The Rössing Uranium Deposit, South West Africa

J. Berning, R. Cooke, S. A. Hiemstra, and U. Hoffman

Abstract

The Rössing uranium deposit is located in the Namib desert about 40 miles northeast of Swakopmund, South West Africa.

The uranium mineralization is associated with a syntectic alaskite that shows wide textural variations ranging from aplitic, granitic, to pegmatitic and that evidences concordant, discordant, and replacement relationships to the heavily folded gneisses, schists, marbles, and limestones of the Khan and Rössing Formations.

The uranium-bearing minerals are mainly uraninite and its alteration products with minor betafite. The winning of uranium will be effected by a sulfuric acid leach followed by ion exchange, solvent, extraction, and ammonia precipitation.

Introduction

The Rössing uranium deposit is located some 40 miles northeast of the town of Swakopmund in South West Africa at approximately latitude 22°25' South and longitude 15°01' East.

The area has a desert climate, dry and at times dusty, with rather large variations in temperature and humidity. Although precipitation is infrequent and averages only 1/2 inches per annum, rainfall of short duration and of high intensity may occur. The mean elevation above sea level is 1,890 feet. Temperature ranges between 40° and 104° F (4.5° and 40° C) and humidity between 5 and 80 percent.

Communications are good, as the rail and tarmac road from the port of Walvis Bay to the interior pass within 7 miles of the deposit. Swakopmund, the nearest town, has a population of 10,000.

The presence of radioactive minerals in the Rössing area has been known since 1928 when Captain Peter Louw and his wife Margery conducted an autoradiography test on a sample of rock found some 12 miles west of the Rössing deposit. During the period 1955 to 1958 the area was investigated by a South African mining company that located a number of radioactive locales upon one of which limited diamond drilling and underground exploration was undertaken. In August 1966 Rio Tinto South Africa Limited acquired the rights to explore for source materials.

The investigation of the Rössing deposit by Rio Tinto commenced in September 1966 and was completed in March 1973. The work included radiometric surveys, geological mapping, percussion and diamond drilling, laboratory-scale testwork on bore-hole cores, underground bulk sampling, pilot plant testwork and geological, mining, metallurgical, and engineering studies. The phasing of some of these operations is schematically shown in Figure 2.

This investigation indicated the existence of a very large, low-grade deposit that will be mined by a low-cost openpit method which, coupled with relatively simple extractive metallurgy, renders the deposit viable. Mine preparation and plant construction commenced in October 1974 and production of uranium is scheduled for July 1976.

Exploration Program

The following techniques were used to determine the spread of uranium mineralization on surface and the grade and distribution of ore and waste to a vertical depth of 1,000 feet which is the planned depth of the openpit.

Radiometric surveys: Both ground and airborne surveys were undertaken using, respectively, a Berthold LGS/C portable scintillometer and a Hammer three-crystal gamma ray spectrometer. A Gulf
fluxgate magnetometer measuring the total magnetic field was phased in with the aerial survey.

The ground survey was confined to 75-sq-mile area that was blanketed with readings taken at 100-ft intervals along traverse lines spaced 300 ft apart, with the probe held 18 in. above ground level. This delineated the Rössing deposit.

Subsequently a larger area 300 sq miles in extent was flown at quarter-mile spacings at an elevation ranging from 350 to 500 ft above surface.

**Geological mapping:** Plane table mapping, to a scale of 1:1,000, was undertaken over an area of 1.5 sq miles that covers the Rössing deposit. Elevation contours at 10-ft intervals were determined and plotted on the geological map that proved to be indispensable when interpreting drill sections and projecting geology and ore grades to the proposed pit bench plans.

**Metallurgical and mineralogical investigations:** Routine beneficiation tests and mineralogical studies of borehole core commenced at an early stage of exploration and provided incentive toward furtherance of the program. This work was undertaken, on a contract basis, by the South African National Institute for Metallurgy.

**Drilling:** Scout percussion drilling was used to determine the near-surface distribution of uranium and involved 250 incline holes aggregating to 30,000 ft. The average incline depth was 120 ft, although individual holes measured as much as 200 ft. An Atlas Copco BVB 14 wagon drill, coupled to a 600 c.f.m. compressor, was used and the spoil collected in a venturi/cone.

A major program of core drilling was initiated in May, 1967, and completed in June, 1971. One hundred and seventy-seven incline holes, aggregating in depth to 182,000 ft, were drilled. The first phase involved drilling at 400-ft centers, along north-south-trending traverse lines spaced 400 ft apart, to a vertical depth of 500 ft. The second phase reduced the borehole spacing to 200 ft along the same traverse lines, but the holes were drilled to a vertical depth of 1,000 ft. Two deeper holes were then drilled to 1,500 ft to probe continuity of mineralization below the planned bottom of the pit. The holes were inclined -45° north, excepting in certain instances where the topography necessitated modification to the angle of the holes. The drill pattern along a single traverse is schematically illustrated in Figure 3, and the drilling progress in Figure 4.

The Bx core (diameter 1.65 in.) yielded good recovery. The holes were surveyed at 10 ft and 100 ft from surface, and thereafter at 200-ft intervals.

**Core sampling, analyses, and extraction tests:** Cores were halved using conventional chisel splitters; one half was kept for record and the other half used for analyses and metallurgical testwork. Five-foot lengths of half-core were crushed to minus ¼ inch and then quartered by means of sample splitters to 12-oz fractions. These were pulverized to 50% minus 200 mesh prior to radiometric analysis.

The samples were analyzed for $U_3O_8$ content by means of a scintillation counter, but every tenth sample and all those of high $U_3O_8$ content were checked by chemical analysis. The amount of sulfuric acid required for uranium extraction, plus that consumed by lime and pyrite in the gangue, was determined for each sample. The specific gravity of core fragments, taken at 10-ft intervals, was determined on a routine basis.

**Underground bulk sampling:** The sinking of a 12-ft-diameter, 375-ft-deep shaft was commenced in May 1970 and the full program of bulk sampling completed in December 1971. Crosscut development from east-west-oriented drifts extending from the bottom of the shaft was undertaken along the trace.
of some surface drill sections. A total of 9,012 ft of underground development, measuring 8 × 7 ft in cross section, was accomplished. All this development was preceded by horizontal drilling (Bx Core) with the object of classifying formations intersected into waste and ore, so that each development round could in advance be assigned to the ore stockpile or waste dump.

This program enabled comparisons to be made between tonnage and grade figures derived from surface drilling with those indicated by underground drilling and development. The results tallied closely. Furthermore, additional information relating to stratigraphy, structure, uranium distribution, waste/ore ratios, and the spread of the alaskitic ore in depth was obtained.
Fig. 5. Drill section zero showing geology, boreholes, and bulk sampling crosscut.
Figure 5 depicts a sectional view of geology as extrapolated from surface mapping, boreholes, and underground development.

**Regional Geology**

The Rössing uranium deposit lies within the central zone of the late Precambrian Damaran orogenic belt that occupies much of northern South West Africa and trends in a northeasterly direction possibly to merge with the Zambezi Belt (Anhaeusser and Button, 1974). Figure 6 depicts this setting and Figure 7 the geology around the uraniferous area.

The stratigraphic column is listed in Table 1, from which it is evident that the early Precambrian Abbabis Formation is overlain unconformably by the Etusis Formation of the Nosib Group. The Abbabis rocks, which include variegated gneisses, phyllites, recrystallized carbonates, and biotite schist, are exposed in the cores of anticlinal and domal structures developed in the younger cover and display intense deformation and high-grade metamorphism (Martin, 1965).

The sediments of the Etusis and Khan Formations consist of psammitic, pelitic, and calcareous strata that are overlain by rocks of the Hakos subgroup. These are divided into the Rössing, Chuos, Welwitsch and Khomas Formations that consist of marble, biotite-cordierite gneiss, conglomerates, and feldspathic quartzites. Still higher in the sequence occur the quartz-biotite schists of the Khomas Formation.

Various types of granitic rocks were generated by syntexis and emplaced into the Damara sequence during and after the Damaran orogeny some 510 million years ago (Clifford, 1967). Dolerite dikes of Triassic age are prevalent.

The Rössing Uranium deposit is situated on the southwesterly flank of a major domal structure that is clearly visible on ERTS photographs.

**Geology and Structure of Mineralized Area**

The deposit occurs in a migmatite zone in which uraniferous alaskitic granite/pegmatites and metamorphosed country rock show concordant, dis-
Fig. 7. Generalized geological plan of the Rossing uranium deposit.
cordant, and gradational relationships. The country rock comprises deformed metasediments as well as metavolcanics, whilst the alaskitic rocks range from small quartz-feldspathic lenses of secretion origin to large intrusive and replacement bodies differing widely in texture, size, and emplacement habit. Some may measure many hundreds of feet (Fig. 11).

**Etusis Formation**

Ringing the intensely granitized core of the domal structure located north of the uranium deposit is a prominent band of feldspathic metaquartzite. Despite the high degree of recrystallization and metamorphism, small-scale cross-bedding structures are excellently preserved throughout this unit, affording useful top and bottom criteria. Smith (1965) quotes the composition of this rock as being 64.4% by volume quartz, 25.6% microcline-perthite, 2.3% plagioclase, 3.0% muscovite, and 5.2% accessory ore, zircon and apatite. A thick succession of biotite-gneiss constitutes the next rock shell surrounding the dome. The dominant minerals present are quartz, plagioclase, potash feldspar, biotite, and opaque oxides. In addition to having been migmatized, largely along the planes of gneissosity, late- to postkinematic uraniferous alaskite has invaded much of the biotite gneiss on a massive scale.

**Khan Formation**

In the gneisses of the Khan Formation clinopyroxene and hornblende are the main dark minerals, whereas in the gneisses of the Etusis Formation biotite prevails. The resultant change in color from greenish to grayish makes it possible to map the contact. Four metasedimentary subunits can be distinguished:

1. lower pyroxene-hornblende gneiss
2. pyroxene-garnet gneiss
3. upper pyroxene-hornblende gneiss
4. biotite-amphibole schist

The lower pyroxene-hornblende gneiss is a migmatitic, banded rock consisting of 16.3% quartz, 47.6% plagioclase, 16.4% clinopyroxene, and 2.4% opaque oxide. Clear metamorphic banding is occasioned by the alteration of dark green hornblende-rich and pale green clinopyroxene-rich layers. The banding is accentuated by the presence of metamorphically secreted granodioritic lenses along the bedding planes.

Like the Etusis gneisses, the lower pyroxene-hornblende gneiss is favored as a site for the emplacement of alaskite in the form of countless veins and dikes, usually parallel to the foliation but also transgressing at any angle.

An interbed of pyroxene-garnet gneiss is present between the upper and lower pyroxene-hornblende gneisses and shows metamorphic banding in the area east of the deposit, whereas to the west it has a massive and mottled appearance. It contains 20.4% quartz, 19.5% potash feldspar, 17.5% clinopyroxene, 5.4% calcite, 10.7% Ca-garnet, and 1.7% sphene.
The calcite present here is peculiar to this rock type and distinguishes it from other gneisses present in the Khan Formation. It carried discontinuous massive bodies and lenses of amphibolite that are exposed in the northwestern prong of the uranium deposit and that have been intersected in drill holes in the eastern sector of the orebody as well. This amphibolite contains 2.1% quartz, 44.4% plagioclase, 50.9% hornblende, 1.1% biotite, 0.4% opaque oxide, and 1.2% sphene. In the upper pyroxene-hornblende gneiss, the amount of amphibole increases at the expense of clinopyroxene, and a banded appearance caused by migmatization products being orientated parallel to the foliation of the gneisses is evident.

The topmost member of Nosib Group is a prominent biotite-amphibole schist, easily recognizable on aerial photographs and in diamond drill core. It contains 2.0% quartz, 8.5% plagioclase, 24.6% potash feldspar, 38.2% biotite, 22.8% hornblende, and 4.3% opaque oxide. The contact with the underlying gneiss is gradational and pebble bands of limited lateral extent are locally present there.

**Rössing Formation**

The monotonous succession of gneisses in the Khan Formation grades upward into the varied lithological sequence of the Rössing Formation. Six subdivisional units have been determined (see Table 1).

The basal unit is the lower marble, which consists of extremely impure, serpentinous recrystallized limestone that grades upward into a coarsely crystalline white graphite-bearing variety. Interbeds of pyritic and quartzitic schists are present, and facies changes are common. Mineral phases in the impure marble are calcite 57.4%, serpentine 33.7%, forsterite 5.8%, diopside 2.4%, and scapolite 0.7%. In the purer carbonate rocks from the upper part of the unit, the calcite content exceeds 90%. The coarse calcite crystals are frequently crushed and blackened.

A migmatic, rather coarse crystalline, strongly foliated unit of cordierite-biotite schist and gneiss overlies the lower marble in the mine area, and consists of 5.69% quartz, 27.2% plagioclase, 42.6% alkali feldspar, 14.1% biotite, 25.7% cordierite, 6.6% sillimanite, and 1.8% opaque oxides. Migmatisation along bedding planes associated with ptygmatic veining is prevalent, whereas heavy alaskite emplacement in the central sector of the assemblage is characteristic.

A useful marker conglomerate is intercalated between the lower cordierite-biotite gneiss and the higher lying upper marble. Flattened egg-sized quartz pebbles are plentiful where the bed occurs in the southern sector of the orebody, whereas farther east gritty arkose preponderates.

The upper marble unit displays a heterogeneous lithological assemblage that includes a fine-grained pyrite-bearing silicious bed overlain by four or five bands of pyritic marble intercalated with green and gray fine-grained pyritic quartzites. Still higher occurs a bed of biotite-cordierite schist containing intercalated marble bands.

The stratigraphically highest unit mapped in the immediate vicinity of the uranium deposit is the upper cordierite-biotite gneiss, consisting of girt bands and serpentinous marble overlain by the cordierite gneiss. It is less severely migmatized than the lower cordierite-biotite gneiss. East and west of the orebody feldspathic quartzites occur still higher in the sequence.

**Chuos-Welwitsch and Khomas Formations**

Only a brief description of these formations will be presented as they occur well to the south of the uraniferous area.

The Chuos tillite has a wide regional spread in South West Africa and could possibly be a correlative of the Grand Conglomerate of the Kundelungu System as developed in Zaire and Zambia. South of the Rössing uranium deposit it has a gray, massive to schistose matrix in which are set unsorted, elongated, angular erratics measuring up to 3 feet in diameter. It is overlain by a succession of white to gray-blue well-bedded marbles containing thin interbeds of quartzose calc-silicates that comprise the Welwitsch Formation. Still higher occur the biotite-cordierite-sillimanite schists of the Khomas Formation, which is riddled with pegmatitic dikes and veins.

**Conjectural depositional history of the Nosib and Damara Groups**

The deposition of shallow-water, cross-bedded coarse clastics now grouped under the Etusis Formation initiated the Damaran sedimentary cycle. Then followed siltstones, graywackes, and marls that, upon metamorphism, were respectively converted to the prolifically developed units of biotite gneiss, pyroxene-hornblende gneiss, and pyroxene-garnet gneiss. Subsequently, stable conditions prevailed during which fine-grained and homogeneous sediments of the Khan Formation accumulated, followed by a rapidly changing depositional environment that resulted in the accumulation of the heterogeneous sediments of the Rössing Formation. Deposition of the glacial drift Chuos tillite preceded the accumulation of a considerable thickness of marine limestones. Finally, deep-water fine-grained argillites were deposited over a prolonged period and subsequently converted into the Khomas schists by metamorphism.
Metamorphism

The rocks of the area reflect dynamothermal and contact metamorphism. Nash (1971) classified the regional dynamothermal metamorphites into psammitic, basic, pelitic, and carbonate compositional groups that were subjected to three metamorphic pulses. Enlarging on this theme Nash states "that the first pulse (M1) took place at temperatures of about 700°C and pressures of 6,000 to 8,000 bars, conditions broadly corresponding to upper amphibolite facies metamorphism of the Barrovian type. The presence of cordierite in rocks of appropriate composition characterizes the M2 pulse, indicating high temperatures and relatively low pressures. Estimated physical conditions point to high level metamorphism of the Abukuma type, the M2 pulse occurring at temperatures of 675° to 750°C and pressures of 3,000 to 5,000 bars."

Contact metamorphic effects are evident in metasediments adjoining the alaskitic intrusives. These are insignificant in the gneisses of the Khan Formation, but in the biotite-cordierite schists and gneisses of the Rössing Formation feldspar blastesis is present along the contacts that are predominantly gradational. The most marked effects are seen where

the pegmatitic alaskites have invaded the marbles of the Rössing Formation. Nash (1971) writes: "Skarn bodies, ranging in size from a few centi-

Fig. 8. Rose diagram incorporating 3,848 readings on vertical joints in the central part of the Rössing uranium deposit.

Fig. 9. Folded lower marble and lower cordierite-biotite gneiss units, Dome Gorge, east of Rössing uranium deposit.
metres to several metres are widespread, the majority being composed of coarse aggregates or pale green clinopyroxene, brown calciferous garnet and varying amounts of scapolite. Although generally hornfelsic, the rocks may contain individual growths of pyroxene and garnet up to several centimeters in size.

Structure

Tight vertical or slightly overturned folds trending northeast-southwest are the most striking feature of the regional structure. The Rössing uraniumiferous body is situated along the northern limb of a complex synclinorium developed between the domal structure clearly evident in Figure 6 and the Khan sediments present about 1½ miles farther south. Three different structural trends are recognizable on a regional scale, but the development of the northeast-southwest-striking structures (F2) has obliterated most of the earlier tectonic imprint. Figures 9 and 10 show that the folding of the marble bands is of a similar type, indicating an appreciable amount of plastic movement of material away from the limbs and into the hinges.

Transverse, vertical oblique-slip faults having horizontal displacements ranging from a few inches to more than 150 feet occur around the domal structure, being most common in the core of the “mine” synclinorium. They are younger than the F2 folds and also younger than the alaskite, but older than the dolerite dikes.

Detailed structural mapping of the proposed open-pit area has revealed strong jointing in the pegmatitic alaskite as well as in the metasediments. Stereo plotting of nearly 4,000 joint measurements indicated two near-vertical sets striking northeast and north-northwest, with the latter being dominant (Fig. 8). The strike of this set is perpendicular to the synclinorium’s fold axis.

Pegmatitic granite

The syntectite termed “Pegmatite” by Smith (1965), “Potash Granite” by Nash (1971), and “Alaskite” by the exploration staff of Rio Tinto is the uranium-bearing rock of the Rössing deposit. Completely barren or very sparsely mineralized alaskite is widespread beyond the limits of the orebody. The biotite gneisses of the Etusis Formation...
and the strata that comprise the Khan and the Rössing Formations form favored host rocks to the emplacement of the alaskite regardless of whether it is radioactive or barren, whereas the feldspathic quartzites present at the base of the Etusis Formation and the Welwitsch Formation are essentially free of it. The field habit of the alaskite ranges from narrow concordant or discordant dikes to large irregular bodies that are transgressive to the foliation or banding of the country rock. For example, the alaskite present in the lower and upper pyroxene-hornblende gneiss forms regular dikes that have been emplaced parallel to the regional bedding and metamorphic foliation of the metasediments, as clearly visible toward the northern sector or the orebody, whereas the alaskite present in the less banded pyroxene-garnet gneiss and amphibolite occurring farther south assumes more massive habit. The structure of the country rock also influences the habit of the alaskite which is in many localities emplaced along the axial planes of F2 folds as dikes that transgress concentric shells of differing lithology. Figure 10 illustrates this clearly, whereas Figure 11 shows apparently concordant dikes of alaskite that nevertheless obliquely truncate metamorphic mineral banding and foliation.

Xenoliths of country rock hundreds of feet wide occur completely engulfed in the large massive alaskite bodies that form the central portion of the orebody (Fig. 12) but show no strike or dip variations from those observed beyond the limits of the alaskite. The inference is clear that the alaskite was emplaced by a passive metasomatic process. Textural variations ranging from aplitic, granitic, to pegmatitic are displayed by the alaskite, with the latter predominating. Graphic fabric is also present in certain localities.

From the field observations detailed above certain conclusions are suggested:

(1) The alaskitic material was derived from a deep seated juvenile source where syntectic processes were active.

(2) The contact metamorphism indicates pronounced temperature differences between alaskite and adjacent wall rock.

(3) The presence of graphic fabric in the alaskite suggests simultaneous crystallization of quartz and feldspar from a magma in eutectic equilibrium; this is of significance in considering the genesis of the uranium mineralization. Mehnert (1971) emphasizes that graphic fabric is more characteristic of pegmatites than of granites.

(4) Passive nonviolent metasomatic emplacement of the alaskite can be inferred from the fact that the strike and the dip of the ghost-layering observed in the alaskite are identical not only to that of the surrounding country rock but also to that of the xenoliths pendant in the alaskite.

(5) The alaskite dikes are of post-F2 age.

Further speculation concerning the emplacement of the alaskite suggests that granitizing fluids saturated and replaced already migmatized country rock by penetrating shears, fractures, joints, bedding planes separating strata of differing competency, axial planes of folds, and foliation planes. As the replacement process proceeded, dikes were progressively widened by metasomatism to eventually form large irregular masses of aplite that still display relict structures of the original country rock. Potash feldspar probably crystallized at an early stage, to be followed by low temperature graphic intergrowths of quartz and feldspar.

The potash-rich composition of the alaskite, and its uniform chemistry and mineralogy regardless of the nature of the host rock or the elevation of intrusion,
suggest that it was derived by the syntesis of underlying Etusis and Abbabis Formations, exposures of which are present in the core of the domal structure situated immediately north of the orebody.

The ultimate source of the uranium could thus be the early Precambrian basement that was heavily eroded during a major time hiatus to provide spoil for redeposition in late Precambrian times as the Etusis Formation. This assemblage was then subjected to syntesis in the core of the developing Damaran geosyncline, with resultant emplacement of alaskite into stratigraphically higher strata.

**Fig. 12.** Massive uraniferous alaskite forming the center of the orebody.

**Fig. 13.** Uraninite (u) grains with inclusions and attached clusters of zircon (z). A flake of molybdenite (m) is present.

**Fig. 14.** Uraninite (u) surrounded by a halo of altered feldspar. A crack is visible in the feldspar.
### Table 2. Secondary Uranium Minerals Found in the Rossing Uranium Deposit

<table>
<thead>
<tr>
<th>Name</th>
<th>Composition</th>
<th>Color</th>
<th>Mode of Occurrence</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gummite</td>
<td>Uncertain</td>
<td>Amber-brown</td>
<td>Position of original uraninite grain from which it was formed</td>
<td>Resinous luster X-ray pattern reveals few indistinct broad lines that coincide with strongest uraninite lines</td>
</tr>
<tr>
<td>Beta-uranophane</td>
<td>Hydrated silicate of calcium and hexavalent uranium</td>
<td>Crystals and radiating groups bright yellow, other forms lighter yellow</td>
<td>Most typically as powdery encrustations or tiny crystals (up to 0.75 by 0.3 mm) in openings. Crystals also occur singly, or as radiated stellated or almost parallel groups, larger rosette-like radiated groups and botryoidal linings of cavities</td>
<td>Occurs in abundance</td>
</tr>
<tr>
<td>Uranophane</td>
<td>Hydrated silicate of calcium and hexavalent uranium</td>
<td>Pale straw-yellow to lemon-yellow</td>
<td>As encrustations in form of aggregates of minute, hairlike crystals or dense, soft, earthy material</td>
<td>Dimorphous with beta-uranophane, and mode of occurrence similar</td>
</tr>
<tr>
<td>Torbernite and metatorbernite</td>
<td>Hydrated phosphates of copper and hexavalent uranium. Torbernite represents the higher hydration state</td>
<td>Greenish</td>
<td>Sheaflike aggregates of thin tablets in coatings and encrustations</td>
<td>On desiccation or slight heating in air, torbernite readily dehydrates and breaks down to meta-torbernite</td>
</tr>
<tr>
<td>Carnotite</td>
<td>Hydrated potassium uranyl vanadate</td>
<td>Yellow</td>
<td>Coatings and encrustations</td>
<td>Similar to beta-uranophane and uranophane in color and occurrence</td>
</tr>
<tr>
<td>Metahaiweeite</td>
<td>Hydrous calcium uranium silicate</td>
<td>Pale yellow to greenish-yellow</td>
<td>Coatings and encrustations</td>
<td>Similar to beta-uranophane</td>
</tr>
<tr>
<td>Thorogummite</td>
<td>Hydrated thorium silicate containing uranium, lead, and rare earths in substitution for thorium</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Uranium Mineralization

#### Distribution

The bulk of the economic mineralization in the Rossing uranium deposit is contained in alaskite that is preferentially emplaced into the pyroxene-garnet gneiss/amphibole unit comprising the northern ore zone, and into the amphibole-biotite schist/lower marble/lower cordierite-biotite gneiss unit that comprises the central ore zone located on the northern limb of the mine synclinorium. On the western edge of the deposit the two ore zones are separated by a considerable width of largely barren upper pyroxene-hornblende gneiss, whereas farther east thinning of the strata coupled with steeping of dip narrow the surface exposures of ore zones and also the gap between them to the point even of local merging. Toward the western end of the orebody rich ore in both zones is exposed on surface, but drilling established that it is of limited vertical extent. Farther east the better grade ore is present at progressively deeper levels, whereas toward the far eastern limit of the pit blind bodies of uraniferous alaskite are encountered in depth.

The alaskite is widely spread beyond the limits of the proposed pit but is not uniformly uraniferous. Most is entirely unmineralized, some only leanly, and still less is sufficiently rich to support exploitation. The reason for the localization of the rich ore is still an open question.

Alaskite hosts all the primary uranium minerals and most of the secondary. The latter do, in cer-
tain localities, show a spread into the country rock and/or into a sporadically developed layer of surficial secondary limestone. Within the uraniferous zone enrichment is present along biotite-rich selvages of the alaskite, at those spots where robust alaskite bodies display sharp upward narrowing to form dike or veins, in alaskite emplaced along the axial plane of folds, and in those localities where amphibolit...
originally present in the ore zones has been replaced by alaskite.

Mineralogy

Uraninite is the dominant primary radioactive mineral. It occurs as grains ranging in size from a few microns to 0.3 mm, with the majority reporting in the 0.05- to 0.1-mm fraction. It is included in quartz, feldspar, and biotite, but also occurs interstitially to these minerals or along cracks within them. The uranite displays a preferential association with biotite and zircon, with the latter mineral occurring as inclusions within uraninite grains or as clusters of grains attached thereto (Fig. 13). Alteration halos around the uraninite grains are common (Fig. 14).

A unit cell value of 5.451 ± 0.002 Å obtained for one uraninite sample indicates a U:Th ratio of about 9:1, according to the graph of Robinson and Sabina (1955). However, the state of oxidation, which also has an effect on the unit cell size, may vary widely from place to place in the deposit so that a consistent U:Th ratio is not necessarily implied. In one instance a chemical analysis of a purified uraninite concentrate indicated a U⁴⁺:U⁶⁺ ratio of 2.46 and a U:Th ratio of 13.05:1.

Monazite is widespread in some samples of ore and is often closely associated with uraninite. Single crystals seldom measure more than 0.04 mm in diameter, with the lower limit falling in the range of 1 to 2 microns.

Betasfite contains a minor proportion of the uranium in the ore. It shows a striking range of colors, from the usual dark brown type possessed of conchoidal fracture to a light, bright yellow color closely resembling that of uranophane and carnitite, but differing as regards its greasy lustre. The betasfite occurs as inclusions in quartz and feldspar and is in many instances surrounded by radial cracks. The betasfite was found to have a high niobium and titanium content, a fair amount of uranium, and small amounts only of tantalum and tungsten.

Zircon, apatite, and sphene are commonly associated with the radioactive minerals. Pyrite, chalcopyrite, bornite, molybdenite, arsenopyrite, and the oxides magnetite, hematite, and ilmenite are encountered occasionally, whilst fluorite is often observed.

The primary uranium minerals uraninite and betasfite give rise to secondary minerals that are usually bright yellow. These occur either in situ, replacing the original uraninite grains from which they were formed, or commonly along cracks as thin films or occasionally as discrete crystals. In Table 2 the names of the secondary uranium minerals so far distinguished are listed, together with their color, mode of occurrence, and other observations.

Of the secondary uranium minerals, beta-uranophane is by far the most abundant. It is not always confined to alaskite but may spread into the enveloping country rocks.

In Figure 15 autoradiographs indicate the spread of radioactive minerals that occur in granular form and as crack fillings in specimens of alaskite.

In Figure 16 various forms of beta-uranophane are shown in color.

Uraninite contains about 55% of the uranium present, betasfite less than 5%, and secondary minerals about 40%.

Origin

During a process of syntesis uranium minerals are considered to have been concentrated in a residual melt of simple alaskitic composition. The localization of mineralization in certain sectors only of the alaskite spread is probably a simple reflection of the uraniferous content of the basement rocks before melting resulted in their upward emplacement into cover rocks. Further concentration could conceivably have involved processes of vertical mineral zoning coupled with the interplay of mechanical and chemical factors that resulted in the trapping of uraniferous melt in fold culminations of marble layers and the fixation of the mobile U⁴⁺ ions as stable minerals containing U⁶⁺ in areas where the Eh was lowered and the pH raised following upon assimilation of basic country rock by acid magma.

Metallurgy

The design of the pilot plant was based on preliminary laboratory-scale testwork, and it processed the underground bulk samples during the period October 1970 to March 1972.

The test program was designed to: (1) verify that the laboratory results were reproducible on a large scale, (2) establish the optimum uranium extraction process and assess the economics thereof, (3) obtain metallurgical and engineering criteria for the design of the full-scale plant.

The extraction process will involve conventional gyratory crushing, cone crushing, and open-circuit rod mill grinding to reduce the ore to a nominal -6-mesh product. A sulfuric acid leach at approximately 40°C will be followed by a sand/slime split, washing of the sands and slime, and liquid solids separation. Concentration and purification will be by means of resin ion exchange, followed by solvent extraction treatment of the eluate from the ion exchange circuit. Ammonia precipitation will produce ammonium diuranate ("yellow cake"), which will be calcined in a roaster to yield the final product.
Acknowledgments

The authors wish to thank Dr. A. J. A. Roux, President of the Atomic Energy Board, Mr. E. W. Hunt, Managing Director of Rössing Uranium Limited, and Dr. R. E. Robinson, Director-General of the National Institute for Metallurgy, for permission to publish this paper.

The following persons made significant contributions to the geological investigation of the Rössing deposit and its mineralogy, and many data in this paper were taken from their reports: C. R. Nash, A. W. W. Paterson, C. J. Hartnady, J. J. Haumann, N. A. Wegerhoff, C. G. A. Marshall, and E. J. Oosthuysen.

J. B. AND U. H.
RÖSSING URANIUM LIMITED
Box 61140
MARSHALLTOWN, 2107, SOUTH AFRICA

R. C.
RIO TINTO SOUTH AFRICA LIMITED
Box 61140
MARSHALLTOWN, 2107, SOUTH AFRICA

S. A. H.
NATIONAL INSTITUTE FOR METALLURGY
PRIVATE BAG 7
AUCKLAND PARK, 2006, SOUTH AFRICA

REFERENCES


