UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Progress Report on Geologic Studies
of the Ranger Orebodies
Northern Territory, Australia

By

J. Thomas Nash and David Frishman

Open-File Report 82-936
1982

Progress Report on Geologic Studies
of the Ranger Orebodies
Northern Territory, Australia

by

J. Thomas Nash[1] and David Frishman[1]

ABSTRACT

The Ranger No. 1 and No. 3 orebodies contain about 124,000 tonnes U_3O_8 in highly chloritized metasediments of the lower Proterozoic Cahill Formation within about 500 m of the projected sub-Kombolgie Formation unconformity. In both orebodies, oxidized and reduced uranium minerals occur chiefly in quartzose schists that have highly variable amounts of muscovite, sericite, and chlorite. The effects of several periods of alteration are pervasive in the vicinity of orebodies where biotite and garnet are altered to chlorite, and feldspars to white mica or chlorite. Oxidized uranium minerals, associated with earthy iron oxides, occur from the surface to a depth of about 60 m. Below the oxidized zone, uranium occurs chiefly as uraninite and pitchblende disseminated through thick sections of quartz-chlorite-muscovite schist and has no apparent association with graphite or sulfides. In fact, graphite is rare and sulfides are generally low in abundance (<0.5 percent). Higher ore grades occur in disrupted zones a few centimeters thick and in some quartz-chlorite vein-like zones of uncertain origin. Uranium correlates strongly with chlorite, but not all of the many ages of chlorite have associated uranium. At least five textural varieties of chlorite are present and represent at least 3 ages. Preliminary microprobe analyses suggest that Mg-Fe-Al contents are relatively uniform. Apatite commonly occurs with chlorite. Uranium is not common in carbonate rocks and seems to occur only in disrupted zones that have chlorite alteration. Chloritization and silicification are more widespread and intense in the No. 1 orebody than in the No. 3. In both orebodies, hematite occurs tens to hundreds of meters below the weathered zone, in both altered and largely unaltered rocks, with and without uranium.

The structure of the orebodies is outwardly simple, particularly in No. 3; dips are less than 40° on most lithologic contacts. The No. 1 orebody is in a basin-like structure about 400 m wide that probably formed in part by progressive removal of carbonate rocks that are as much as 200 m thick adjacent to the No. 1 orebody and below the No. 3 orebody. Quartz-chlorite breccias have formed in the zone of carbonate thinning; uranium is spotty and low grade in these breccias. Chloritized and uraniferous broken and sheared zones, a few centimeters to a few meters thick, have an unknown attitude but must have small displacement. Blocks of altered Kombolgie sandstone are downfaulted into the No. 3 orebody and locally contain reduced uranium minerals. One or more shear zones 5-30 m thick of crushed and smeared fine to coarse rock fragments occur below the orebodies, and other low-angle shears probably occur in the orebodies. The shear zone dips about 40° and

1

displacement on it is not known. The footwall rocks generally are less retrograded than those in the hangingwall (orebody) and consist of quartz-biotite-feldspar schists and gneisses flanking the Nanambu Complex. A few scattered fractures in the footwall sequence contain pitchblende of unknown age and origin.

Major element chemical analyses confirm the lithologic observations of large changes in composition during multiple stages of alteration. Granitic dikes and pelitic schists have gained Fe and Mg and lost Si, Ca, Na, and K during chloritization. Marbles have gained Si, Al, Fe, and P, and lost Mg, Ca, and K during jasperoid-chlorite alteration. Total net chemical gains and losses in the Ranger No. 1 orebody were huge: equal to about 37 percent of the mass of the ore-bearing rock that will be mined. There were net gains in Si and P and net losses in Al, Fe, Mg, Ca, K, and Na.

The geologic age(s) of uranium emplacement are obscure because there are few age criteria. Reduced uranium minerals are younger than 1.8-b.y.-old granite dikes, and some occur locally in 1.65-b.y.-old Kombolgie Formation. Diabase dikes (age not known) are thoroughly chloritized and contain sparse ore minerals. Oxidized uranium minerals are redistributed from older minerals and probably formed from Cretaceous to present time.

INTRODUCTION

In the fourteen years since they were first recognized at Rabbit Lake, Saskatchewan, unconformity-type deposits have become a dominant factor in the world uranium scene. More than a dozen significant deposits have been drilled out, but only the Rabbit Lake deposit has been systematically mapped and has been described in the literature. Genetic hypotheses for these deposits remain controversial and contradictory. Recognizing the importance of this class of deposits, and the problem of resource evaluation in the U.S. because of lack of experience and unsatisfactory geologic and genetic understanding, T. W. Offield of the U.S. Geological Survey (USGS), with the support of the U.S. Department of Energy, made arrangements to study and sample drill core from the Ranger and Jabiluka deposits Northern Territory, Australia. In 1980, four USGS geologists visited Australia for five weeks, and with the cooperation and assistance of Ranger Uranium Mines and Pancontinental Mining, logged drill core and took numerous core samples. This is the first of a series of papers that will report on lithology, mineralogy, chemistry, and geochronology of the Ranger deposits.

Our studies at the Ranger mine included only the general description of lithology, structures, and mineralization of 20 drill cores from the Ranger No. 1 orebody, 4 drill cores from the Ranger No. 3 orebody, and 4 drill cores distant from ore zones. The core holes in No. 1 orebody were selected in an H-shaped pattern to provide three-dimensional coverage (see fig. 2). About a thousand samples were collected for lab study; these were generally quarter sections of core, weighing about 200 grams. In USGS laboratories, we have prepared 370 samples for chemical analyses and are making petrographic, X-ray diffraction, and microprobe studies of rocks and ores. U-Pb isotopic studies are being made by K. R. Ludwig, U.S. Geological Survey.

2

This is a preliminary report of investigations in progress, in which only the most important features are described. Nearly all of our work confirms or extends the earlier studies by Ranger geologists and reported by Eupene et al. (1975) and Eupene (1980). Although our studies are far from complete, we hope that the descriptions, and occasional speculation, will be of value to geologists faced with the problem of evaluating unconformity-type uranium resources.

GEOLOGIC SETTING

The Ranger deposits occur in lower Proterozoic metasedimentary rocks on the east flank of the Archean Nanambu gneiss dome complex. The two Ranger orebodies, along with neighboring major deposits at Nabarlek, Jabiluka, and Koongarra, are in the Alligator Rivers Uranium Field (ARUF) (Needham and Stuart-Smith, 1980; Needham, this volume), located about 225 km east of Darwin, in the Northern Territory (Fig. 1). This district contains at least 20 percent of the Western World's low-cost reserves of uranium (Eupene, 1980).

The regional geology of the Pine Creek geosyncline and of the ARUF has been summarized elsewhere (Needham and Stuart-Smith, 1980; Eupene, 1980; Needham, this volume) and will be briefly reviewed here. Geology of the Ranger mine area (Fig. 2) is based chiefly on exploration drilling, as outcrops are rare. The oldest rocks in the area are granitic rocks of the Nanambu Complex, the core of which yields zircon U-Pb ages of about 2470 m.y. (Page et al., 1980). A thick sequence of marginal marine carbonate and pelitic rocks and chemical sediments were deposited unconformably on the granitic basement about 2300-2200 m.y. ago, and the region underwent amphibolite grade metamorphism about 1800 m.y. ago. During the metamorphism, lower Proterozoic sediments were accreted onto the reactivated granite core to create mantled gneiss domes, and rocks were complexely folded. Post-orogenic granitic dikes were intruded. The host for the major uranium deposits and numerous incompletely explored prospects is the Cahill Formation, near the base of the lower Proterozoic sequence (Needham and Stuart-Smith, 1980). The Cahill Formation, about 3,000 m thick, contains a lower member, 200 to 500 m thick, composed chiefly of Mg-rich marble with minor schist and gneiss. Textures interpreted to indicate former evaporite minerals have been described from the carbonate rocks (Crick and Muir, 1980). The upper member, originally carbonaceous pelite and impure sandstone, is now chiefly quartz-biotite-
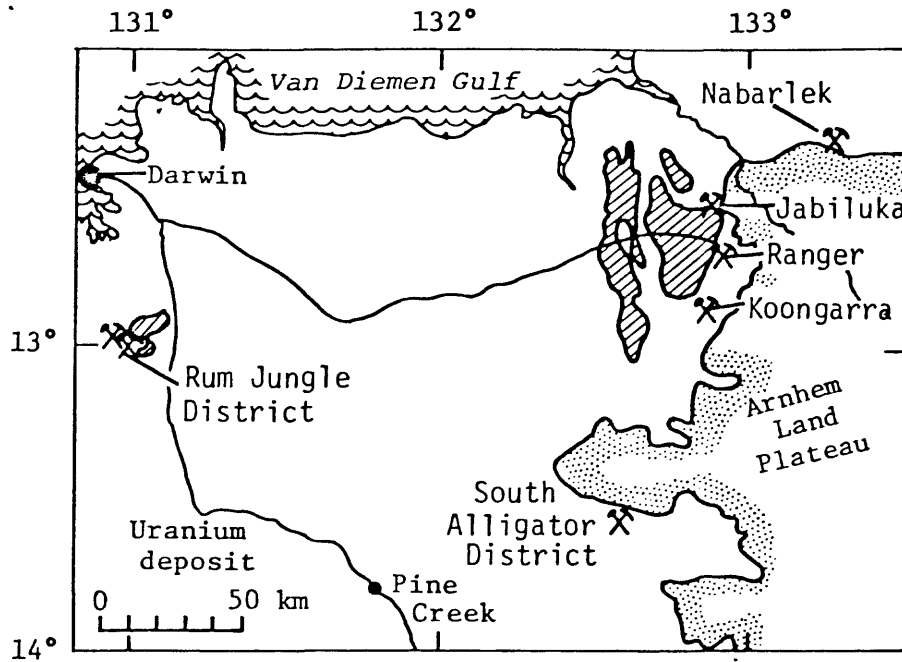
Figure 1.--Map of a portion of the Northern Territory, Australia showing the location of uranium mines and deposits. Archean-Lower Proterozoic granite gneiss domes are shown by diagonal ruling.

273,000E
AMG

9950E

No.1 Orebody

No.3 Orebody

-N-

9950N

see
inset

0   200 m

Kombolgie Formation

Shear Zone

Diabase dike

Granitic dike

Hangingwall Schist

Upper Mine Schist

Jasperoid

Lower Mine Marble

Footwall Schist and
Gneiss

Surface expression of
orebody

● Drill holes studied by
USGS

—— Fault, inferred

— — Contact, approximately
located

AMG = Australian Map Grid

0   500 m

8,594,000N
AMG

Figure 2.--Geology of the Ranger mine area modified from Eupene et al., (1975)
and Ranger Uranium Mines (1979). Precambrian geology is projected
to the surface and is based chiefly on drill data. Inset shows the
outline of the No. 1 orebody; dots show the location of drill holes
studied.

feldspar schist and gneiss. Eupene (1980) breaks out a middle member, 100 to 500 m thick, of quartz-biotite-feldspar microgneiss and schist that he believes is the chief host for uranium ore in the Ranger deposits. Un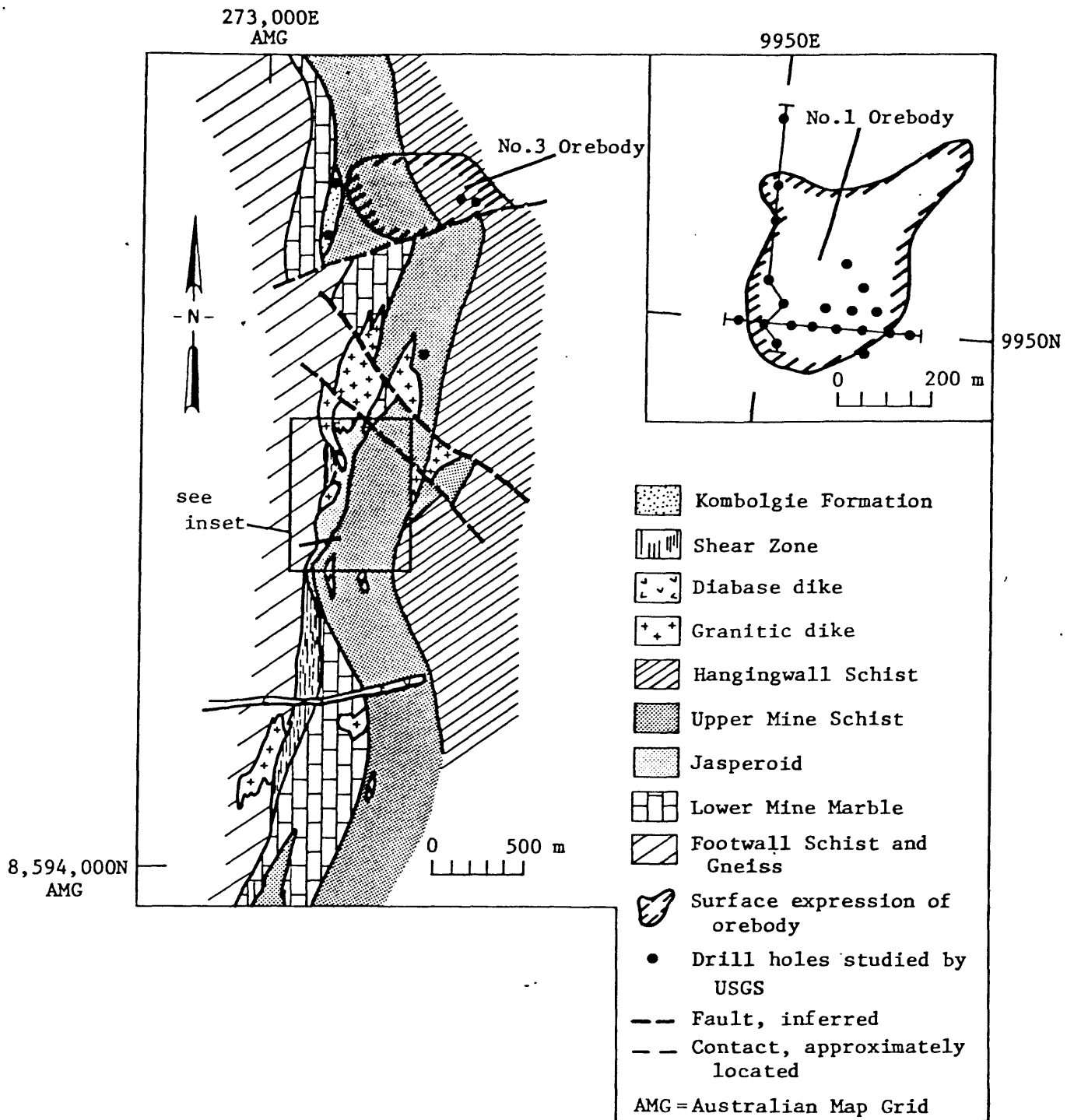conformably overlying the Cahill Formation in the ARUF is the middle Proterozoic Kombolgie Formation, about 400-500 m of well sorted quartzose sandstone of fluvial origin. Several volcanic units occur within the Kombolgie, one of which yielded a K/Ar age of 1648 m.y. (Page et al., 1980). Chloritic retrograde metamorphism is widespread in the ARUF (Eupene, 1980) and difficult to distinquish from uranium-associated chloritization; geologic and isotopic evidence are ambiguous but suggest pre- and post-Kombolgie events in the age range 1745 to 900 m.y. (Page et al., 1980; Riley et al., 1980).

The Ranger 1 area was detected as a major radioactive anomaly in an aerial survey flown in 1969 (Eupene et al., 1975). Ranger Uranium Mines has defined about 70 radioactive occurrences on its concession, but has drilled out only two of these in defining the No. 1 and No. 3 orebodies (Fig. 2). Announced resources are: No. 1 orebody, 52,000 tonnes U_3O_8 probable resources at 0.30 percent U_3O_8; and No. 3 orebody, 43,100 tonnes U_3O_8 probable resources at 0.18 percent U_3O_8 plus 28,700 tonnes U_3O_8 possible resources at 0.20 percent U_3O_8 (Eupene, 1980; Anonymous, 1981). The No. 1 orebody (Fig. 2) measures about 400 by 250 m and has ore extending from the surface to 180 m, as well as some deeper occurrences which will not be reached by the planned open pit. The No. 3 orebody, about 1 km north of No. 1, is roughly 500 by 750 m in area and extends from the surface to more than 300 meters depth, with mineralization known at depths of 350 to 400 m (Eupene, 1980). Three types of ore are recognized by Ranger based on mineralogy and milling properties (Eupene et al., 1975; Ranger Uranium Mines, 1979): (1) laterite type, in which uranium is in lateritic clays and ferricretes that pose a milling problem (about 5 percent of the ore); (2) oxidized ore consisting of hexavalent uranium minerals in oxidized schists; and (3) reduced ore consisting of quadrivalent uranium minerals in unoxidized schist and chloritic marble (more than half of the ore). The No. 1 orebody and the nearby Koongarra orebody are unusual among unconformity-type deposits for the amount of ore in the oxidized zone. Radiometric disequilibrium at Koongarra (Dickson and Snelling, 1980) indicates that uranium and daughter products in the oxidized zone have moved within the past million years. The oxidation zone at Ranger probably was also created relatively recently.

This study is affected by two problems of regional geology that we cannot resolve because we made no studies of rocks more than 1 km from deposits. The first problem is that the structure of the region is poorly defined because of generally sparse outcrops. Some exposures in ARUF show faults, isoclinal folding, two foliations, and crenulation cleavage (Needham and Stuart-Smith, 1976; 1980). Such details of deformation are not evident in the drill core at Ranger, possibly because of severe overprinted alteration; thus we cannot decipher structure that might be present according to some observations at distant localities. Surface exposures at Ranger offer even less information. The other problem is the nature of the widespread chloritization. Some chlorite is produced by retrograde metamorphism, some is produced by Mg-Fe-Al metasomatism some of which is related to uranium deposition, and some chlorite may be produced during weathering. Petrographic, microprobe, and geochronologic studies by others demonstrate

that there is no simple objective characteristic of the various fine-grained phyllosilicates. Terminology probably has not been consistent from study to study, which adds to the confusion. We will term all post-prograde metamorphic transformations "alteration," with no genetic connotations intended.

LITHOLOGY OF HOST ROCKS

The seven units defined by Eupene et al. (1975) are useful and reliable in the mine area, but we cannot attest to their stratigraphic identity, because very few rocks from outside of the ore zones were studied. The petrology of these units is incompletely understood at present, but we offer the following descriptions to supplement the brief descriptions of Eupene et al. (1975).

Footwall Sequence

The oldest rocks in the mine area are a sequence of quartzose schists and gneisses that generally are distinctive, particularly where biotite and pink K-feldspar are present. Although most drill holes penetrate only about ten meters of this unit, some holes penetrated about 100 m, sufficient to display a wide variety of lithologies. Lithologies most typical of the Footwall Sequence are light-colored quartz-biotite-K-feldspar-plagioclase gneiss and microgneiss, and medium- to dark-green quartz-feldspar-biotite $\pm$ chlorite schists. Less common are dark-green amphibolite, white quartzite, and leucocratic granitic zones presumed to be intrusive dikes (described later). We observed no carbonate (marble) beds, and none have been reported by Eupene et al. (1975). In core the foliation and compositional layering in the sequence have conformable attitudes which consistently dip about 30 degrees. We have no doubts that the Footwall Sequence formed from layered rocks. Eupene et al. (1975) call the unit "migmatitic," and it may be so in places, but the parts we observed were not mixed rocks.

The petrographic microscope reveals few unusual features of the fabrics or minerals. Biotite is well formed in many samples and has bronzy pleochroism where fresh. Biotite is in some cases partly or completely replaced by chlorite. K-feldspar is untwinned and tends to be very dusty from numerous minute inclusions or incipient sericitization. Some plagioclase is fresh and well twinned, but more typically plagioclase has been replaced by sericite. Muscovite is commonly present as crisp, well-formed laths. Accessory tourmaline is brownish green, in contrast to the blue-green variety that is abundant in granitic dikes.

Pitchblende veinlets occur in the Footwall Sequence at scattered locations. These veinlets are always thin and accompanied by chlorite or sericite. Although the veinlets are far too thin and scattered to constitute ore, they nonetheless are an intriguing part of the uranium story. Ryan (1979) mentions the veinlets and implies they may be in some way related to migmatite and granitized sediments. Hills and Richards (1976), with guidance from Eupene, sampled the Footwall Sequence, but we cannot tell if one of the 1700 m.y. ages they reported for No. 1 orebody came from the Footwall Sequence because they listed no sample descriptions or locations. Our impression is

7

that the Footwall veinlets are generally similar to ores in overlying rocks, but there is no way of establishing age relations until U-Pb isotopic studies are made.

Lower Mine Sequence (LMS)

White to dark-green or black magnesian marble and "chert" (jasperoid)[1] of many colors occur below the orebodies and locally contain ore-grade uranium zones. The general composition of the LMS ranges from nearly pure Mg-Ca carbonate to nearly pure SiO_2 (jasperoid) or chlorite as bedded or vein material. Only rarely does the marble effervesce with concentrated (20%) acid, and we generally could not differentiate between dolomite and magnesite in the field. The carbonate grains are medium to coarse, and have equant, rhombic, and tabular forms. Layers of green chlorite and talc are common, some of which probably represent marl (Si-Al-rich) layers, but other zones are replacements and veins that are not concordant with presumed bedding. Within individual drill holes are distinct zones 5 to 30 m thick of light-colored marble, chloritic-banded marble, coarsely crystalline marble, and stylolytic marble, but these units could not be correlated with units in adjacent holes. Many of the carbonate lithologies reflect alteration and thus can not be used for stratigraphic correlation. Stylolites are abundant in the marbles, commonly accentuated by thin films of chlorite. Layers of quartz-chlorite schist (meta-shale) greater than 10 cm thick are not common, although one distinctive unit termed "lenticle schist" (described below) occurs in the upper part of the LMS.

Under the microscope the LMS marbles are distinctive intergrowths of carbonate and chlorite or talc. As we have not treated the samples with specific stains for dolomite and magnesite, we cannot optically identify specific carbonate minerals, but we have identified these minerals by X-ray diffraction. Magnesite and dolomite are equally common, and no calcite has been observed. In some localities, pink carbonate veinlets or vug fillings consisted of dolomite crosscutting magnesite; magnesite also crosscuts dolomite. Preliminary microprobe analyses confirmed the presence of magnesite and dolomite, which contained some iron (1 to 2%) and essentially no manganese. Rosettes and blades of talc are prominent. Chlorite in the marbles has a pale- to medium-green color and a fine to coarse grain size; the coarse-grained chlorite probably is a pseudomorph of biotite. Fine crystals of translucent red hematite are commonly dispersed through the carbonate; the hematite seems to be an exsoultion or alteration product. Clastic quartz grains are rare to absent. Phlogopite was observed in a few samples. Apatite

---

[1]The nomenclature of these fine-grained siliceous rocks is a problem. Because most definitions of chert include the connotation of sedimentary rock or chemical sediment, we feel that such terminology would be misleading. The origin of this silicified rock is complex but probably was a post-metamorphic replacement of carbonate minerals in a marble. The nongenetic definition of jasperoid proposed by Lovering (1972)--"an epigenetic siliceous replacement of a previously lithified host rock"--carries the meaning we wish to convey. Henceforth we will use the term "jasperoid" in place of G. S. Eupene's "chert."

occurs with chlorite in some veins in marble, but has not been observed in marble without chlorite.

Uranium has not been detected in relatively unaltered or merely recrystallized carbonate rocks, but does occur in chloritized zones. This association of uranium with Mg-Al silicates is most striking in the No. 3 orebody where, in two holes, highly radioactive chloritic bands 0.2 to 1 m thick occur every few meters within a carbonate unit many tens of meters thick. Throughout this entire unit, radioactivity in the unaltered carbonate is at background levels.

Jasperoid (>90% SiO_2), jasperoid-chlorite breccias, and chloritic jasperoid occupy the stratigraphic position of LMS marble under the ore zones in No. 1 orebody (Fig. 3), as pointed out by Eupene et al. (1975). Our core logging confirms Eupene's generalization: the marble unit is thin or absent under the No. 1 orebody, and there is an inverse relationship between marble and jasperoid abundance. In the No. 3 orebody, jasperoid is much less common and jasperoid-chlorite breccias are rare. The jasperoid is fine grained and massive and commonly contains faint relicts of chloritic bands or beds. The jasperoid has highly variable grain size, from a few micrometers to several millimeters, and is commonly cut by veinlets of coarser grained quartz. Hematite is dusted through some of the jasperoid; in places repeated alternations of clear quartz and quartz containing numerous hematite inclusions can be observed. Cores from drill holes at the margins of the No. 1 ore zone contain centimeter-size veinlets of jasperoid that have vague boundaries with adjoining carbonate minerals, suggesting replacement. Where the jasperoid zones are more than several meters thick they usually are complexly brecciated. Chlorite is the matrix of the breccias and is present in amounts from 5 to more than 75 percent over a meter interval. Some of the jasperoid-chlorite breccias contain uranium (>500 ppm), but in general the breccias do not constitute ore in thickness or grade.

The upper part of the Lower Mine Sequence generally contains a distinctive chlorite-mica schist layer about 10 m thick named "lenticle schist." As pointed out by Eupene et al. (1975), this unit typically contains lenticular spots of chlorite about 1 to 3 mm by 1 mm. The chlorite seems to have replaced a former metacryst, which we strongly suspect was garnet because some garnet metacrysts are preserved in Cahill Formation schists outside of the deposits and impart a similar texture to the schist. The lenticle schist, in the context of the enclosing jasperoid or marble zones, is one of the few marker horizons in the mine section. Under the hand lens, and particularly under the microscope, the lenticle schist is seen to have well formed flakes of muscovite which impart a very well developed foliation; only rarely do the Upper Mine Sequence schists contain this type of muscovite. Within the mine area, the lenticle schist invariably contains abundant chlorite as a replacement of biotite and garnet(?).

Upper Mine Sequence (UMS)

This sequence of predominantly quartz-chlorite schist, with or without muscovite or sericite, is the chief host for uranium in the No. 1 and No. 3 orebodies. These rocks are generally dark to medium green, well foliated and

9

West   East

165   32   73   70   64   80   138   161

UMS   Chlorite   Muscovite   Schist

S.L.

50   60   50   50   10   10

Jasper-oid

Oxidized

Reduced

-50

50   50   50   55   10

105.0   Chlorite

-100   45   Breccia   75   70

135.0 Footwall   Schist   60

Explanation

Dip of shear foliation

Dip of foliation

Shear   Schist   Lenticle

178.6

-150

196.6 and

Mg-Marble   60

70

— Contact

— Fault

-200

Gneiss   70

234.1   235.0

$U_3O_8 \geq \sim 0.05\%$

70

73

105.0 Depth in meters
10,000 E Ranger Mine Grid coordinate
See text for description

254.8

0   50   100
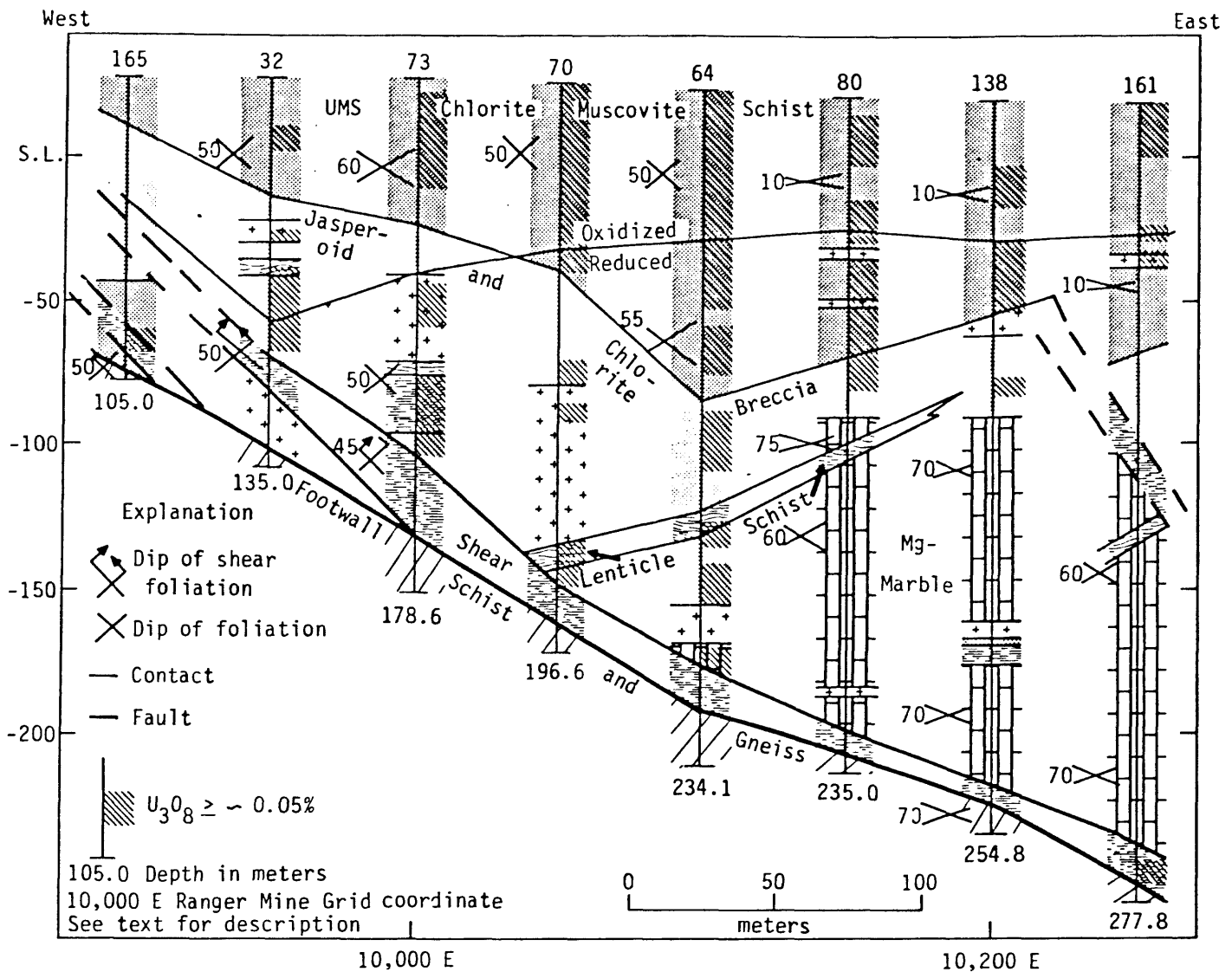
meters

277.8

10,000 E   10,200 E

Figure 3.--Generalized east-west cross section showing the distribution of
rock types and of uranium in the No. 1 orebody at Mine Grid 9950
N. See text for description of units; patterns used are the same
as those in Figure 2 with the exception of the Lenticle Schist unit
(not present in Figure 2); Hangingwall Schist is not present in
this cross section and diabase dikes are not shown. The
oxidation/reduction boundry shown is drawn at the base of earthy
iron oxides or the top of unweathered sulfides. Numbers along the
top of the figure are Ranger drill hole numbers. Dips are measured
relative to core axis.

have relatively indistinct compositional banding. Graphitic beds are rare, probably constituting only a few percent of the section in the mine area. Primary bedding features are nowhere evident, and we presume that original sedimentary layering is generally parallel to foliation. The typical dark color and fine grain size of these rocks makes megascopic description difficult and gives the impression that this is a very homogenous, monotonous unit. Other dark-green, fine-grained, chlorite-rich veins and shear zones resemble the UMS schist but can be distinguished in thin section.

Petrographic study of these rocks reveals many additional characteristics that cannot be seen megascopically. Quartz content is highly variable and ranges from about 20 to 70 percent, with most samples containing about 30 percent. The fabric of quartz also is highly variable from isolated sand-sized grains to welded polycrystalline bands. Muscovite, generally in well formed plates along foliation, is present in amounts from 0 to about 30 percent. Muscovite generally survives the effects of multiple stages of retrograde and later alteration. Fine-grained white mica, appropriately termed sericite, coexists with muscovite but doesn't seem to form from it. Sericite, ranging from 0 to about 40 percent, appears to be an alteration product of feldspars. Chlorite of many colors and fabrics constitutes 0 to about 90 percent of these schists and commonly amounts to about 60 percent of the rock. Accessory minerals include apatite, about 0.5 to several percent; TiO_2 as rutile or anatase, 0.2 to about 1 percent; and small amounts of tourmaline with yellow-brown or green-dark green pleochroism. Sulfide minerals are generally very low in abundance, less than 0.5 percent, and chalcopyrite tends to be about as abundant as pyrite. These sulfides are ubiquitous in reduced rocks. Galena, probably with Pb of radiogenic origin, is common in ore-bearing samples. Only extremely rarely do feldspars survive within or near the uranium orebodies. Also, carbonate minerals rarely occur in the schists or in veins within them.

Approximately half of the uranium in UMS schists is in the form of yellow hexavalent uranium minerals reported to be saleeite $[Mg(UO_2)_2(PO_4)_2 \cdot 8\text{-}10\ H_2O]$ sklodowskite $[Mg(UO_2)_2Si_2O_7 \cdot 6H_2O]$ gummite $[UO_3 \cdot nH_2O]$, and metatorbernite $[Cu(UO_2)_2(PO_4)_2 \cdot 8H_2O]$ (Eupene et al., 1975).[3] These yellow minerals generally occur with earthy iron oxides as coatings along joints and foliation planes. At approximately the lower limit of earthy iron oxides, uranium mineralogy changes to black, quadravalent varieties, pitchblende, uraninite,[2] coffinite, and some other phases not yet identified by X-ray diffraction or microprobe. We have not yet established the details of uranium distribution and mineralogy in the reduced zone. Rich uranium grades occur in many chlorite-rich zones in which foliation has been disrupted. Very little uranium ore is in graphitic schist and little is in discrete veinlets. Most uranium minerals are dispersed somewhere within the schist, probably obscured by chlorite. The uniformity of radioactivity at centimeter to meter scales is an indiction of

[2]Black uranyl oxides in the Ranger deposits do not appear to contain significant amounts of thorium or rare earth elements which are indicative of "uraninite" by some definitions. Here we will use the term uraninite for the oxide phase with cubic crystal forms greater than about 20 micrometers in size.

the disseminated nature of the ore. Measurement of drill core radioactivity with a shielded geiger counter detector having a 5-cm-diameter window yields counts that usually vary by only $\pm$ 100 percent when the core is probed at 10-cm intervals.

Hangingwall Sequence (HWS)

Quartz-chlorite-mica schists of the Hangingwall Sequence occur in part of the No. 1 orebody, in part of the No. 3 orebody, and between the No. 1 and No. 3 orebodies. Where least retrograded, these schists are typical metapelites composed dominantly of quartz, muscovite, and plagioclase $\pm$ biotite $\pm$ garnet. Other common constituents are hematite, probably pseudomorphous after magnetite, and a TiO_2 polymorph that is pseudomorphous after sphene in some specimens. Pyrite, tourmaline, and epidote occur as accessory phases. Where altered, biotite and garnet are replaced by chlorite, whereas muscovite and plagioclase are most commonly replaced by sericite. None of the HWS core we examined was mineralized.

Kombolgie Formation

Unconformably overlying the metamorphosed lower Proterozoic meta-sedimentary rocks is the largely unmetamorphosed Kombolgie Formation. It is chiefly a medium-grained, well sorted quartz sandstone. Lava flows within the Kombolgie yield an age of 1648 m.y., the best estimate for the formation (Page et al., 1980). Our observations are limited to two of three drill holes in the No. 3 orebody that penetrate altered quartz sandstone that apparently is a downfaulted block of Kombolgie Formation (Eupene et al., 1975). In these drill cores, the sandstone is altered and the intensity of alteration ranges from slight to almost total obliteration of clastic grains. In the most highly altered portions, essentially all of the quartz has been replaced and the sandstone has been converted to a dark-green, black, or mottled red rock composed of very fine-grained chlorite $\pm$ sericite $\pm$ hematite. Ore grade uranium mineralization occurs locally.

Granitic Dikes

Leucocratic dikes composed of fine to very coarse quartz, K-feldspar, and muscovite intrude the lower Proterozoic metasediments. All granitic rocks close to the uranium orebodies have been altered to quartz-chlorite-muscovite masses, the chlorite totally and faithfully replacing former coarse K-feldspar. Sparse biotite also is altered to chlorite, and, in the most highly altered sections, quartz is also replaced. Other primary minerals, most strikingly the large books of muscovite, are not modified. Tourmaline, black in hand specimen and pleochroic blue under the microscope, is a distinctive and locally abundant accessory mineral. The felsic composition and variable grain size suggest the general name "granitic" is more appropriate than "pegmatite" (Eupene et al., 1975) for these dikes. The Rb/Sr age of an intrusive pegmatite at Ranger is 1815 $\pm$ 60 m.y. (Page et al., 1980). Some ore grade concentrations occur in granitic dikes, but generally the dikes are barren or low grade.

12

Diabase Dikes

Fine-grained, massive, dark-green diabase dikes (dolerite of Eupene et al., 1975) are common in No. 1 but rare in No. 3 orebody. Nearly all dikes are thoroughly chloritized, but they appear to be only slightly deformed. Phenocryst textures (hornblende and plagioclase lathes) survive chloritization and permit reliable identification relative to other dark, fine-grained rocks. The geologic age of diabase dikes in the Ranger deposits is not known, except that they are post-metamorphic. Four ages of dikes in the range 1648 to 522 m.y. are known in the region, and a K/Ar age of about 1370 m.y. was determined on a "dolerite dike...near Ranger 1" (Page et al., 1980, p. 62). Small amounts of uranium occur locally in fractured diabase in the No. 1 orebody; the occurrence of thin films of pitchblende suggests it probably is younger than, and redistributed from, the ore in the enclosing schists.

STRUCTURAL GEOLOGY

The structure of the Ranger orebodies is outwardly simple (Figs. 3, 4) but is complex in detail. The basin-like structure of the No. 1 orebody reported by Eupene et al. in 1975 is substantiated by our observations. However, our study of drill holes on 50-m centers leaves room for much uncertainty. Also, as with most core studies, the strike of foliation, bedding, and fractures is not known. Another problem is the scarcity of marker beds upon which to base structural relations. We would like to describe and speculate on three structural systems: (1) low angle faulting (reverse or thrust faults?), (2) high-angle or normal faults, and (3) carbonate thinning and collapse breccias.

Figure 3 is an E-W longitudinal section through the No. 1 orebody at mine coordinate 9,950 N. Eupene et al. (1975) published similar sections at 10,100 N. and 10,050 E. The general framework is the Footwall sequence at depth, overlain by a section of marble (LMS) as much as 130 m thick at the east end, overlain by UMS schists. The structure is emphasized by the most reliable contacts--between UMS schist and LMS marble or jasperoid and between the LMS marble and the Footwall Sequence--and by the attitude of the Lenticle Schist subunit. A low-angle fault-shear system dipping about 45^0 at the west end and about 20^0 at the east end is shown (Fig. 3). This interpretation agrees well with measured shear foliations of 45^0 to 20^0. This shear zone shows essentially no dip on a north-south section (Fig. 4), and so we infer that the strike is about north-south and that the east-west section (Fig. 3) shows approximately the true dip. This shear zone is probably the same one shown on figure 2 with a northerly strike. Other low-angle faults do not seem to have been recognized in the region, possibly because of poor outcrop. We suspect that there are numerous other strands of this low-angle fault system within the No. 1 orebody but have insufficient control to demonstrate their existence. We hope that geologic mapping of the No. 1 open pit will properly describe this somewhat speculative system.

An important structural control on higher grade uranium ores are buckled zones in which the normal foliation is disrupted and broken for an interval from about 10 cm to 2 m. These disrupted zones are particularly evident in the No. 3 orebody where there are no collapse breccias to confuse them with.
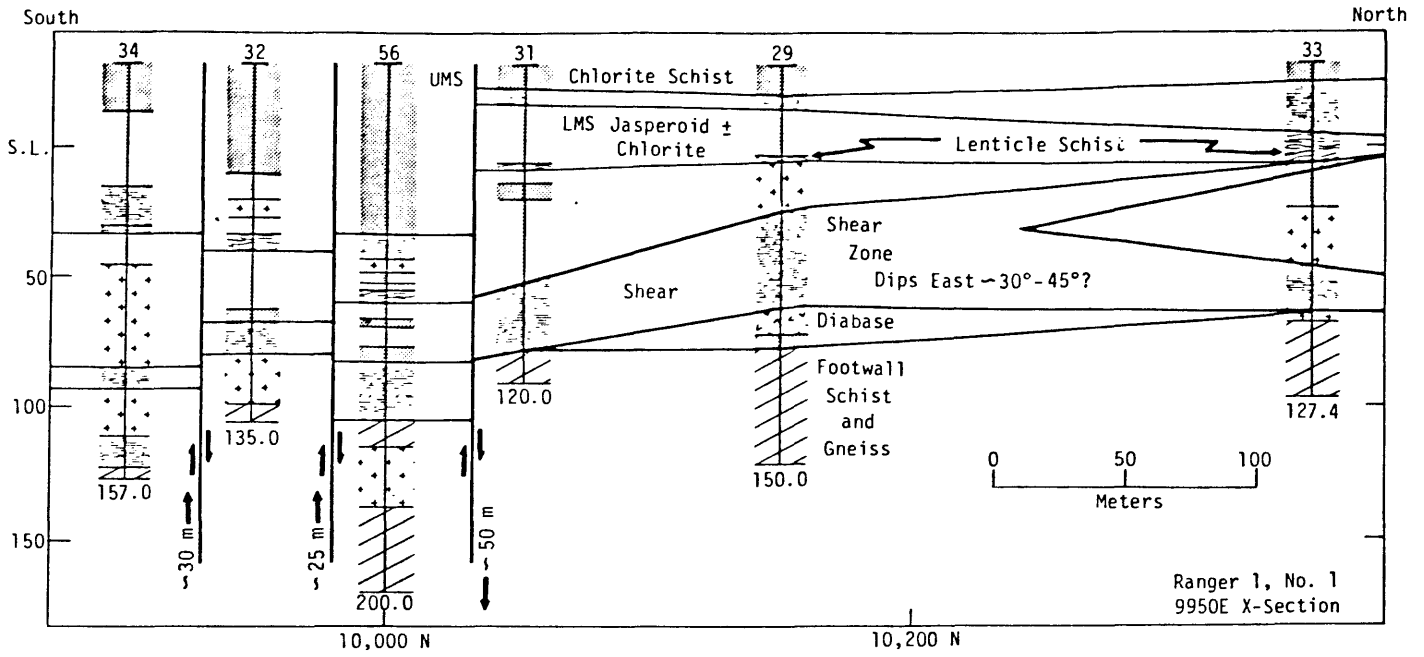
13

Figure 4.--Generalized north-south cross section showing the distribution of rock types in the No. 1 orebody at Mine Grid 9950 E. Patterns and symbols used are the same as those in Figure 3. Arrows and numbers indicate inferred direction and approximate magnitude of offset on faults.

These disrupted zones contain fragments of quartz schists that have been rotated to all angles relative to the core axis; the matrix between the fragments is rich in chlorite. These disrupted zones might be related to the low-angle fault system.

The age of the low-angle system is not known, but it appears to be younger than the metamorphism and older than the high-angle faults and collapse breccias. In some areas granitic dikes seem to occupy relatively flat structures, possibly of the low-angle system. Gouge within the shear zones is very chloritic but is not recrystallized, as constituent minerals show considerable strain.

Another important structural system, high-angle normal faults, is shown on figure 4. Vertical displacements of about 25 to 50 m are apparent. We suspect these faults have more or less E-W strike because they are not obviously present in the E-W section (Fig. 3). Block faulting such as this is required to explain the downfaulted blocks of Kombolgie Formation in the No. 3 orebody (see Eupene, 1980, Fig. 9). Faults with N-S and E-W strike are shown cutting the Kombolgie Formation on the 1:100,000 scale Cahill sheet (Needham and Smart, 1981). We have observed some high-angle fractures in drill core but did not recognize major fault strands, hence we cannot assess its influence on uranium distribution.

The third structure we wish to comment on is the bowl-shaped zone of collapse in the center of the No. 1 orebody and associated jasperoid-chlorite breccias. Our observations of marble-jasperoid relations are consistent with those of Eupene et al. (1975) and Eupene (1980): the LMS marble is thin or absent in the central area of the No. 1 orebody (Fig. 3, 4). In drill holes containing both marble and jasperoid, such as numbers 80, 138, and 161 (Fig. 3) we observed centimeter- to meter-thick zones of white jasperoid that have vague boundaries showing no evidence for faulting; hence, we interpret these to be replacement fronts. In other drill holes having thick intercepts of jasperoid, breccias of jasperoid and chlorite are common. The breccias have complex textures indicating alternating and overlapping deposition of jasperoid and chlorite and multiple periods of fragmentation. Significantly, essentially no carbonate minerals or marble fragments occur in the breccias. The available evidence suggests that the zone of jasperoid ± chlorite occupies the stratigraphic position of the LMS marble beds and formed by chemical replacement of pre-existing marble.

The genesis of the jasperoid is complex, but a major constraint is provided by the ubiquitous fluid inclusions in quartz of the jasperoid. The fluid inclusions in dozens of samples we have examined (at 1,200x oil immersion, no heating stage tests) are predominantly of the liquid-plus-vapor type and have a relatively consistent vapor fraction (20 ± 5%). These inclusions are observed in samples close to the surface (e.g., holes 29 and 34, Fig. 4), as well as at depths greater than 100 m. We do not have sufficient information to make comparisons with the observations of Ypma and Fuzikawa (1980), but we can point out that these fluid inclusions MUST have formed at temperatures in excess of about $150^{\circ}C$; fluids trapped at less than $100^{\circ}C$ would have a vapor phase of only a few percent or would possibly form single-phase fluid inclusions with no vapor bubble (Roedder, 1979).

The age of the jasperoid and collapse breccias is moot. We found no evidence for fragments of Kombolgie Formation in the collapse breccias. The Kombolgie in the No. 3 orebody is underlain by chlorite-jasperoid rock but appears to be a large coherent block bound by faults. Further, the matrix of the breccias contains chlorite and iron oxides that are very similar to the alteration products and vein fillings elsewhere in the No. 1 deposit: they do not have the appearance, to us, of surficial matter washed into a cavern open to the pre-Kombolgie erosion surface, as proposed by Ferguson et al. (1980). The distribution of jasperoid shown in figure 4 is consistent with it being older than the high-angle faults. As pointed out by many others, the breccias must have once had considerable open space, which is suggestive of relatively near-surface conditions (very roughly, less than 1 or 2 km), but we have no knowledge as to what the covering rocks were, whether metasedimentary or sandstone.

ALTERATION MINERALOGY

Several types and ages of rock alteration have been alluded to in previous sections. The minerals formed during alteration processes are relatively diagnostic and should ultimately provide insights into the physical and chemical properties of the fluids that produced the alteration and the uranium deposits.

Mg-Fe-Al Silicates

The most prominent and widespread alteration in the Ranger deposits is the formation of post-prograde metamorphic Mg-Fe-Al silicates. Chlorite is ubiquitous in both uraniferous and barren alteration zones. Talc also occurs in some altered schists and in many altered marbles. Cross-fiber textures suspected to be serpentine have so far proven to be chlorite or talc by X-ray diffraction and microprobe analysis.

Dark layers and veins in LMS Mg-marbles are composed chiefly of chlorite and talc. The latter is pale colored and highly birefringent in thin sections and is easily mistaken for phlogopite or sericite. X-ray patterns and microprobe analyses are diagnostic where appropriate material can be isolated. Preliminary analyses of talc in ten spots of two samples showed 29 to 32 percent MgO, 0.2 to 2.4 percent FeO, 0.2 to 1.0 percent Al_2O_3, and 62 to 64 percent SiO_2. Contents of Mn, Ti, Na, K, and Ca were less than 0.1 percent. Talc alteration does not appear to be related to uranium deposition.

Chlorite occurs in virtually all rocks within the Ranger deposits, and its abundance ranges from traces in weakly altered rocks to essentially 100 percent in some chlorite veins and intensely altered rocks. In various locations, chlorite replaces all rock-forming minerals in the following approximate sequence, reflecting mild to severe metasomation: garnet, biotite, plagioclase, K-feldspar, sericite(?), Mg-carbonate, muscovite, quartz. Chlorite occurs in the oldest to youngest rocks and in at least five textural varieties. Because chloritic alteration is so pervasive and rarely has well defined boundaries, we have had great difficulty determining how many periods of chloritization occurred. Some chloritization must be younger than the Kombolgie Formation, which is locally almost completely chloritized, and

16

some retrograde alteration could be about 1600-1700 m.y. old as suggested by Rb-Sr isotopic systematics (Page et al., 1980). Complex textures in jasperoid breccias show several periods of fragmentation and chlorite veining, all of which could have happened in a geologically short time period. Chloritization of diabase dikes could represent a fourth period of alteration or could have occurred in the same period as the chloritization of the Kombolgie.

Five textural varieties of chlorite are common: (1) Coarse (>200 μm) pleochroic grains with the form of biotite and containing abundant inclusions of TiO_2 and other minerals; this chlorite probably is a pseudomorphic replacement of metamorphic biotite. (2) Fine-grained (10 to 100 μm), nonfoliated, generally nonpleochroic masses; some of this probably is a replacement of former feldspar, and some occupies veinlets. (3) Fine-grained, vermicular or cross-fiber chlorite that fills veinlets. (4) Coarse flakes (>200 μm) of pale-green chlorite with characteristic gray-white birefrigence; the original flakes probably were metamorphic micas, possibly muscovite, because other type-1 chlorite grains, formerly biotite, typically occur near these pale flakes. (5) Sheared chlorite with apparent fine grain size but in optical continuity across about a millimeter; this chlorite has pale-gray to blue-gray birefringence similar to that of type 4, and possibly formed from it by some unknown process. The textures of chlorite are highly complex; the five described here occur in many samples and presumably further work will identify additional varieties.

Chlorite compositions determined to date by microprobe seem to be surprisingly uniform despite differences in color and optics that suggest large compositional differences. In hand specimen, chlorite colors range from black to medium green and silvery pale green. In thin section, color ranges from relatively dark green to pale green or tan, and birefringence ranges from nil (isotropic) to first-order white, and anomalous gray-brown, blue-violet, or copper-bronze birefringence is very common. The general optical properties suggest Mg-rich to Fe-rich compositions according to some compilations (e.g., Albee, 1962). Powder X-ray diffraction patterns are similar but do show minor variation in the intensity of the 14Å basal reflection. No patterns to date lack the 14Å peak required to define "septechlorite" as reported from Jabiluka by Binns et al. (1980). Several hundred preliminary microprobe analyses of various textural types of chlorite in 13 samples (Fig. 5) suggest similar Mg-Fe-Al contents.

Microprobe analyses can be discussed in either weight percentages or structural positions in the structural formula $(Mg, Al, Fe)_{12}(Si, Al)_8 O_{20}(OH)_{16}$. Because differences in atomic weight obscure coupled substitutions, structural units are most useful for discussing compositions. Our preliminary microprobe analyses suggest the following general range in composition: MgO, 28.6 to 17.2 percent or 8.04 to 4.49 octahedral positions; FeO, 17.4 to 1.8 percent or 2.79 to 0.27 octahedral positions; Al_2O_3, 31.8 to 21.0 percent, or 6.52 to 4.5 octahedral and tetrahedral positions; SiO_2, 36.4 to 29.8 percent, or 6.37 to 5.73 tetrahedral positions. Contents of CaO, Na_2O, K_2O, MnO, and TiO_2 are less than 0.1 percent, except that some chlorite replacing former coarse mica flakes appears to contain about 0.2 to 0.3 percent K_2O that does not seem to reflect an admixed potassic phase. Our probe analyses to date show no obvious correlation of chlorite composition with rock or ore type except for the tendency for chlorite replacing feldspar
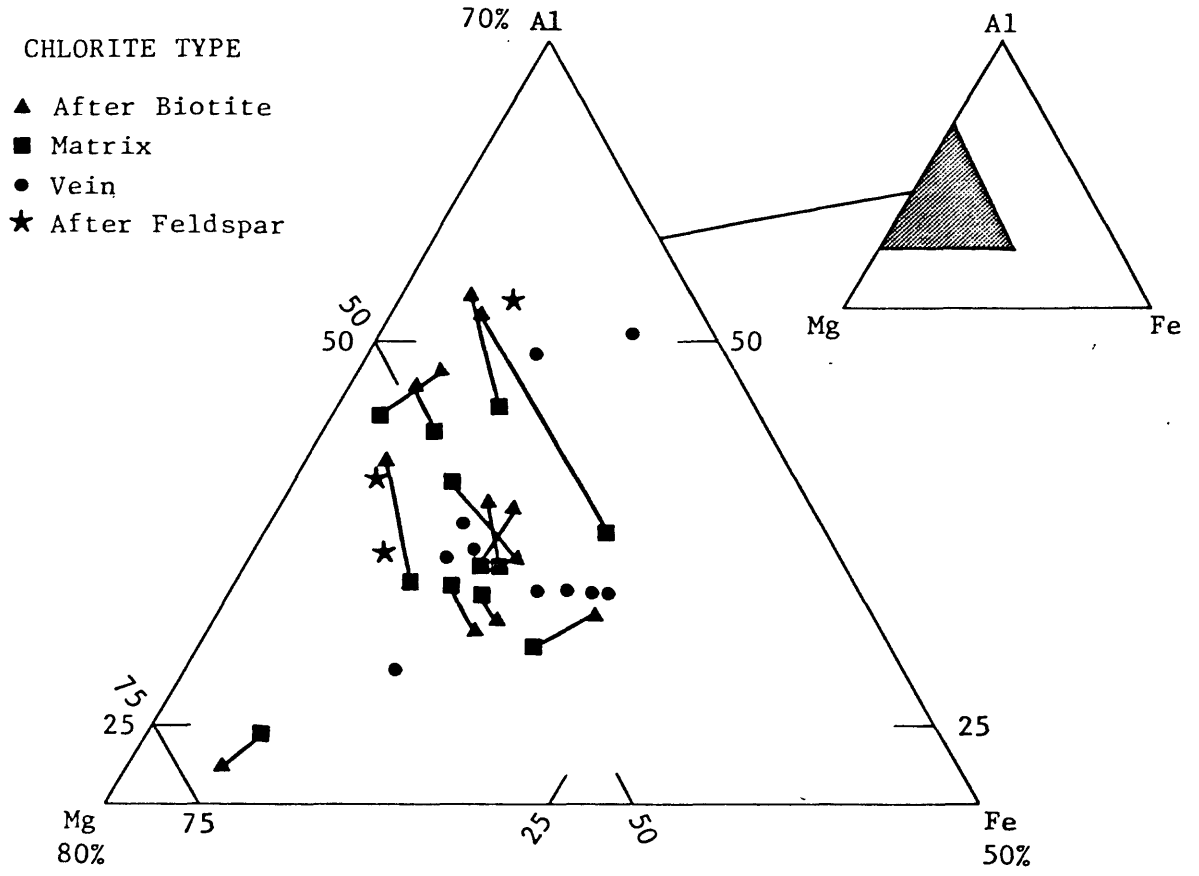
Figure 5.--Composition of chlorites from the Ranger No. 1 orebody plotted on a
portion of an Mg-Fe-Al ternary diagram (atomic proportions). Tie
lines connect analyses from grains in a single thin section. Each
point represents an average of 4 to 6 individual spot microprobe
analyses.

in granitic dikes to be somewhat enriched in Mg, Al, and Si and depleted in Fe. Preliminary calculations of structural formulas based on 28 oxygens (several other methods can also be used) suggest that one type of highly aluminous chlorite has many vacancies in the octahedral layer, about 10 cations relative to the ideal 12. Such chlorites are termed "dioctahedral," but we do not have the X-ray diffraction data to establish that possibility. The chlorite compositions are consistent with other chemical evidence for considerable mobility of aluminum that could lead to the formation of gibbsitic layers in dioctahedral chlorite.

K-Al Silicates

Two textural varieties of white mica occur in the deposits: muscovite, in characteristic coarse flakes; and sericite, in fine grains less than about 50 μm in size. Both micas yield characteristic 10Å X-ray peaks, and preliminary microprobe analyses demonstrate normal compositions; specifically, they contain about 9 to 10 percent K_2O and only traces of magnesium, iron, calcium, and sodium. Muscovite, of prograde metamorphic and igneous origins, is surprisingly resistant to chloritization. Among the rock-forming minerals present in the area, only quartz is more refractory to alteration. Some muscovite grain boundaries are chloritized, and one variety of flaky, pale chlorite may be chloritized muscovite. Sericite is present in amounts as great as about 40 percent in several rock types. The distribution of sericite is poorly understood; much was not recognized during logging because it is masked by dark chlorite or has a green appearance similar to that of chlorite. At least two zones of sericite are now apparent. One is in weakly altered Footwall Sequence gneisses and schists, where it replaces feldspars; this alteration has no associated uranium enrichment. The other zone is in the upper part of the UMS schists and is generally rich in uraninum. In the upper zone, sericite occurs as a massive matrix, apparently having replaced former feldspars and biotite. The sericite zone includes the lateritic soil profile and extends about 10 m below the oxidation zone. It generally overlies the main zone of pervasive chlorite alteration, but in some drill core it occurs sporadically within chloritized UMS schists. Because the sericite is pervasive and not related to simple veins, textural relations relative to chlorite are generally ambiguous. In thin sections there are textures suggesting that sericite replaces some chlorite and elsewhere chlorite replaces sericite. The upper sericite zone seems to be more than a weathering profile and may be similar to the sericite-muscovite zones at Jabiluka ("greisen" of Binns et al., 1980), which likewise is of uncertain significance.

Mg-Ca-Fe Carbonates

Coarse-grained carbonate minerals formed during prograde metamorphism and subsequent alteration. Magnesite and dolomite are equally abundant, but we have not identified any calcite. Because of the very similar physical and optical properties of magnesite and dolomite, we have very limited data on their paragenetic relations. Limited X-ray diffraction and microprobe data indicate that there are several reversals of the sequence. Specifically some relatively late euhedral carbonate is dolomite that rests on magnesite. Preliminary microprobe analyses indicate that there is about 2 percent iron in

19

the magnesite and dolomite, but esentially no manganese. None of the transformations can be related to uranium introduction.

Apatite

Content of apatite in altered host rocks ranges from traces to major amounts. The apatite typically occurs as stubby euhedral prisms 50 to 200 μm in greatest dimension that are scattered through alteration minerals. Added apatite seems to be most commonly associated with chloritic alteration (Fig. 6), and to a lesser extent with jasperoid. The identity of apatite was confirmed by microprobe, but the variety of apatite has not been established. There is no simple correlation between apatite and uranium; added apatite occurs in both ore-grade and barren chloritic alteration zones. Radiographic studies indicate that apatite contains very little uranium.

Fe-Ti Oxides

Original Fe-Ti oxides in all metamorphic and igneous rocks in the deposits have been totally altered to hematite, pyrite, chlorite, or TiO_2. Anatase has been identified, and rutile probably also is present. Formerly coarse grains of ilmenite in diabase dikes now are a mesh of milky TiO_2; the iron was mobilized and probably went into the pervasive chlorite. Titanium also was expelled during chloritization of biotite and stayed in the chlorite pseudomorphs as fine (10 to 50 μm) TiO_2 grains. Ferric oxides in the deposit are best described as either earthy brown ("limonite") or red, crystalline hematite. The earthy iron oxides are in the oxidized near-surface zone, which extends as deep as 80 m but typically is about 50 m deep (Fig. 3). Hematite, however, occurs to depths greater than 500 m and is found in all rock types. Hematite is particularly abundant in some chloritic vein fillings, in some chlorite-altered granitic dikes, and in some recrystallized marble zones that have a distinct pink or red color. Some of the hematite is associated with faults, but other zones are not obviously related to oxidation along faults. There was one, or more, deep and widespread stage of oxidation in the No. 1 orebody. The implications of this oxidation to uranium mobilization and deposition have not been established, but some very high grade uranium zones (>1 percent U_3O_8) contain coexisting hematite and pitchblende.

Quartz

Silica appears to have been very mobile in post-metamorphism alterations, as evidenced by a variety of leaching and depositional textures. Jasperoid is the most obvious example of quartz deposition, but quartz in veins and disseminations was also added to many zones of the UMS schists. The silica that moved within these rock units, or was added epigenetically, has a variety of habits. Some is coarse-grained and euhedral, some occurs as equant-shaped intergrown crystals, and some is in elongate to feathery, 10- to 200-μm grains. Dusty inclusions of iron oxides are common. In contrast to the zones with abundant added quartz are other chlorite and sericite zones that are notably free of added quartz. Skeletal quartz grains in the Kombolgie Formation are the best evidence of leaching. Chemical conditions appear to have been highly variable relative to the stability field of quartz.
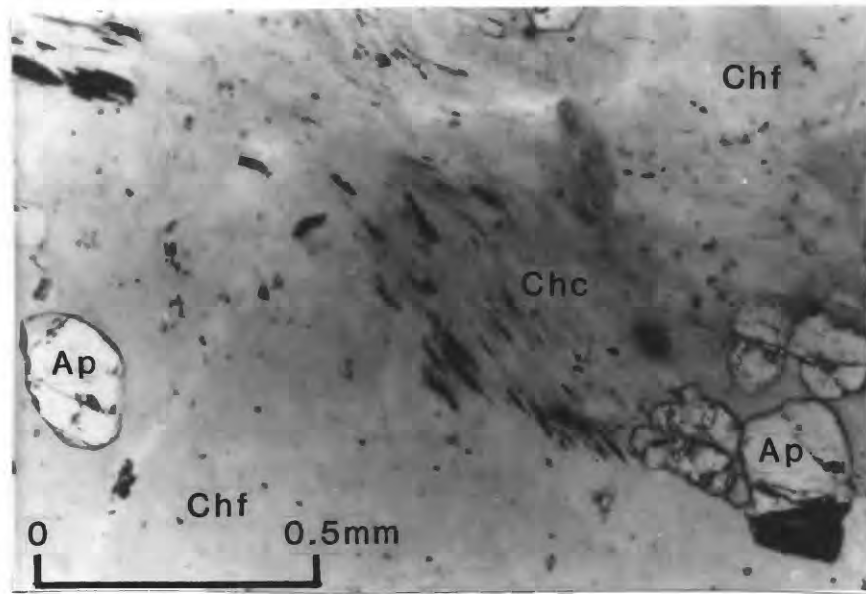
20

Figure 6.--Photomicrograph of chlorite-apatite alteration in
Mg-Marble. Sample R1-80-178.7. Ap, apatite; Chc, coarse-
grained chlorite replacing biotite; Chf, fine-grained
chlorite vein filling.

MAJOR-ELEMENT CHEMICAL CHANGES DUE TO ALTERATION

Chemical analyses of host rocks indicate that large chemical changes have occurred during alteration, consistent with the lithologic observations described previously. We are in the process of evaluating relationships among 60 elements determined in 370 samples but at this time will report only some major-element relationships in 219 samples (Table 1). Our chemical analyses should be compared with those published elsewhere (Eupene, 1980; Ferguson and Winer, 1980; Needham and Stuart-Smith, 1980). Our purpose here is to describe changes in chemistry during rock alteration rather than dwelling on absolute abundances. This approach poses some problems because reliable backgound data for unaltered rocks are difficult to obtain due to deep weathering and the fact that most drill holes are in altered ground. With guidance from G. S. Eupene we did log and sample some drill core remote from the orebodies, and our suite of analyses for completely unaltered rocks will be expanded when we receive analytical results for a suite of samples provided by R. S. Needham of the Australian Bureau of Mineral Resources. In the following paragraphs, chemical changes caused by alteration of granitic dikes, UMS schists, and LMS marbles will be described in turn.

Chemical changes during chloritization of granitic dikes are relatively easy to describe because the alteration chiefly involves chlorite replacing K-feldspar under conditions of relatively constant volume. Not surprisingly, there are large increases in magnesium and iron contents, about 750 and 550 percent respectively, and large decreases in sodium and potassium (minus 60 and 86 percent respectively). Some silica has been removed (about 12 percent), and other elements are essentially unchanged.

Chemical changes during chloritization of UMS schists can be calculated by comparing analyses of chloritic schists with those of unretrograded biotite schists outside of the mine area. The 79 samples of chlorite schist included in the calculation are relatively free of chlorite veins. The approximate increases for various constituents: FeO, +9 percent; MgO, +145 percent; and P_2O_5, +13 percent. Constituents showing losses include: SiO_2, -5 percent; CaO, -83 percent; Na_2O, -90 percent (or more); K_2O, -51 percent; and F, -30 percent. Aluminum, manganese, and titanium show essentially no change.

For the LMS marbles at least two alterations must be considered--one is possible changes in the carbonate portion (i.e., calcite-dolomite-magnesite relations) and (or) chloritization of marble, and the other is the large changes during the postulated formation of jasperoid. A major problem is the scarcity of data on carbonate rocks distant from ore; Needham and Stuart-Smith (1980) report a 2-sample average and Ferguson and Winer (1980) do not break out a carbonate subgroup in their Cahill Formation analyses. The two analyses indicate a Mg:Ca atomic ratio of 2.4, and the normative composition of the rock is roughly 25 percent quartz, 30 percent dolomite, 40 percent magnesite, and 5 percent Mg-Fe silicate and other minerals. The Mg:Ca atomic ratio of chloritic marble in the mine area is 3.25, and the normative composition is about 35 percent dolomite, 30 percent magnesite, 20 percent chlorite, 10 percent quartz, and 5 percent other. Thus the proportion of magnesite is roughly the same (possibly lower) in the mine area as in the unmineralized marble.

Table 1.--Major-element composition of six rock units, Ranger mine area.

[Major-elements determined by X-ray spectroscopy, J. S. Wahlberg, J. Taggart, and J. Baker, analysts; total iron expressed as Fe_2O_3; F determined by ion-sensitive electrode, H. Neiman and E. Engleman, analysts; U determined by neutron activation analysis. For each lithologic type the number of samples is given in parentheses (); $\bar{x}$, mean value; σ, standard deviation; L, less than; NC, not calculated, ---, not determined]

| Constituent | Lower Mine Sequence | | | | Upper Mine Sequence | | | | Granitic Dikes | | |
| | Marble (43) | | Jasperoid (19) | | Biotite Schist (12) | | Chlorite Schist (79) | | "Unaltered" (2) | Chloritized dikes (11) | |
(Wt %)	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	$\bar{x}$	σ
SiO_2	18.7	15.5	67.8	19.7	66.3	4.99	62.7	11.4	72.5	64.4	6.68
Al_2O_3	5.35	6.06	8.27	4.46	14.4	1.43	14.3	3.46	15.2	14.8	1.45
Fe_2O_3	3.39	2.36	4.31	2.32	4.32	2.16	4.72	2.93	0.60	3.87	2.55
MnO	0.19	0.15	0.02L	NC	0.06	0.02	0.02L	NC	0.02	0.02L	NC
MgO	27.0	9.02	8.18	4.11	3.30	2.06	8.07	4.33	0.90	7.63	5.77
CaO	11.6	11.0	2.81	8.60	1.61	1.40	0.28	0.59	0.36	0.35	1.23
Na_2O	0.22	0.05	0.15L	NC	1.74	0.92	0.15L	NC	2.15	0.87	1.52
K_2O	0.84	1.88	0.51	0.78	4.27	1.20	2.10	1.40	5.77	0.81	1.31
TiO_2	0.20	0.20	0.28	0.33	0.42	0.15	0.46	0.17	0.02	0.02L	NC
P_2O_5	0.16	0.28	1.25	3.07	0.16	0.15	0.18	0.26	0.22	0.27	0.10
F[1/]	0.15	0.14	0.09	0.06	0.11	0.07	0.07	0.04	---	0.08	0.03
U(ppm)	358	1600	3849[2/]	8181	8.6	6.7	2264	6656	---	662	1650

1/ F not determined on all samples; number of determinations are marble, 7; jasperoid, 5; biotite schist, 10; chlorite schist, 47; chloritized dikes, 8.

2/ Not representative of unit; U content typically an order of magnitude lower.

Chemical changes during the formation of jasperoid obviously were very large, as evidenced by the total change in mineralogy. The changes are best approximated by comparing the average composition of 19 jasperoid samples with the average for 43 samples of chloritic marble (Table 1). Our choice of samples for chemical analyses and the resulting chemistry of jasperoid agree quite closely with those reported by Eupene (1980). However, our sample population and chemistry for "chloritic marble" differ considerably from Eupene's in that our data show much higher values for magnesium and calcium, and lower values for silicon; this discrepancy must reflect our inclusion of more pale, clean carbonates with less chlorite-quartz veining. If we assume a volume for volume replacement, which we feel is not the best estimate (see below), the chemical changes are approximately as follows: increases of 260 percent for SiO_2, 55 percent for Al_2O_3, 27 percent for FeO, 680 percent for P_2O_5, and 40 percent for TiO_2. There were losses of about 70 percent in MgO, 76 percent in CaO, 40 percent in K_2O, and 60 percent in F. Data for Na_2O and MnO in jasperoid contain too many qualified values (not detected) for numerical computations, but suggest that in general these elements were removed during silicification. These computations should be considered minimum estimates, because structural and textural features discussed earlier indicate that there was a large decrease in volume during silicification.

A better estimate of chemical gains and losses during formation of jasperoid-chlorite rocks from LMS marble can be calculated from the volume reduction indicated by changes in thickness of the LMS under the ore zone (Fig. 3). The thickness of LMS is abut 200 m under the No. 3 orebody, but in No. 1 orebody some LMS was cut out by faulting prior to jasperoid formation. For the 20 drill cores we logged in the No. 1 orebody the average thickness of jasperoid and marble is 37 m and 28 m respectively. The thickness of marble in drill holes 138 and 161 (Fig. 3) is about 120 m, and about 28 m of jasperoid is in the upper part of these holes, suggesting the LMS marble was about 150 m thick in this area. To the west, at least part of the marble was cut out by the large shear zone, probably prior to silicification, and now is represented by about 50 m of jasperoid and sheared chloritic rock. In the No. 1 orebody the average thickness of LMS marble prior to silicification but following low-angle faulting and injection of granitic dikes was probably about 100 m. This 100 m was converted to about 37 m of jasperoid, with 28 m of marble surviving; this is an overall volume reduction of about 35 percent. Using these average thicknesses, and assuming densities of 2.75 g/cm^3 for marble and 2.5 for jasperoid, and an area of about 120,000 m^2 for the silicification in the No. 1 orebody, we can calculate the mass of material gained and lost. The calculations indicate that about 31 X 10^5 tonnes (t) SiO_2 and about 1.1 X 10^4 t of P_2O_5 were added, and these were the only two constituents showing net gains. All other constituents show major net losses: Al_2O_3, -3.6 X 10^5 t; FeO, -3.8 X 10^5 t; MgO, -55.1 x 10^5 t; CaO, -24.3 X 10^5 t; K_2O, -1.4 x 10^4 t; TiO_2, -1.7 x 10^4 t; and F, -2.6 X 10^4 t. These calculations are based on specific assumed compositions and thicknesses and are not presumed to be accurate.

Finally, the total gains and losses for the No. 1 orebody can be calculated. Here we assume (1) the average thickness of UMS schist is 65 m, (2) the average thickness of chloritized granitic rocks is 15 m, and (3) the schists and granitic rocks were chloritized at constant volume but the LMS was

altered with a volume loss, as previously described. The calculated gains and losses are shown in Table 2; note that the unit of mass is 10^5 tonnes. The large net gain indicated for SiO_2 and the small gain in P_2O_5 probably mean that these elements were extracted from rocks outside of the area considered in the calculations. There were large losses of iron, magnesium, calcium, potassium, and sodium. The final resting place of these elements is not known. To add perspective to these numbers we can point out that the 6.28 million tonnes of material removed is about 37 percent of the mass of ore-bearing rock (16.97 million tonnes) that will be recovered from the No. 1 open pit. Again these calculations are not presumed to be accurate, but are presented to dramatize the magnitude of mass transfer in this ore system.

DISCUSSION

The general conditions of formation of some of the minerals present at Ranger can be constrained by evidence presented here. The structural setting of the uranium ores is imperfectly known, partly because data are scanty and partly because the ore does not appear to reside in a specific type of structure. We have described a low-angle fault system and suggest that it may have provided the structural control for retrograde alteration throughout the deposits. The low-angle fault system may also have provided general structural control for solution of LMS marbles at some later date.

Chlorite of many textural types and ages is ubiquitous in the Ranger deposits. Chlorite and hematite are reported from most unconformity-type deposits and are reminiscent of chlorite ± hematite alteration in sulfide ores such as massive sulfide deposits and in some Pb-Zn-Cu-Ag-Au veins (e.g., Nash, 1973; Barton et al., 1977) where magnesium-iron metasomatism is well developed. Chemical analyses of rocks and minerals from Ranger demonstrate mobility of Mg, Fe, and Al and localization typically in chlorite and less commonly in talc. The complex chemistry of chlorite has hampered thermochemical understanding, but the recent interpretation by Walshe and Solomon (1981) provides possible limitations on conditions of chloritization. Typical Ranger chlorites have about 6.0 to 6.2 Si atoms in tetrahedral sites and Mg/Mg+Fe ratios of about 0.7. These values suggest a pH of about 5.5 and temperature of about 350°C (Walshe and Solomon, 1981, Fig. 19); neutral pH at this temperature is about 5.7. If some of the Ranger chlorites are dioctahedral and have about 2 octahedral vacancies, as previously described, these would possibly be stable at lower temperatures near 250°C. These are, obviously, only rough estimates based on preliminary analyses and approximate thermochemical data.

The significance of chlorite at Ranger and elsewhere is uncertain. Is it merely symptomatic of an environment, or is it an active and necessary part of ore-forming processes? The near-neutral pH and Mg-Al-Fe-rich environment suggested by chlorite would not appear to be necessary for uranium deposition. However, chlorite may have an active role through participation in reactions in the Si-Mg-Al-Fe-S-O-H system in limiting sulfur and oxygen fugacity (Barton et al., 1977). At Ranger, chlorite coexists with one or more of pyrite, hematite, and quartz and would seem to preempt the position of magnetite as proposed by Barton et al. (1977). Thus chlorite, or technically the iron-chlorite molecule, might act as a reductant of uranyl ions and lead

Table 2.--Net gains and losses during alteration, Ranger No. 1 orebody, in tonnes $x10^{-5}$.

	Chloritization of schist	Chloritization of granitic dikes	Silicification of marble	Net
SiO_2	-7.6	-4.3	+31	+19
Al_2O_3	NC'	NC	-3.6	-3.6
Fe_2O_3	+0.8	+1.6	-3.8	-1.4
MgO	+10	+3.4	-55	-42
CaO	-2.8	NC	-24	-27
K_2O	-4.6	-2.6	-0.1	-7.2
Na_2O	-3.3	-1.0	NC	-4.3
P_2O_5	NC	NC	+0.1	+0.1
			Net Total	$66.4 \times 10^5 t$

NC, not calculated.

to the precipitation of pitchblende or uraninite. Although the thermodynamic relations reported by Barton et al. (1977) and by Walshe and Solomon (1981) suggest that chlorite should be capable of reducing uranyl ions, we cannot be sure that this is kinetically feasible or that chlorite with low O_2 to moderate Fe content will behave as postulated for the Fe end member. Fe^{+2} in chlorite has been proposed as a reductant by Ewers and Ferguson (1980), but in a different manner than we envisage.

The lithologic and chemical changes involved in formation of jasperoid and jasperoid-chlorite breccias from marble are enormous, but the significance to ore formation is not clear. The jasperoid itself contains relatively little ore, but Eupene et al. (1975) suggested that ore-bearing disrupted zones in schists may have formed in response to solution and collapse of LMS marble. It seems that the jasperoid, the solution, and the collapse of the marble are at least symptomatic of one chemo-hydrologic process that contributed to ore formation. Constraints on the process are provided by the solubilities of the major phases dolomite, magnesite, and quartz (Holland and Malinin, 1979). Deposition of quartz from a fluid is most typically caused by cooling; factors such as pH, salinity, and CO_2 pressure have very little effect. Carbonate mineral solubility, on the other hand, is very sensitive to pH, salinity, and P_{CO_2}, and in general carbonate minerals are more soluble at lower temperatures. A significant constraint on the system is the lack of carbonate minerals in veinlets in schist overlying the LMS marble; Mg-Ca carbonates apparently were not redeposited in schist following the widespread leaching. The restriction of recrystallized and vein-filling carbonate minerals to the LMS marble would seem to preclude the related processes of pressure decrease, boiling, and CO_2 loss (Holland and Malinin, 1979), all of which are possible factors in uranium deposition. Fluid-silicate reactions, which probably consumed H^+, probably could not have proceeded far enough to produce the alkaline conditions and the increased CO_3^{-2} activities that would have tended to cause precipitation of carbonate minerals. The leaching of marble and the deposition of abundant quartz and chlorite appear to require introduction of acid solutions (such as those produced by oxidation of pyrite), cooling, and neutralization. General temperature estimates from chlorite compositions and fluid inclusions in jasperoid, previously described, are in the range 100° to 350°C. Research to confirm and refine the physical and chemical conditions of silicification and chloritization are under way, but the preliminary evidence appears to rule out surficial supergene processes.

The causes of uranium deposition remain obscure. Uranium probably was transported in the hexavalent state, although the oxidation observed in the host rocks cannot be uniquely assigned to passage of uranium-bearing solutions. Reduction probably was required prior to precipitation of pitchblende, uraninite, and coffinite, but no reduction mechanism can be specified from our information. We agree with Eupene (1980) that relatively little reduced uranium occurs in graphitic rocks and that graphite cannot be a direct cause of reduction. Sulfide minerals are not abundant in the host rocks, and the association with uranium minerals is not intimate. Carbon-rich compounds derived from graphite, or sulfide ions derived from sulfide minerals, may have acted as reductants, but no textural or chemical evidence for such reactions has been documented.

REFERENCES CITED

Albee, A. L., 1962, Relationships between mineral association, chemical composition, and physical properties of the chlorite series: Am. Mineral., v. 47, p. 851-870.

Anonymous, 1981, Reserves at the No. 3 orebody at Ranger: Eng. Mining Jour., v. 182, no. 7, p. 147.

Barton, P. B., Jr., Bethke, P. M., and Roedder, Edwin, 1977, Environment of Ore Deposition in the Creede Mining District, San Juan Mountains, Colorado: Part III. Progress toward interpretation of the chemistry of the ore-forming fluid for the OH-vein: Econ. Geology, v. 72, p. 1-24.

Binns, R. A., McAndrew, John, and Sun, S. S., 1980, Origin of uranium mineralization at Jabiluka, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 543-562.

Crick, I. H., and Muir, M. D., 1980, Evaporites and uranium mineralization in the Pine Creek Geosyncline, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 531-542.

Dickson, B. L., and Snelling, A. A., 1980, Movements of uranium and daughter isotopes in the Koongarra uranium deposit, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 499-508.

Eupene, G. S., 1980, Stratigraphic, structural, and temporal contol of mineralization in the Alligator Rivers Uranium Province, Northern Territory, Australia, in Ridge, J. D., ed., Proceedings Fifth Quadrennial IAGOD Symposium, v. 1,: Stuttgart, Sweizerbertsche Verlagsbuchhandlung, p. 347-376.

Eupene, G. S., Fee, P. H., and Colville, R. G., 1975, Ranger One uranium deposits, in Knight, C. L., ed., Economic geology of Australia and Papua New Guinea. 1. Metals: Parkville, Australian Inst. Min. Metal. Mon. 5, p. 308-317.

Ewers, G. R., and Ferguson, John, 1980, Mineralogy of the Jabiluka, Ranger, Koongara, and Nabarlek uranium deposits, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 363-374.

Ferguson, John, Ewers, G. R., and Donnelly, T. H., 1980, Model for the development of economic uranium mineralization in the Alligator Rivers Uranium Field, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 563-574.

Ferguson, John, and Winer, Paul, 1980, Pine Creek Geosyncline: Statistical treatment of whole rock chemical data, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 191-208.

Hills, J. H., and Richards, J. R., 1976, Pitchblende and galena ages in the Alligator Rivers Region, Northern Territory, Australia: Mineralium Deposita, v. 11, p. 133-154.

Holland, H. D., and Malinin, S. D., 1979, The solubility and occurrence of non-ore minerals, in Barnes, H. L., ed., Geochemistry of Hydrothermal Ore Deposits, Second Edition: New York, John Wiley and Sons, p. 461-508.

Lovering, T. G., 1972, Jasperoid in the United States--its characteristics, origin, and economic significance: U.S. Geol. Survey Professional Paper 710, 164 p.

Nash, J. T., 1973, Geochemical studies in the Park City District: I: Ore fluids in the Mayflower Mine: Econ. Geology, v. 68, p. 34-51.

Needham, R. S., and Smart, P. G., 1981, Geologic map of the Cahill sheet, Northern Territory (scale 1:100,000), sheet 5472: Bureau of Mineral Resources, Geology and Geophysics Australia.

Needham, R. S., and Stuart-Smith, P. G., 1976, The Cahill Formation--host to uranium deposits in the Alligator Rivers Uranium Field, Australia: BMR Jour. Australian Geol. Geophys., v. 1, p. 321-333.

Needham, R. S., and Stuart-Smith, P. G., 1980, Geology of the Alligator Rivers Uranium Field, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 233-258.

Page, R. W., Compston, William, and Needham, R. S., 1980, Geochronology and evolution of the late-Archaean basement and Proterozoic rocks in the Alligator Rivers Uranium Field, Northern Territory, Australia, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 39-68.

Ranger Uranium Mines [1979], Ranger Uranium Project: Ranger Uranium Mines Pty. Ltd., Jabiru East, N.T., Australia, 36 p.

Riley, G. H., Binns, R. A., and Craven, S. J., 1980, Rb-Sr chronology of micas at Jabiluka, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 457-468.

Roedder, Edwin, 1979, Fluid inclusions as samples of ore fluids, in Barnes, H. L., ed., Geochemistry of Hydrothermal Ore Deposits, Second Edition: New York, John Wiley and Sons, p. 684-737.

Ryan, G. R., 1979, The genesis of Proterozoic uranium deposits in Australia: Roy. Soc. London Phil. Trans., Ser. A, v. 291, p. 339-353.

Walshe, J. K., and Solomon, Michael, 1981, An investigation into the
environment of formation of the volcanic hosted Mt. Lyell copper deposits
using geology, mineralogy, stable isotopes, and a six-component chlorite
solid solution model: Econ. Geology, v. 76, p. 246-284.

Ypma, P. J. M., and Fuzikawa, Kazuo, 1980, Fluid inclusion and oxygen isotope
studies of the Nabarlek and Jabiluka deposits, Northern Territory,
Australia, in Ferguson, John, and Goleby, A. B., eds., Uranium in the Pine
Creek Geosyncline: Vienna, Int. Atomic Energy Agency, p. 375-398.