Mineralogical and radiometric studies of monazite and sphene occurrences in the Namib Desert, South-West Africa

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[Taken as read 23 September 1965]

Summary. Monazite and sphene from the central zone of the Damara orogen of South-West Africa, have yielded ages of 500 ± 20 Myr and 600 ± 25 Myr respectively; these results are discussed in relation to the late Precambrian to early Palaeozoic tectono-thermal history of the region. Although chemically similar to that found in carbonatites, the monazite is probably genetically related to the widespread granitic pegmatites that characterize the central zone of the orogen.

IN 1959, during the course of geological investigations in central and northern South-West Africa, a number of pegmatite and related mineral occurrences were studied. Of these, monazite and sphene from Farm Eureka and the Khan mine respectively are of particular interest in that they provide new U–Th–Pb ages that have a bearing on the late Precambrian to early Palaeozoic tectono-thermal history of the territory.

The monazite deposit has recently been described by von Knorring and Clifford (1960); it is, however, germane to discuss more recent chemical data that have a bearing on the origin of this unique rock. In addition, previously published data on the paragenetical mineralogy of the Khan pegmatite, notably by Söhnge (1939), are supplemented by a new chemical analysis of the constituent sphene and petrographic descriptions of the pegmatite host.

Regional setting

The dominant feature of the structure of South-West Africa is the orogenic folding of the widespread rocks of supposed Upper Proterozoic

age (Martin, 1961). Two distinct but correlative facies are recognized
in the rocks of that age: the Otavi Facies in the north and north-east,
an essentially unmetamorphosed carbonate–arenite sequence; and the
Damara Facies in the north-western and central parts of the territory, a
regionally metamorphosed succession of pelitic and arenaceous rocks
with a carbonate marker horizon. In central and south-eastern South-
West Africa a further sequence of rocks that is undoubtedly correlative,
in part at least, with these facies includes the Tsumis–Auborus Series
and the Nama System.

Of these extensive rock sequences, the Damara Facies occupies two
structural zones: a NE.–SW. trending segment from the coast to the
Kalahari Desert; and a roughly north to south trending segment parallel
to the coast (Du Toit, 1954). Within the north-east-trending segment,
the generalized stratigraphic sequence of this facies is, from oldest to
youngest: Quartzite Series; Marble Series with Tillite Horizon; and
Khomas Series (*ibid.*). This segment is, moreover, characterized by a
central zone profusely intruded by granite and pegmatite and exhibiting
the effects of high-grade regional metamorphism with the development of
cordierite, scapolite, wollastonite, and sillimanite. To the south of this
central zone, the correlative metasediments are characterized by the
Barrovian index minerals garnet, kyanite, and staurolite; while to the
north, scapolite-, garnet-, and epidote-bearing assemblages are, ap-
parently, more common. Further to the north, the Otavi Facies and its
underlying crystalline basement have, in certain areas, undergone the
low-grade (biotite–chlorite) effects of this regional metamorphism
(Clifford, Nicolaysen, and Burger, 1962).

Published radiometric ages from the north-east-trending segment of
the Damara orogen fall within the range 450–570 Myr and include
U–Th–Pb and Rb–Sr ages of pegmatite and granite minerals from the
central zone (Nicolaysen, in Holmes and Cahen, 1957; Jamieson and
Schreiner, 1957; and Burger and Nicolaysen, in Clifford *et al.*, 1962),
Rb–Sr ages of biotite and biotite+chlorite from the pre-Otavi granite
in the low-grade metamorphic zones of the Otavi Facies (*ibid.*), and five
K–Ar ages of biotites from the metasediments of the Khomas series of
the Damara Facies (Clifford, 1963).

Monazite from Farm Eureka

Field and petrological studies. This deposit is situated some 21 miles
WNW. of Usakos and has been described by von Knorring and Clifford

(1960). The monazite occurs as randomly orientated reddish-brown platy crystals or aggregates embedded in a coarse dolomitic marble belonging to the Marble Series of the Damara Facies.

The groundmass of this rock consists largely of dolomite, with about 5 % of calcite and 5 % of accessory constituents. The monazite varies in size from minute rounded grains to handsize crystals, and its presence within the marble of the Damara Facies, in the profusely pegmatized central zone of the north-east-trending segment of the Damara orogen, led to the conclusion that the '. . . marble host rock . . . acted as a reservoir for migrating liquors bearing rare-earths and phosphorus . . . related to the regional phase of pegmatite emplacement' (*ibid.*, p. 652). The random orientation and coarse grainsize of the monazite indicate that mineral growth post-dated the principal orogenesis of the Damara metasediments in that area; the larger crystals are, however, bent and fractured, indicating a degree of post-crystallization deformation at a late tectonic date.

Although the monazite occurrence is areally associated with granitic pegmatites, it has been pointed out that in its high Ce and La and low Th contents the monazite has greater chemical affinities with carbonatite monazites than with granitic (pegmatitic) monazites. It is of added interest to note that the dolomite matrix of the rock is surprisingly high in strontium; a partial analysis of this matrix has given: CaO 24·00, MgO 15·00, SrO 3·47 % (analyst: O. von Knorring).

Turekian and Kulp (1956) found that the average strontium content of limestones is 610 ppm. In addition, trace-element data by Weber (1964) show that the mean strontium content of sedimentary dolostones and dolomites is less than 200 ppm. Clearly, the composition of the Eureka carbonate reflects the addition of strontium to the dolomite of the Marble Series.

Similar monazite-bearing carbonate rocks have been described by Heinrich and Levinson (1961) from Ravalli County, Montana, U.S.A., where the carbonate rocks contain important amounts of strontium (Sr) up to 1·7 % by weight; cautiously, Heinrich and Levinson then conclude (p. 1445) that the deposits are '. . . alkalic-type hydrothermal lodes and veins generally developed in compositionally favorable layers of marble'.

Radiometric dating studies. A small concentrate of the Eureka monazite was magnetically purified. The powdered sample was then processed in a manner almost identical with that employed by Tilton *et al.* (1957). Dithizone extraction of the lead failed, however, due to

the presence of excess rare-earth phosphates, and could only be effected after the introduction of a Dowex AG 50 cation column.

The isotope concentrations were determined by application of the stable-isotope dilution technique (Inghram, 1954). A 12-inch radius of curvature, 60° sector-field mass spectrometer, utilizing surface-ion emission and ion detection by means of an electron multiplier, was used to determine the relative compositions and concentrations. The suitability of this instrument for micro-quantitative studies of Pb, U, and Th was efficiently demonstrated by Burger (1959). As a result of the low concentrations encountered throughout this work, special care had to be exercised to limit laboratory contamination.

The isotopic compositions used for primary lead corrections were taken from the curves of Cummings *et al.*, given by Wilson *et al.* (1956): $^{206}Pb/^{204}Pb = 18.0$, $^{207}Pb/^{204}Pb = 15.8$, and $^{208}Pb/^{204}Pb = 38.2$. The following values of the decay constants and isotope ratios were used to calculate the isotope ages: $\lambda^{235}U = 0.972 \times 10^{-9}$ yr.$^{-1}$, $\lambda^{238}U = 1.54 \times 10^{-10}$ yr.$^{-1}$, $\lambda^{232}Th = 4.88 \times 10^{-11}$ yr.$^{-1}$, and $^{235}U/^{238}U = 137.8$ (Stieff *et al.*, 1959, p. 2).

The concordant age pattern presented by the data in table I marks a rare occasion in age measurements on monazites, and irrefutably dates the Eureka monazite at 500 ± 20 Myr of age.

Sphene from the Khan mine pegmatite

Field and petrological studies. The Khan pegmatite is situated 35 miles ENE. of Swakopmund, and is one of the few copper-bearing deposits of any importance within the regime of the Damara Facies in the central zone of the Damara orogen. Söhnge (1939, 1958) and Smith (1962) have presented descriptions of the deposit and have summarized previous work; the field setting and general paragenesis of the pegmatite described below are drawn from these published data modified by more recent field observations.

The Khan pegmatite is a tabular body up to 8 feet in width and some 1100 feet in length. It dips north-westwards in concordance with the dip of the enclosing calc-silicate granulites of the country rock (Smith, 1962). Mineralogically, it consists of microcline, quartz, pyroxene, hornblende, and albite. Accessory minerals include sphene, apatite, and zircon; in addition, calcite, wollastonite, and garnet are locally present.

The country rocks belong to the Khan Quartzite horizon of the Quartzite Series of the Damara Facies (Gevers, 1934; Smith, 1962) and are a sequence of massive-bedded calc-silicate granulites composed of quartz,

TABLE I. Analytical data for Eureka monazite and Khan sphene

Sample	Concentrations (Weight %)			Isotopic Ratios			Calculated Ages (Myr)			
	U	Th	Pb	$\frac{206\text{Pb}}{204\text{Pb}}$	$\frac{207\text{Pb}}{204\text{Pb}}$	$\frac{208\text{Pb}}{204\text{Pb}}$	$\frac{207\text{Pb}}{206\text{Pb}}$	$\frac{207\text{Pb}}{235\text{U}}$	$\frac{206\text{Pb}}{238\text{U}}$	$\frac{208\text{Pb}}{232\text{Th}}$
Monazite										
Sample L1	0·01888 ±0·0004	0·670 ±0·02	0·0170 ±0·0003	202·0 ±4·0	26·2 ±0·5	2060·6 ±40·0	490 ±20	520 ±20	520 ±20	510 ±20
,, X1				138·2 ±2·0	22·8 ±0·5	74·2 ±1·5				
				114·3 ±2·2	21·5 ±0·4	64·7 ±1·3	570 ±30			
Sphene										
,, X2	0·0669 ±0·002	0·0685 ±0·002	0·00906 ±0·0002	140·8 ±2·1	23·3 ±0·3	74·8 ±1·3	660 ±30	530 ±40	500 ±40	460 ±30
,, L3				84·3 ±1·3	20·0 ±0·2	56·4 ±0·8				
,, X3	0·0492 ±0·002	0·0496 ±0·002	0·00622 ±0·0002	561·8 ±8·0	48·3 ±0·5	186·5 ±2·0	610 ±25	590 ±30	590 ±30	500 ±30

K-feldspar (microcline, orthoclase), plagioclase, and epidote; diopside, scapolite, calcite, and garnet have all been identified in varying amounts. Gevers (1934, p. 303) considers that these rocks are the products of metamorphism of calcareous sandstones.

The presence of calc-silicate minerals (diopside, garnet, wollastonite, sphene, etc.) in the Khan pegmatite reflects the reaction between the pegmatite and the calcium- and magnesium-bearing country rocks. Subsequent hydrothermal activity produced amphibole and other hydrous phases; during and after this activity, the pegmatite was subjected to deformation prior to the deposition of the main ore minerals bornite, chalcocite, and chalcopyrite (Söhnge, 1939, p. 31).

Sphene is widely distributed as an accessory in the pegmatite; one particularly spectacular specimen containing individual twinned euhedral crystals up to 3 inches in length is the source material for the chemical and radiometric dating studies presented below. Excluding the sphene, the pegmatite specimen consists largely of a graphic intergrowth of quartz and feldspar, with large euhedral crystals of diopside. The quartz shows strong strain-shadowing and cataclastic fracturing. The feldspar is largely oligoclase-andesine (Ab_{65-70}) and is sericitized and epidotized for the most part, but still shows obvious twin lamellae and antiperthitic inclusions of microcline; post-crystallization deformation of the plagioclase is indicated by the bent twin lamellae. The large crystals of diopside are rimmed by and have inclusions of tremolite and hornblende, both of which are in optical continuity. Traversing the rock are numerous small fractures filled with calcite and an unidentified fine-grained brown mineral.

A large crystal of sphene from this sample, measuring $7 \cdot 5 \times 2 \cdot 7 \times 0 \cdot 8$ cm., was analysed and gave: SiO_2 30·08, TiO_2 34·49, $Al_2O_3 + R_2O_3$ 5·44, FeO 2·15, MnO 0·05, MgO 0·31, CaO 27·08, Na_2O 0·24, K_2O 0·03, H_2O+ 0·36, H_2O- 0·06, total 100·29 % (analyst: O. von Knorring); R_2O_3 in this analysis is mainly rare-earths.

Radiometric dating studies. Powdered samples of a large sphene crystal measuring several centimetres in length were leached for half an hour in boiling $6N$ HNO_3. Both the leach solution (L) and the leached sphene (X) were chemically processed following procedures similar to those outlined by Tilton *et al.* (1957). Because of the interference, particularly of silica, a third sample ($X3$) was dissolved in a hydro-fluoric–hydrochloric acid mixture. Isotope concentrations were determined by application of the stable-isotope dilution technique (Inghram, 1954). Thallium and bismuth were extracted from the solution by means

of a Dowex AG 1–X8 ion exchange column. To minimize laboratory contamination, all chemical procedures for sample (X3) were confined to a dust-free laboratory in which favourable conditions were established by a positive pressure of air purified by mechanical and electrostatic filters. Other experimental and analytical procedures were identical with those employed for the Eureka monazite. The isotopic composition
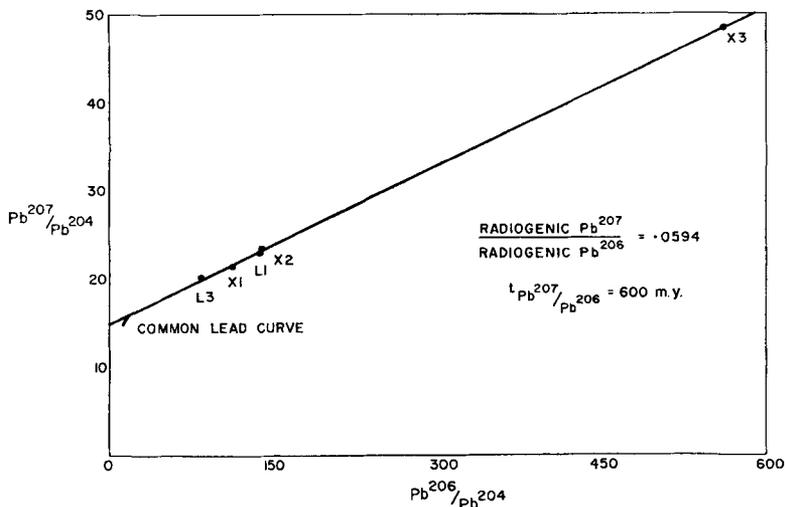

FIG. 1. Pb isotopic ratios of Khan sphene (X) and HNO_3 leach solutions (L); see table I for analytical data.

of the primary lead was taken as $^{206}Pb/^{204}Pb = 17.8$, $^{207}Pb/^{204}Pb = 15.8$, and $^{208}Pb/^{204}Pb = 37.9$.

The lead isotopic ratios for leached sphene (X) and leach solutions (L), listed in table I, are presented on a graph of $^{207}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ in fig. 1. The straight line through these points indicates that these samples represent the addition of a radiogenic lead (generated within the sphene and characterized by the ratio radiogenic ^{207}Pb/radiogenic $^{206}Pb = 0.0594$) to a particular primary lead. This graphical procedure yields an age of 600 ± 25 Myr for the sphene.

Although the three calculated Pb–Pb ages for (X1), (X2), and (X3) differ considerably, the experimental error in the mass-spectrometrical analyses was such that the significance of these differences is uncertain. The U–Pb ages of sample (X2) may have been influenced by laboratory procedures and conditions, especially when compared with the

concordant array exhibited by sample ($X3$), which was processed in a dust-free laboratory. However, the predominant lead loss experienced by sample ($X2$) could also be attributed to sublimation during the borax fusion. Davis *et al.* (1962) showed that borax fusions could be made without loss of lead below a temperature of 1020° C; above that temperature, however, loss of 5–10 % of lead could result from fusion for periods of an hour or longer (Tilton *et al.*, 1957). Furthermore, relatively low ^{208}Pb/ ^{232}Th ages have become a common feature of U–Th–Pb patterns and their usefulness is questionable because of the difficulties encountered in the evaluation of the age discrepancies (Stieff *et al.*, 1963).

In the light of these considerations, it is evident that an age of 600 ± 25 Myr for the Khan sphene by the graphical procedure is consistent with the data presented above (table I).

Conclusions

In southern Africa, major zones of late Precambrian to early Palaeozoic orogenesis broadly follow the present coastline. In addition, an important 'transcontinental' segment trends NE.–SW. from South-West Africa into central Africa (Clifford, 1963); the north-east trending prong of the Damara orogen in South-West Africa forms the south-western end of this 'transcontinental' segment. Widespread radiometric ages in the range 450–650 Myr (Cahen, 1961) reflect the most recent regional impress of tectono-thermal episodes within this system of orogenic belts.

Monazite and sphene from the central zone of the Damara orogen in South-West Africa yield ages of 500 ± 20 Myr and 600 ± 25 Myr respectively. Previously published radiometric studies of the principal tectono-thermal imprint within the orogenic zone have yielded U–Th–Pb, Rb–Sr, and K–Ar ages of 510 ± 60 Myr, which reflect the imprint of the *Damaran episode* (Clifford *et al.*, 1962). The regional extent of the effects of this episode have been discussed elsewhere (Clifford, 1963), and it has been tentatively suggested that the main orogenesis took place during the interval 500–550 (570) Myr ago (Clifford, 1964).

The age of the Eureka monazite falls within the age range of the Damaran episode. Even so, the crystal form indicates that the growth of this mineral post-dated the principal orogenesis of the Damara Facies; the larger crystals do, however, show a degree of post-crystallization deformation of a late tectonic date and add some support to the lower age limit of the main orogenesis of the Damaran episode given above.

There is evidence in the chemistry of the monazite and in the high strontium content of the host carbonate that the Eureka monazite

occurrence has 'carbonatitic' affinities. However, a genetic connexion with the regionally developed granitic pegmatites is supported by their areal association and similarity of radiometric age. The 'alkalic' affinities of the monazite rock were presumably imprinted by migrant liquors genetically related to the pegmatites. If this was the case, caution must be exercised in the use of monazite chemistry or the strontium content of carbonates in support of a carbonatite origin for carbonates of doubtful kinship elsewhere in the world.

It should be noted that, within the north-east-trending segment of the Damara orogen, carbonatite complexes do occur as members of a post-Triassic suite of volcanic and plutonic igneous rocks. The plutonic representatives include: plutons of granitic composition; differentiated basic complexes; and carbonatitic complexes (Martin, Mathias, and Simpson, 1960). Biotite from an aquamarine-bearing drusy cavity in the Klein Spitzkop granitic pluton has been dated for one of us (T. N. C.) by Dr. J. A. Miller of Cambridge; the K–Ar age of 190 ± 8 Myr yielded by this mica, together with the stratigraphical evidence from other complexes, precludes a genetic connexion between this suite of subvolcanic complexes and the Eureka monazite dated at 500 ± 20 Myr.

In addition to the Damaran episode, there is evidence within the zones of late Precambrian to early Palaeozoic orogenesis in southern Africa of an earlier episode, which affected Upper Proterozoic and older rocks prior to the Damaran episode. This earlier event is reflected by ages in the range 580–660 Myr and includes the effects of the Katangan orogenic episode of central Africa, and the West Congolian orogeny of the Lower Congo region (Cahen, 1963). The age of 600 ± 25 Myr yielded by the sphene from the Khan mine falls within this Katangan episode range, and is a particularly significant date in view of the fact: that the pegmatite is regarded as syntectonic; that the age represents the first published evidence of the effects of the Katangan episode in the regime of the Damara Facies in South-West Africa; and that the age confirms the Precambrian age of at least the lower part of the Damara Facies.

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[Manuscript received 1 January 1965]