shale Formation a similar sedimentation model is proposed, and the limestone facies of the São Paulo-Mato Grosso area is visualized as having been a relatively shallow, restricted part of the greater Paraná embayment [Oelofsen and Araujo, 1983]. This facies contains mesosaurids not fully adapted to a diving, free swimming mode of life, e.g., Stereosternum and Brazilosaurus. It has been proposed that the Irati sea extended across the central Brazilian shield area and formed the evaporite succession of the Pedra do Fogo Formation of northern Brazil [Oelofsen and Araujo, 1983].

In conclusion it can be stated that during Irati and Whitehill times, the Great Karoo basin appears to have been relatively deeper than the Paraná basin. This difference was inherited, the Prince Albert Formation underlying the Whitehill being clearly a deep-water sediment, especially in the southern part of the Great Karoo basin. In contrast, the coal-bearing Rio Bonito and bioturbated, sandy Palermo formations that underlie the Irati (Figure 3) clearly are fluviatile deposits. The Palermo Formation has a much closer parallel in the Aub Sandstone that underlies the Whitehill Shale Formation in the Kalahari Karoo basin. The presence of small coal lenses in the Kalahari Karoo basin therefore is not fortuitous and mirrors something of the coal-forming conditions that prevailed in the Rio Bonito Formation of the Paraná basin.

The Setting of the Karoo and Whitehill Seas in Gondwanaland

Before the deposition of the Whitehill and Irati shale formations, western Gondwanaland and especially southern Africa underwent a history of marine transgressions. These transgressions are well documented, starting in the Upper Ordovician [Teichert, 1970] or Lower Silurian [Rust, 1967; Potgieter and Oelofsen, 1983] with the deposition of the Table Mountain Group. This was superseded by the marine Bokkeveld Group [Theron, 1972] and the Witteberg Group, which also show marine influences. Unambiguous marine fossils occur at the base of the Prince Albert Shale Formation that underlies the Whitehill Shale [Schroeder, 1908; Range, 1912; McLachlan and Anderson, 1973]. The first land vertebrates in the Great Karoo basin appear in the deltaic sediments of the Waterford Formation of the Ecca Group (Figure 3) [Rubidge and Oelofsen, 1983] above the Whitehill Shale Formation. The evaporitic minerals and marine fossils [Oelofsen and Loock, 1981] in the Whitehill Shale Formation point to a connection of the basin with the world oceans. A connection of the Karoo basin toward the south or southeast, as was suggested by Cooper and Kensley [1984], is ruled out, as in this direction lay a positive orogenic source that delivered material into the Karoo basin both before [Cooper and Oosthuizen, 1974] and after [Rubidge, 1984] Whitehill times. Moreover, shallow shoreline conditions are found in the eastern and southeastern outcrops of the Whitehill Shale Formation (e.g., driftwood and the development of intercalated shales and limestones (Figure 1, sections 9, 10, and 11). A connection between the Irati and Whitehill epicontinental basins through the Torres geosyncline was suggested by Oelofsen and Araujo [1983].

Evidence that marine conditions prevailed, not only over southern Africa, as was pointed out, but especially between Africa and South America, is abundant. Marine faunas that document this regime are known from the Precambrian [Germs, 1974], Silurian [Rust, 1967; De Loczy, 1971], and Devonian [De Loczy, 1971]. As these deposits are found in both western southern Africa and eastern Brazil, it has been argued that a central epicontinental sea existed in Gondwanaland between the present southern African and South American continents. Transgressions of this epicontinental sea onto the adjacent landmasses resulted in the deposition of the Irati and Whitehill shales. These landmasses, with a similar glaciated immediate prehistory, could not have housed embayments other than ones almost identical in nature. The embayments, connected to an already landlocked sea arm, were bound to be euxinic in nature. It is visualized that the epicontinental sea arm between the continents was connected to the world oceans toward the south (Figure 3). An intimate connection between the two basins (that is, the basins forming a unit, with South America in juxtaposition against Africa) is, furthermore, contraindicated by the fact that different, albeit closely related, crustaceans, Notocaris tapscotti and Pygaspis braziliensis, occupied the same niche in the two basins. The failure of the least aquatic mesosaurid, Brazilosaurus sanpauloensis, to reach the African basins also argues against a close connection. On the other hand, the presence of the same species of the aquatic reptiles Mesosaurus and Stereosternum and the presence of equal chronostratigraphic units in the two formations can only be explained through a direct link between the embayments. The existence of a Whitehill-Irati connection via a central sea arm between Africa and South America seems to account for the facts much better than the continuous "highland" barrier between the basins, as was suggested by Araujo [1976] and Anderson and McLachlan [1979].

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