

Abstract: A study of epigenetic mineralisation in the Central Zone of the Damara orogen, Namibia with special reference to gold, tungsten, tin and rare earth elements

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Epigenetic, rare-earth element, gold, tin and tungsten, mineralisation in the northeast-trending, intracratonic branch of the deeply eroded, late Proterozoic/early Palaeozoic, Pan-African Damara Orogen is hosted by meta-arkoses, marbles and metaturbidites in the magmatic arc (Central Zone; CZ) of the orogen, a tectonostratigraphic entity that is characterised by multiple deformation, green-schist/amphibolite- facies, low -pressure/high-temperature metamorphism and numerous granitic and pegmatitic intrusions. This memoir integrates regional and detailed geological mapping with petrographic studies, whole rock geochemistry (obtained by X-ray fluorescence spectrometry, atomic absorption spectrometry, fire assay and infrared spectroscopy), mineral chemistry studies (electron microprobe and X-ray diffraction) and geochronological work (Rb-Sr whole-rock and mineral age determinations and Pb-Pb model ages) to examine six examples of metasediment-hosted epigenetic mineralisation in the Usakos-Karibib-Omaruru district, central Namibia. The investigated area straddles the magnetically defined Omaruru Lineament, which divides the CZ into southern (SCZ) and northern (NCZ) portions. Geological mapping and lithostratigraphic work support the geophysical evidence for this subdivision: in the SCZ, predominantly continental and shallow marine Damaran metasediments are flooded by a 1.7-2.0 Ga granite gneiss basement inlier, that is transected by numerous east-northeast-trending auriferous megashears. These structures controlled late-Proterozoic mafic dyke emplacement, Damaran rifting and sedimentation, alkaline volcanism and the localisation of hydrothermal fluids in the overlying cover rocks. In the NCZ, where basement inliers are not exposed, the metamorphosed equivalents of Damaran shallow marine carbonates are overlain by deeper water sediments and turbidites. Sedimentation was controlled by rifting, facies belts being oriented parallel to the axis of the orogen. Felsic and mafic volcanic rocks comprise only a fraction (<5%) of the Damara Sequence.

Isoclinal folds in the Damara Sequence provide evidence for extensive crustal shortening across the CZ during early Damaran deformation (D_1 and D_2), but not for significant lateral displacement: facies belts remained essentially where they evolved. D_3 deformation (F_3 folding) and concomitant granite intrusion were re-

sponsible for the north-east-trending structural grain and domal structures of the CZ. Late orogenic semi-ductile and brittle D_4 deformation was confined to the vicinity of major structural breaks such as the north-northeast-trending Abbabis and Welwitschia lineament zones. Buchan-type metamorphic assemblages are described for the first time from central Namibia. Mineral assemblages of metapelitic units have been used to construct a petrogenetic grid for the CZ: results agree well with P/T estimates made from calcite-graphite geothermometry and dolomite-calcite solvus thermometry. Peak metamorphic conditions of ~ 3 kbar and 650°C were attained in the field area at 520 Ma; the geothermal gradient was $55\text{-}65^\circ\text{C}/\text{km}$.

The majority of Damaran intrusions in the CZ are granitic in composition: the economically significant late-orogenic suite is dominated by leucogranites and pegmatites. No Damaran granitoid in the CZ contains any significant sulphide or precious metal mineralisation. Early and late orogenic granites are mildly peraluminous, those granites intruded at the peak of regional metamorphism are strongly peraluminous; most intrusions are S-type, have high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios and $\delta^{18}\text{O}$ values, and do not have a calc-alkaline chemistry. Most plutons have trace element signatures of intraplate granites. Three rare-element pegmatite provinces are present in the CZ: the lithium pegmatite province of the SCZ and the stanniferous pegmatites of the Sandamap-Davib Ost and Nainais-Kohero tin belts in the NCZ. New Rb-Sr whole-rock dates refute recent suggestions that Damaran stanniferous pegmatites have been modified by Jurassic-Cretaceous or post-Karoo greisenising fluids.

At the enigmatic Eureka rare earth occurrence west of Usakos, disseminated magnetite and monazite, both minerals part of a high-temperature assemblage in a dolomite-carbonate rock, are hosted by Etusis Formation quartzites. The monazite mineralisation formed at 500 ± 20 Ma; slightly after the peak of metamorphism, but the carbonate enclosing the monazite has a mantle $(^{87}\text{Sr}/^{86}\text{Sr})_i$ signature. There is no field or petrographic evidence for the presence of a carbonatite intrusion of any size. The Eureka occurrence bears some similarities with the middle Proterozoic Bayan Obo iron-rare earth-niobium deposits in Inner Mongolia, China, that were

formed by the hydrothermal replacement of syn-rift sedimentary dolomite by fluids from a hidden alkaline-carbonatite in an intracontinental rift setting. Mineralising fluids at Eureka probably ascended via deep-seated tectonic breaks such as the Omaruru Lineament and the Welwitschia lineament zone during Etusis times.

At the Otjua Tungsten Prospect north of Omaruru, the largest scheelite-fluorite replacement skarn in Namibia is developed within Okawayo Formation marble in the aureole of the late-tectonic, highly fractionated but unmineralised Otjua leucogranite. Three zones or facies of skarn, successively vesuvianite facies, scheelite-bearing garnet-facies and tungsten-barren pyroxene-facies, represent increasing degrees of replacement of calcitic marble. Systematic changes in mineralogy, mineral chemistry and whole-rock compositions of the skarn facies show that the subvertical calcitic marble acted as a reactive conduit for a channelised mineralising fluid that emanated from a point source at depth. The presence of widely distributed, pre-existing, tungsten/scheelite mineralisation in the metamorphosed marls (scheelite-bearing granofels) of the lower Swakop Group suggests that the Otjua granite, rather than being the source of the fluids as previously suggested, may merely have acted as a "heat-engine" and mobilised fluids from the metasediments within its thermal aureole.

Carbonate-hosted auriferous quartz veins and associated alteration of hydrothermal origin that can broadly be referred to as distal skarn are widespread in the Karibib Formation in the Karibib area. Gold mineralisation is not spatially associated with a particular type of igneous rock: only the ubiquitous lithium pegmatites contain minor sulphide and gold-bearing phases. In the skarn, sulphide minerals include chalcopyrite, sphalerite, pyrrhotite, bismuth and silver tellurides, while silicate alteration commonly comprises massive tremolite and more rarely vesuvianite, garnet and pyroxene. Mineralisation is hosted by late-tectonic, brittle deformation structures and locally thrust faults. The style of alteration and the Au-Bi-As-Te association bears certain similarities to the gold skarns of the western United States. Previous models for the origin of the gold skarn mineralisation of the Karibib area have stressed the importance of the relatively minor mafic volcanic rocks of the Daheim Member as a gold source. New geological mapping and geochemistry emphasise the auriferous nature of the megashears in the underlying granitic basement. Largely circumstantial evidence suggests that the sources for the gold-bismuth mineralisation are hidden, late-/post-tectonic felsic intrusions, specifically lithium pegmatites and/or hydrothermal fluids derived from the basement.

Metaturbidite-hosted gold mineralisation discovered during the course of field work is believed to be of a style previously unknown in southern Africa. A 2500-metre-long zone of gold mineralisation is hosted by altered Kuiseb Formation schist, quartz veins and

mylonite rocks in the aureole of a leucogranite and rare-element pegmatite dome on the farm Sandamap Noord, west of Usakos. Au/As fluids, either mobilised from the metasediments by and/or expelled from the stanniferous pegmatites, were concentrated in north-northeast-trending structures. The three main types of alteration/mineralisation are: a kaolinite-alunite rock (advanced argillic alteration) that contains <1 g/t Au, a jarosite schist that contains up to 46 g/t Au and a massive grunerite rock that contains up to 0.5 g/t Au. Associated alteration includes a massive calcite-graphite-tourmaline rock and galena- and pyrite-bearing quartz veins. Some of the high strain zones surrounding the domal structure formed during the diapiric intrusion of the granites and pegmatites and are thus unrelated to the regional tectonism, but only the north-northeast-trending portions are mineralised with gold. The gold zone lies within 10 km of the north-northeast-trending Welwitschia lineament zone which played an important role in the localisation of late-/post-tectonic uraniumiferous alaskites at the Rössing Uranium Mine. The mineralisation on Sandamap Noord has similarities with Archaean mesothermal gold deposits: epigenetic Au-As-W mineralisation is structurally controlled in late-tectonic (D_3/D_4) structures; the wallrock alteration is retrograde with respect to peak metamorphism; the mineralisation is "gold-only" with high gold enrichment factors (10^3 - 10^4), moderate enrichments of As, B and W and low enrichment Cu, Zn and Pb.

A structural analysis of metaturbidite-hosted tourmalinites on the farm Ohere, west of Omaruru revealed that, although tourmalinite is a stratiform rock on the decimetre scale, this type of mineralisation is confined to the hinge of an F_2 fold. Elsewhere tourmalinites are oriented parallel to an axial planar s_2 fabric and commonly occupy kink bands. The subvertical s_2 cleavage in the aureole of a granitoid provided a channel way for boron-rich fluids resulting in the selective replacement of schist and formation of crosscutting tourmalinites. Subsequent replacement of the metaturbidites along the essentially bedding-parallel s_1 fabric in the hinge zone led to the formation of stratiform tourmalinites. Tourmalinites contain significant B-F-W-Sn mineralisation: scheelite is present, but no tin or fluorine phases have been identified. A mass balance calculation shows that the elements Si and Zr remained stationary during boron metasomatism, there was a net introduction of the elements B, C, Al, Mg, Na, Ca, F, S, Sr and V and a net loss of the elements H, K, Fe, Ba and Rb. The amount of transfer of elements (in $\mu\text{mol g}^{-1}$) during the tourmalinisation on Ohere was not too dissimilar from that reported in North America and was caused by a fluid derived from a granitic or pegmatitic melt. An exhalative origin for the CZ tourmalinites, a currently popular model for tourmalinites in general, is rejected.

Scheelite-bearing vesuvianite-quartz skarnoid rocks in the Kuiseb Formation on the farm Ohere represent a significant stratiform tungsten reserve that has cer-

tain characteristics in common with the Corruga-type, scheelite-bearing, bedded calc silicate lithologies of the Broken Hill District, Australia. In Namibia, they are regional metamorphic rocks with a skarn-like mineral assemblage occurring as poorly layered to massive, discontinuous lenses several hundreds of metres in length and contain significant concentrations of W, Sn, Zn and F. Petrography and electron microprobe analysis of small (< 50 µm) reddish-brown inclusions in sphene revealed the presence of stanniferous rutile and an unidentified zirconian titanium mineral. This lithology is a type of metamorphogenic skarn whose development is related to the Buchan-style metamorphism that affected the area. There is no evidence that vesuvianite rocks are metamorphosed coticule rocks as has been suggested for the morphologically similar Australian examples.

The currently fashionable Andean-type collision model involving the northwestward subduction of the Kalahari Craton below the Congo Craton is unsuccessful in explaining the continental nature and paucity of the CZ magmato-hydrothermal deposits. The epigenet-

ic mineral occurrences of the CZ have a strong intracratonic signature and bear some similarities with the Sn, W, Mo and U deposits of back -arc magmatic belts of the Eastern Cordillera of Bolivia and the Western Tin Belt of Thailand and Burma. Partial melting of pre-Damaran crust and the mobilisation of fluids from these inliers and the Damaran metasediments played the most important role in producing the relatively small, epigenetic gold, tin and tungsten deposits of the CZ. Late-tectonic, dextral movement on the Omaruru Lineament is believed to have been the underlying control on the localisation of late-D₃/D₄ epigenetic mineralisation. Peak metamorphic temperatures increased along the axis of the orogen from northeast to southwest: the Usakos-Karibib-Omaruru area lay within the 400°C-700°C "window", spanning the greenschist amphibolite facies transition. Thermal conditions were ideal for the emplacement and preservation of late-tectonic pegmatites and high-temperature skarns (400-650°C) and at a later stage, because of the rapid uplift, lower temperature (< 300°C), epigenetic vein-type mineralisation.