The alteration-mineralization of the Krantzberg tungsten deposit, South West Africa/Namibia

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The Krantzberg tungsten deposit was formed through an episode of alteration-mineralization connected with the emplacement and fractionation of the Erongo granite. The granite was intruded after the collapse of the Erongo caldera, an anorogenic volcano-plutonic complex of post-Karoo (Jurassic-Cretaceous) age. The Erongo granite is an A-type, water-poor granite, rich in boron and fluorine. Fractionation of this granite resulted in the development of H^+ and B-enriched fluids which metasomatized and mineralized the roof country rocks. Early H^+ metasomatism (greisenization) and later more advanced H^+ metasomatism (sericitization) were accompanied by dominant wolframite, fluorite, minor beryl, and sulphide mineralization. This alteration-mineralization was emplaced along major lithological and structural breaks, and dominantly affected lithologies of granitic composition. The ore zones are developed at the contact between Kuiseb schist and Damara granite, and along the unconformity with the overlying Karoo Sequence rocks. Tourmalinization is extensive and in places is associated with hydraulic-type breccia testifying to violent degassing. Wolframite (variety ferberite) was probably formed during a stage of high F activity in the hydrothermal system.

Die Krantzberg-wolframafsetting is tydens 'n episode van verandering en mineralisasie verbonde aan die indringing en fraksionering van die Erongo-graniet gevorm. Die Erongo-kaldera, n anorogeniese vulkano-plutoniese kompleks van na-Karoo ouderdom (Jurassies tot Kryt), is na sy instorting deur die Erongo-graniet ingedring. Die graniet is 'n A-tipe, waterarme graniet, ryk aan boor en fluoor. Fraksionering van hierdie graniet was aanleidend tot die ontwikkeling van H^+ - en B-verrykte vloeistowwe wat die omringende dakgesteentes gemetasomatiseer en gemineraliseer het. Aanvanklike H^+ -metasomatisme (greisenisering) en latere meer gevorderde H^+ -metasomatisme (serisietisering) het met oorheersende mineralisering van wolframiet, fluoriet, ondergeskikte beriel, en sulfiedminerale gepaard gegaan. Hierdie verandering en mineralisering is langs opvallende onderbrekings van litologiese en strukturele aard ingeplaas, en het hoofsaaklik gesteentes van 'n granitiese samestelling beïnvloed. Die ertssones is langs die kontak tussen Kuisebskis en Damaragraniet ontwikkel, sowel as langs die diskordansie met die oorliggende gesteentes van die Karoo-opeenvolging. Toermalinisering is wydverspreid, en is op sekere plekke verbonde aan hidroliesagtige breksie, 'n aanduiding van heftige ontgassing. Wolframite (var. ferberiet) het waarskynlik tydens 'n stadium van hoë F-aktiwiteit in die hidrotermiese stelsel gevorm.

Introduction

In west-central South West Africa/Namibia there is a 200-km wide, northeast-trending zone, which contains a number of anorogenic alkaline ring-type complexes of post-Karoo (Jurassic-Cretaceous) age (Figure 1). These complexes were emplaced within the Damara Belt and, together with the Luderitz Alkaline Province in southern South West Africa/Namibia (Marsh, 1973), represent intracontinental magmatism in response to movements related to the break up of Gondwana. The complexes, which also include carbonatites, were emplaced along northeast-trending lineaments and are interpreted by Marsh (1973) as continental extensions of oceanic transform faults (Figure 1).

This type of magmatism is characterized by both oversaturated and undersaturated rocks, with the former including A-type granites. In South West Africa/Namibia, as elsewhere in Africa (see Bowden, 1985), the alkaline ring complexes represent remnants of volcanic structures in various stages of erosion. Anorogenic alkaline ring complexes, worldwide, are spatially and genetically associated with mineral deposits containing elements such as Th, U, W, Sn, Nb, Ta, and Zn (Bowden, 1985). For reviews on this type of magmatism the reader is referred to Black & Bowden (1985) and Bonin (1986). A comprehensive work on the ring complexes of the Damara province was carried out by Prins (1981).

Mineralization in the Krantzberg area (Figure 2) is essentially greisen-hosted W with minor F, Sn, Be, Bi, Mo, and Fe-Cu sulphides, and quartz-tourmaline-hosted Sn. However, W, in the mineral ferberite, by far constitutes the dominant ore element for which at least three mineralized zones were exploited. The Krantzberg W deposit is one of a number of mineral deposits related to a late intrusive phase of the Erongo Complex, which is the largest and one of the best exposed alkaline ring-type complexes in west-central South West Africa/Namibia. In this paper the results of research work on the geology and alteration-mineralization of the tungsten ore zones at Krantzberg are reported. Further studies on fluid inclusions of the mineralized material are in progress.

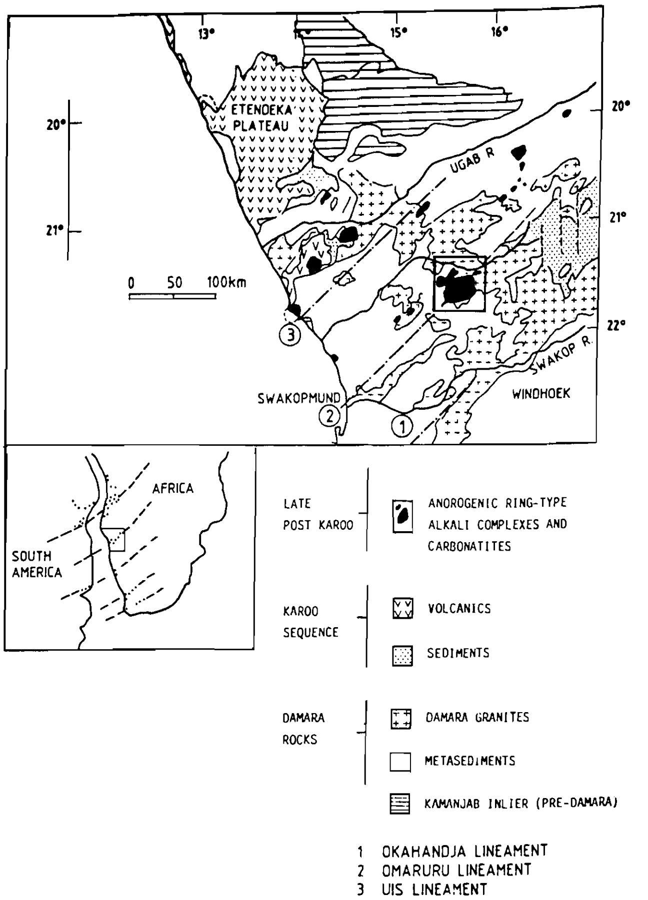

Figure 1 Locality map, showing distribution of the Jurassic-Cretaceous anorogenic complexes in Damaraland, Namibia. The Erongo Complex is framed by the square. The inset illustrates the relationship of the complexes with transform directions in the South Atlantic (Marsh, 1973).

Geological setting

A brief account of the geology and evolution of the Erongo Complex is necessary to the understanding of the Krantzberg W deposit. A simplified geological map of the Erongo Complex, which forms the rugged Erongo mountains, and is located between the towns of Omaruru to the northeast and Usakos to the south, is shown in Figure 2. The Erongo Complex is an anorogenic alkaline ring-type volcano-plutonic structure emplaced into a basement of Damara rocks, comprising metasediments and granitoids. The Damara rocks are part of a late Proterozoic Pan African tectogen, and the Damara granitoids were emplaced between 580 and 450 Ma ago (see Miller, 1983). No published age dating is available at present for the Erongo Complex, but Rb/Sr and K/Ar dates of 123–190 Ma were obtained from other Jurassic-Cretaceous complexes in Damaraland (Erlank *et al.*, 1984). The main part of the Complex is the remnant Erongo volcano, which forms a central caldera, and consists predominantly of ash-flow tuffs overlying mafic lavas. After cauldron subsidence the volcano was intruded by volatile-rich, subvolcanic plutons, one of which, the Erongo granite forms a ring dyke-like body. The Erongo caldera has a diameter of about 30 km, whereas the whole Complex including an outlying cone sheet intrusion (Figure 2) has an E–W diameter of about 48 km, making it one of the largest of its kind. Similar complexes in Nigeria have maximum diameters of about 30 km (Bowden *et al.*, 1984).

Regional geomagnetic and gravity data (Aldrich, 1986) indicate that the Erongo Complex may be part of widespread magmatism extending for at least 40–50 km to the southwest, where the Jurassic-Cretaceous Grosse

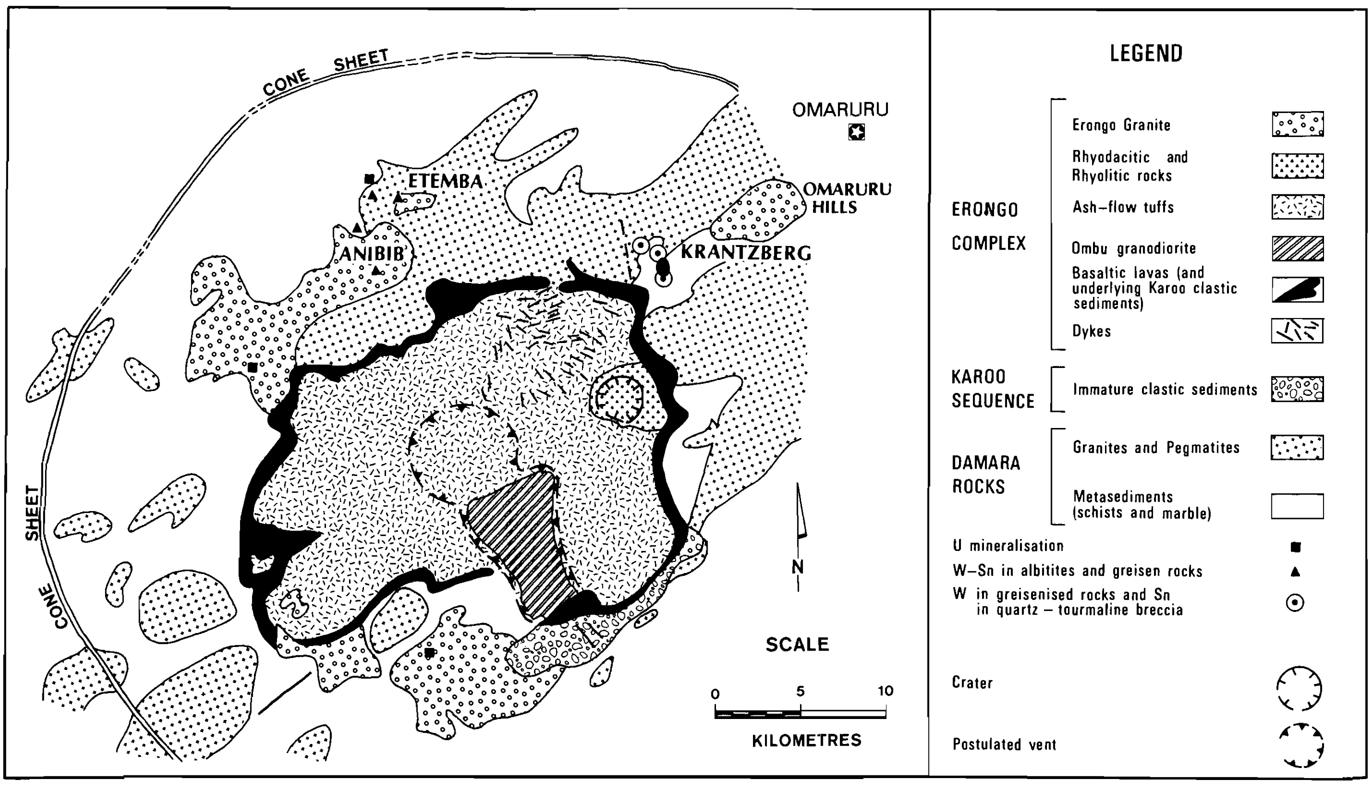

Figure 2 Simplified geological map of the Erongo Complex and distribution of associated mineral deposits. Thickness of cone sheet is exaggerated.

and Kleine Spitzkoppe granite plutons form prominent inselbergs in the desert plain. The Erongo-Spitzkoppe igneous activity appears to be associated with the northeast-trending Omaruru lineament (Corner, 1983; Aldrich, 1986).

The Erongo volcanic products accumulated on immature clastic sediments of the Karoo Sequence. The sedimentological features of these sediments suggest that they were deposited for the greater part in a subaerial environment possibly formed by a series of small fault-controlled grabens. The Karoo sediments rest unconformably on a basement formed by rocks of the Damara Sequence (Kuiseb schist and Karibib marble) and Damara granitoids. The Erongo volcano was built up through a series of continuous events as shown by the lack of sedimentary material intercalated with the lavas and pyroclastics. The magmatic sequence commenced with the eruption of basaltic lavas through a number of dykes and cone-sheet feeders. An olivine-gabbro cone-sheet is preserved to the west and north of the Complex (see Figure 2). The basaltic lava flows reached a total thickness of up to 300 m in places.

Extrusion of the mafic lavas was followed by voluminous felsic volcanic products, including ash-flow and air-fall pyroclastics, with minor rhyodacitic and rhyolitic lavas (Pirajno, 1987). Current geological mapping of the Erongo Complex by one of the authors (FP) reveals that at least 2 major pyroclastic-dominated eruptive events, each with distinct petrological and geochemical characteristics, originated from postulated vents, now expressed as a major topographic depression in the central and southeast areas of the caldera (Figure 2). The southern part of this depression is underlain by the Ombu granodiorite, a subvolcanic intrusive charged with numerous xenoliths of both Karoo and Damara rocks. The Ombu granodiorite is interpreted as the feeder to the rhyodacitic volcanic rocks. The eruption of voluminous ignimbrites resulted in the collapse of the roof of the magma reservoir, cauldron subsidence, and the formation of a caldera structure at surface. In the eastern portion of the caldera, flow-banded and fragmental rhyodacites and rhyolites may possibly belong to a resurgent, and therefore later, intra-caldera eruptive centre.

After cauldron subsidence the Complex was intruded by the Erongo granite. This granite is important from a metallogenic viewpoint as it is thought to represent the source of heat as well as of extensive alkali and boron metasomatism, greisenization and mineralization of its roof zones and of the surrounding country rocks. The Erongo granite crops out as isolated stocks all around the caldera structure, but at depth it may possibly form a continuous body above and around a subsided block, thus forming a ring-dyke. Two types of granite are recognized in the field. The principal type is a massive, coarse-grained, equigranular, subsolvus biotite-granite. An average modal composition of this granite near the Krantzberg mine is as follows : 36% quartz, 33% orthoclase-perthite, 25% albite, 4,5% biotite, and 1,5% accessories (tourmaline, zircon, fluorite, apatite, topaz). The second type is also a subsolvus granite, and is represented by a quartz-feldspar porphyry, which occurs as a roof facies in the northeast of the Complex (Omaruru Hills) and contains about 40% quartz, 10% albite, 43% K-feldspar, and 3–4% or traces of biotite (Kujawa, 1986).

Geochemically the Erongo granite conforms to an A-type granite (anorogenic, alkaline, anhydrous) as defined by Collins *et al.* (1982), Bowden (1985), and Bonin (1986). The Erongo granite is H_20-poor (less than 0,2%) and contains high Ga (44 ppm), Nb (14 ppm), Y (53 ppm), Rb (536 ppm), Zr (118 ppm), F (4 100 ppm), and B (1 000 ppm) (Pirajno, unpublished data; Schlögl, 1984).

A prominent and important feature of the Erongo granite, is the presence of quartz-tourmaline nests up to 30 cm in diameter. They are disseminated throughout, but are locally extremely abundant and may coalesce, especially in the roof zones of the granite stocks. The nests have a leucocratic reaction halo containing quartz and K-feldspar with no biotite. In these nests, tourmaline and quartz have either replaced the feldspar and biotite of the original granitic mineral assemblage, or fill open spaces. In addition to tourmaline and quartz, the nests also contain accessory amounts of fluorite, apatite, topaz, and cassiterite, with relict feldspar and biotite. Tourmaline veins, breccias, and dyke-like bodies as well as more pervasive tourmaline replacements are widespread in all rocks around the Erongo granite up to several hundred metres from its contacts, both vertically and horizontally. Kujawa (1986) put forward the hypothesis that the tourmaline nests and veins were formed by entrapment of B-rich vapours during and after the crystallization of the granitic magma. He proposed the following reaction: biotite + alkali feldspar + B = tourmaline + quartz + K^+

The Krantzberg tungsten deposit

The Krantzberg mine, now inoperative, is situated about 20 km southwest of Omaruru. The mine was at one time a major producer of tungsten ore in South West Africa/Namibia, with about 1 000 t of concentrate produced during the 1940s and into the middle 1950s. Intermittent mining continued into the 1970s, but ceased altogether in 1979. Subsequent exploration work, mainly by drilling in selected areas within the mine grounds, did not result in finding economically feasible grades and tonnages.

Local geology

The simplified geology of the Krantzberg area is depicted in Figure 3. In this area, rocks of the Damara basement predominate and include quartz-biotite schist of the Kuiseb Formation, intruded by Damara granitic rocks (Miller, 1983). On this basement the Krantzberg rises, (elevation of 1 714 m a.s.l.), formed by Damara rocks, overlain by Karoo sediments and lavas of the Erongo Complex.

The lower part of the mountain is made up of quartz-biotite schist in contact with pegmatites and megacrystic biotite-granite on its northern side. The Karoo unconformity is located at an altitude of approximately

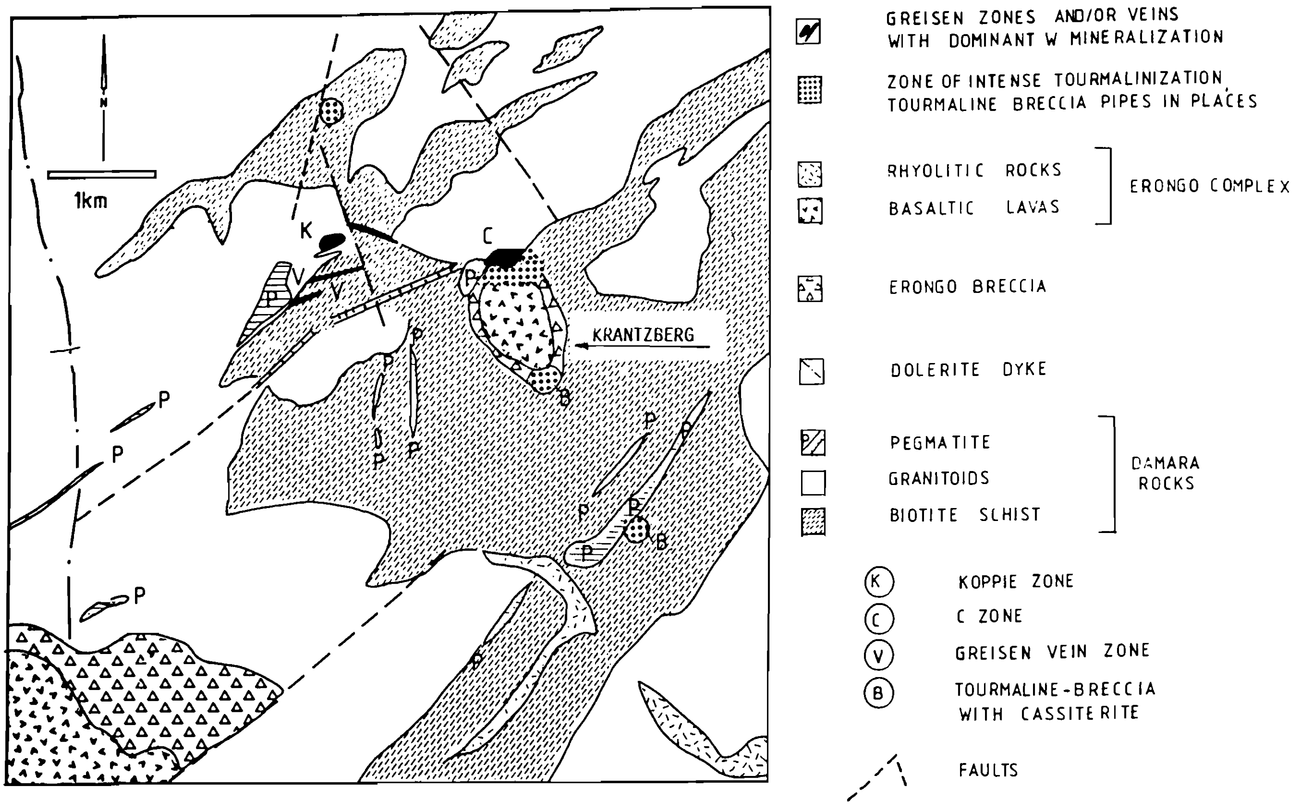

Figure 3 Simplified geological map of the area around the Krantzberg W deposit. For location see Figure 2.

1 650 m a.s.l. and is overlain by coarse clastic sediments of the so-called Erongo breccia. Basaltic flows overlie this unit and form the top of the Krantzberg. To the south are southwest-trending Damara pegmatites and rhyolitic dykes. The latter probably belong to the Erongo magmatism.

The quartz-biotite schist of the Kuiseb Formatlon in the Krantzberg area consist of approximately 46% quartz and 34% biotite, with variable amounts of feldspars and other minerals (mostly secondary due to alteration). The foliation of the schists has a regional northeast trend.

The Damara granitic rocks in the area are represented by two main types. One is a massive, coarse-grained megacrystic K-feldspar biotite-granite and the other is a medium-grained gneissic granite. Zoned tourmaline-bearing pegmatites of Damara age intrude the granitic rocks in several places. The megacrystic biotite-granite consists of approximately 26% microcline, 32% plagioclase, 31% quartz, and 9% biotite, with the balance made up by accessories such as sphene, apatite, rutile, and various alteration minerals. The medium-grained granite has a gneissic fabric, which is defined by biotite and elongated quartz grains, and trends more or less parallel to the foliation of the schists. This granite contains approximately 30% K-feldspar, 16–17% plagioclase, 41% quartz, 8% biotite, and 4,5% accessories (including alteration minerals).

The Erongo breccia, which at Krantzberg forms steep cliffs and is up to 120 m thick, is stratigraphically correlated with the Omingonde Formation of the Karoo Sequence (SACS, 1980), some 50 km to the northeast. The Erongo breccia dips 10–15° towards the south and consists of a very immature clastic unit containing rock fragments ranging in size from 1 to 20 cm. The fragments include biotite schist, Damara granite, pegmatite, and discrete quartz and feldspar grains. The breccia is generally tourmalinized and sericitized, in places pervasively. This tourmalinization is locally so intense that it masks both the lower and upper contacts of the unit.

The overlying basaltic lava flows also dip 10–15° to the south. There are amygdaloidal and non-amygdaloidal types. The lavas are composed of olivine phenocrysts set in a groundmass of pyroxene and plagioclase microlites. The lower part of the lava sequence is brecciated, tourmalinized, and hydrothermally altered. The Erongo granite does not outcrop in the mine area. The nearest outcrops of this granite are located some 5 km to the northeast (Omaruru Hills, see Figure 2), and it is thought that this granitic body extends in depth below the Krantzberg area.

Mineralization

Cloos (1911; 1919) was the first to report on the geology and mineralization of the Krantzberg area. He also recognized the importance of the B-rich fluids in the genesis of the mineralization. Later, Haughton *et al.* (1939) described in detail the distribution, field relationships, and mineralogy of the mineralized rocks of the Krantzberg area. They too recognized both the post-Karoo age of the mineralizing event and its relationship to B-rich fluids. In addition to W, Sn (cassiterite) mineralization is also present at Krantzberg and it occurs mainly associated with late quartz-tourmaline veins and tourmaline breccias (Haughton *et al.*, 1939). However this work deals principally with the greisen-hosted W mineralization.

Wolframite, fluorite, beryl, and associated minor sulphide mineralization at Krantzberg, occurs mainly in greisen bodies hosted in Damara granitic rocks, and in greisen veins hosted in quartz-biotite schist. Greisenizatlon and hydrothermal alteration also invade the overlying Erongo breccia unit and the basaltic lavas. The geometry of the mineralization and alteration zones and their relationships with the enclosing rocks and with the postulated Erongo granite below surface are shown schematically in Figure 4.

There are three main zones of alteration-mineralization and they are designated: (i) Koppie Zone, (ii) C Zone, and (iii) Greisen Vein Zone. Their positions are indicated in Figures 3 and 4, and they are briefly described below.

The *Koppie Zone* consists of a number of wedge-shaped greisen bodies that define a westerly trending zone. The greisen wedges are developed within the Damara gneissic granite along its northeast-trending contact with schist rocks. The wedges protrude into the granitic body for up to 60 m, are up to 45 m in width, and may extend to a depth of 150 m. Wolframite disseminations are more abundant near the schist-granite contact and gradually decrease with distance from this contact, like the greisenization effects. Grades in this zone ranged from 0,35 to 1% WO_3.

The *C Zone* greisen bodies occur along the northern and northeastern slopes of the Krantzberg. They are distributed along a 450 m northeast-trending contact zone between Damara megacrystic biotite-granite and quartz-biotite schist. The C Zone is formed by wedges and stockworks of greisenized material, with a gentle dip to the southwest, and largely developed within the megacrystic granite. The vertical extent of the stockwork was proved to be about 100 m, and individual greisen bodies may reach thicknesses of up to 30 m. Wolframite and pyrite occur disseminated in these greisens. The greisen alteration in the C Zone area extends upward into the overlying Erongo breccia and to a lesser degree

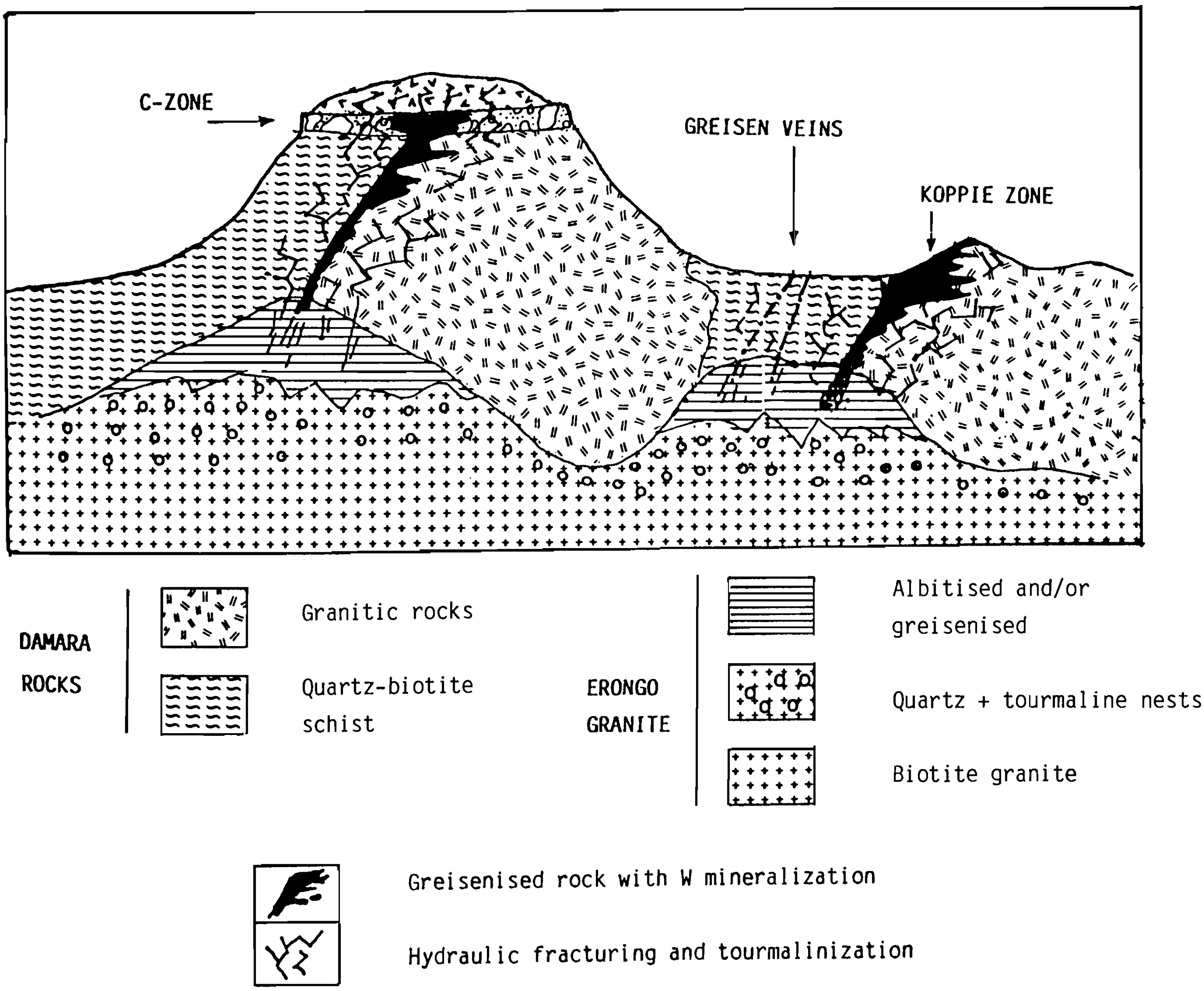

Figure 4 Idealized, not to scale, west-facing cross-section of the Krantzberg showing configurations and positions of the mineralized zones, in the roof region of postulated Erongo granite in subsurface.

into the basaltic lavas above. Details of this greisenisation will be discussed later.

The *Greizen Vein Zone* occupies 3 to 6-cm wide fractures in the schists. These fractures are more or less parallel to foliation but dip at shallower angles of 25–30°. However one vein trends west-northwest, dips 75° towards the south, is over 500 m long and extends to a depth of 110 m (see Figure 3). In addition to wolframite, scheelite and beryl are present in these veins.

The ore mineralogy of all mineralized zones is more or less consistent. The main ore mineral is wolframite, essentially ferberite ($FeWO_4$), accompanied by substantial quantities of fluorite and minor amounts of chalcopyrite, pyrite, arsenopyrite, molybdenite, scheelite, and Bi minerals. The amount and distribution of ferberite in the mineralized bodies is variable. This mineral is often associated with the more quartz-rich zones within the greisenized material, and occurs as disseminated fine to medium grains, or as veinlets and pockets associated with fluorite. Ferberite is locally intergrown with rutile and may show alteration to scheelite and/or goethite. Fluorite is economically important because in places it may have concentrations of up to 20% by volume. Both ferberite and fluorite occur along quartz grain boundaries. These quartz grains are fractured and/or comminuted, and cross-cut by veinlets of turbid material, perhaps clay. Arsenopyrite and pyrite are generally associated with tourmaline and are usually found near the contacts between the Damara granite and the Erongo breccia.

Alteration

Greisen-type alteration has selectively affected rocks of granitic composition, including the Erongo breccia, a sedimentary unit largely derived from granitic rocks. Quartz-biotite schist and mafic rocks, although they may be extensively tourmalinized, are much less affected by greisen-type alteration.

Greisenization is a post-magmatic phenomenon due mainly to hydrogen ion metasomatism (Kinnaird, 1985; Bowden *et al.*, 1984). Shcherba (1970) defined greisenization as 'the high temperature post-magmatic alteration of rocks by volatile-rich fluids associated with the cooling of granitic intrusives'. Burt (1981) defined it as 'hydrothermal alteration of granitic rocks to a mixture of quartz and mica with variable topaz, tourmaline, fluorite, or other fluorine or boron-rich minerals'.

The Krantzberg greisen bodies were formed as a result of the destabilization of K-feldspar, plagioclase, and biotite in the Damara granites and the Erongo breccia. This destabilization took place in the presence of fluids containing hydrogen ions (H^+), fluorine ions (F^-) and boron ions (B^-), leading to acid metasomatism, or greisenization (Bowden *et al.*, 1984). Greisenization is often preceded by alkali metasomatism (e.g. albitization, microclinization). (Kinnaird, 1985; Bowden *et al.*, 1984). Although not recorded at Krantzberg, albitization is common along the northern sectors of the Erongo Complex (farms Etemba and Anibib; Figure 2), where it is spatially and genetically associated with the Erongo granite.

The alteration-mineralization assemblages at Krantzberg were identified by petrographic studies of thin and polished thin sections. This study revealed that there are three main assemblages. They are: (i) quartz + topaz + muscovite; (ii) quartz + topaz + sericite + fluorite ± ferberite ± beryl ± sulphides; and (iii) quartz + tourmaline.

The Krantzberg greisens are composed of quartz (50–60%), topaz (5–30%), tourmaline (up to 30%), fluorite (up to 20%), white mica (muscovite and sericite), chlorite, calcite, and the ore minerals (ferberite and sulphides). The greisen veins hosted in quartz-biotite schist contain less topaz, have higher tourmaline and scheelite, and also contain beryl (Schlögl, 1984). These veins are emplaced in fractures in the schists and may represent a distal and terminal vein stage. The presence of beryl and scheelite in these veins may indicate a lower HF activity in the system (Burt, 1981).

On the basis of textural and field evidence the timing of the alteration-mineralization processes can be broadly subdivided into 4 stages. These occurred in response to advancing degrees of H^+ metasomatism both in time and space, accompanied first by increasing and then decreasing HF activity (Burt, 1981), which led to the breakdown of feldspars and biotites and the growth of new mineral phases. A tentative mineral paragenesis is shown in Figure 5.

The mineralogical changes deduced from petrographic studies are qualitatively outlined below. The main changes that took place during early H^+ metasomatism (the greisen stage in Figure 5) are manifested by the replacement of K-feldspar and plagioclase by quartz and muscovite resulting in the release of Na, Ca, and some K. Biotite is replaced by quartz, muscovite and topaz I, with release of K, Fe, Mg, Ti, and other metals.

Increasing HF activity in the system induced further destabilization of the feldspars which are continuously replaced by topaz I. The end result of this stage is a coarse-grained quartz + topaz ± muscovite assemblage which is largely confined to a narrow zone within and close to the zone of entry of the fluids along the schist-granite contact. With more advanced stages of H^+ metasomatism, the complete destabilization of K-feldspars and plagioclase took place in zones further away from the channel of entry of the fluids. K-feldspar and plagioclase are replaced by quartz + sericite, forming a fine-grained assemblage. Continuing HF activity resulted in granular quartz + topaz + fluorite + ferberite (Figure 6). which replaced the earlier assemblage. In more distal zones biotite is replaced by quartz, chlorite, and pyrite. This is the quartz-sericite-pyrite (QSP) stage in Figure 5.

Late and distal stages of the alteration-mineralization processes occur with decreased HF activity resulting in the emplacement of the greisen veins referred to earlier, and containing quartz + topaz ± ferberite ± fluorite ± beryl ± scheelite.

The quartz + tourmaline assemblages form pervasive replacements (Figure 7) as well as cross-cutting veins and

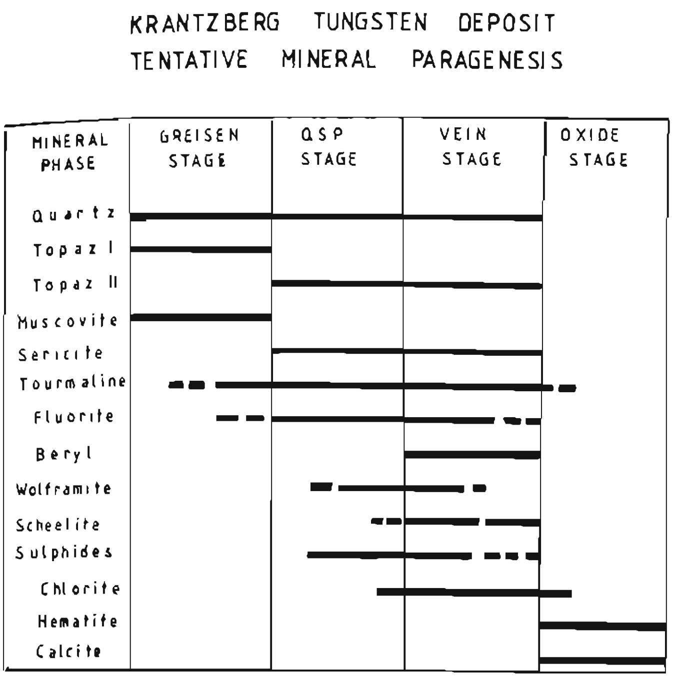

Figure 5 Tentative mineral paragenesis at Krantzberg.

veinlets. Whether this assemblage relates to a continuous pulse throughout, or to a number of sequential but distinct pulses, is not clear. In all cases this tourmalinizatlon is spatially and temporally associated with the emplacement of the Erongo granite, and at Krantzberg it is also spatially and temporally related to ore deposition, and this is confirmed by the geochemical signature of the tourmalines, as explained in the following section.

Geochemistry of tourmaline

In the Krantzberg area tourmaline is one of the most common minerals. It occurs as large crystals in the Damara pegmatites, in veins, stockworks, and replacements in Damara granitoids, in immature Karoo clastic sediments, and in the overlying basaltic lavas of the Erongo Complex. These tourmalines are generally of the schorl variety, as deduced from optical and geochemical determinations (Figure 8,A).

Partial major and trace element analyses of tourmaline separates from the greisen bodies and Erongo granite reported by Schlögl (1984) are shown in Table 1. Plots for selected elements incorporating data from Kujawa (1986) are shown In Figure 8 (A to D). A trend indicating Fe depletion and Mg enrichment is observed from the tourmalines in the Erongo granite to those in the greisen bodies and the metasediments (Figure 8,A). This trend may be a reflection of exchange of Fe and Mg (relative loss and enrichment respectively) during fluid/wall rock interaction with increasing distance of the B-rich fluids from their source, i.e. the Erongo granite. A similar trend is observed in tourmalines from the Brandberg West-Goantagab area (Pirajno, unpublished data).

The WO_3 contents of the Erongo granite tourmalines is low (<4 ppm), whereas concentrations of up to 380 ppm are recorded in the greisen tourmaline. This indicates that the greisen tourmalines are temporally and genetically related to the ore depositing system, which was formed by late-stage hydrothermal fluids segregated from the Erongo granite. A genetic relationship between the greisen tourmalines and the Erongo granite is also indicated by the parallel positive trends displayed for Zr-Y, Rb-Sr, and Th-U as shown in Figure 8, B,C, and D. The Erongo granite tourmalines (samples 6–8, Table 1) may be of an earlier generation, perhaps formed from trapped interstitial B-rich fluids in the nearly consolidated pluton. This is substantiated by their chemical composition, which shows a general depletion in Th, U, Zr, and Y with respect to the greisen tourmalines.

Summary and conclusions

Alteration-mineralization at Krantzberg was probably caused by fluids derived from volatile-rich, fractionated phases of the Erongo granite. This biotite-granite occurs as a series of plutons surrounding the Erongo caldera. Alkali metasomatism (albitization) and hydrogen ion

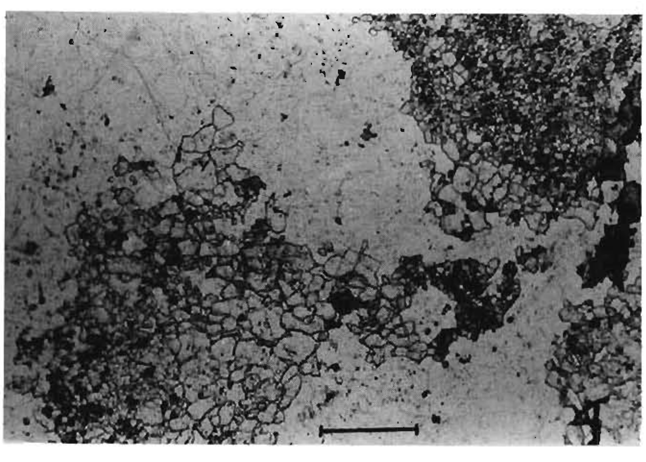

Figure 6 Granular quartz + topaz + fluorite aggregate. Opaque minerals are wolframite crystals. Scale bar is 0,5 mm. Plane polarized light.

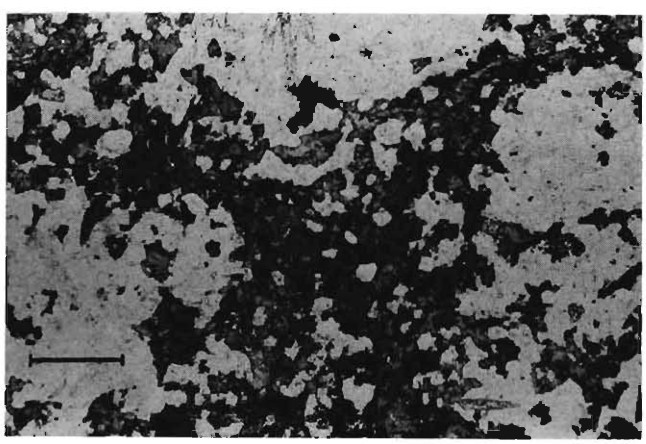

Figure 7 Tourmalinized Erongo breccia. Scale bar is 0,5 mm. Plane polarized light.

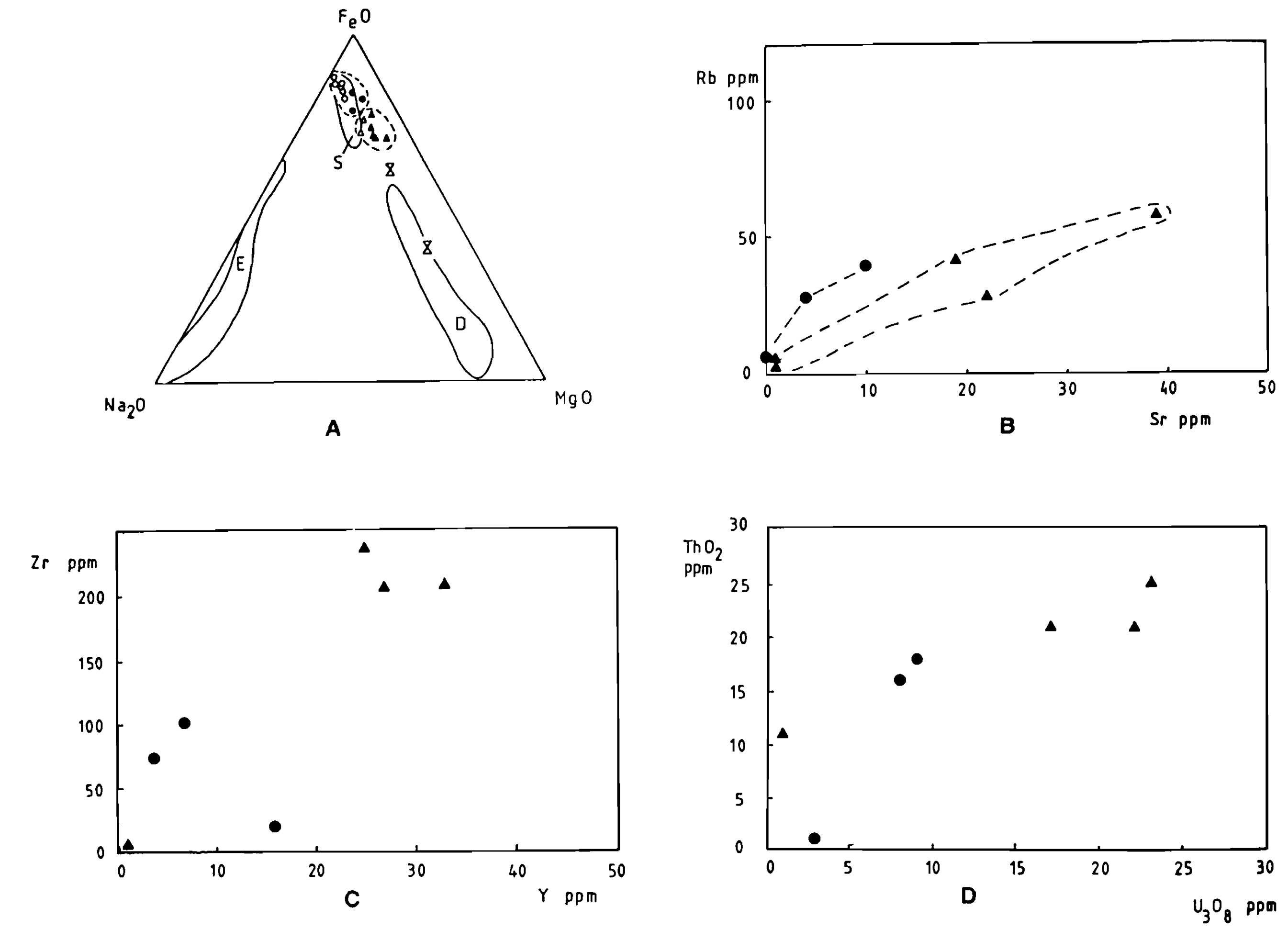

Figure 8 Diagrams showing chemical variations of tourmalines from mineralized greisen rocks and Erongo granite. **A.** A-F-M diagram showing trend of Fe depletion and Mg enrichment in tourmalines from Erongo granite (circles) to greisen rocks (triangles) to metasediments (double triangles). This figure incorporates tourmaline analyses from Kujawa (1986), shown by unfilled symbols. E = elbaite field; D = dravite field; S = schorl field (from Deer *et al.*, 1962). **B.**, **C.**, and **D.** illustrate Rb-Sr, Zr-Y and ThO_2–U_3O_8 plots of tourmalines from quartz-tourmaline nests in the Erongo granite (circles) and greisen rocks (triangles). See text for discussion.

(H^+) metasomatism (greisenization and sericitization) are the dominant features of the post-magmatic activity connected with the Erongo granite. This post-magmatic activity is associated with W, minor Sn, and beryl mineralization (Krantzberg, Etemba, Anibib; see Figure 2). Albitization at Etemba and Amibib occurred in the early stages of post-magmatic activity and was possibly followed by intense degassing involving H^+, B, and F. The effects of H^+ metasomatism in roof country rocks is particularly evident at Krantzberg, where greisen bodies with disseminated ferberite are present. It is thought that the mineralizing fluids streamed out of a fractionated granitic cupola into the overlying country rocks. These fluids moved mainly along existing structural discontinuities such as lithological contacts (e.g. older granite-schist rocks, and the unconformity between the Karoo clastic sediments and Damara sequence rocks). Hydrogen ion metasomatism destabilized the granitic rock-forming minerals (feldspars and micas). New mineral assemblages containing mainly quartz, topaz, white mica, and fluorite were formed, resulting in alteration-mineralization assemblages which largely reflect varying degrees of H^+ metasomatism and fluid-rock interaction.

Therefore the greisen alteration and mineralization event was highly selective, affecting rocks containing granitic minerals (e.g. the Damara granitoids and the immature clastic sediments of the Karoo Sequence), whereas tourmalinization affected all rock types. This is seen, for example, in the basaltic lavas at the top of Krantzberg which are fractured and tourmalinized. Hydraulic fractures, infilled with tourmaline, and tourmaline breccias testify to the high fluid pressure and vigorous expulsion of B-rich fluids. These features are believed to be spatially associated with the tourmaline-rich Erongo granite, which was postulated to occur at depth (Cloos, 1911; 1919; Haughton *et al.*, 1939), and extend several hundred metres laterally and above this granite.

The geochemistry of tourmalines in the Krantzberg area revealed some interesting features. They are generally of the schorl variety and exhibit variations in

Table 1 Partial major and trace element analyses of tourmaline separates obtained from : mineralized greisen rocks (samples 1 to 5); Erongo granite tourmaline nests (6,7) and a fine-grained early phase of Erongo granite (8). Analyses were performed by XRF, data from Schlögl (1984). Values are given in weight per cent for major oxides, and parts per million for trace elements.

	1	2	3	4	5	6	7	8
TiO_2	0,70	0,80	1,30	1,20	0,90	0,90	0,50	0,40
FeO	13,76	11,70	9,77	9,26	7,07	15,60	7,97	5,79
MgO	2,98	2,98	2,98	2,65	2,49	1,49	1,16	0,83
Ca0	0,56	0,70	1,96	2,38	2,94	0,56	0,98	0,84
Na_2O	1,35	1,48	1,21	1,21	0,67	1,62	0,67	0,81
K_2O	0,36	0,36	0,60	0,72	0,72	0,36	0,72	0,96
Ni	14	2	23	18	17	2	5	4
Cu	9	3	54	21	5	3	2	2
Zn	709	604	399	464	79	499	277	204
Pb	16	2	2	3	14	2	22	9
Mo	4	6	2	4	4	12	6	7
Bi	2	6	13	9	62	2	2	2
Sr	1	1	19	22	39	1	4	10
Ba	222	187	159	120	169	209	182	197
U_3O_8	1	1	23	17	22	3	8	9
ThO_2	11	11	25	21	21	1	16	18
Sn	20	18	26	21	91	8	14	
WO_3	76	23	295	243	380	4	4	4
Nb_2O_5	4	2	72	44	24	6	4	5
Zr	1	3	235	205	208	21	75	102
Rb	2	6	41	28	57	6	28	39
Y	1	1	25	27	33	16	4	7

their relative Fe and Mg contents which may be a function of both the increasing distance from the source of the fluids (Fe-rich) and host rock composition (Mg-rich).

The Krantzberg W mineralization consists of greisen-hosted wolframite (variety ferberite) with fluorite, beryl, minor scheelite, some sulphides, and Bi minerals. Vein type mineralization is poorly represented, but this may be a function of the erosion level. The quartz + tourmaline ± fluorite nests of the Erongo granite suggest *in situ* exsolution of a B and F-rich vapour phase from an originally volatile-rich melt. These fluids probably accumulated in the upper regions of the Erongo granite, forming endogreisens, which locally exceeded the confining pressure resulting in hydraulic fracturing and brecciation of the roof rocks. Tungsten metal was probably partitioned into this vapour phase and transported as a halide complex as envisaged by Foster (1977).

Ferberite was possibly formed in preference to scheelite due to high F activity according to the reaction proposed by Burt (1981):

$$CaWO_4 + FeO + 2HF = FeWO_4 + CaF_2 + H_2.$$

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