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Sn–W metallogeny in the Damara orogen, South West Africa/Namibia

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The geodynamic evolution of the late-Proterozoic Pan African Damara orogen was accompanied by magmatic activity of essentially granitic character. Broad swarms of zoned and unzoned pegmatites with contained U, Sn, and rare-metal deposits are associated with the late- to post-tectonic stages of granite intrusion. Later, during the Jurassic and Cretaceous, widespread magmatic activity occurred in response to processes of rifting and the break-up of Gondwana. Magmatic products of this period include predominant mafic extrusives and intrusives of the Karoo Sequence and late- to post-Karoo, within-plate, anorogenic, ring-type alkali complexes. In some areas Sn–W greisen-type mineralization can be directly linked with this activity. The numerous granite-related Sn–W deposits in the Damara orogen can be assigned to a Northern Group (Brandberg West–Goantagab area), a central group (Strathmore–Uis and Neneis–Kohero belts), and a Southern Group (Karibib–Erongo area). The deposits are classified as (a) hydrothermal quartz veins and Fe-rich replacement bodies in metasediments, and as concentrations in (b) pegmatites and (c) greisen rocks. The mineralization generally post-dates the strain fabrics of Damara age. In the Brandberg West–Goantagab area the hydrothermal quartz-vein and replacement deposits are associated with circular structures. These are interpreted as the surface expressions of intense degassing from deep magmatic centres, with associated Sn–W deposition. The Central Group pegmatites are mainly unzoned and they become stanniferous where greisenized. In the Southern Group the Sn and/or W mineralization hosted in zoned pegmatites is confined to an area close to the late- to post-Karoo Erongo Complex. The W-bearing greisens of the Karibib–Erongo area are related to a B-rich granitic phase of the Erongo Complex. The Sn–W metallogeny of the Damara orogen appears to be the result of two separate magmatic events. Initially, Damara-aged magmatism produced mineralized pegmatites. Much later, during the Mesozoic late- to post-Karoo magmatism produced hydrothermal and greisen deposits. The metallogeny has striking similarities to that of the Nigerian Province, where Pan-African magmatism resulted in the emplacement of 'older' granites and pegmatites and where later anorogenic magmatism gave rise to ring complexes and greisen mineralization.

Die geodinamiese evolusie van die laat-Proterosoïese Pan-Afrikaanse Damara-orogeen het gepaard gegaan met magmatiese aktiwiteit van 'n essensieel granitiese aard. Breë swerms gesoneerde en ongesoneerde pegmatiete wat U, Sn, en seldsame-metaalneerslae bevat, is met die laat- tot na-tektoniese stadiums van granietintrusie geassosieer. Later, tydens die Jura en Kryt, het wydverspreide magmatiese aktiwiteit as gevolg van skeuring en die opbreek van Gondwana plaasgevind. Magmatiese produkte van hierdie periode sluit oorheersende mafiese ekstrusiewe en intrusiewe gesteentes van die Opeenvolging Karoo en laat- tot na-Karoose, binneplaatse, anorogeniese, ringtipe alkalikomplekse in. In sommige gebiede kan Sn–W-mineralisasie van die greisentipe direk aan hierdie aktiwiteit gekoppel word. Die groot aantal graniet verwante Sn–W-afsettings in die Damara-orogeen kan ingedeel word in 'n Noordelike Groep (Brandberg-Wes-Goantagabgebied), 'n Sentrale Groep (Strathmore-Uis- en Neneis-Koherogordels) en 'n Suidelike Groep (Karibib-Erongogebied). Die neerslae word geklassifiseer as (a) hidrotermale kwartsare en Fe-ryk vervangingsliggame in metasedimente, en as konsentrasies in (b) pegmatiete en (c) greisengesteentes. Die mineralisasie is oor die algemeen jonger as die vervormingsmaaksels van Damara-ouderdom. In die Brandberg-Wes-Goantagabgebied is die hidrotermale kwartsaar- en vervangingsneerslae geassosieer met ringstrukture wat geïnterpreteer word as die oppervlaktemanifestasies van intense ontgassing vanuit diep magmatiese sentrums, met geassosieerde Sn–W-neerslag. Die pegmatiete van die Sentrale Groep is hoofsaaklik ongesoneer en hulle word tinhoudend waar hulle gegreiseneer is. In die Suidelike Groep word die Sn- en/of W-mineralisasie wat voorkom in gesoneerde pegmatiete slegs in 'n gebied na aan die laat- tot na-Karoose Kompleks Erongo aangetref. Die W-draende greisens van die Karibib-Erongogebied is verwant aan 'n B-ryk granitiese fase van die Kompleks Erongo. Die Sn–W-metallogenie van die Damara-orogeen skyn die resultaat van twee afsonderlike magmatiese gebeurtenisse te wees. Aanvanklik het magmatisme van Damara-ouderdom gemineraliseerde pegmatiete gelewer. Veel later, tydens die Mesosoïese laat- tot na-Karoo, het magmatisme hidrotermale en greisenneerslae gelewer. Die metallogenie het treffende ooreenkomste met dié van die Nigeriese Provinsie, waar Pan-Afrikaanse magmatisme geresulteer het in die inplasing van 'ouer' graniete en pegmatiete, en waar latere anorogeniese magmatisme ringkomplekse en greisenmineralisasie tot gevolg gehad het.

The Damara orogen

The geodynamic evolution of the Damara orogen, its magmatism, and an overview of general metallogeny are considered in this introductory section. The Damara orogen is one of the late-Proterozoic Pan-African orogenic belts (Figure 1). It lies partly between the Congo and Kalahari cratons, and it comprises a northeast-trending intracontinental arm, about 400 km wide, and two coastal arms (northern and southern). The meeting point of the three arms is considered to be a triple junction from which South America and Southern Africa separated, leading to the break up of a late-Proterozoic supercontinent between 625 and 555 Ma ago (Bond *et al.*, 1984; Miller, 1983a).

Various aspects of the geodynamic evolution, general geology, structure, metamorphism, isotope systematics, and geochemistry of the orogen are discussed and reviewed in a large number of publications. In particular the interested reader is referred to Martin & Porada (1977), Hartnady (1978), Porada (1979), Miller (1979; 1980), Barnes & Sawyer (1980), Mason (1981), Miller & Hoffman (1981), Kröner (1982), Tankard *et al.* (1982), Coward (1983), Martin (1983a; 1983b), Porada (1979, 1983, 1985), Hartmann *et al.* (1983), Hartnady *et al.* (1985). Special Publication No. 11 of the Geological Society of South Africa (Miller, 1983a), includes a wealth of contributions dealing with the Damara orogen.

On the basis of structural, tectonic, and metamorphic patterns, stratigraphy, geochronological, and geomagnetic data, the Damara orogen is subdivided into

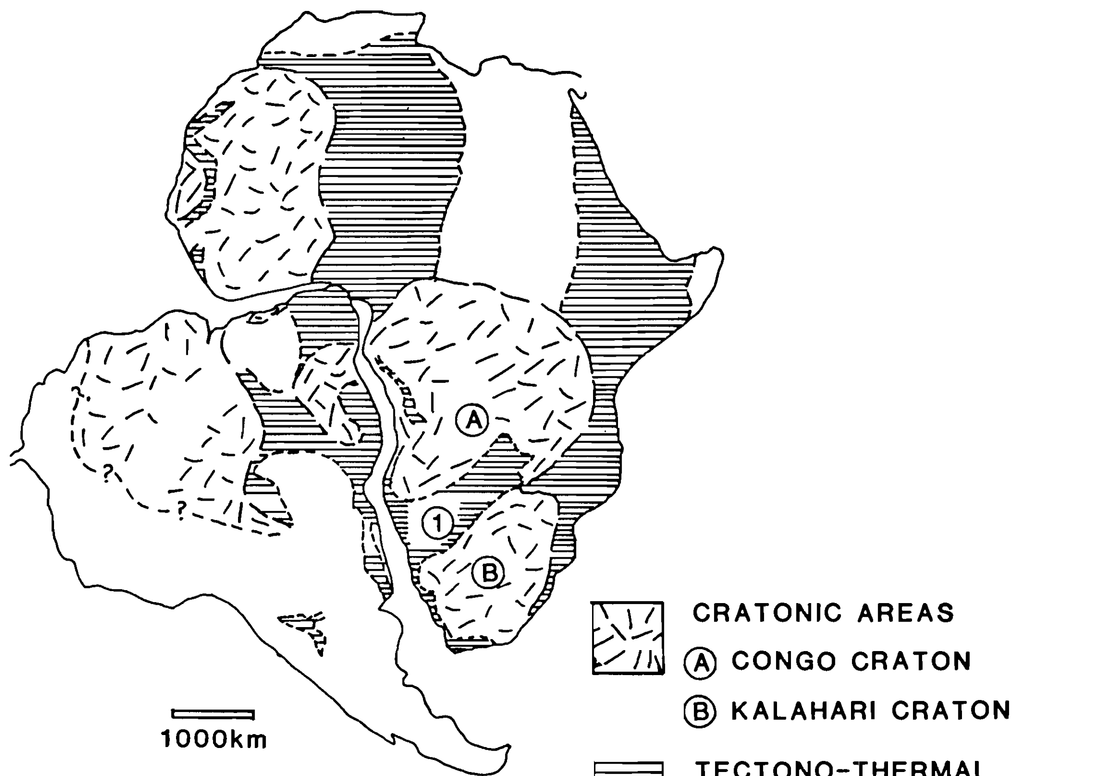

Figure 1 The Damara orogen in relation to other Pan African belts, on a Gondwana re-assembly (adapted from Porada, 1979).

a number of tectono-stratigraphic zones (see Figure 3, Miller, 1983c). Pertinent to this work are the Southern Kaoko Zone (SKZ) in the northern coastal branch, and the Northern Zone (NZ), the Central Zone (CZ), and the Okahandja Lineament Zone (OLZ) in the intracontinental branch.

Several models have been proposed to explain the evolution of the Damara orogen. In essence these comprise:

a) aulacogen and delamination models in which some form of limited continental subduction is envisaged (Martin & Porada, 1977; Kröner, 1977a, 1977b; 1982), and
b) models involving oceanic floor spreading and subduction, ranging from opening and closure of a narrow ocean (limited Wilson-cycle), to opening and closure of a wide ocean (Kasch, 1979; 1980; 1983; Barnes & Sawyer, 1980; Hartnady *et al.*, 1985).

The last movements to affect the Damara orogen are linked with the fragmentation of Gondwana during the Mesozoic, when the western continental margin of southern Africa was formed by tensional rift faulting (Tankard *et al.*, 1982). The separation of southern Africa from South America resulted in the re-activation of pre-existing northeast-trending lineaments (Marsh, 1973), with the formation of incipient graben structures. Although little publicised, these tectonic disturbances appear to be of importance, not only because they may be related to the emplacement of the anorogenic igneous complexes, but also because they may have provided active channels for the metasomatic and mineralizing fluids discussed in this work.

Magmatism played a major role in the geological history of the Damara orogen, and was directly linked with the Sn–W metallogeny discussed in this paper. By far the most voluminous period of magma generation and emplacement was related to the tectonic events that shaped the orogen between 1000 and 500 Ma ago. A second and less voluminous period of magmatic activity is related to the fragmentation of Gondwana between 190 and 120 Ma ago and is manifested by Karoo and late- to post-Karoo extrusive and intrusive activity. The distribution of Damaran, Karoo, and late- to post-Karoo igneous rocks is schematically shown in Figure 2, A and B.

The Damara granitoids occupy some 74 000 km^2 with over 200 syn- to post-tectonic plutons ranging in composition from gabbro to granite within the CZ, NZ, and OLZ (Miller, 1983c). Based on isotopic, geochemical, and field evidence the emplacement history of the Damara granites can be summarized as follows (Jacob, 1978; Winkler, 1983; Haack *et al.*, 1983; Miller, 1983c):

a) 650–540 Ma: Gabbro, diorite and tonalite of I-type affinity were generated during the subduction phases of the Damaran geodynamic development. These were followed between 580 and 550 Ma by the emplacement of syn- to late-tectonic biotite-bearing granitoid suites (Salem-type).
b) 540–450 Ma: Continental collision and post-collision activity produced a range of granitoids with S-type affinities (e.g. Red Granite, alaskites, Donkerhoek batholith) including 2-mica granites. In general, the overall predominance of granites with S-type affinities has been taken to suggest a Hercynotype orogenic process and hence collision-related magmatogenesis (Miller, 1983c).

Rocks of the Karoo Sequence occupy small areas in the CZ and along the junction between the CZ and the northern coastal branch (Etendeka Plateau) (Figure 2, A,B). The oldest Karoo intrusives are dykes and sills along the coast, dated at 161–199 Ma. Other dolerite dykes have ages of 126–146 Ma and the Etendeka lavas are 110–124 Ma old. A number of sub-volcanic and plutonic anorogenic ring-type complexes were emplaced along northeast trends between 125 and 135 Ma ago (Figure 2, B). These trends appear to represent transform fault directions in the South Atlantic (Figure 2, C) (Marsh, 1973). The complexes have been investigated by Gevers & Frommurze (1929), Mathias (1956; 1957), Korn & Martin (1954), Martin *et al.* (1960), Simpson (1954), Siedner (1965), Verwoerd (1967), Siedner & Miller (1968), Hodgson (1973), Hodgson & Botha (1974), Prins (1981), and Blümel *et al.* (1979).

Following Prins (1981), these ring complexes can be grouped as follows:

a) Granitic-types (Brandberg, Erongo, Gross, and Klein Spitzkoppe)
b) Differentiated basic complexes (Cape Cross, Doros, Messum, and Okenyenya)

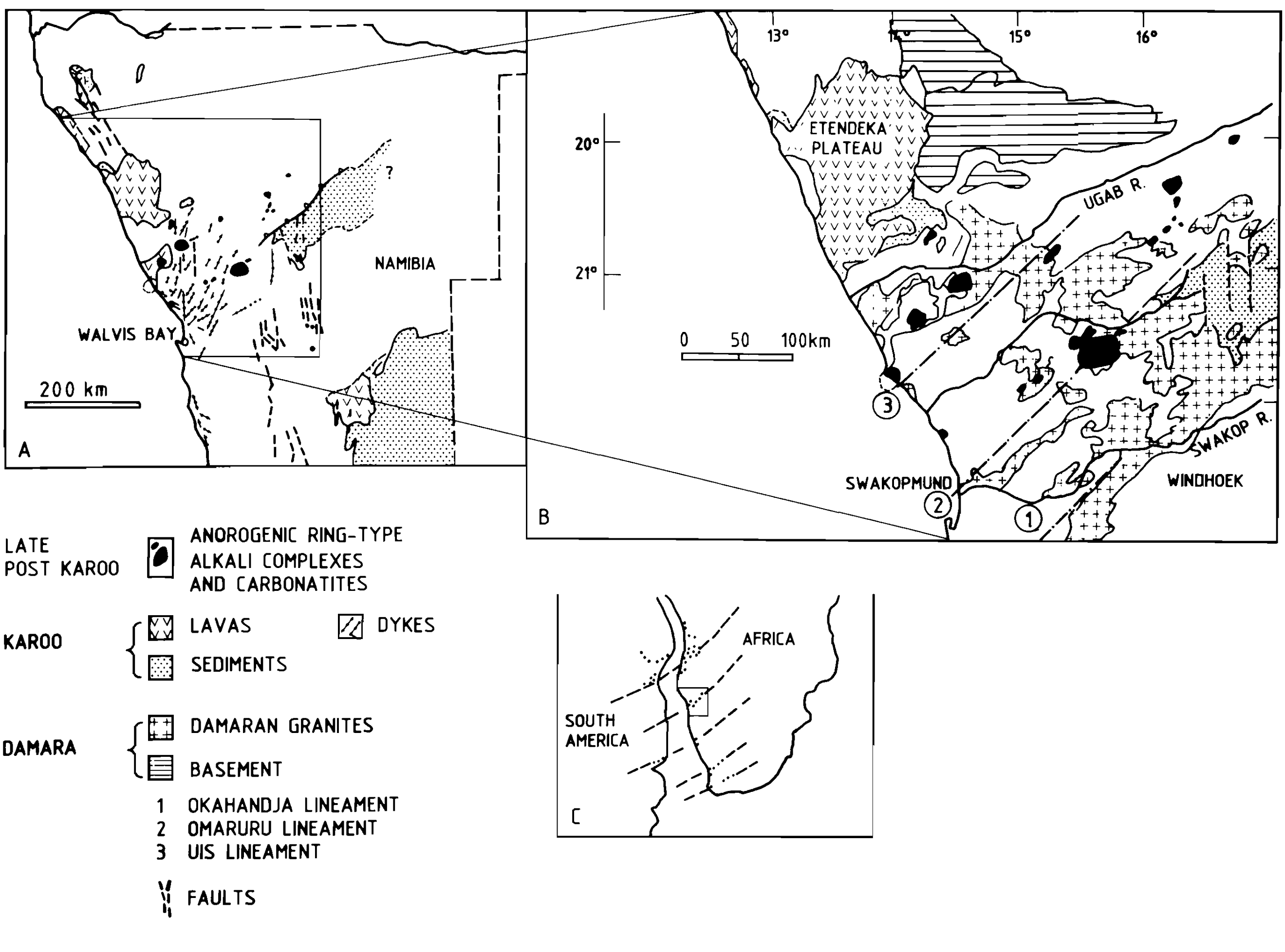

Figure 2 **A.** Distribution of Karoo-age lavas, sediment, and dykes in central-north South West Africa/Namibia (adapted from Korn & Martin, 1954). **B.** Distribution of Karoo, post-Karoo, and Damaran igneous rocks in the northern coastal arm and intracontinental branch of the Damara orogen (adapted from Siedner & Mitchell, 1976; lineaments are from Corner, 1983). **C.** Schematic distribution of alkali complexes along transform directions in Africa and South America (Marsh, 1973).

c) Peralkaline complexes
d) Carbonatite complexes

Relevant to the present work are the granitic types. The Erongo Complex in the Karibib area forms a central caldera structure consisting of lavas (mafic to felsic), and pyroclastic products. The structure is believed to have formed by a mechanism of cauldron subsidence, following which granitic rocks were passively emplaced in the space provided by the subsidence. The Brandberg circular granitic stock probably formed through a similar mechanism of cauldron subsidence, but in this instance most of the volcanic superstructure has been eroded off.

There are a multitude of mineral deposits and occurrences in the Damara orogen. Overviews of the metallogeny have been given by Martin (1978) and Miller (1983b), whose basic schemes have been followed in this introduction.

During the pre-orogenic phase of rifting, mineral deposits were formed around rift-controlled margins (evaporitic types and acid volcanogenic types), in continental shelves (Pb, Zn, V). and in deep troughs (sulphide deposits associated with mafic volcanic rocks and turbiditic sediments). W (scheelite) mineralization is present in calc-silicate layers and is possibly of exhalative origin (Scoon, pers. comm., 1986). At the time of writing very little is known about this type of mineralization, which is currently being investigated by the Geological Survey in Windhoek.

Mineral deposits formed during the orogenic magmatic phase are genetically related to episodes of metamorphism and igneous activity. A large number of pegmatites were emplaced during and after deformation, at deep to shallow stratigraphic levels (see Miller, 1983b). These include uraniferous alaskites derived from anatexis of crustal material (Hawkesworth *et al.*, 1983; Von Backström & Jacob, 1979; Miller, 1983b) and pegmatites, containing Sn, Li, Ta, and Be, derived through fractional crystallization of Damaran calc-alkaline granitic plutons (Miller, 1983b).

Hydrothermal Au-bearing quartz veins and Pb-Zn and Cu mineralization on thrust planes are ascribed to deposition from ore-bearing brines formed by dewatering processes during prograde metamorphism of Swakop Group sediments (Miller, 1983b).

Other mineral deposits localized within the Central Zone, Northern Zone, and Southern Kaoko Zone are hydrothermal quartz veins with Cu–Au and Sn–W mineralization.

After the Damara orogeny, the next recorded thermo-tectonic events occurred in response to the break-up of Gondwana. Greisen-type W mineralization is related to the granitic magmatism, and, as proposed later, there is evidence that some of the Sn–W mineralization may also be related to late- to post-Karoo magmatism.

In this paper an attempt is made to assess and characterize the 'granite-related' Sn–W metallogeny in the Northern, Central, and Southern Kaoko Zones of the Damara orogen, and to put forward a unified model of ore genesis. This work is based on field relations, structural, mineralogical, and petrological studies, and is augmented by data gained from the existing literature.

Sn–W mineralization

Numerous Sn and Sn–W deposits, mostly uneconomic, occur in the NZ, CZ, and SKZ. Figure 3 shows the distribution of the 'granite-related' Sn and Sn–W deposits, in which we do not include the W (scheelite) deposits hosted in calc-silicate rocks.

In Figure 3 three major groups are distinguished:

a) Northern Group (Brandberg West–Goantagab area): north and northwest of the Brandberg alkaline granite intrusion are a number of Sn–W and Sn deposits in hydrothermal veins and Fe-rich replacement bodies hosted in metasediments, and a number of Sn-bearing pegmatite occurrences (Ousis pegmatites).
b) Central Group: This comprises the northeast-trending Strathmore–Uis belt, and the east-west trending Neneis–Kohero belt, both containing unzoned Sn + Ta bearing, syn- to post-tectonic pegmatites.
c) Southern Group (Erongo–Karibib area): This includes a number of W dominated greisen deposits, and Sn ± Ta ± W in zoned pegmatites.

In almost all cases the mineralization is associated with greisenization (quartz ± muscovite), and albitization. Metasediment-hosted vein and replacement type mineralization in the Northern Group is possibly related to proximal and distal emanations from underlying highly differentiated magmatic centres. Albitization and greisenization in the stanniferous pegmatites are later than the emplacement of the pegmatites. The W dominated greisen deposits in the Southern Group are spatially and genetically related to the Erongo Granite.

Sn–W and Sn deposits in quartz veins and Fe-rich replacement bodies hosted in metasediments

The Brandberg West–Goantagab area (Northern Group) extends for some 75–80 km in an east-northeast direction in the lower Ugab River region and northwest of the Brandberg alkaline granite intrusion. This area is part of the SKZ and is underlain by turbidite facies metasediments and intercalated thin marble bands, which are correlatives of the Khomas Subgroup formations (Miller *et al.*, 1983).

Mineralization is characterized by a number of Sn–W, and Sn (± minor Ag and base metals) deposits in quartz-vein systems and Fe-rich replacement bodies. These mineralized systems clearly post-date Damara-age fabrics in the host rocks. Circular structures, visible on LANDSAT imagery, are present in this area. These structures are associated with quartz veins and, in places, breccias and thermally metamorphosed schists, all of which overprint Damara-age fabrics. At least 8 out of 16 mineral occurrences and deposits are located within or along the margins of the structures. The circular structures are interpreted as resulting from degassing of igneous intrusions at depth.

The simplified geology of the Brandberg West–Goantagab area, and distribution of deposits and circular structures are shown in Figure 4. Investigations carried out to date on four key deposits (Brandberg West, Frans, Gamigab, and Goantagab) indicate that

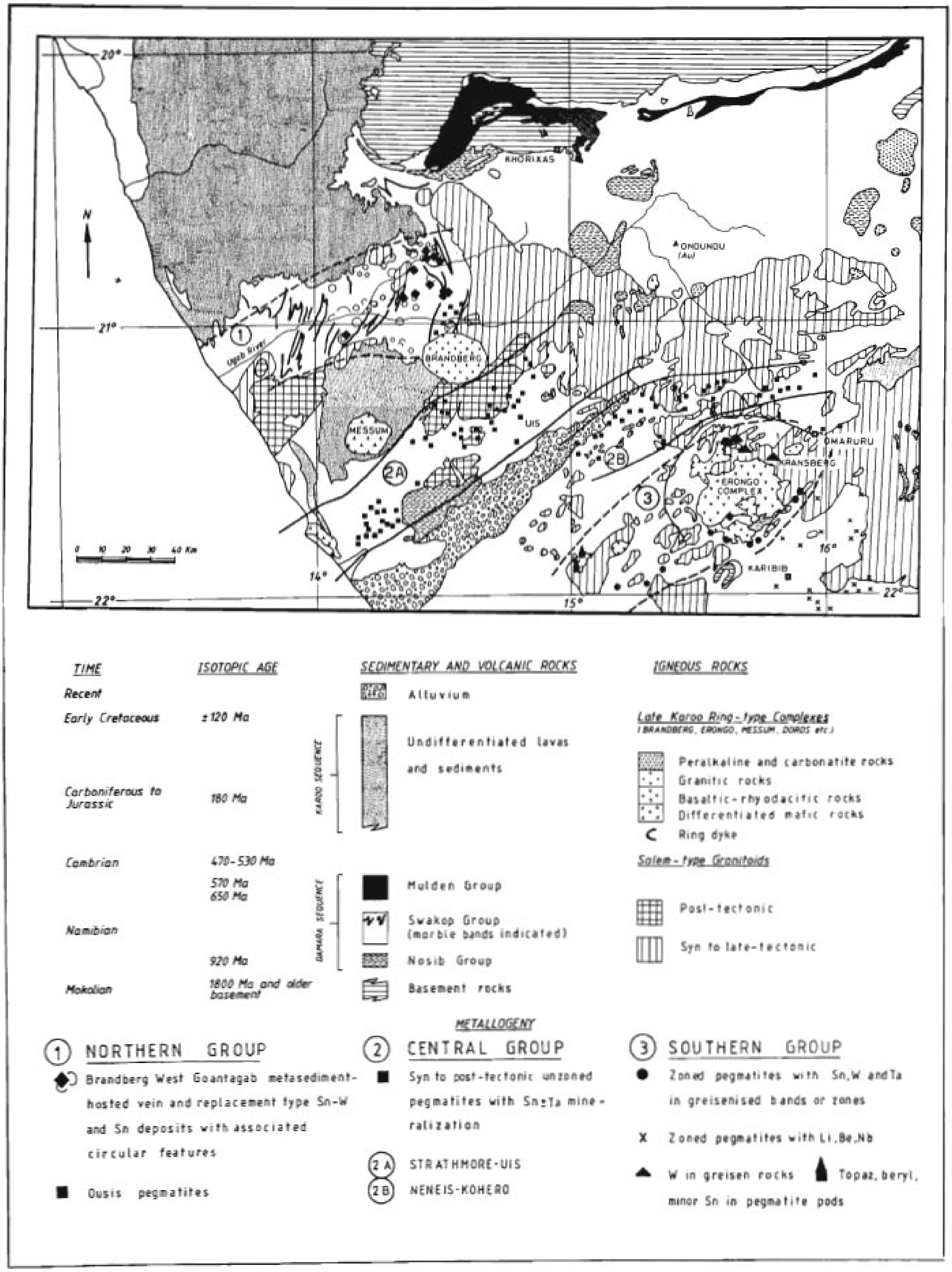

Figure 3 Distribution of Sn, Sn–W and W greisen-related deposits in the north-central parts of the Damara orogen (geology taken from Geological Map of South West Africa/Namibia, scale 1:1 000 000).

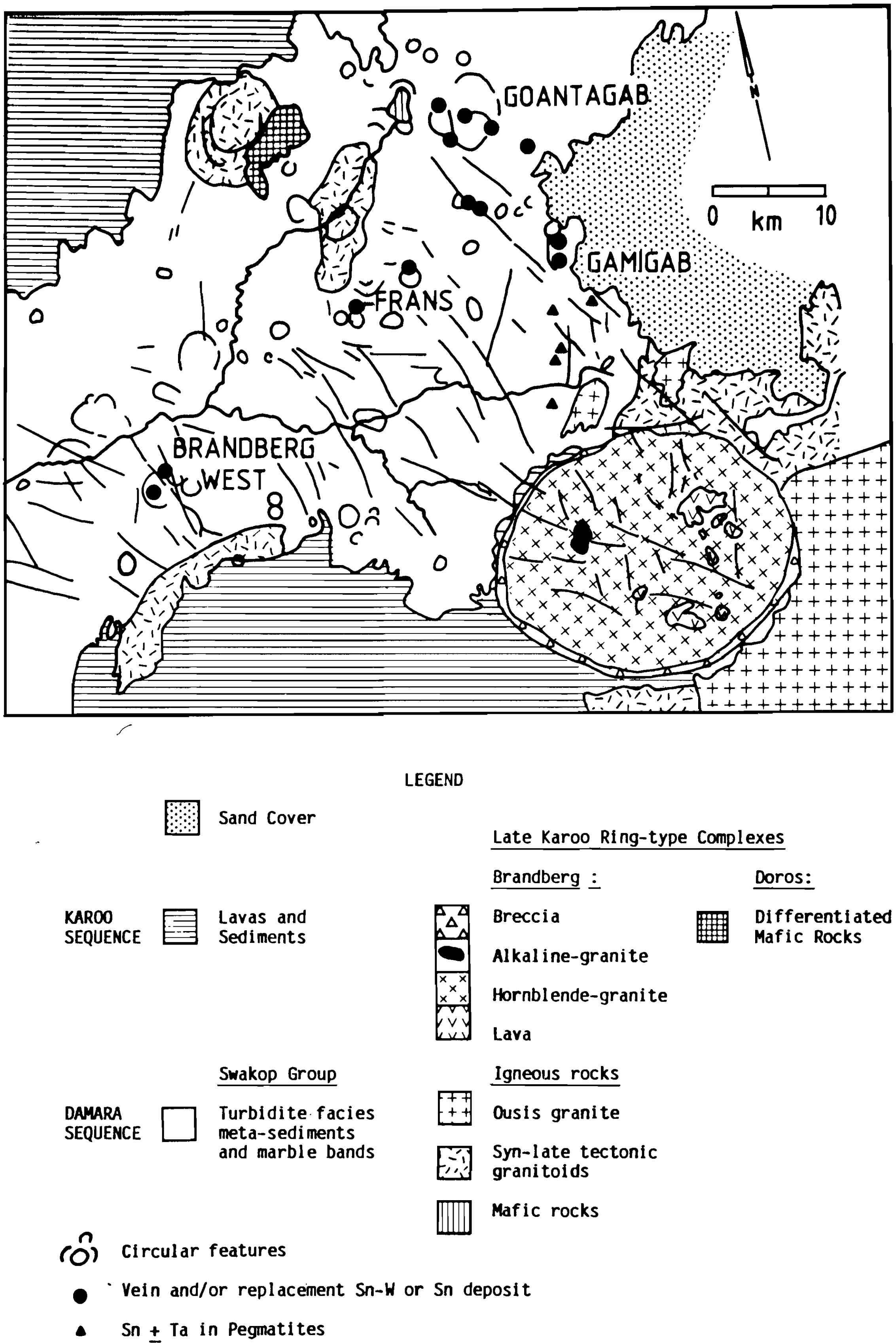

Figure 4 Brandberg West–Goantagab area with distribution of key Sn, Sn–W deposits, and circular structures. Adapted from Geological Map of South West Africa/Namibia, scale 1:1 000 000, and interpretation of LANDSAT imagery (Pirajno & Jacob, 1986).

multiple hydrothermal systems were active in the area, and they were probably linked with underlying (depth unknown) volatile-rich intrusions (Pirajno & Jacob, 1986).

The *Brandberg West* deposit and surrounding mineralized areas are located close to the intersection of two ring structures and a north northwest-trending fracture zone (Pirajno *et al.*, 1987) (Figure 5). Sn–W and minor sulphide mineralization is hosted in quartz veins forming a sheeted and anastomosing system, extending for about 4 km along a general northeast trend. The veins are emplaced in quartz-biotite schist and quartzite and they dissipate against a marble unit. The host rocks display regional metamorphism in the upper greenschist facies, and are overprinted by thermal metamorphism (biotite), and hydrothermal alteration in the mineralized areas.

At Brandberg West five vein sets are recognized (Petzel, 1986). One regionally distributed set is barren and may be of Damara age, whereas the other four are locally developed, mineralized and cut across Damara fabrics. The vein mineralogy is varied and complex and is related to at least three pulses of mineralizing fluids (Pirajno *et al.*, 1987). Apart from quartz (70 to 95 per cent by volume) other vein minerals include muscovite, tourmaline, fluorite, graphite, beryl, apatite, and microcline. Ore minerals are pyrite, chalcopyrite, sphalerite, stannite, cassiterite, wolframite, scheelite and hematite. Studies of hydrothermal alteration indicate a number of phases of alteration-mineralization. An early phase of potassic metasomatism is represented by the development of biotite poikiloblasts. This was followed by a greisen phase (muscovite + quartz + tourmaline ± cassiterite ± wolframite) and a phase of hydrothermal activity with quartz + sericite ± fluorite ± cassiterite. A late hydrothermal phase produced hematite ± cassiterite ± sulphides ± graphite. An important feature is the presence of an east-west trending post-tectonic dyke that is affected by the hydrothermal alteration-mineralization processes. Another important feature is the presence of a small quartz-albitite plug, which intrudes the schist about 2 km northwest of the open pit (Figure 5). This rock has abundant miarolitic cavities containing quartz and calcite. This quartz-albitite is indicative of Na-metasomatism (Pirajno *et al.*, 1987).

The *Frans Prospect* is a deposit which is situated within a small ring structure located near the marble-schist contact on the eastern limb of a tight isoclinal fold (Petzel, 1986; Pirajno & Jacob, 1986). Sn–W mineralization is present in quartz veins emplaced in quartz-biotite schist. There are three major vein systems in the area trending respectively north, north northeast, and northwest, and forming a zone about 3 km long. The veins are fractured and contain cassiterite, wolframite, pyrite, and chalcopyrite. Processes of wall-rock alteration from the vein margins outward include tourmalinization, hematitization, and sericitization. The

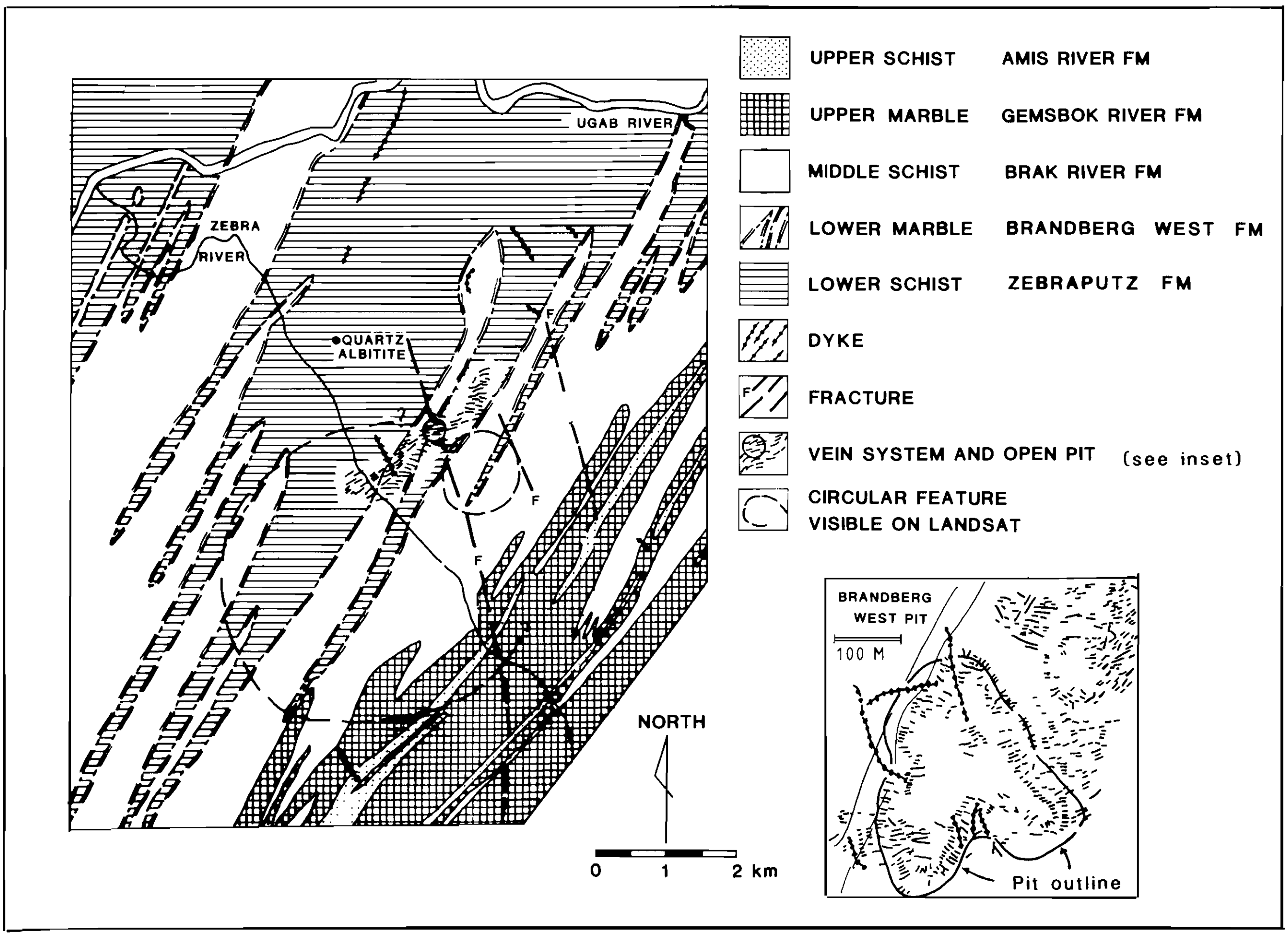

Figure 5 Geology of the area around Brandberg West and trends of vein system (adapted from Petzel, 1986). Stratigraphic nomenclature is from Jeppe (1952) on the left, and from Miller *et al.* (1983) on the right.

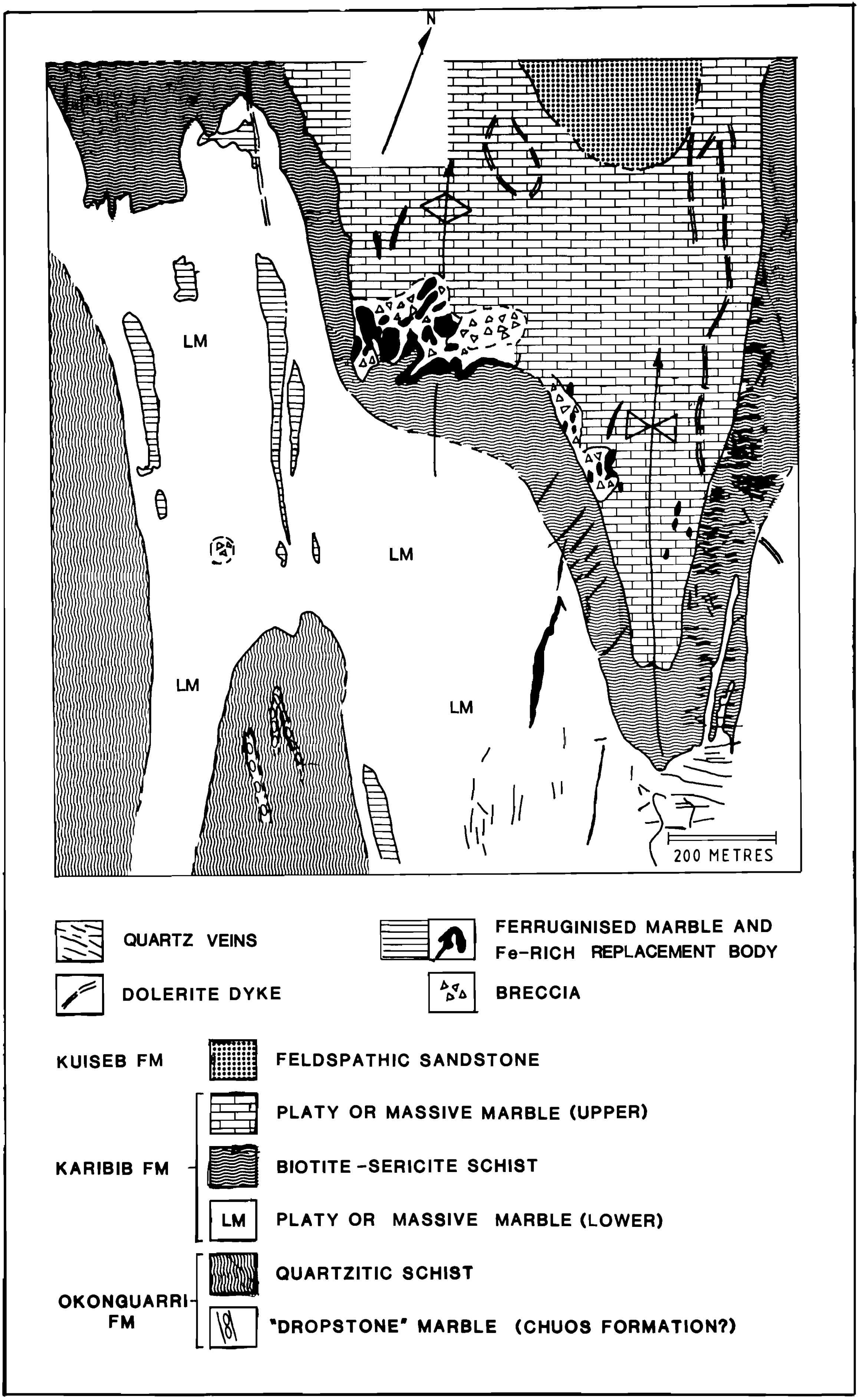

Figure 6 Geology and distribution of vein and replacement-type tin deposits at Goantagab (Petzel, 1986).

marbles near the mineralized vein system exhibit strong to moderate ferruginization (hematite + siderite).

At *Gamigab* cassiterite mineralization is hosted in quartz veins, which trend east-west and terminate against ferruginized and brecciated marble units. The vein material is fractured and infilled with calcite, hematite, and cassiterite. Alteration of wall rocks includes tourmalinization, hematitization, and carbonatization. About 500 m to the north of the main prospect trenches are outcrops of amygdaloidal lavas and volcanic breccias of probable Karoo age. These rocks intrude marble units, which exhibit well-developed haloes of ferruginous alteration. This type of alteration is also found surrounding zones of brecciated marble, where the breccias appear to have formed by hydraulic fracturing.

In the *Goantagab* area, hydrothermal Sn (± Ag and base metals) mineralization is hosted in rocks of the Karibib Formation (intercalated marbles and schist) (Figure 6). The mineralization, spatially associated with two circular structures, occurs as Fe-rich, cassiterite-bearing replacement bodies in marble and as quartz veins (cassiterite + sulphides) in schists. The veins underlie and connect with the replacement bodies, and for this reason the quartz veins are thought to represent feeder systems. The structure at Goantagab is very complex, and at least three folding phases were recognized by Petzel (1986). The F_2 episode resulted in the transposition of bedding into the north-northwest trending axial-plane foliation. The transposition structures have exerted some control over the mineralized quartz veins. The replacement bodies have irregular shapes. They are preferentially located at the contact between schist and overlying marbles, and along zones of brecciation along the transposition zones. These deposits consist of hematite + cassiterite and smaller amounts of carbonate and quartz. Cassiterite is associated with chlorite, carbonate, and fine tourmaline. A zonation is evident in places, from massive, quartz-poor hematite + carbonate + cassiterite in the centre to more quartz-rich zones at the periphery. The quartz veins in the schists are numerous and form three main sets, one of which is commonly mineralized (north northeast-trend). The veins contain more than one generation of quartz, and have tourmaline, sericite, chlorite, calcite, pyrite, pyrrhotite, sphalerite, galena, and cassiterite. A distinct mineral zoning is present, with hematite + cassiterite (replacement bodies) in the upper levels, passing downward to quartz + pyrite + cassiterite, passing in turn to a pyrrhotite-rich zone with little or no cassiterite.

The wall rocks of the veins are intensely altered. Alteration includes tourmalinization and silicification close to the veins, followed outward by sericitization. Some graphite occurs in the tourmaline zone. Carbonatization and ferruginization are late and overprint the earlier alteration assemblages.

Mineralization hosted in pegmatites

On a regional scale the pegmatites of the Damara province form a huge field occupying most of the CZ and parts of the NZ (Figure 3). Some of these pegmatites are economically important sources of U, Sn, Li, Be, Ta, Nb, Cs, and Bi. The uraniferous alaskites occur at a deeper stratigraphic level and are located in that part of the CZ where higher temperatures of metamorphism are recorded (Miller, 1983b). Sn mineralization in the pegmatites of all belts, described later, is closely related, spatially and genetically, to zones of greisen and albite alteration. In almost all cases it can be shown that this alteration is cross-cutting and later than the emplacement of the pegmatites, a feature noted by Gevers & Frommurze (1929).

Between the Erongo Complex and the Brandberg are the stanniferous, mostly unzoned, syn-to post-tectonic pegmatites of the *Central Group*. These form the northeast-trending Strathmore–Uis belt, and the east northeast-trending Neneis–Kohero belt. The Strathmore–Uis belt is located in a regional graben structure, marked by a prominent geomagnetic signature forming the Uis Lineament (Figure 2, B) (Richards, 1980; Corner, 1983). At the southwest end of the Strathmore-Uis belt the stanniferous pegmatites are enriched in Li and Ta. This regional zonation may be attributed to increased depth of emplacement and metamorphic grade towards Strathmore (Sheeran, 1984). North of the Brandberg granite intrusion is a third and smaller, north-trending belt of predominantly unzoned, syn- to post-tectonic, locally stanniferous pegmatites. These are informally known as Ousis pegmatites and they are being studied in some detail by De Waal and co-workers (De Waal, pers. comm., 1986). The Ousis pegmatites are important because they display evidence of their derivation from a compositionally similar, highly differentiated granite (Ousis granite) thought to be a derivative of Salem granitic rocks. The Ousis granite is geochemically specialized, having up to 200 ppm Sn, up to 55 ppm W, and high Rb/Sr ratios (5,2 to 5,7) compared with the Salem granite (0,97), and Sorris-Sorris granite (1,25) (De Waal unpubl. data, pers. comm., 1986).

The Sn-bearing pegmatites around Uis were discovered in 1911, and today the Uis Tin Mine exploits some of the largest pegmatites in the belt. The Uis pegmatites are hosted in rocks of the Kuiseb Formation, which contain up to 60 per cent fine-grained tourmaline in the immediate vicinity of the pegmatites (Figure 7, A) (Richards, 1980). This is interpreted as alteration due to intense B metasomatism. Another feature of the schists in the Uis area is the presence of abundant nodules or spots. Indeed, this association is a constant feature not only at Uis, but also in most other areas (Ousis, Neneis–Kohero belt, Karibib–Erongo belt). These zones of spotted schist probably represent the effects of thermal metamorphism. In thin section they are seen to be composed of biotite, quartz, sericite, chlorite, in places with a core containing cordierite. The Uis pegmatites range in length from 50 to 1500 m and in width from 1 to 130 m. They are lenticular, or sigmoidal in shape, and consist of albite, microcline, quartz, and muscovite. Other minerals are topaz, garnet,

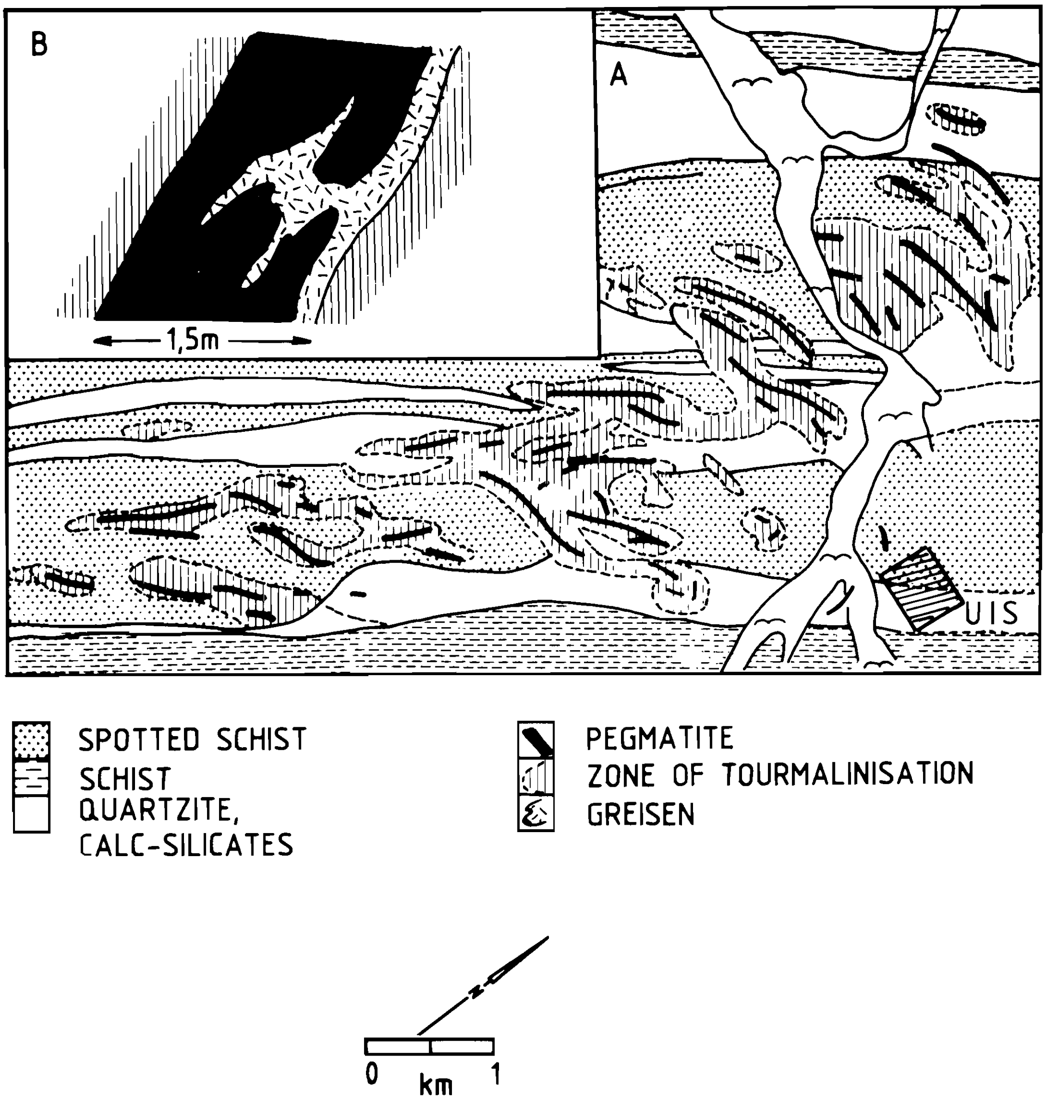

Figure 7 **A.** Schematic geological map showing the distribution of pegmatites around Uis, and associated tourmaline alteration haloes (adapted from Richards, 1980). Open pits and other excavations not shown. **B.** Inset shows Sn-bearing greisen in pegmatite at Kohero. Note that the greisenization affected the footwall contact from which it penetrated across the pegmatitic body (modified from Haughton *et al.*, 1939).

tourmaline, apatite, amblygonite, tantalite, columbite, lepidolite, etc. The Sn-bearing pegmatites show varying degrees of albitization and greisenization. The latter consists of a quartz + muscovite assemblage. Late-stage chlorite and epidote alteration may be present locally. Cassiterite is abundant in the greisenized portions. This mineral is erratically distributed, varying in size from 1 to 50 mm, with about 60 per cent in the 1–5-mm range (Sheeran, 1984).

The *Karibib–Erongo* field of pegmatites (Southern Group) (Gevers & Frommurze, 1929; Frommurze *et al.*, 1942; Roering & Gevers, 1964), occupies an area around the Omaruru Lineament and Erongo Complex. The Karibib–Erongo pegmatites are usually zoned (quartz core, muscovite-feldspar margins) and they become stanniferous in the vicinity of the southern margin of the Erongo Complex, and between it and the coeval Klein–Gross Spitzkoppe granite intrusions.

The zoned pegmatites intrude metasedimentary rocks and Salem-type granitoids, in an area of predominantly 'basin-and-dome' structures formed by the Damara Supergroup and basement rocks. The pegmatites contain Li, Be, Cs, and Nb-Ta bearing minerals. Their most common features are well-developed quartz-rich cores, usually at the centre of the pegmatite bodies. In some cases Fe-rich tourmaline is present as large crystals along the margins of the pegmatite with the c-axis perpendicular to the contact with the wall rocks. Roering & Gevers (1964) give an idealized pattern of internal zoning in pegmatites around Karibib.

As mentioned earlier, the pegmatites of the Karibib–Erongo field become stanniferous in a restricted zone to the south, southeast, and southwest of the Erongo Complex. Some of the formerly productive pegmatites (e.g. Davib Ost, Sandamap) are almost coincident with the Omaruru Lineament, whereas others (e.g. Ameib, Onguati, Brabant) are in close spatial association with the Erongo granite. Von Knorring (1985) also noted that Sn-bearing pegmatites occur near the Erongo Complex, and separated them from the rarer Sn-bearing pegmatites in the Karibib area.

The Brabant (Erongo Schlucht of Frommurze *et al.*, 1942) pegmatites are intruded into an inlier of Salem granite and Kuiseb schist within the Erongo Complex. One of these pegmatites has a strike length of approximately 500 m, and thickness of 10 to 20 m, with steep westerly dips along the margin of the Salem granite stock. The host rock is a massive, equigranular, leucocratic, biotite granite, which is traversed by numerous 'satellite' smaller pegmatites and tourmaline veins both parallel and almost perpendicular to the strike of the main pegmatite. Zoning is asymmetrical and, from the quartz core outwards, consists of feldspar + quartz + muscovite + tourmaline on the hangingwall side, and zinnwaldite + tourmaline + muscovite on the footwall side. Other minerals in the pegmatite are albite, apatite, topaz. Tantalite is associated with altered muscovite (chloritized) and the quartz core. Cassiterite mineralization is associated with fluorapatite and it occurs within bands or patches of greisen material, generally along the footwall. The greisen rock is made up of an anhedral aggregate of quartz + muscovite which replaced the feldspars and quartz constituents of the core zone. Muscovite is poikiloblastic, and small euhedral to anhedral blue tourmaline and fluorapatite grains are disseminated throughout the rock.

The Sandamap pegmatites contain Sn, W, and Ta. They intrude schist and marble and have general east-west and northwest trends. One of the pegmatites exhibits a spatial association with dykes of probable Karoo age. The host rocks are 'knotted' and tourmalinized around the pegmatite veins. Greisen bands surround the core zones, replacing and cross-cutting the main pegmatite body. Cassiterite and wolframite are confined to the zones of greisen alteration. Greisenization is characterized by intensive quartz flooding and fine, anhedral and poikiloblastic muscovite and tourmaline. These minerals generally nucleate at grain boundaries and along microfractures. Late sericite forms aggregates overprinting the greisen assemblage.

Numerous pegmatitic pods and veins occur in the Gross and Klein Spitzkoppe granitic stocks. The Spitzkoppe pegmatites contain well-formed crystals of topaz, beryl, aquamarine, amazonite, feldspar, smoky quartz, and fluorite. In one place a pegmatitic pod contains a zone of sulphides (arsenopyrite, covellite, chalcocite) with tourmaline and some cassiterite.

Mineralization hosted in greisen rocks

A number of W–Sn and W deposits, which occur along a zone north of the Erongo Complex, are spatially and genetically related to the Erongo granite (Figure 3). The Erongo granite is a coarse-grained, biotite-K-feldspar granite, with a modal composition of 36 per cent quartz, 33 per cent K-feldspar, 25 per cent albite, 4,5 per cent biotite, and 1,5 per cent accessories including tourmaline, zircon, fluorite, apatite, and topaz (Schlögl, 1984). The Erongo granite is characterized by the presence of quartz + tourmaline 'nests' up to 30 cm in diameter. These occur disseminated throughout, but according to Blümel *et al.* (1979) they are more numerous towards the roof zones. Tourmaline is subhedral to anhedral, it replaces plagioclase and quartz, and it fills microfractures. Other minerals in the 'nests' are mica, fluorite, fluorapatite, topaz, and cassiterite. Geochemically the Erongo granite is specialized having high F(0,41 %), B(0,11 %), W(400 ppm), and an average Rb/Sr ratio of 42; $Si0_2$ contents range from 72 to 76 per cent (data from Schlögl, 1984; Blümel *et al.*, 1979).

The *Kranzberg Mine* was a major producer of W metal until 1979 when it was closed down due to falling metal prices. A comprehensive geological study of this deposit was carried out by Schlögl (1984). The Kranzberg deposit occurs in an area to the northeast of the Erongo Complex which is underlain by quartz-biotite schist (Kuiseb Formation) and syn-to post-tectonic Salem-type granitoids, rocks of the Erongo Complex, and north-south trending Karoo-age dykes (Figure 8). The 'Kranzberg' is a prominent hill formed by the basal Erongo breccia overlain by basaltic rocks. Figure 8, modified after Schlögl (1984), shows the simplified geology of the area around Kranzberg and the distribution of the alteration-mineralization zones. Mineralization occurs in greisen bodies (Koppie Zone, C Zone, and Erongo breccia), greisen veins and breccia pipes. Hydrothermal alteration-mineralization principally affects the Salem granites along the contacts with the schist, and the Erongo breccia above the C-Zone (Schlögl, 1984).

At the Koppie Zone the mineralization is characterized by a large number of wedge-shaped greisen bodies, projecting up to 60 m away from the main mass, which is 40 to 50 m wide and located along the contact with the metasedimentary rocks. Alteration and mineralization are largely confined to the granitic rocks. Detailed mineralogical studies reveal that processes of alteration-mineralization involved increasing degrees of H^+ metasomatism (greisenization and sericitization), which resulted in the destabilization

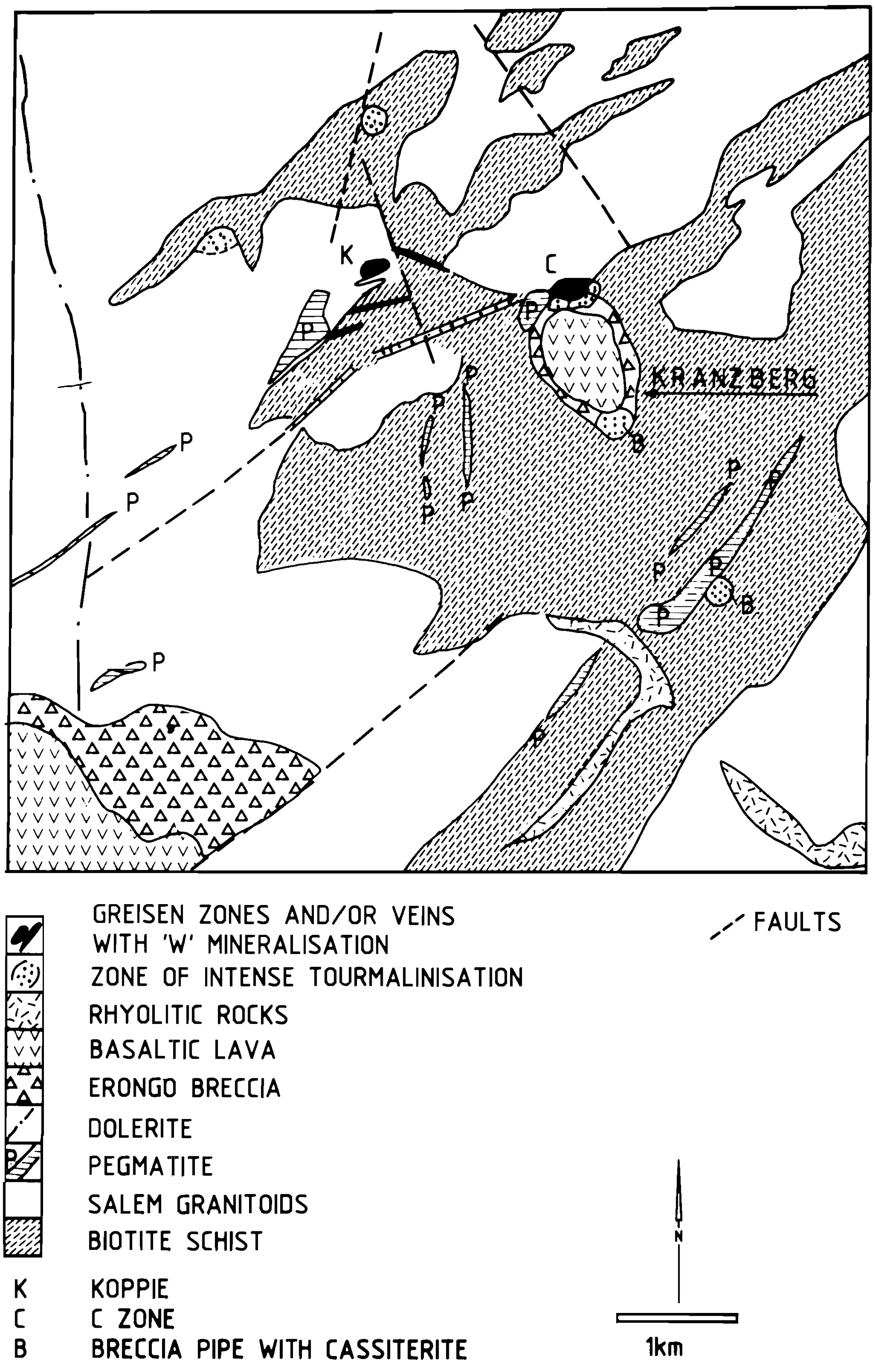

Figure 8 Schematic geological map of the area around Kranzberg tungsten deposit, and distribution of mineralized zones (adapted from Schlögl, 1984).

and destruction of the feldspars and micas in rocks of granitic composition. The greisen material consists of an assemblage of quartz + topaz ± muscovite ± fluorite ± tourmaline ± wolframite, whereas advanced H^+ metasomatism resulted in assemblages containing sericite + chlorite ± tourmaline ± fluorite, accompanied by later pulses of hematite and wolframite deposition.

Ore minerals are wolframite (variety ferberite), chalcopyrite, pyrite, arsenopyrite, native bismuth, molybdenite, and scheelite (alteration of wolframite) (Schlögl, 1984).

The Erongo breccia near the C-zone is locally greisenized and tourmalinized up to 70 m from the lower contact (Schlögl, 1984). The matrix of the breccia, in addition to tourmaline, also contains fluorite, muscovite, topaz, beryl, sericite, quartz, and cassiterite. Finer-grained breccia material consists of quartz fragments set in a pervasively sericitized matrix with disseminated tourmaline.

Two pipe-like bodies, with diameters of 100 and 30 m, reported by Haughton *et al.* (1939) occur on the southeast slopes of Kranzberg (Figure 8). They consist of Karoo volcanic fragments cemented by quartz and tourmaline. Cassiterite is the main ore mineral and it occurs as fine disseminations.

Other mineralized localities occur about 20 km west northwest of Kranzberg (Figure 3). One is located within a small stock of Erongo granite and contains beryl and cassiterite. The host granite is rich in tourmaline veins and nests and is albitized and greisenized (quartz + muscovite aggregate) ± cassiterite. Selective-pervasive sericite alteration of the feldspar constituents is common.

Processes of ore genesis and metallogeny

The granite-related Sn–W metallogeny in the Damara orogen has certain features which can be explained as being the result of related phenomena. An attempt will be made to explain, in the light of the geological evidence available and along generalized lines, the processes that have led to metallic concentrations containing mainly Sn and W.

Except for the Ousis pegmatites, a feature common to all deposits is that the alteration-mineralization is post-tectonic with respect to strain fabrics of Damara age. Also, on the regional scale the deposits of the Central and Southern groups are associated with zones of crustal weakness re-activated during Karoo times, probably in response to stresses generated by the Gondwana break-up. In the Northern Group, the Brandberg West and Gamigab deposits are spatially associated respectively with a quartz-albitite plug and a volcanic breccia which penetrate the Damara schists. The nature of these rocks and their alteration suggest a genetic relationship with the mineralized veins.

Petrographic and mineralogical evidence of alkali metasomatism, greisenization, and subsequent hydrothermal alteration-mineralization is compelling in all cases. In the Erongo area, evidence indicates that greisenization and hydrothermal activity selectively affected rocks of granitic composition (e.g. Kranzberg), and possibly some of the larger pegmatites (e.g. Brabant and Sandamap). Here both greisen rocks and pegmatites show clear evidence of interaction with volatile phases rich in B and, to a lesser extent, F.

It is suggested that extensive degassing of the Erongo granite may have been responsible for the observed effects of this volatile metasomatism. The quartz + tourmaline nests in this granite support the hypothesis. A magmatic-hydrothermal regime in the sense advocated by Taylor & Pollard (in press; and pers. comm., 1985) could have operated. According to these workers, following upon the crystallization of more than 90 per cent of a volatile-rich granitic melt, magmatic-hydrothermal fluids collect in available spaces within the nearly solidified granitic mass. At this stage the granite body would contain, concentrated in the apical regions, a reservoir of hydrothermal fluids. These may be released during a fracturing event and channelled upward towards areas of low pressure. If no fractures are present, or if isolated portions of the reservoirs are not connected by fractures, pegmatitic and/or hydrothermal phases will crystallize *in situ*.

In the Brandberg West–Goantagab area circular structures are associated with thermal metamorphic effects, quartz-veins and breccias. The association of circular structures with mineralization has been reported from many areas around the world (see Norman, 1982). In Portugal circular structures are common in the Hercynian orogenic areas in the north (Goinhas & Viegas, 1983). In New Zealand well-defined circular structures occur in a terrane characterized by turbiditic sequences intruded by granite batholiths (Pirajno, 1982).

Gabelman (1984) presented some interesting cases of 'circular geomorphic features', which he attributed to mantle degassing. Degassing and upward streaming of volatiles from underlying magma bodies is a hypothesis which could explain some of the geological features summarized in this paper. The following model is proposed: underlying, cooling, volatile-rich magma bodies will accumulate the volatiles in their apical portions. Fracturing in the overlying rocks allows the volatiles to move upward forming a relatively narrow, central pipe-like structure. A number of stages of degassing and associated structures are recognized by Gabelman (1984). An incipient to early stage of 'pipe-formation' would form curved joints. Heat flux would result in thermal metamorphic assemblages in the overlying rocks, with intensity decreasing upwards intensity. Mature stages would result in the formation of well-defined multiple ring features. Collapse may take place at lower levels, leading downward to shattered and brecciated rocks. Advanced stages will result in more complex fracture patterns, including overlapping circular structures. Venting may occur, leading to breccia pipes. Late stages may involve hydrothermal activity which will finally move mineralizing fluids through the channels provided by the extensive fracturing.

A schematic model of Sn–W metallogeny for the Damara orogen is proposed and schematically illustrated in Figure 9. During the Pan-African event syn- to late-tectonic granitic rocks were formed as a result of partial melting of basement rocks and/or Nosib Group rocks, and perhaps in places of Khomas Group pelitic and psammitic schists. Some of these source rocks may have been enriched in U, as proposed by Jacob (1978). Similarly some lithologies of basement rocks and/or Damara sediments may have been enriched originally in Sn and W. Boron enrichment of evaporitic sedimentary horizons is also likely. Following differentiation of the granitic melts, the residual liquids gave rise to pegmatites which were emplaced in major zones of weakness. Zoned pegmatites concentrated rare metals (Be, Li, Ta, Nb) and Sn, whereas unzoned pegmatites concentrated more Sn and less rare metals. The reasons

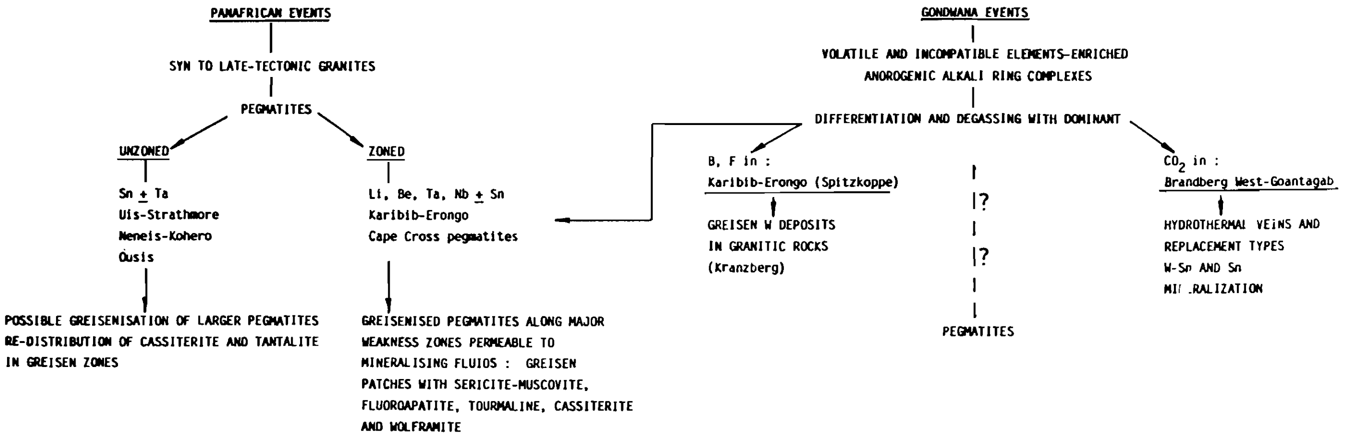

Figure 9 Scheme of Sn–W metallogeny in the Damara orogen during Pan-African granitic magmatism, and during Gondwana within-plate magmatism related to the opening of South Atlantic ocean.

for these differences are not known but they may be due to variations in the nature of the source rocks and residual liquids.

Connected with the Gondwana break-up and the opening of the South Atlantic ocean, anorogenic continental magmatism resulted in the emplacement of alkali ring-type complexes ranging from mafic through granitic, nearer the coast, to carbonatitic towards the interior (Prins, 1981). These sub-plutonic to volcanic magmas followed lines of pre-existing weakness within the Damara orogen (Marsh, 1973). Structural controls of these magmas are mainly along northeast and north-south trends. These same trends were used for the injection of the Karoo dykes and outpourings of basaltic lavas.

The association of alkaline magmatism with rifted continental regions is well known. This within-plate magmatism is essentially characterized by the small volumes of its products and by the high concentrations of incompatible elements and volatiles, especially CO_2, F, Cl, and B. The generation of these magmas is thought to occur in regions of thick lithosphere following the uprise of partial melts from metasomatized regions of the mantle, where metasomatism is possibly due to extensive escape of C gases with high halogen contents (Bailey, 1978; Lloyd & Bailey, 1977). The enrichment of these magmas, in non-hydrous volatile components such as CO_2 and halogens, results in the concentration in the residual melts, of B and F and HFS elements (Zr, Y, Nb). Concentrations of fluorite, tourmaline, cassiterite, tantalite, and wolframite are present in the consolidated products of this type of magmatism.

Greisenization, hydrothermal alteration, and mineralization are the main effects of the upward movement of the fluids and volatiles. Emplacement of proximal Sn–W vein systems and distal Sn-bearing replacement Fe-rich bodies, characterizes the region of predominant CO_2 degassing (Brandberg West–Goantagab). Greisenizing fluids, with dominant F and B, largely affected older granitic rocks and perhaps pegmatites, generating W and Sn deposits (e.g. Kranzberg and Erongo pegmatites).

Conclusions

Field-based studies, and petrological and mineralogical investigation of Sn–W deposits in the Damara orogen, have revealed a complex and perhaps multi-stage metallogeny. Hydrothermal vein, replacement, and greisen deposits show evidence that intense and multiple hydrothermal systems were operative in the orogen and resulted in the development of alteration-mineralization in a variety of hosts (schists, marble, pegmatite, and granites).

An early stage of Sn ± Ta mineralization may be connected with the emplacement and subsequent fractionation of Damara-age plutons, leading to a number of stanniferous, mostly unzoned, pegmatites. Magmatic-hydrothermal systems and volatile metasomatism were prominent following the emplacement of anorogenic alkali ring-type complexes during the opening of the South Atlantic ocean.

In this context the analogy of the Damara orogen and its attendant mineralization with the Nigerian Province is tempting. The Nigerian Province is part of a north east-trending system of graben structures, constituting the failed arm of a rift which separated America from Africa. The Province contains belts of mineralization of two ages. One is Sn-Ta-Nb mineralization in pegmatites which are connected with the 'Older Granite Complex' of Pan-African age (Matheis *et al.*, 1982). The other is Sn-Nb and W mineralization related to anorogenic alkaline ring complexes of Jurassic age (Matheis *et al.*, 1982; Matheis, 1979; Bowden, 1982; Ekwere & Olade, 1984; Ekwere, 1985; Imeokparia, 1985).

The pegmatite belt of Nigeria extends for about 400 km in a northeast direction. The pegmatites, zoned and unzoned, are products of the residual liquids of late granitoids of the Older Granite Suite. Later phases of albitization and greisenization contain the Sn-Ta-Nb mineralization. This belt joins the Jos Plateau at its northeast end, where some 40, north-trending, anorogenic ring-type alkali complexes extend as far as northern Niger (Air Province). These are known as the 'Younger Granites', characterized by Sn-Nb and Sn–W mineralization types (Imeokparia, 1985). These complexes are dominantly granitic in composition and have high Li, F, Rb contents, and high Rb/Sr ratios (Ekwere, 1985). Cassiterite and columbite occur in albitized and greisenized biotite-granite with topaz and Li-mica. Wolframite and cassiterite are present in quartz veins in the contact rocks (Olade, 1980).

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