

**ECONOMIC GEOLOGY
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GENESIS OF LATE PROTEROZOIC
SEDIMENTARY MANGANESE DEPOSITS
AT OTJOSONDU, DAMARA MOBILE BELT,
EAST CENTRAL NAMIBIA

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by

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ABSTRACT

The Otjosundu manganese mining area is located at the eastern exposed extent of the inland branch of the Late Proterozoic Damara Orogen. It displays a facies evolution unique for the conventional Damaran lithostratigraphy. Despite intense deformation and a high-grade metamorphic overprint, the sedimentological interpretation of the rocks has led to a palaeoenvironmental model which gives insight into ore genesis. At least two manganese-silicate ore horizons (manganese formations) are incorporated in a banded iron-formation. This sequence is sandwiched between supermature metaquartzarenites interpreted as a shoreface sandcover derived from a cratonic basement and deposited under high-energy conditions.

Manganese ore varieties and their countryrocks have been classified using their texture, mineralogy, and geochemistry and have thereupon been interpreted in sedimentological and facies terms. The evaluation of the vertical and lateral facies sequences and their contact relationships renders the spatial reconstruction of the environmental setting for the manganese ores possible. The development of facies from a near-shore clastic regime to manganese-bearing hemi-pelagic sediments and ultimately to pelagic mangano- and ironstones reflects a zonation on a marine shelf. The facies evolution indicates transgressive conditions on a large scale onto a tectonically stable but subsiding shelf: starting with (1) the transgressive quartzarenites overlying an unconformity to the pre-Damara basement followed by (2) chemical sediments of the ore-bearing horizon and overlying carbonates and ending up with (3) pelitic schists. On a smaller scale both transgressive and regressive conditions prevailed during manganese precipitation. Small-scale sedimentary cycles are interpreted as glaciogene influenced fluctuations in sea-level.

The source of manganese and iron is assumed to be situated in the deeper parts of the Damara inland branch trough. The initial spreading in the Khomas Sea and the formation of oceanic crust is documented by tholeiitic volcanics and associated base metal ore bodies representing more proximal manifestations of the exhalative activity. These base metal sulphide deposits are associated with pyrite-bearing graphitic pelagic sediments and this is the first site to partition iron and other base-metals from manganese. Upwelling along the shelf edge may have been involved and additional separation of Mn was due to differing Eh/pH conditions in a highly oxidizing shelf environment. The evolution of the Khomas Sea provided the ore-forming solutions and initiated the subsidence of a passive margin and of the adjacent shelf platform. The basin development interacted with glacial episodes responsible for fluctuations in sea-level and for the amount of terrigenous input in an otherwise pelagic regime.

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INTRODUCTION

Throughout geological time sedimentary manganese deposits vary greatly in terms of their differing palaeoenvironmental setting. These contrasts become most obvious in the overwhelming predominance of shelf-related depositional sites during the Precambrian which contrasts with modern deep-sea manganese nodule genesis in oceanic basins. Late Precambrian manganese deposits occur predominantly in transgressive sequences deposited in shelf environments as in the Early Proterozoic of South Africa (Beukes, 1983), India and Gabon and the Late Proterozoic of Brazil (see Roy, 1988 for a review).

Shallow-marine environments also appear to be the favoured depositional milieus for manganese accumulations during the Mesozoic and Cenozoic Eras (Glasby, 1988). In this respect, Cannon and Force (1983) and Force and Cannon (1988) have proposed a genetic model of manganese giants mostly of Phanerozoic age, taking into account high sea-level stands and associated bacterial activity in stratified seas.

Late Proterozoic manganese deposits are often connected with a banded iron-formation facies which itself is related to glaciogenic events. Banded iron-formations and associated manganese deposits in Urucum/Brazil have been attributed to glacial and periglacial episodes (Barbosa and Oliveira, 1978; Ferran, 1980). Late Proterozoic iron formations connected with glacio-marine sediments lacking associated manganese precipitation have been reported from Australia (Trendall, 1973), from the Rapitan Group in Canada (Young, 1976) and from Alaska and California (Yeo, 1984). On the other hand, Late Proterozoic manganese oxide ores in India have no connection with any iron-rich facies (Roy, 1988).

Both the inland and the coastal branches of the Damara Belt in Namibia developed widespread iron-formations intercalated with mostly glacio-marine sediments within the Chuos Formation of the Damara Sequence. The Otjosundu area is the only known occurrence of economic manganese accumulations which correlates with the Chuos iron-formations in the Damara Belt (Bühn et al., in prep.).

At first sight there appears to be a discrepancy between the transgression-related iron and manganese deposits and closely associated glacio-marine sediments which imply low sea-level stands. However, sea-level fluctuations with large amplitudes are not restricted to glaciogenic events (Cloetingh et al., 1985; Cloetingh, 1986). Large-scale transgressions confined to the evolution of passive margins and additional mechanisms to produce, separate, and accumulate concentrated ore solutions seem to be of greater importance with respect to the generation of this type of ore deposits. Glacial events may interact with the lithospheric evolution and may account for favourable Eh/pH conditions for manganese and iron precipitation and for fluctuations in sea-level; they thus have an influence on the separation and accumulation of manganese and iron and on the amount of terrigenous input.

One of the most effective tools for deducing the palaeo-environmental setting and mode of formation of sedimentary manganese deposits is a detailed facies analysis of their associated sedimentary record. This has been undertaken for Cenozoic manganese giants by Frakes

and Bolton (1984) and Bolton and Frakes (1985) who related sedimentary environments and manganese deposition to transgressive-regressive cycles. Comparable sedimentological and genetic studies on Early Proterozoic manganese and iron deposits have been done e.g. by Beukes (1983, 1984). Roy (1988) summarized the genetic studies of Precambrian manganese deposits. Most Precambrian BIF-related manganese deposits have not yet been investigated in similar detail; this is generally because of a medium- to high-grade metamorphic overprint of the rocks.

The rocks at Otjosondou have undergone a Damaran metamorphic overprint of at least upper amphibolite facies conditions which has previously militated against a facies analysis of the ores and country rocks. Conclusions on the nature of protoliths can, however, be drawn using the primary features and the compositional variety of the lithologies present. This study uses the facies interpretation and the geochemistry of the ores and their host rocks to deduce their palaeoenvironmental setting of formation and it evaluates the interaction of the basin evolution of the Damara inland branch with glacial episodes which accounts on the one hand for the generation of the ore-forming fluids and on the other hand influences the sea-level stand and therefore the Mn/Fe ratio in the sediment.

GEOLOGICAL SETTING

The Otjosondou manganese mining area is situated close to the Okahandja Lineament which is one of the major shear zones defining the limits of the tectono-stratigraphic zones of the Damara inland branch (Fig. 1). This has acted in Damaran times as a depositional boundary between a northern shelf/platform-style area of sedimentation and the southern turbidite-dominated Khomas Trough (Porada and Wittig, 1983; Kukla et al., 1988) (Fig. 2). The Okahandja Lineament also coincides with a change in tectonic style and metamorphic overprint (Miller, 1979; Sawyer, 1981). Kasch (1988) questions however the significance and influence of this lineament in sedimentological and structural terms for the area east of Okahandja. In this regard the Otjosondou region is of primary importance for understanding the palaeogeography of the eastern extent of the Damara inland branch.

The Otjosondou area represents a highly deformed region as seen from the geological map of Figure 2. The mining area extends over tens of kilometres of lateral extent but the overall exposure is poor and is restricted to individual mine pits particularly well developed in the western part of the mining area. The rocks have undergone a major Damaran metamorphic overprint. The ore mineralogy (Katz, 1978) and the presence of sillimanite and K-feldspar-corundum-bearing gneisses point to upper amphibolite facies metamorphic conditions at least. Concordant and discordant pegmatitic veins have intruded the ore horizons. Furthermore, the area was overprinted by three phases of deformation (Bühn et al., 1990). Although the deformation has locally affected some primary features, primary sedimentary facies criteria are still discernible.

A lithostratigraphic overview of the Otjosondou area is shown in Figure 3. The manganese ores are incorporated in a unit associated with banded iron-formations consisting of hematite-quartzites and hematite-rich gneisses. The two major ore horizons underlie and overlie this banded iron-formation, and are referred to in this paper as the Lower and the Upper Ore Horizons. A third horizon occurs locally in the middle of the

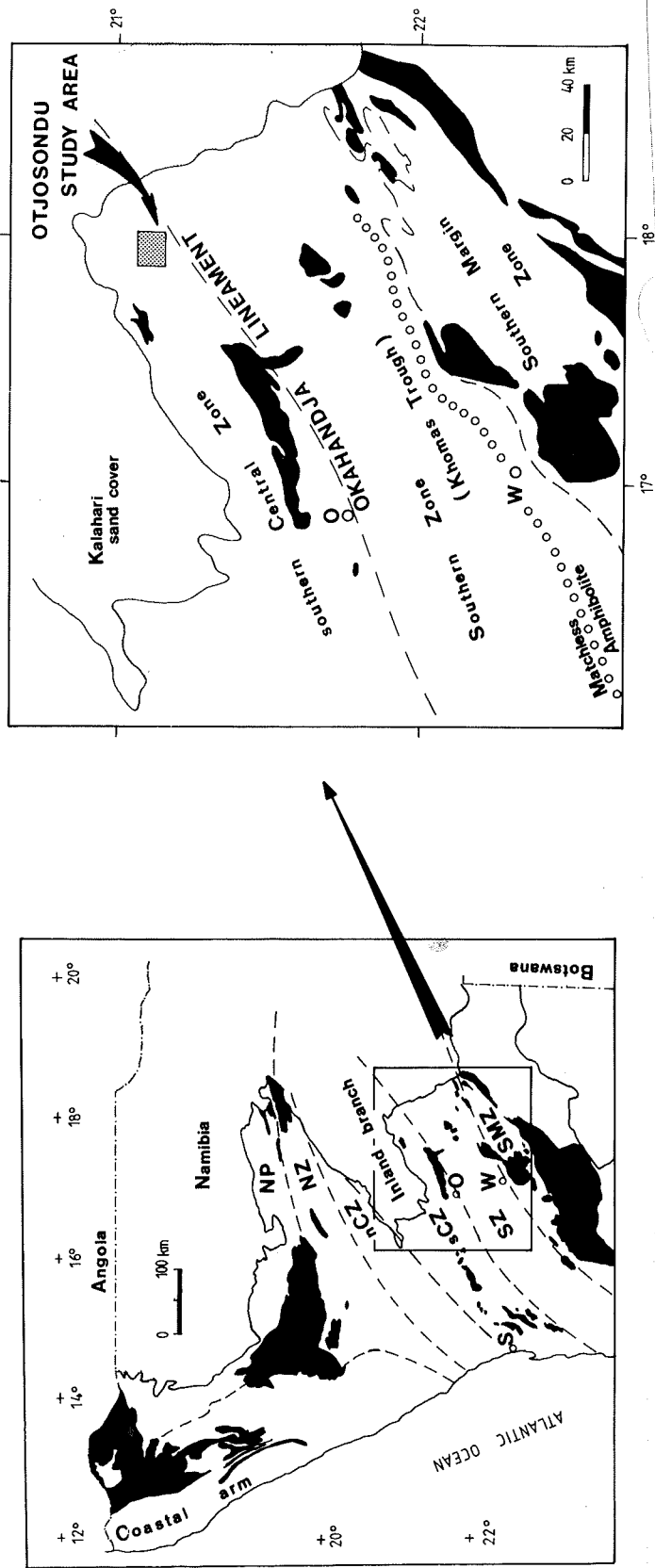


Figure 2: Location map of the Otjosondú manganese deposits. The regional position of the study area in relation to the tectono-stratigraphic sub-division of the Damara inland branch is outlined. Black = pre-Damara basement outcrops; O = Okavango; W = Windhoek; S = Swakopmund; NP = Northern Platform; NZ = Northern Zone; ns CZ = northern/southern Central Zone; SZ = Southern Zone; SMZ = Southern Marginal Zone.

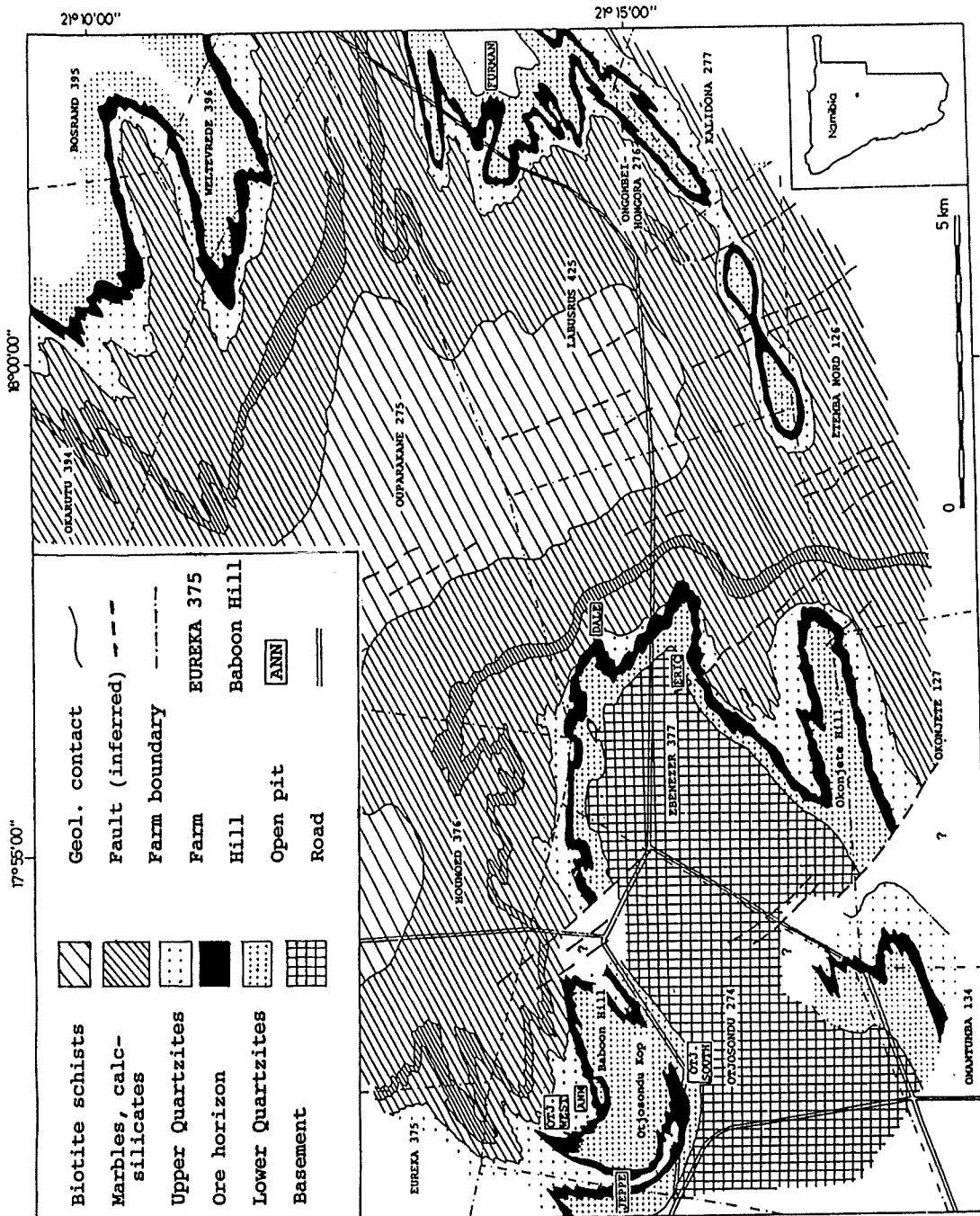


Figure 2: A blow-up of the geology of the Otjosondou mining area which indicates intense deformation of the strata. The localities of the mining areas investigated in this study are outlined.

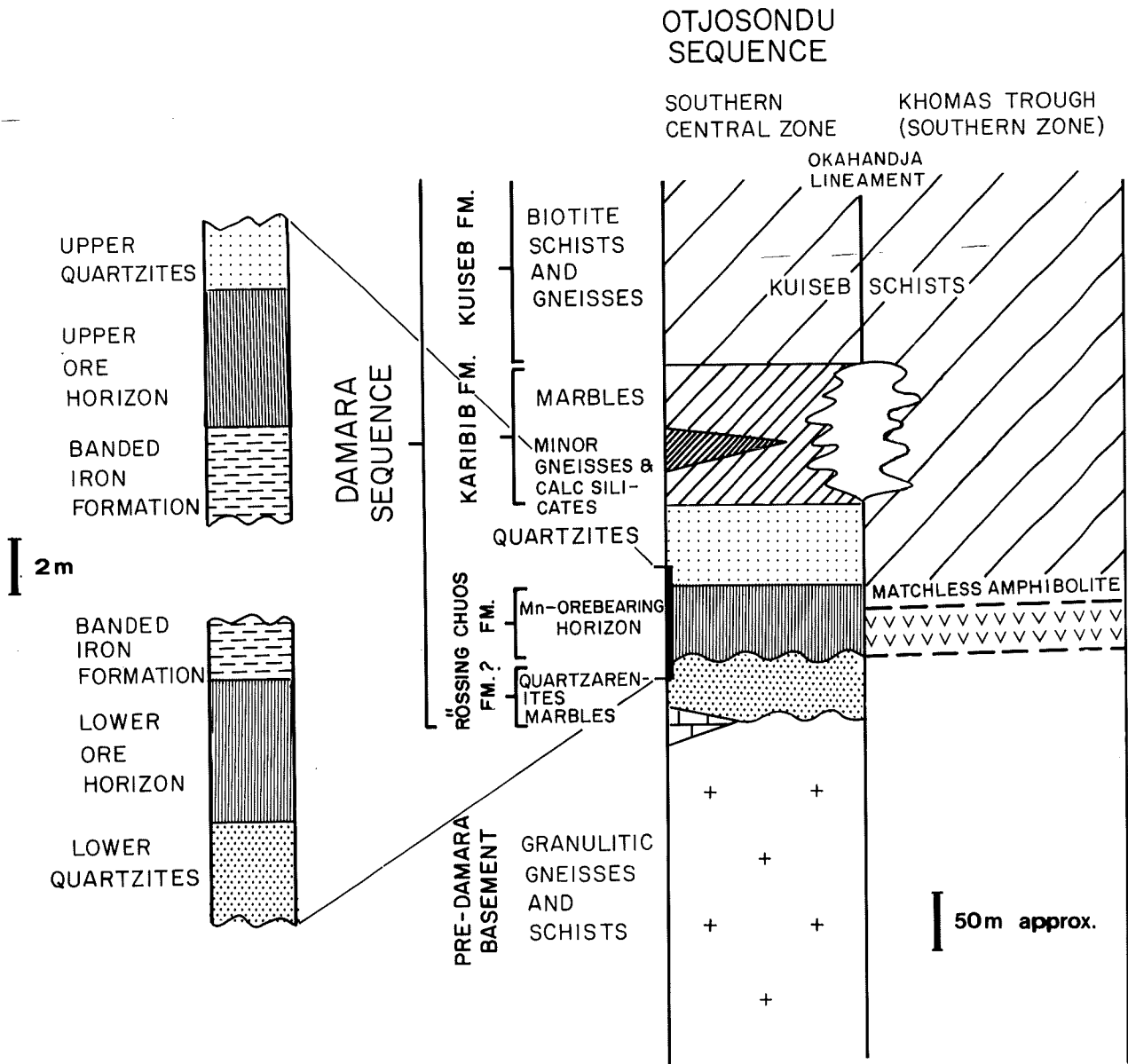


Figure 3: The lithostratigraphy of the Otjosondü area (partly after Roper, 1959) and of the Southern Zone (Khomas Trough) of the Damara inland branch. Note the unconformity at the base of the Lower Quartzites. The banded iron formation and associated manganese ores are sandwiched between the Lower and Upper Quartzites. In the Southern Zone the opening of the Khomas Sea produced an oceanic crustal sequence whose remnant is the Matchless Amphibolite Member.

sequence (Roper, 1959), but this occurrence may be due in some cases to structural repetition of the strata. The entire sequence is sandwiched between mostly pure, 'glassy' quartzites possessing sharp contacts.

The occurrence of ironstones associated with the Otjosondou manganese ores has led to the correlation of the Otjosondou Sequence with Chuos Formation iron-formations elsewhere in Namibia (Roper, 1959; Martin, 1965; Miller, 1983). The Kuiseb schists represent the youngest Damaran strata in this area and provides an upper stratigraphic bracket for the manganese-bearing sequence. Unequivocal correlation of the underlying thick quartzite sequence and associated manganese ores, unique to the Damara Sequence, are, however, less certain. The calcareous unit immediately underlying the Kuiseb schists, together with the quartzites and the manganese ores are correlated with the Chuos and the Karibib Formations (Fig. 3).

LITHOTYPES AND THEIR FACIES INTERPRETATION

Depending on their mineralogy and texture, the ores and adjacent countryrocks have been subdivided into several lithological associations which can be interpreted in sedimentological terms as facies types. Most rocks are very poor in sheet-silicates, the ores are mostly mica-free and exhibit only rare quartz. In contrast, Mn-rich garnets, Mn-clino-pyroxene, rhodonite, baryte, hyalophane, as well as some plagioclase, are the dominant non-opaque phases. The metamorphic assemblages are due to dehydration reactions which consumed micas and quartz to produce K-feldspar. These reactions will be described in a forthcoming paper.

To the writers' knowledge there is no descriptive term in the literature for such manganese-rich rocks other than the poorly defined term 'manganolite' (Bates and Jackson, 1987). According to the classification of Kimberley (1978, 1989a) an ironstone is a 'chemical sedimentary rock which contains over 15% Fe. In like manner the writers propose the term 'manganostone' for equivalent chemical sedimentary manganese-rich rocks. From geochemical analyses (Bühn et al., in prep.) a lower limit of about 15% Mn appears to be appropriate. A manganese formation would then be a rock unit composed mostly of manganostones with the uppermost and the lowermost units being manganostones (cf. Kimberley, 1989b). In the descriptions that follow the first name is the specific name of the metamorphic rock type and the second describes the inferred lithology of the precursor rock.

A. Braunite-hematite-jacobsite Ores/Manganostones

These rocks contain variable amounts of hausmannite, hematite and other Mn-Fe ore minerals (De Villiers, 1951; Katz, 1978). Little disseminated feldspar has been observed. The ore is massive and exhibits no banding. Their geochemistry is shown in two ternary diagrams (Fig. 4). The pure A-type ores have low Fe, Si, Al, and Ti contents in comparison with all other ore types. Mn/Fe ratios range from 2,2 to 14,8. High Ba-contents (up to 7,9% Ba) are probably due to the primary precipitation of baryte and Ba-rich cryptomelane/hollandite which was later transformed into Mn-silicates and Mn-oxides as well as Ba-K-feldspars. The low aluminium and titanium values suggest that the protoliths were chemical sediments deposited in a pelagic palaeoenvironment. This comprised a shelf setting in which were deposited variable amounts of Mn, Fe, and Si.

B. Banded Ores (Gondites; Fermor, 1909)/Layered Manganostones

Banding consists of 1-3 mm-thick layers of Mn-clinopyroxene and/or Mn-garnet. Garnets mostly consist of spessartine-rich varieties but other compositions have also been recorded. Thicker layers with pods of ore are also developed. Small amounts of feldspar may be present within the garnet/clinopyroxene layers. The layering, which is parallel to lithological contacts, is therefore interpreted as primary; it compares with unequivocal sedimentary quartz-feldspar layers which define bedding in other facies. Mn/Fe ratios are between 0,3 and 2,8. These silica-rich ores take an intermediate position between A-type ores and ores of type C which have increased amounts of Fe, Si, Al, and Ti (Figures 4 a,b). A variation between pelagic, pure manganoan precipitates and layers of Al- and Ti- bearing terrigenous sediments result in this banded ore type. Dasgupta et al. (1990) have assumed an admixed portion of clay, quartz, and other minerals as protoliths of such gondite ores. The banding of the rocks at Otjosondú is, however, primary.

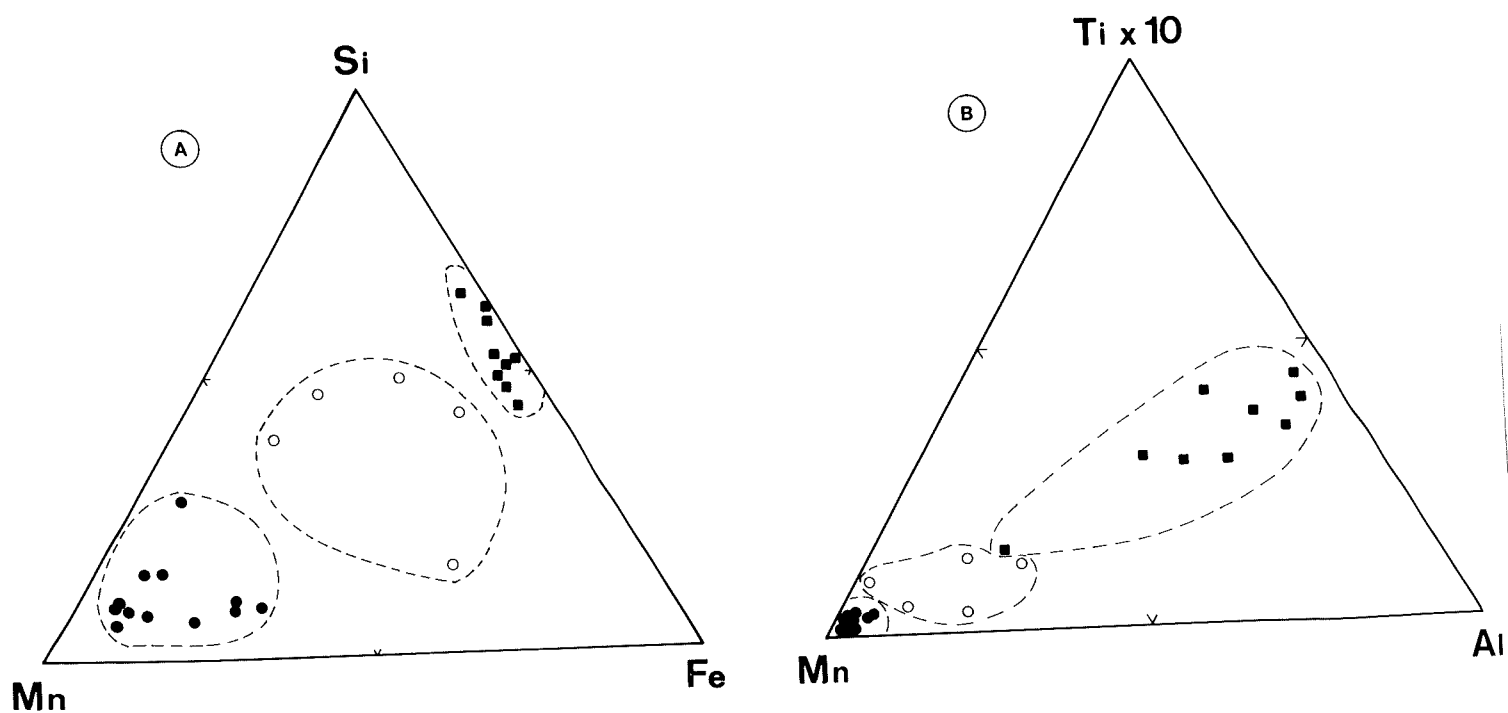


Figure 4: Bulk rock geochemistry of the manganese ores. (a) Mn-Fe-Si discrimination triangle for various manganese ore types. Full circles indicate pure manganostones (facies type A), full squares = feldspathic ores (facies C). An intermediate position is represented by impure manganostones of facies B (open circles). (b) The distinction of ore type A, B and C from their major element chemistry is also reflected by their minor elements Al and Ti. The element distribution in this triangle plot suggests that C-type ores involve an increased terrigenous component deduced from high Al and Ti contents. Pure manganostones (facies A) are pelagic formations lacking any clastic components. Banded manganostones (facies B) take an intermediate position.

C. Feldspathic Ores/ Manganiferous, Ferriferous Sandstones

These rocks have lower Mn contents than pure ores of types A and B which is also expressed in their Mn/Fe ratios below 0,3. Increased contents of K₂O (up to 5.4 wt%) and Al₂O₃ (up to 10 wt%) reflect increased proportions of K-feldspar in the rock. The high Al₂O₃ content of this lithotype correlates with increased portions of hematite and enriched values of Si and Ti (Figure 4). Precipitation of this ore type occurred in a hemi-pelagic environment as a transitional facies between a pelagic and a terrigenous dominated sedimentation regime.

Two types have been identified:

Cb (banded): A banded rock type which exhibits a millimetre-thick interlayering of a feldspar-rich lithology free of ore minerals and ore layers. It is assumed that either sand or silt grains and/or clayey components were transported sporadically into an otherwise pelagic environment in which chemical precipitation was the norm. Clays or micas have been consumed during metamorphic reactions resulting in the formation of K-feldspar-rich interlayers.

Cd (disseminated): This type is a random mixture of ore minerals and non-opaque phases. K-feldspar, plagioclase and quartz occur disseminated within the manganese ore, often in association with garnet and clinopyroxene. Grain sizes are 1-2mm, mica is not present. A protolith resulting from a continuous silty/clayey admixture to chemical Fe-Mn precipitates is probable. As this facies occurs mostly in the hanging-wall of the banded feldspathic ores it might also be interpreted as a reworked banded manganostone facies type.

D. Hematite-feldspar-quartzites/Impure Ironstones

This is a layered rock which contains hematite (up to 30 vol.-%) and in which K-feldspar occurs in appreciable quantities. Mica and plagioclase are rare, and zircon has been observed. The feldspar occurs disseminated in the quartzitic matrix but no layering is present. The bulk rock composition exhibits increased Ba-contents (up to 4600 ppm Ba). By comparison with data of Puchelt (1978) this high concentration points to a chemical origin of these rocks rather than to clastic protoliths. From 11 analyses the Zr contents were found to range from 33 to 268 ppm with a mean of 104 ppm Zr. Titanium does not exceed 0.43 wt.-% TiO₂. Moore (1986), and Gross and McLeod (1980) gave mean Zr contents of banded iron-formations in the range 81 and 98 ppm Zr. Sugisaki et al. (1982) reported a mean of 23 ppm Zr in cherts. A good positive Zr correlation index with Ti (0,83), Al (0,82), Na (0,70) and K (0,71) points to a supply of detrital zircon together with other clastics and thus to a hemi-pelagic formation with the dominance of the pelagic realm. This is a comparable manganese-poor facies to the manganese-rich facies C although the former shows a higher clastic admixture than facies D. In the former facies type C, the chemical precipitate is manganese whereas the latter type D is dominated by iron and silica precipitation with some detrital influx (i.e. banded iron formation). Thus, the difference between types C and D, apart from the slightly different clastic amounts, depends solely on the proportion of manganese and iron supplied to the system.

E. Fine-banded Hematite-quartzites/Pure Ironstones

These rocks exhibit a thin layering of pure quartz and hematite-quartz laminae on a millimetre-scale. Feldspar is hardly present in these rocks; the boundaries with facies type D are not distinct and all transitions may occur depending on the detrital supply. Bed thicknesses in both types range from 2 to 20 cm. Protoliths have constituted chemical sediments with only very minor clastic influx (MECS-type iron formation after Kimberley, 1989a).

A geochemical distinction between these hematite-quartzites and the clastic quartzarenites (facies G and H described later) is given in Figure 5. Increased amounts of Ba and Al in the former facies contrast with very low Ba and Al contents in the quartzarenites.

F. Quartz-feldspar-biotite Gneisses and Biotite-clinopyroxene-gneisses/Impure Sandstones

These rocks contain biotite and increased amounts of clinopyroxene and plagioclase. Hematite and K-feldspar are approximately 10 vol.-%, respectively, and sphene may be present. Precursor rocks were probably clastic, immature sandstones.

G. Layered Metaquartzites/Stratified Quartzarenites

These show a distinct stratification of up to 2 cm-thick hematite-rich strata. Feldspar is very rare; locally some disseminated clinopyroxene crystals may occur. Rutile often occurs intergrown with hematite, but has also been found as separate grains (Woermann, pers. comm.). Zircon has also been observed.

H. Massive Metaquartzites/Pure Quartzarenites

These rocks consist mostly of coarse-grained quartz, with minor amounts of disseminated hematite in places. In contrast to facies type G, no lamination is present. Feldspar and mica are mostly very rare.

The extremely pure quartzites of facies G and H, consisting of up to 99 wt.-% SiO_2 exhibit distinctively lower Ba- and Al-contents than the chemically precipitated quartzites of facies D and E (Figure 5). In contrast, they bear relatively high amounts of Zr (up to 368 ppm) with an average of 126 ppm Zr determined from 15 analyses; K_2O , Al_2O_3 , Na_2O and CaO contents are very low. In contrast to the chemical facies type D there is no correlation between Zr and other clastic components like K (0.01) and Al (-0.19). This indicates that feldspar, mica, and zircon were not transported together into this environment, but that zircon and other heavy minerals (hematite/magnetite) were separated from lighter detrital minerals in a high energy environment. Protoliths were supermature quartzarenites probably deposited in a shoreface setting. Analogues are the highly mature blanket sandstones of considerable lateral extent deposited throughout the Late Precambrian (Johnson and Baldwin, 1986).

I. Biotite-amphibolites/Marls:

This facies can only be observed in one outcrop but may be more extensively developed in the poorly exposed central portion of the manganese-bearing unit. Hornblende and plagioclase make up approximately 40 vol.-% and biotite and opaques about 5 to 10 vol.-% while apatite and

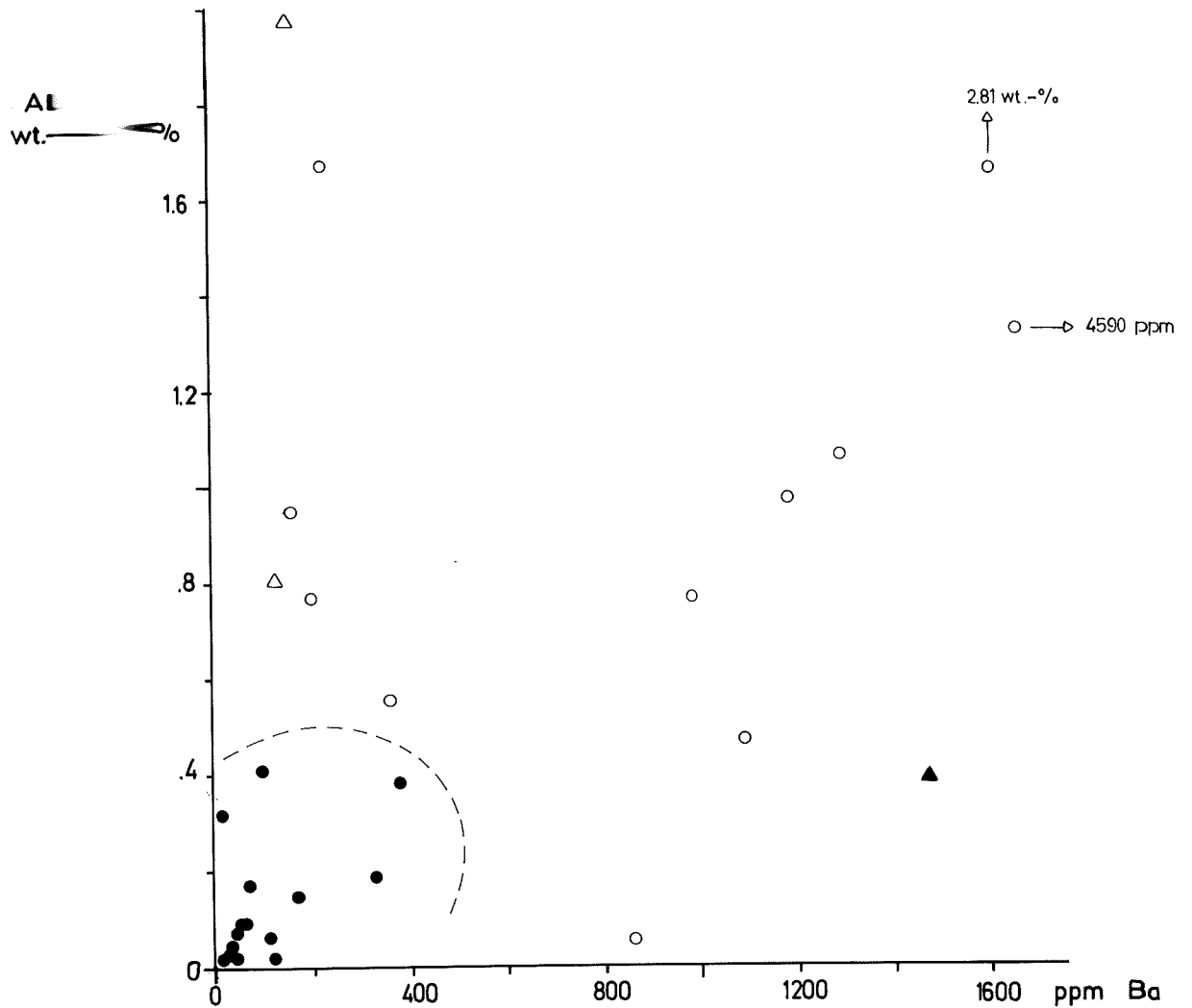


Figure 5: Al-Ba plot for quartzitic lithologies. Open circles represent the chemical banded iron formation (facies D and E), full circles are siliciclastic quartzarenites of the Lower and the Upper Quartzites (facies G and H). This plot is a useful geochemical tool to discriminate between these two quartzitic lithologies and a dividing line can be drawn. For reference, mean values for iron-oxide rich quartzites (full triangle) from Moore (1986) are given. Mean values of banded iron formations (data from Gross and McLeod, 1980) are given as open triangles.

zircon occur in accessory amounts. Roper (1959) described, with the aid of borehole core, a complete gradation from the iron formation into the hornblende and biotite schists. Lastly this facies is interpreted as a marl although a volcanogenic origin cannot entirely be ruled out.

FACIES SEQUENCES

Measured sections through the manganese formations and adjacent country-rocks have shown a correlatable vertical sequence in several mining areas, as shown in Figures 6 and 7. This is even more striking as the outcrops are located up to 15 km apart, not taking into account the palinspastic distance between depositional sites which has been considerably shortened by the intense folding.

A. Facies Cycles Associated with the Lower Ore Horizon

The Lower Ore Horizon was examined at three locations (Fig. 6) where the manganese ore is 4 to 6 m thick. At some locations a thickening might be due to tight folding of the strata, but the good correlation of facies in different mining areas shows that a major structural repetition of the primary sedimentological column is unlikely.

Pure orthoquartzites below the Lower Ore sequence (Fig. 6) grade into stratified quartzarenites which are overlain, with a sharp contrast, by the ore horizon itself. A three-part subdivision of the manganese formation can be observed: the manganese succession always starts with manganostones of facies B or A. Above this the sequence is made up mainly of feldspar-rich, hemi-pelagic ores. The manganiferous sandstones (facies C) represent an increase in terrigenous input prior to the second development of manganestone ores. Pure ores of type A are developed above, in contact with an impure banded iron formation composed of facies D rocks. This grades into a pure banded iron-formation (type E) and then back to the impure variety.

In Figures 6 and 7 the clastic input is indicated as qualitative offsets on the horizontal axis. The particular environments are characterized by the amount of terrigenous input and thus the cycle trends in these figures also indicate the transitions of more pelagic to more clastic environments of deposition and vice versa. Transitions from a clastic towards a more pelagic environment indicate transgressive conditions whereas gradually increasing terrigenous input is interpreted as a regression. The cycle of third order in the Lower Ore Horizon indicates a large-scale transgression which cut off terrigenous input and led to the deposition of Mn- and Fe-rich pelagic sediments. These large-scale cycles are confined to the overall basin evolution of the Damara trough discussed later.

Facies transitions observed in the Lower Ore Horizon and their contact relationships are outlined in Figure 8a. It becomes obvious that interfingering and gradational contacts are restricted to particular environments. In contrast, facies changes exhibit sharp geological contacts where a facies transition to a different subenvironment occurs. Several conclusions can be drawn from these transitions concerning the facies development of the Lower Ore Horizon:

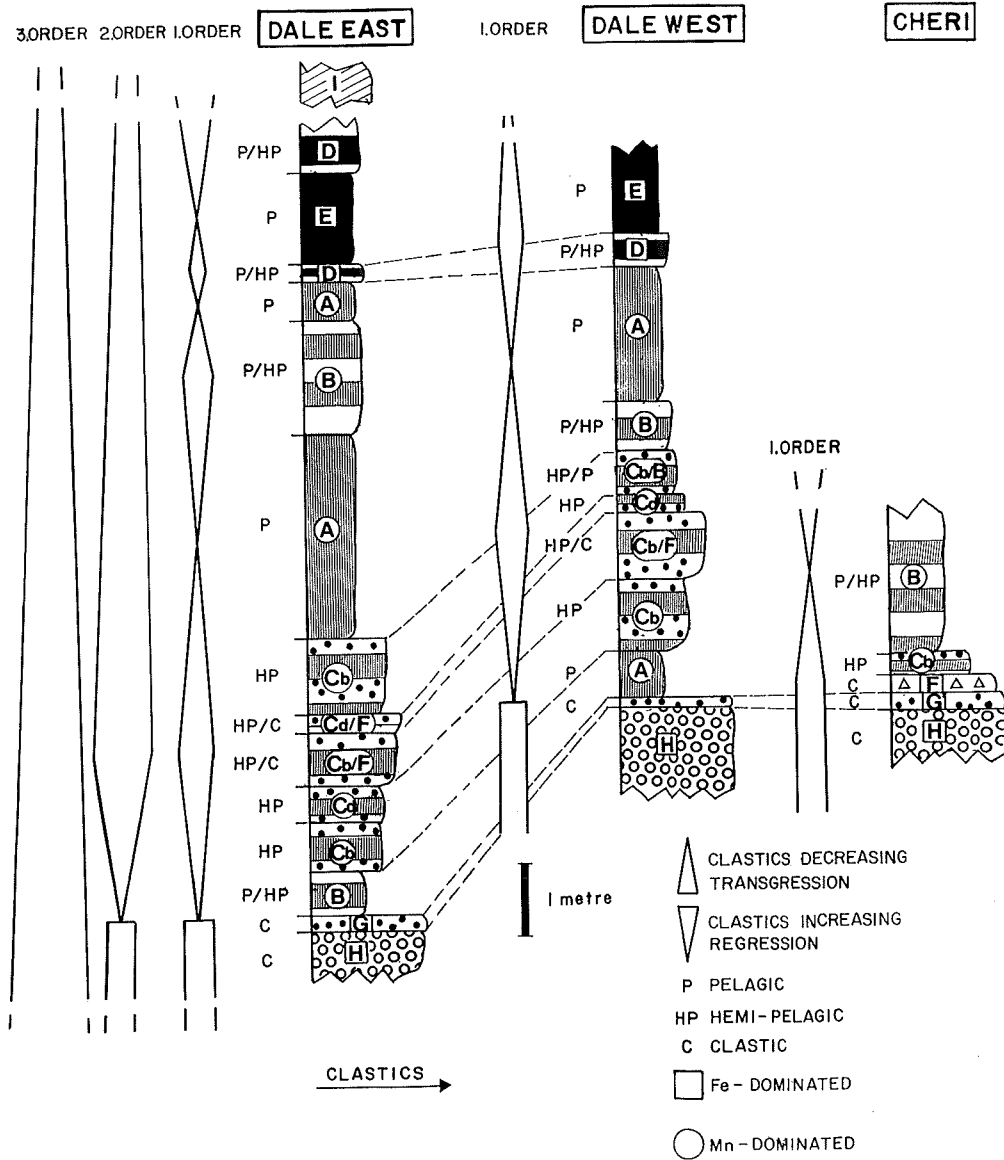


Figure 6: Facies cycles of the Lower Ore Horizon in various mine pits. The facies types outlined are explained in the text.

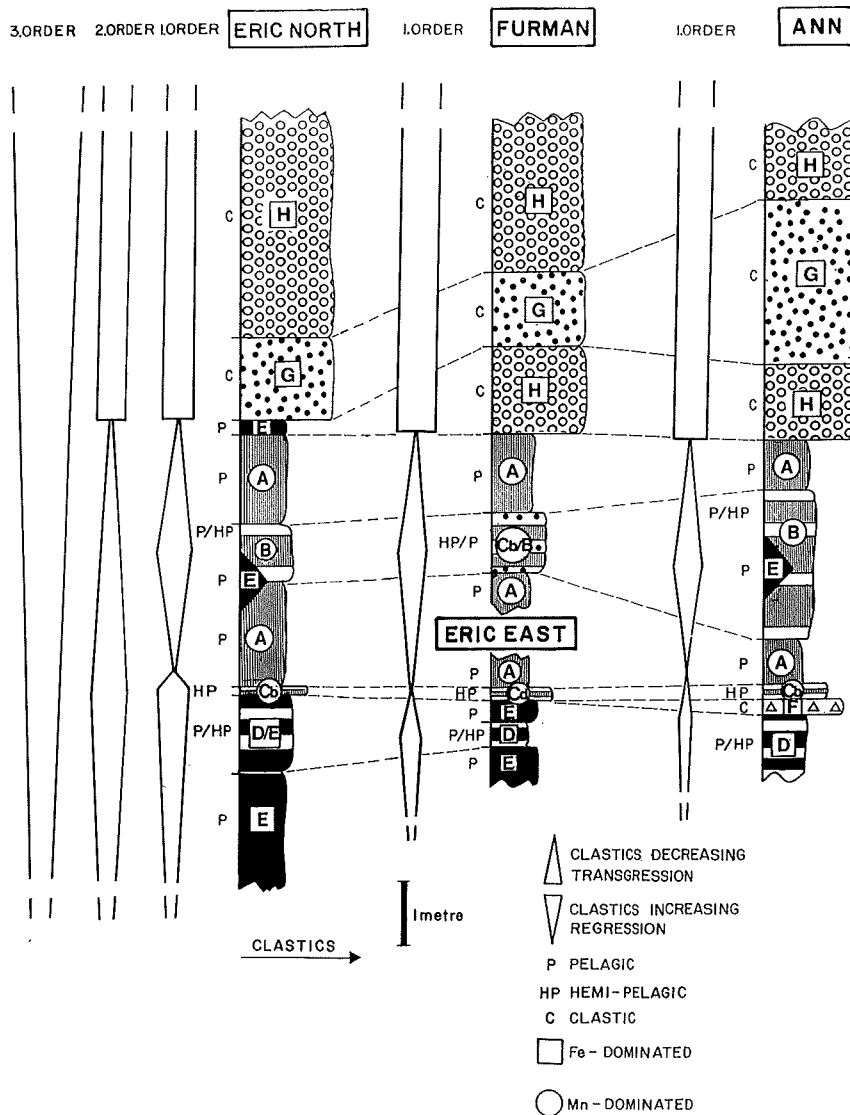


Figure 7: Facies cycles of the Upper Ore Horizon.

(1). the Mn-bearing hemi-pelagic and pelagic lithotypes exhibit interfingering or gradational contacts within the facies environments outlined as large boxes. Facies transitions often occur within the hemi-pelagic environment of feldspathic ores (type C).

(2). intra-facies changes are also indicated by gradational/interfingering contacts within the pelagic/hemi-pelagic Fe-rich chemical realm of facies D/E and the quartzarenites of facies G/H.

(3). sharp geological contacts always occur between the facies outlined as boxes;

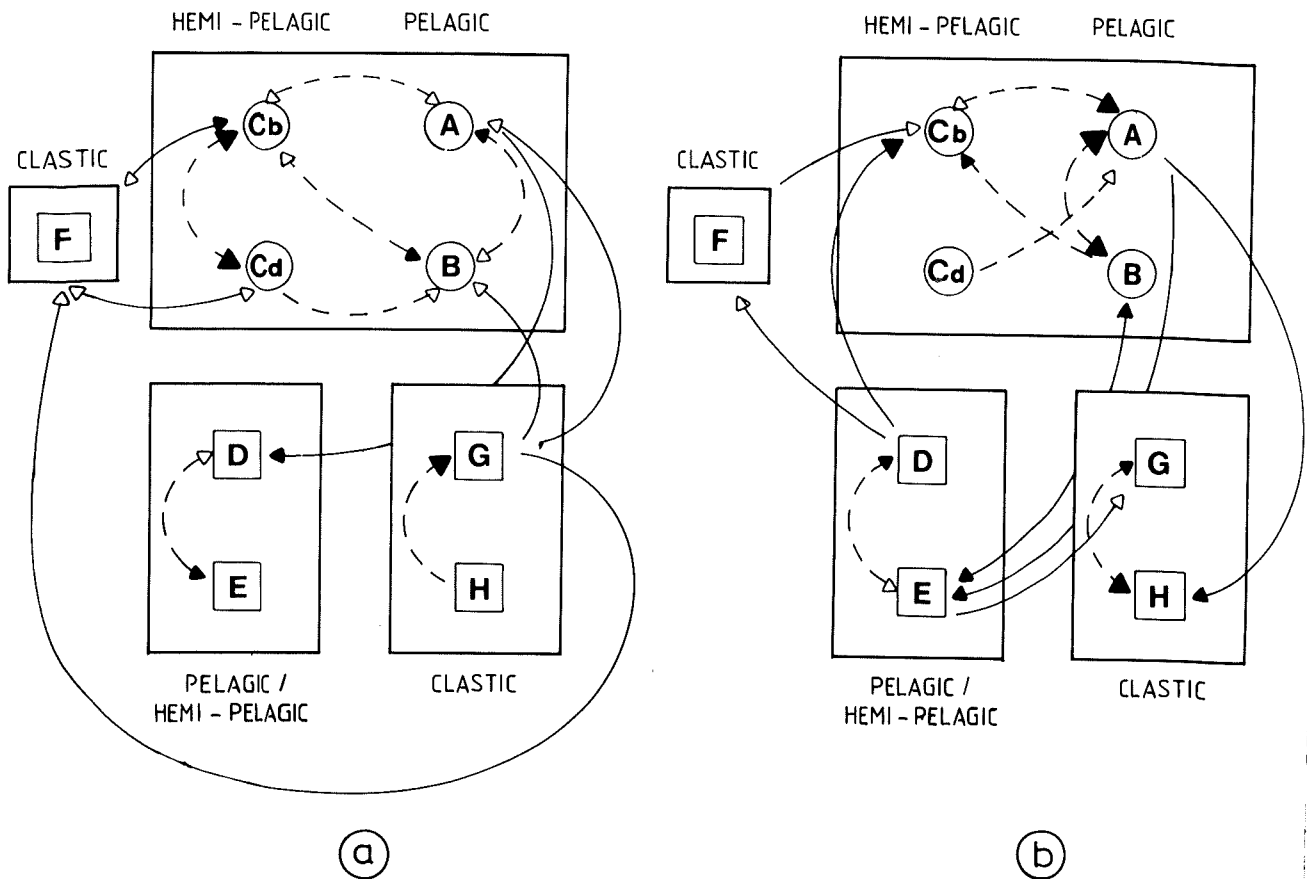


Figure 8: Facies transitions in (a) the Lower and (b) the Upper Ore Horizons and their country-rocks. Broken lines indicate gradational or interfingering contact relationships, solid lines represent sharp contacts. Environments within which gradational/interfingering facies transitions were recognized are marked as boxes. Δ, ▲, ▲ = number of facies transitions counted: 1, 2, 3.

(4). feldspathic ores of type C are intimately associated with pelagic manganostones, always exhibiting gradational contact relationships; and

(5) within the mature, clastic realm of the quartzarenites, the transitions always run from H- to G- type facies.

B. Facies Cycles Associated with the Upper Ore Horizon

An even better lateral correlation of the vertical facies development for first order cycles is recognized in the Upper Ore Horizon (Fig. 7). The mines examined are situated several kilometres apart (see Fig. 2 for location). Layers of pure ironstones (facies E) within hematite-feldspar-bearing quartzites (facies-type D) thin up towards the top: bed thicknesses from 10 to 20 cm and more decrease up to 2-3 cm near the overlying ore horizon in Eric North Mine. The manganese formation itself always lies directly on top of a thin layer of feldspathic ores. An A-B-A facies type succession overlying the banded ores is present in all

mining areas investigated. An approximately 1 m thick interlayer of pure quartzite in the central part of this succession can be observed in the Eric and Ann mining area. Quartzarenites, partly banded, which overly pure manganostones, represent the lower part of the Upper Quartzite unit. The quartzarenites become progressively less pure towards the top with the gradational development of very thin (< 1 mm) layers of muscovite and interspersed feldspar grains.

Concerning the facies transitions, the same observations can be made as in the Lower Ore Horizon. Again, interfingering and gradational contacts are only possible within the boxes indicated in Figure 8b. Intra-facies transitions occur mostly, however, within the pelagic realm of manganostones and transitions within this box run predominantly from feldspathic (type C) towards pure manganostones. In this case, the facies transitions within the quartzarenites extend mainly from stratified to massive quartzarenites. This implies the same relative position of facies G and H as in the Lower Ore Horizon, namely the more proximal position of facies G relative to facies H.

RECONSTRUCTION OF THE DEPOSITIONAL SETTING

Based on possible facies transitions between adjoining sedimentation regimes and their contact relationships, a spatial reconstruction of the depositional subenvironments is possible and is illustrated in Figure 9 for both ore horizons. The spatial reconstruction and the relative position of the environments has been formulated by employing the transgressive/regressive cycles (Figs. 6 and 7) which take into account the amount of clastic input. Within particular environments, however, the spatial reconstruction can be deduced directly using the facies transitions outlined in Figure 8. Using the quartzarenites, (interpreted as subtidal, near-shore, and high-energy level-sands) as a depositional reference point, the spatial reconstruction can be transformed as shown in Figure 9. This shows facies developments in their respective positions on a marine shelf, varying from shallow water sediments to deeper shelf pelagics. The interpretation for the Lower and the Upper Ore Horizon leads to the same palaeoreconstruction. Impure sandstones were deposited seaward from the pure quartzarenites. The manganese-rich pelagic facies occurs more proximal to the terrigenous source area and in chemical conditions of higher Eh values than the iron ores.

INTERPRETATION OF SEDIMENTARY CYCLES

The breakup of the Khomas Sea at the base of the Chuos Formation (Henry et al., 1990) resulted in a large-scale transgressive sequence unconformably overlying older formations across the Central Zone of the Damara Belt. This transgression is a response to the deflection of the lithosphere caused by sedimentary loading of the passive margin (Cloetingh, 1986) and the cooling of the lithosphere. At Otjosondou, this breakup unconformity (i.e. the base of the Chuos Formation) may be located at the base of the Lower Quartzite unit or, alternatively, at the base of the Lower Ore Horizon (Fig. 3). The writers follow Henry et al. (1988) in interpreting the lower unconformity (non-conformity) as the transgression associated with the breakup of the Proto South Atlantic (Adamastor Ocean of Hartnady et al., 1985) and the upper unconformity with the later breakup of the Khomas Sea.

Cycles of third order occur in the enlarged profiles of both ore horizons and indicate transgressive (Lower Ore Horizon, Fig. 6) as well as

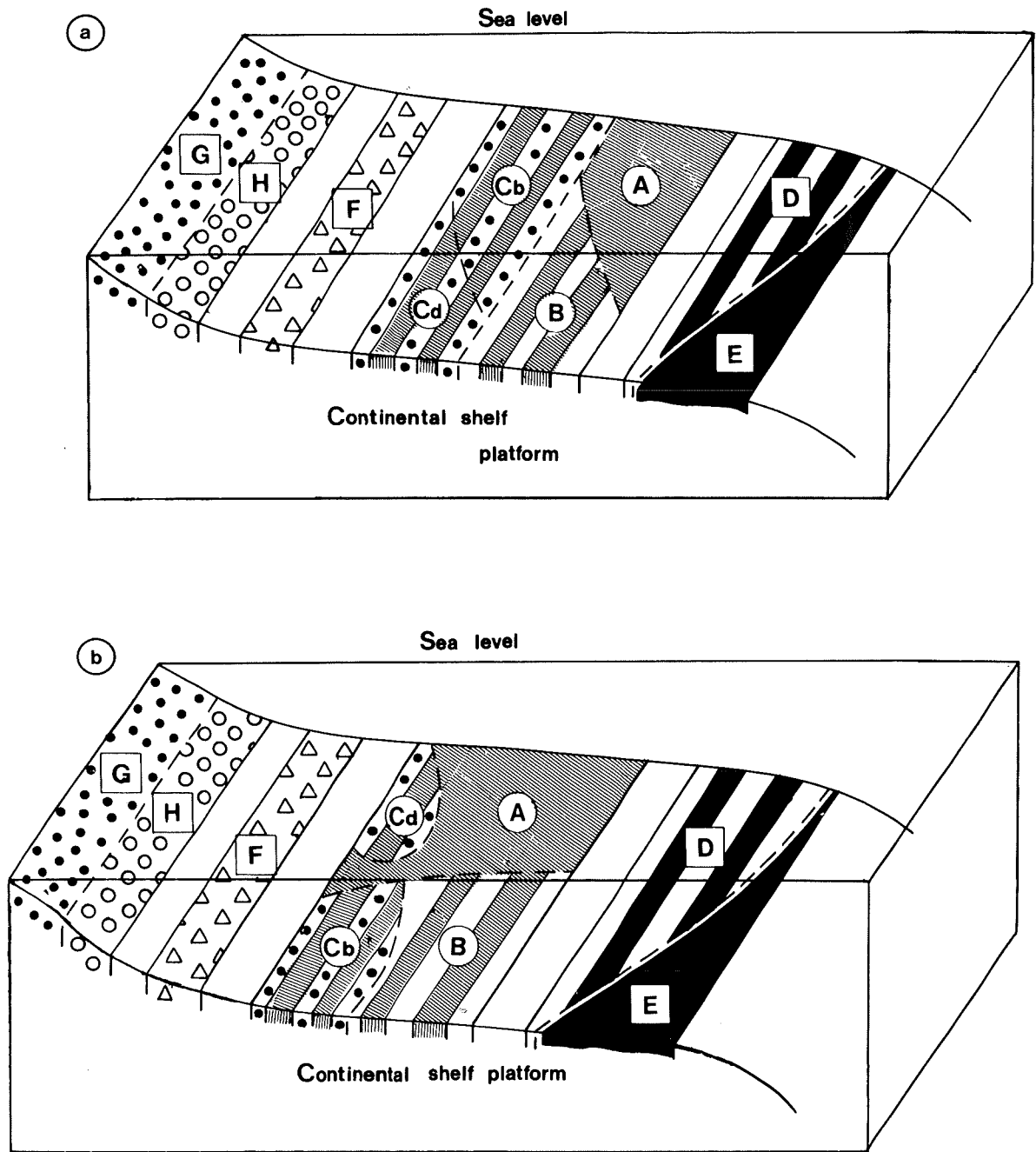


Figure 9: Facies distribution on a shelf platform and relative position of the facies environments distinguished for the Lower (a) and the Upper Ore Horizon (b). Broken lines indicate gradational/interfingering geological contacts, solid lines represent sharp contact relationships as outlined in Figure 7. The palaeogeographic reconstruction is similar for both ore horizons.

regressive (Upper Ore Horizon, Fig. 7) conditions during manganese precipitation. Although the manganese-formations are always related to the same country rocks, occurring between a pelagic banded iron-formation and clastic quartzarenites, there are contrasting cycle trends associated with manganese precipitation. This apparent contrast of transgressive and regressive conditions during manganese precipitation may be reconciled by the fact that comparable findings are also reported from the literature: transgressive conditions during manganese precipitation have been described by Cannon and Force (1983) and Force and Cannon (1988), whereas Frakes and Bolton (1984) and Bolton and Frakes (1985) preferred a regression model leading to the precipitation of manganese.

The sedimentary cycles of first order within the ore horizons of the Chuos Formation (Figs. 6 and 7) are interpreted as glaciogene influenced fluctuations in sea level. Interglacial transgressions are correlated with the deposition of pure manganostones whereas glacial episodes led to fine mud layers related to small-scale regressive cycles. These alternating glaciogenic fluctuations in sea level may be induced by climatic alternations at low latitude as suggested recently by Young (1990). The overall maximum transgression associated with the breakup of the Khomas Sea had produced a disequibrated shelf on which pelagic sedimentation prevailed (equivalent to a marine condensed sequence of Vail et al., 1977). Only glacial advances produced glacio-marine sedimentation which could bring terrigenous sediments directly into this otherwise starved environment.

DEPOSITIONAL MODEL

In continental run-off, transport of Mn in solution is not tenable in the Late Proterozoic due to the oxidizing environment which then prevailed (e.g. Borchert, 1980; Schneider, 1984). Thus, manganese-bearing solutions should have been generated exclusively in the marine environment (Borchert, 1978), i.e. by leaching from sediments or through volcano-genic-hydrothermal activity (cf. Kimberley, 1989b).

Protoliths bearing significant amounts of manganese do not occur in other areas close to the Otjosondú region: mostly siliceous granulitic basement-gneisses are overlain directly by pure quartzites and hematite-quartzites (Fig. 3). Consequently, the leaching of pre-existing sediments is unlikely. However, during deposition of the Chuos Formation, oceanic crust was developing in the Southern Zone of the Damara inland branch: the protolith of the Matchless Amphibolite Belt is interpreted as part of an oceanic crustal sequence (Kukla and Stanistreet, 1990) and can be traced for about 350 km along strike (compare Fig. 1). This, therefore, represents the most likely candidate for the source of the manganese supply for the Otjosondú shelf setting involving hydrothermal activity connected with the evolution of oceanic crust and the possible leaching of overlying sedimentary strata.

The tholeiitic Matchless Amphibolite is associated with economic base metal sulphide deposits (Killick, 1983; Breitskopf and Maiden, 1987; Klemd et al., 1989; Preussinger, 1989). The exhalative ore bodies occur in sediments overlying the volcanic sequence which also contain intercalated high pyrite-bearing graphitic schists (Fig. 10). The sulphides indicate the generation of metal-bearing solutions and represent the first sites to partition iron from manganese. In accordance with the above, the base metal deposits of the Damara basin are depleted in Mn in comparison with

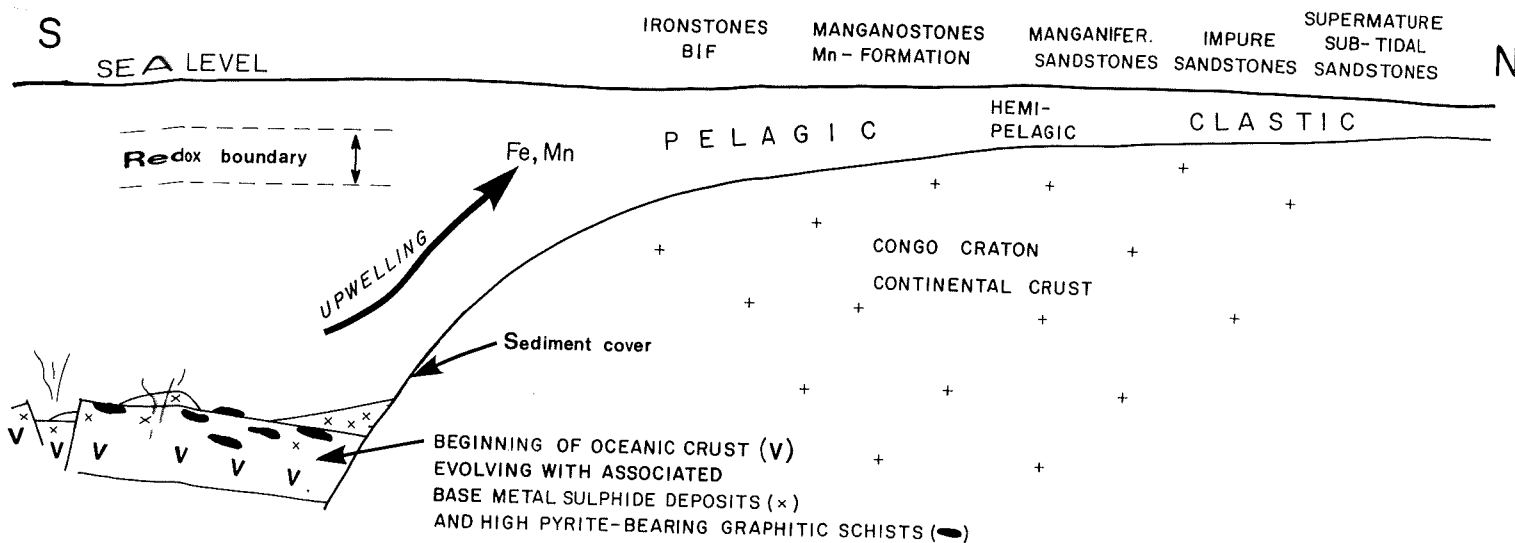


Figure 10: Suggested provenance of the ore-forming solutions deriving from hydrothermal vents developed in newly formed oceanic crust in the Khomas Trough to the south of the Otjosondu shelf platform. The hydrothermal activity was associated with the generation of base-metal sulphide deposits and the development of pyrite-bearing graphitic schists. This points to an early fractionation of Mn from Fe and other base-metals. Additional separation of Fe and Mn occurred in the shelf environment when iron was precipitated while Mn still remains in solution at high Eh values. A transgression due to thermal cooling and subsidence moved the redox interface onto the shallow shelf realm. The transgression cut off the terrigenous input and allowed precipitation of Mn and Fe in pelagic middle to outer shelf environments; upwelling may have occurred additionally.

other Besshi-type deposits (H. Häussinger, pers. comm.). A sea-level rise due to the breakup of the Khomas Sea raised the redox interface which then intersected the ocean floor on the shelf (Force and Cannon, 1988). Additionally, upwelling of solutions enriched in manganese along the shelf edge may be involved. Additional separation of Fe and Mn occurred on the stabilized shelf by the variations in Eh/pH conditions. Thus the accumulation mechanism involves both early separation of Mn and Fe as well as differential precipitation (cf. Kimberley, 1989b, p.118). The development of oceanic crust probably propagated from the SW to the NE (Fig. 11). The generation and separation of Fe and Mn may have occurred initially in the western regions of the Khomas Trough and the Mn-bearing solutions may have been transported laterally along the trough axis to the NE.

The Chuos equivalents of the Otjosondu ironstones in the western part of the Damara Basin are banded iron-formations deposited in shelf environments and associated with diamictites and metagreywackes (Henry et al., 1986). The banded iron-formations developed on both sides of the basin (Fig. 11), those on the south sides having been interpreted to be volcanogenic in origin (Breitkopf, 1988). Whereas Fe has been deposited at the shelf edges of the basin, Mn has been precipitated in suitable stable shelf environments under highly oxidizing shallow marine conditions.

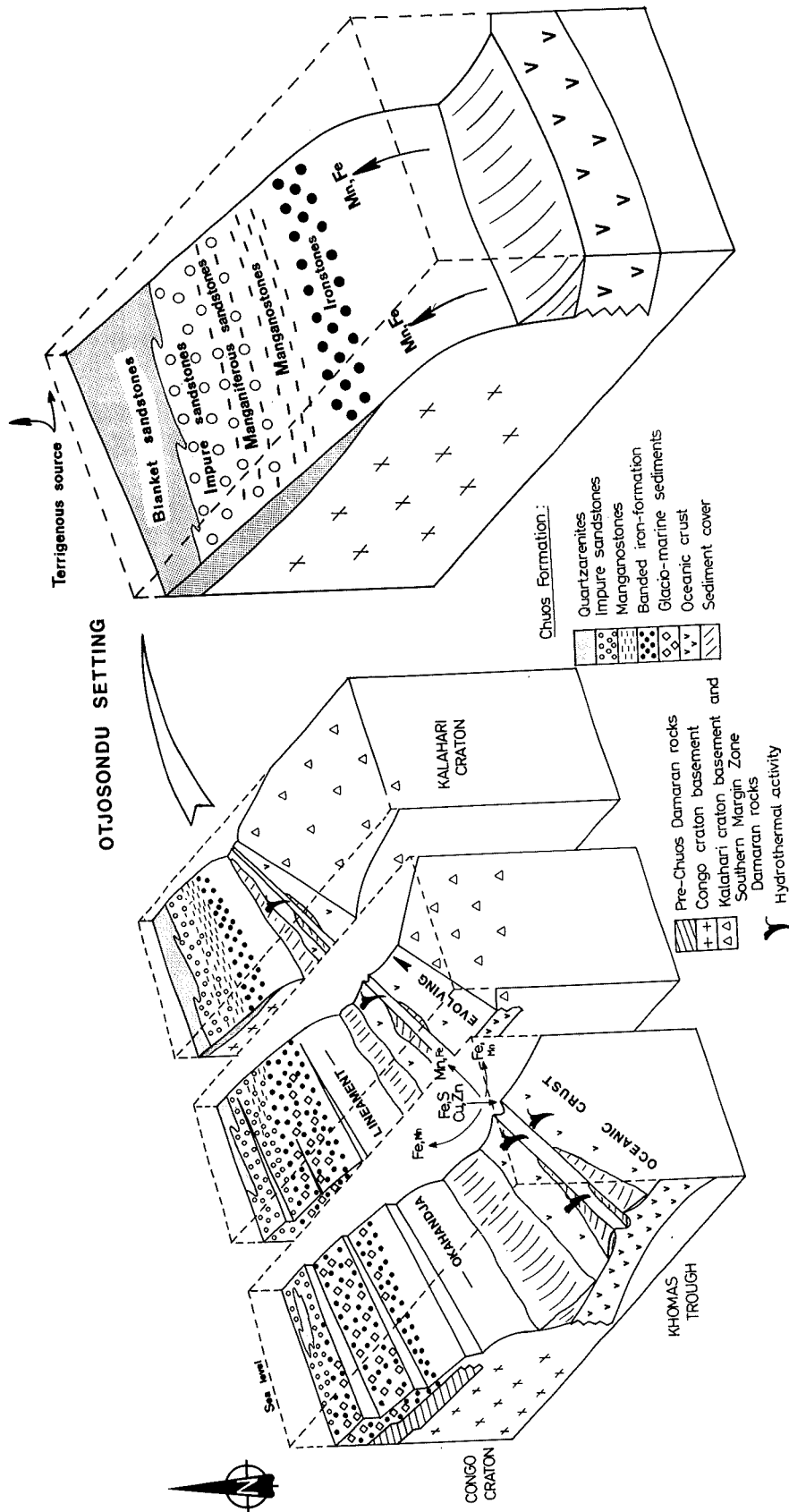


Figure 11: A genetic model for the Otjosundu manganese deposits in relation to the Late Proterozoic Damara in-land basin. See text for further explanations.

The transport of Mn in the marine environment is common. Martin and Knauer (1984) have shown that Mn may be transported by horizontal diffusive processes over several hundreds of kilometres towards environments of manganese undersaturation. Iron may be removed early along the way by precipitation as sulphides or iron silicates (Force and Cannon, 1988). The transport of Mn works well in stratified seas where more or less stable vertical conditions in the water column prevail and lateral transport is possible.

The model presented here implies that shallow marine manganese accumulations need not necessarily be associated with clearly identified volcanic rocks to deduce a volcanogenic origin of metal-enriched solutions. The source may be located elsewhere in the marine environment, e.g. in deeper parts of the basin. The depositional sites are then typically situated at some distance from the volcanogenic source (Roy, 1976). Rapid facies changes like those between chemically precipitated manganese ores and high-energy sands in Otjosondu may be characteristic for such distal ore deposits (Plimer, 1978). Typically enough, magmatism and ore-concentration may intimately relate to each other: the breakup of the Khomas Sea at the base of the Chuos Formation led to a predominantly basin-centred volcanism; this may account for the thermal cooling to develop mature shelf environments and admit the chemical sedimentation in tectonically stable shelf environments.

DISCUSSION

The reconstruction of the basin topography presented here is based on the observation that no serious distortions of primary facies patterns and their vertical evolution have occurred either by diagenetic mobilization of manganese or during the metamorphic overprint or by structural repetition. The latter can be ruled out to a large extent by comparison of vertical profiles from different mines which show a similar facies evolution through time. The fractionation of Mn and Fe in a metamorphic environment is very small and does not account for the accumulation of manganese in well-defined horizons (Wedepohl, 1980).

The Fe-Mn partitioning effect may, however, be significant in the diagenetic stage. Diagenetic mobilization of Mn requires a reducing environment to allow upward diffusion towards the sediment/water interface and later precipitation by oxidation, possibly favoured biochemically (Roy, 1980; Serdyuchenko, 1980). This reducing environment is normally provided by organic-rich detritus, often related to carbonate precipitation which is not the case at Otjosondu.

Furthermore, diagenetic separation of Mn and Fe would have influenced the relative Mn content of the ores, expressed by a deficiency of Fe and a resulting high Mn/Fe ratio (Roy, 1980). This does not hold true for the Otjosondu ore, since high Fe-bearing Mn phases and hematite are present and the Fe content is very variable within the ore horizons. The Mn/Fe ratio in A and B type ores ranges from ,3 up to 14,5. Thus, the organic-poor environment and low Mn/Fe ratios show that no drastic modifications must be assumed during diagenesis of the Otjosondu ores and that sedimentary facies types have been preserved.

A stratigraphic situation at or above unconformities is typical of Proterozoic shallow-marine Mn-deposits which represent the most important source of continent-based manganese ores (Laznicka, 1985). The unit above the unconformity to the pre-Damara basement at Otjosondu

consists of supermature quartzarenites. Pettijohn et al. (1987) have pointed out that this facies often occurs in the late Precambrian and the early Palaeozoic. They suggested that this is due to wide, stable shelf platforms developed during these times in contrast with modern shelf environments.

A large number of offshore sandstone bodies are recorded during the Late Precambrian opening of the Iapetus ocean (Anderton, 1976; Levell, 1980; Johnson and Baldwin, 1986). The resulting laterally extensive supermature quartzarenites reach purities of up to 99.5 wt.-% SiO_2 (Pettijohn et al., 1987) and record the advance of a transgressive shoreline. Well-sorted sandstones have been reported by Simonson (1984) to occur mostly below Proterozoic iron-formations. Early Palaeozoic transgressive quartzarenites are reported for example from Arizona (Hereford, 1977) and the Cape Province (Hobday and Tankard, 1978). In the latter example the thick mature sandstone bodies also occur as transgressive sequences above unconformities over the Precambrian basement. The interaction of tide- and storm-dominated processes on a slowly subsiding shelf produces maximum sediment transport and resulting high purities of the quartzarenites (Johnson and Baldwin, 1986; Hereford, 1977). This substantial sediment supply is related to conditions of rising sea level (Bridges, 1976; Hobday and Tankard, 1978), an observation which correlates well with the opinion of Force and Cannon (1988) who saw a direct interdependence between high sea level stands and manganese accumulation in shelf environments.

CONCLUSIONS

The following conclusions can be drawn concerning the palaeogeography and the source of the ore-bearing solutions which produced the Otjosondou manganese deposits.

1. The sedimentary manganese ores of Otjosondou have been deposited in a shallow shelf environment together, and intercalated with, a banded iron-formation. The ore-bearing sequence is sandwiched between supermature quartzarenites of which the lowermost unit lies above an unconformity to the basement. The quartzarenites indicate a transgression onto Precambrian basement rocks and derived their detritus from a stable craton.
1. The manganese ores are associated with a major transgression related to the oceanic crustal spreading of the Khomas Sea. The Mn-bearing solutions are deduced to have been derived from deeper parts of the associated Khomas basin. The evolving tholeiitic oceanic crust and associated hydrothermal activity provided a source for the Mn-bearing solutions.
3. Separation of iron from manganese occurred near to the exhalative vent by precipitation of iron-bearing base metal sulphides and pyritic schists. Lateral transport of Mn may have occurred and the solutions appear to have been precipitated during transgressive and regressive cycles. Upwelling along the continental shelf edge may have provided an additional component to the transport of the solutions onto the shelf.
4. Glacial/interglacial episodes and resultant fluctuations in sea level account for the amount of terrigenous input into a predominantly pelagic regime; it furthermore influences the location of the redox interface and thus the Mn/Fe ratio in the sediment.

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