

Geology and ore deposits of the  
Section 23 mine, Ambrosia Lake district,  
New Mexico

By

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Open-File Report 82-207  
1982

## CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	2
Geologic setting.....	6
Prefault Ore.....	10
Mineralogy of prefault ores.....	20
Deep oxidation and weathering.....	27
Destruction of primary ore.....	31
Postfault ore.....	37
Mineralogy of postfault ores.....	40
Hydrology.....	45
Water table.....	46
Ground-water recharge.....	47
Porosity and permeability.....	48
General classification of ground water.....	50
Uranium content of ground water.....	52
Discussion and summary.....	54
Conclusion.....	64
References cited.....	65

## ILLUSTRATIONS

	<u>Page</u>
Figure 1. Map of northwestern New Mexico showing the location of the Grants mineral belt.....	3
2. Location of major mines in the Ambrosia Lake district.....	4
3. Map of sec. 23 uranium deposits.....	9
4. Photomicrograph of typical uraniferous humate ore.....	11
5. Photomicrograph showing corrosion of sand grains by uraniferous humate.....	12
6. Roll in a pre-fault ore layer.....	15
7. Photograph showing displacement of a pre-fault ore layer.....	17
8. Graph showing distribution of selected elements in sample suite collected across original humate layer.....	18
9. Graph showing distribution of selected elements in sample suite collected across redistributed humate zone.....	19
10. Photomicrograph showing black jordisite coating sand grains....	24
11. Diagram of roll-type ore at boundary between oxidized and unoxidized sandstone.....	29
12. Graph showing distribution of selected elements in sample suite collected across pre-fault ore layer and parallel halo band.....	33
13. Sketch of mine wall at sample suite 40G62.....	36
14. Cross section of the Homestake-Sapin Section 23 mine.....	38
15. Change in uranium content of waters being fed to a surface settling pond.....	55

## TABLES

Table 1. Earliest recorded static water levels in section 23.....	46
2. Porosity and permeability of 17 drill core samples from the Westwater Canyon Member in sec. 23, T. 14 N., R. 10 W.....	49
3. Analyses of mine waters, Ambrosia Lake district.....	51

## ABSTRACT

The section 23 mine is one of about 18 large uranium mines opened in sandstones of the fluvial Westwater Canyon Member of the Jurassic Morrison Formation in the Ambrosia Lake mining district during the early 1960's. The Ambrosia Lake district is one of several mining districts within the Grants mineral belt, an elongate zone containing many uranium deposits along the southern flank of the San Juan basin.

Two distinct types of ore occur in the mine. Primary ore occurs as peneconcordant layers of uranium-rich authigenic organic matter that impregnates parts of the reduced sandstone host rocks and which are typically elongate in an east-southeast direction subparallel both to the sedimentary trends and to the present-day regional strike of the strata. These are called pre-fault or trend ores because of their early genesis and their elongation and alignment.

A second type of ore in the mine is referred to as post-fault, stacked, or redistributed ore. Its genesis was similar to that of the roll-type deposits in Tertiary rocks of Wyoming and Texas. Oxidation, related to the development of a large tongue of oxidized rock extending from Gallup to Ambrosia Lake, destroyed much of the primary ore and redistributed it as massive accumulations of lower grade ores bordering the redox interface at the edge of the tongue. Host rocks in the southern half of sec. 23 (T. 14 N., R. 10 W.) are oxidized and contain only remnants of the original, tabular, organic-rich ore. Thick bodies of roll-type ore are distributed along the leading edge of the oxidized zone, and pristine primary ore is found only near the north edge of the section.

Organic matter in the primary ore was derived from humic acids that precipitated in the pores of the sandstones and fixed uranium as both coffinite and urano-organic compounds. Vanadium, molybdenum, and selenium are also associated with the ore. The secondary or roll-type ores are essentially free of organic carbon and contain uranium both as coffinite and uraninite. They also contain vanadium and selenium but are virtually devoid of molybdenum.

Although much has been learned about these deposits since the time this study was conducted, in 1966, a great deal more study will be required to completely elucidate their geologic history.

#### INTRODUCTION

Although it has poorly defined boundaries, the Ambrosia Lake uranium district, in northwestern New Mexico, constitutes a significant portion of the Grants mineral belt (fig. 1). The main, northwestern, part of the district contains 18 large mines (> 1 million lbs  $U_3O_8$ ) and as many smaller mines developed in the Westwater Canyon Member of the Morrison Formation. Brief descriptions of several mines in the district appear in New Mexico Bureau of Mines and Mineral Resources Memoir 15 (1963, V. C. Kelley, chm.) but, at the time of the present study, no comprehensive data on any one mine had yet been published. This report is intended to present the geology of the deposits developed in one mine in the district and to relate it to the geologic framework of the area. The Section 23 mine in T. 14 N., R. 10 W. (fig. 2) was chosen because it contains a variety of features and types of ore typical of the district and because these are discernible in a relatively less intricate setting than at many of the other mines in the area. A profusion of

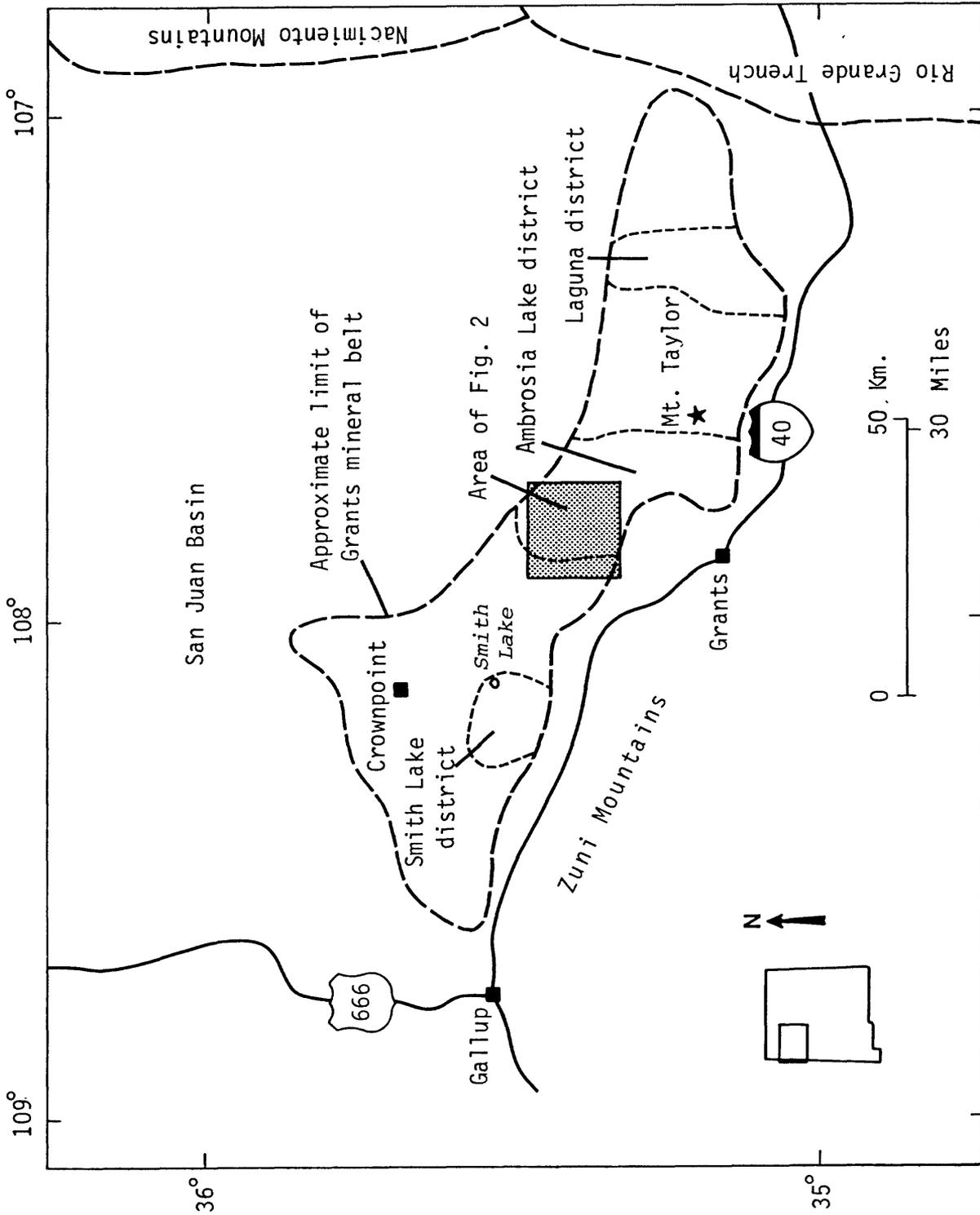


Figure 1.--Map of northwestern New Mexico showing the location of the Grants mineral belt

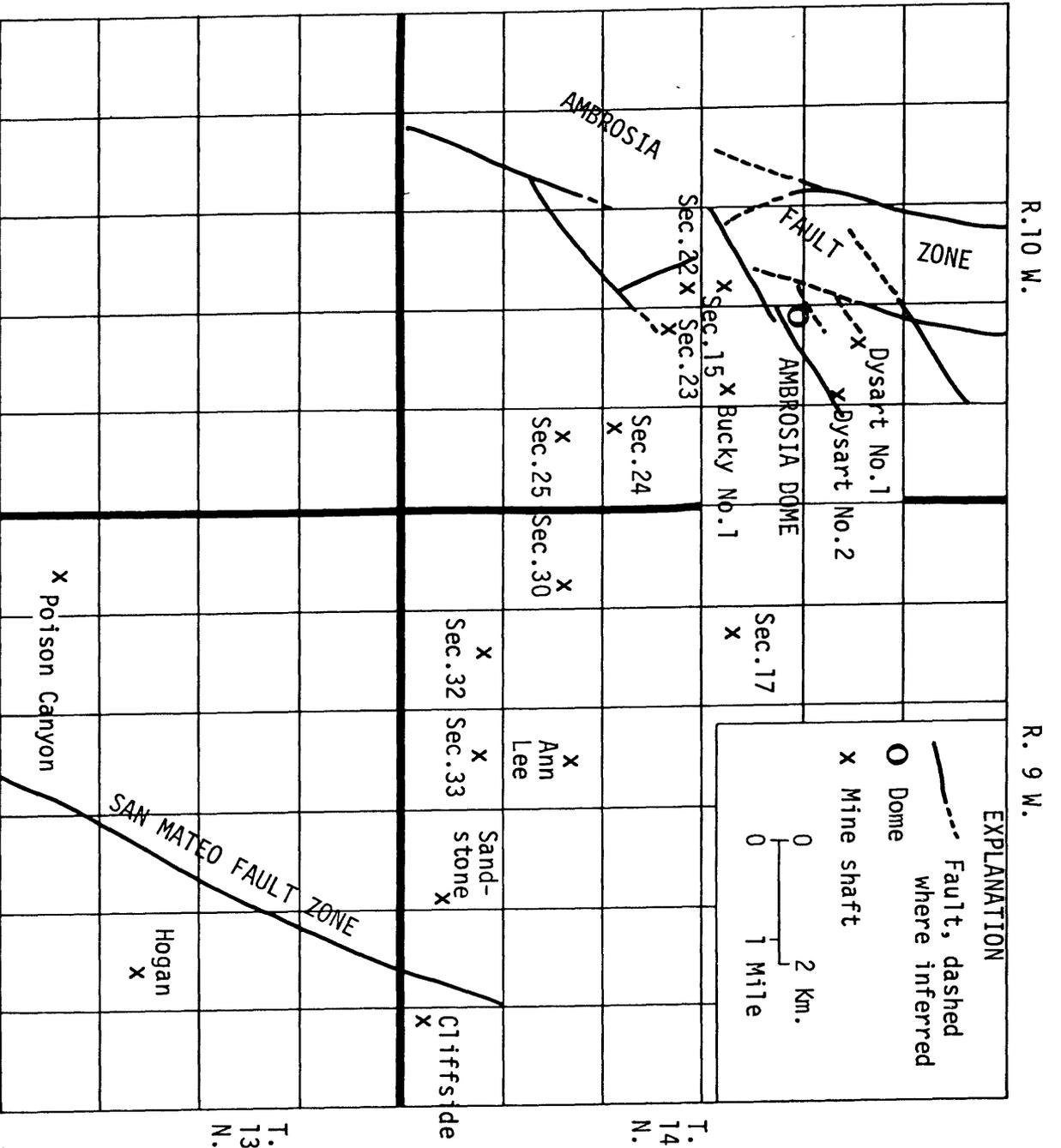


Figure 2.--Location of major mines in the Ambrosia Lake district, 1966

data on the sec. 23 deposits are available because of extensive surface and subsurface drilling and ready accessibility of most of the workings that have served to develop a large portion of the known ore.

Two distinct types of uranium ore, of markedly different ages, are distinguishable in the Section 23 mine. These have been termed pre-fault and post-fault ore (Granger and others, 1961). The pre-fault ores, also called trend ores and run ores, comprise primary deposits which have the form of broad, undulatory layers controlled principally by stratigraphic features. The post-fault ores, also called stacked ores and redistributed ores, comprise deposits which are irregularly shaped and are controlled by a combination of tectonic structures and stratigraphic features. A more thorough understanding of the geologic history of the deposits would, no doubt, permit further subdivision of the two types but, for practical purposes, the two-fold division is adequate for the scope of this report.

In this paper we emphasize not only the destruction of pre-fault deposits by oxidation, but also the shape and position of oxidation zones as a control for the post-fault deposits.

The authors' experience in the district dates from the mid-1950's, but much of the field work on which this report is based was done in the summer of 1966. During this period, the officials of the Homestake-Sapin Partners were most generous in giving us full run of the mine with permission to map and take samples. They also provided us with base maps, drill hole data, and information compiled by the mine personnel. We would like, particularly, to express our appreciation to geologists Paul Melancon, Charles Chisholm, Robert Smith, and Steven Potter, but this is by no means a complete list of company personnel to whom we are grateful.

Since our field work was completed, several new orebodies, which we have not seen, were developed on sec. 23; these are distinguished on figure 3. The descriptions in this report apply principally to those deposits that were developed as of the summer of 1966.

#### GEOLOGIC SETTING

The structural and stratigraphic setting of the Grants mineral belt has been described adequately elsewhere (Kelly, 1963; Moench and Schlee, 1967; Hilpert, 1969; Santos, 1970) and will only be summarized briefly here.

The Grants mineral belt extends west-northwestward along the southern part of the San Juan basin, a broad structural depression lying principally in northwestern New Mexico and considered to be a part of the Colorado Plateau physiographic province (Kelley, 1963). With the exception of a few uranium deposits in the Todilto Limestone of Late Jurassic age and in the Dakota Sandstone of Late Cretaceous age, nearly all the deposits that define the mineral belt are in sandstones of the Late Jurassic Morrison Formation.

The Morrison is divided into 3 members in the southern part of the San Juan basin. These are, in ascending order, the Recapture Member, the Westwater Canyon Member, and the Brushy Basin Shale Member. The Recapture consists of variegated red, white, and purple fine-grained and silty sandstones which were deposited in dominantly eolian, fluvio-lacustrine, and flood plain environments. It is not known to contain economic uranium deposits in this region.

The Westwater Canyon consists of braided-fluvial, cross-bedded, feldspathic sandstone units interspersed with both lenticular and persistent mudstone beds that probably represent overbank and ephemeral-lacustrine deposits. From thicknesses of about 100 m (Craig and others, 1955) north of

Gallup, the Westwater Canyon thins southeastward along the outcrop to where it becomes a series of intermittent lenses (Moench and Schlee, 1967) north of Laguna. (Subsequent drilling has shown that it thickens markedly north of Laguna and that relatively thick Westwater is probably continuous from the Ambrosia Lake area eastward under and north of Mount Taylor to the Rio Grande trench.)

The Brushy Basin Shale Member is composed of montmorillonitic mudstones containing discontinuous, intercalated, lenticular, fluvial-channel sandstone units. It reaches thicknesses of about 90 m north of Laguna but probably averages about 35 m in thickness throughout much of the mineral belt. It was beveled and truncated by Early Cretaceous erosion during uplift along the entire southern perimeter of the San Juan basin.

Most of the uranium deposits occur in sandstone within the main body of the Westwater Canyon Member, but two distinctive sandstone units have proved to contain enough ore to merit separate recognition. These are the Poison Canyon sandstone of economic usage, a fluvial tongue that extends from the top of the Westwater Canyon in the Ambrosia Lake district, and the Jackpile sandstone of economic usage, a large fluvial-channel sandstone in the upper part of the Brushy Basin Shale in the Laguna district.

During diagenesis or early epigenesis most of the feldspathic sandstones of the Westwater Canyon, Poison Canyon, and Jackpile within the mineral belt became very light gray reduced rock containing disseminated pyrite and scattered fragments of coalified fossil wood. The Brushy Basin and many similar mudstone units in the Westwater Canyon became dominantly pale-grayish-green mudstones. Wherever the feldspathic to arkosic Morrison sandstones are overlain by the Cretaceous Dakota Sandstone, the contact is a pre-Dakota erosion surface. The sandstones beneath this surface are nearly white for

depths of a few meters to several tens of meters, kaolinized by humic acids produced in a boggy environment that existed on this surface prior to or during Dakota deposition.

Subsequently, probably in Tertiary time, the Westwater Canyon from Gallup to Grants was mostly oxidized by infiltrating meteoric waters that produced an immense tongue of oxidized rock which expanded basinward from outcrops along the southern edge of the basin. Erosion has exposed this oxidized tongue in most of the present-day outcrop belt where the Westwater Canyon appears principally as a fairly continuous red unit along a bluff that extends westward from the vicinity of Grants. Downdip, however, the oxidized tongue terminates at various distances from the outcrop and is in contact with light-gray to nearly white reduced sandstones. Away from the tongue, the weathered Westwater Canyon has a buff limonite-stained aspect on the outcrop.

The Section 23 mine lies in a shallow eastward-trending trough along the south flank of the Ambrosia dome, an anticlinal structure disrupting the generally gentle, northerly, basinward dip of the host rocks. The ore occurs mostly below the premining water table, at depths ranging from about 170 to 250 m., and mostly in the upper half of the Westwater Canyon. The leading edge of the oxidized tongue extends eastward from a point north of center on the western section boundary and forms a broad curve extending to the southeast corner of the section (fig 3). Within the oxidized tongue much of the primary ore was destroyed only to be redistributed as secondary orebodies along the leading edge of the tongue.

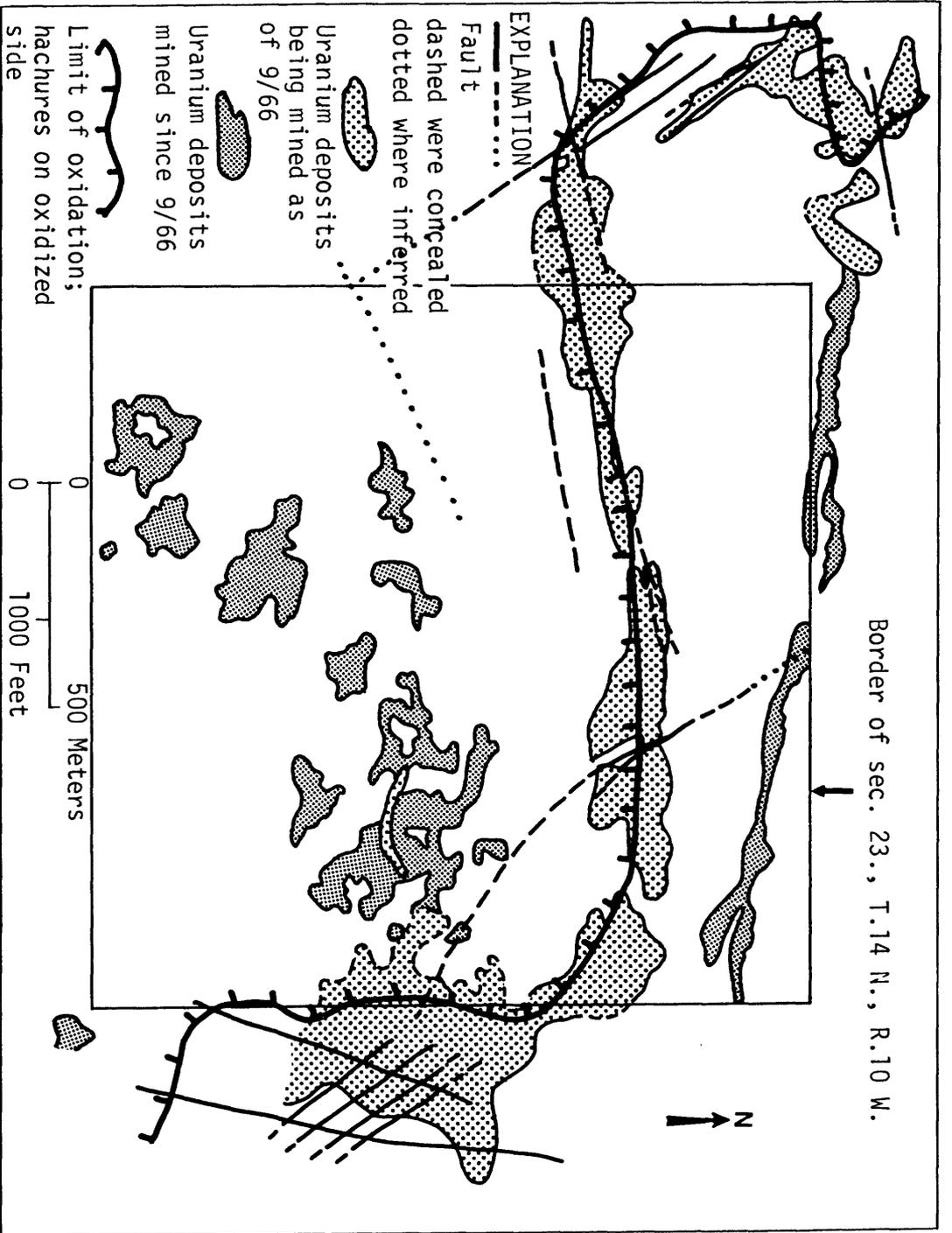


Figure 3.--Map of sec. 23 uranium deposits. Deposits localized along the hachured line, which represents the limit of oxidized rock, are principally roll-type postfault deposits locally bisected by a pre-fault ore layer. Deposits within the oxidized zone are principally remnants of pre-fault ore. The east-southeast-trending deposit that transects the north section line is a pre-fault (trend) orebody

## PREFault ORE

Prefault deposits are uranium-rich humate concentrations in the form of undulatory, peneconcordant layers or blankets suspended in the host sandstones. In prefault deposits the humate substance is everywhere coextensive with uranium ore and is believed to have preceded and to have been the primary control of the shapes and positions of these uranium deposits. The dark shades of the humate mask the primary uranium mineral, and it is the humate that provides visible evidence of the prefault uranium concentrations.

Humate is a term denoting the carbonaceous matter described and defined by Granger and others (1961). Studies since 1961 have further convinced us of its vegetal origin and its close relation to humic acid. We believe the material in Florida described as humate by Swanson and Palacas (1965) is comparable to our humate except that it is much younger and unmineralized.

Uraniferous humate (fig. 4) coats sand grains, fills interstices, and locally replaces highly altered detrital grains in distinct zones within the host sandstone. Within the richest accumulations, detrital quartz grains are marginally corroded and partly replaced by the humic derivative (fig. 5). In the Section 23 mine the humate layers typically are 0.3 to 1.0 m thick and seem nowhere to exceed 1.5 m. Elsewhere in the district the prefault ore

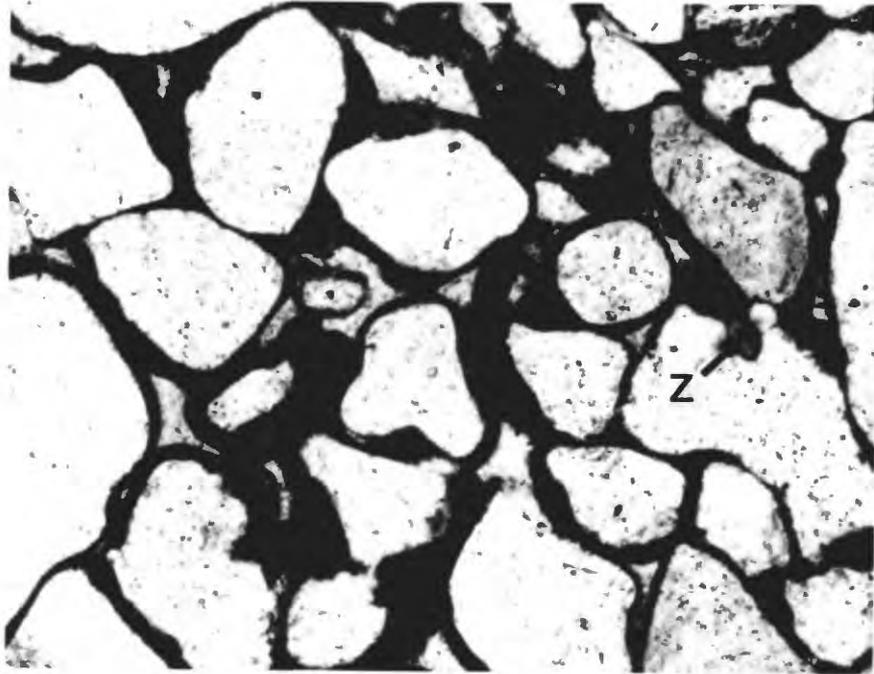


Figure 4.--Photomicrograph of typical uraniumiferous humate ore (thin section of sample 4G66e). Black humate coats sand grains, all of which are quartz in this field. Interstices are open in this field, but some are filled either with calcite or with kaolinite elsewhere in the same thin section; Z = zircon. Plane polarized light; length of field - 0.95 mm

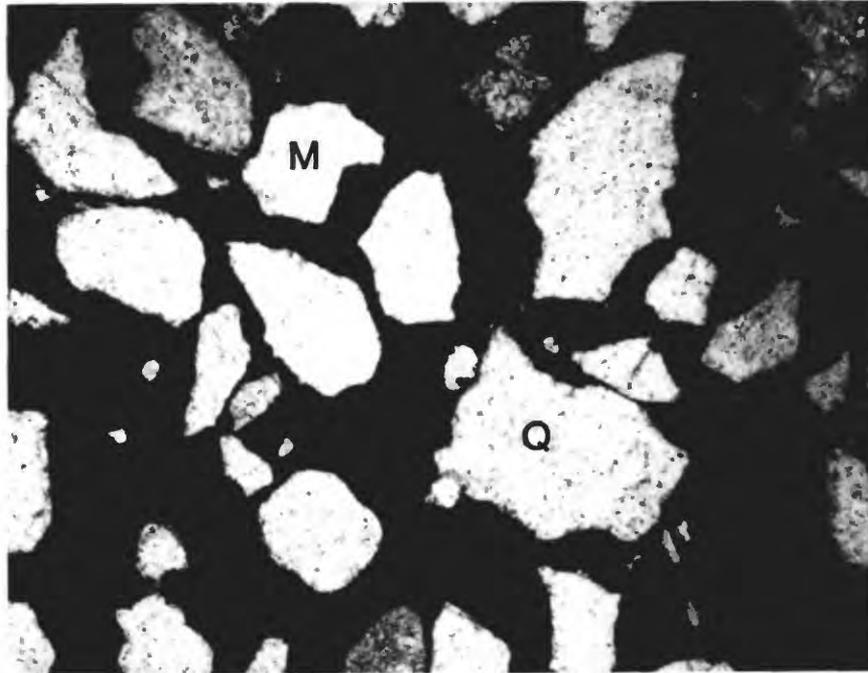


Figure 5.--Photomicrograph showing corrosion of sand grains by uraniferous humate in high grade ore (thin section of sample 8G66b). Black is uraniferous humate; M = microcline; Q = quartzite; the remainder of the sand grains are quartz. Plane polarized light; length of field = 1.9 mm

layers reportedly reach thicknesses of nearly 15 m (H. E. Whitacre, written communication, 1967), but it is not well demonstrated that these thicknesses represent a single discrete humate layer.

A nearly continuous uraniferous humate layer can be traced in the workings of the Section 23 mine and in many drill holes in the northern one-third of the section (fig. 3). In the south half of sec. 23, where most of the ore has been removed by extensive oxidation, only remnant patches of the original layer have been preserved (Gould and others, 1963, p. 67). Drill hole data available in 1966 suggested that the uraniferous humate was very thin, low grade, or missing in the northernmost part of sec. 23. After 1966 a narrow deposit of pre-fault ore was found in this area (fig. 3). Remnants of ore extend as far as the southeast corner of the section, and pre-fault ore was mined in the adjacent sec. 24, the northwest part of sec. 25, and the northeast part of sec. 26. It seems likely, therefore, that prior to oxidation and redistribution, one or more layers of pre-fault ore extended throughout nearly all of sec. 23.

The blanket of uraniferous humate has many fairly continuous, well-aligned undulations, and the thickness and grade of ore varies greatly within this blanket. Some undulations, where the humate layer abruptly crosses strata, are called S-rolls because of their similarity in cross-section to the letter S. Some ore layers thicken along an S-roll but, even where they do not, a vertical section or drill hole intersecting the roll axis crosses a greater thickness of ore than it would in the upper and lower limbs on either side.

The axes of S-rolls commonly are aligned in a southeasterly direction roughly parallel to depositional trends; this direction is also subparallel to the elongation of orebodies in the district and to the mineral belt as a whole. Although most rolls in other mines in the district almost invariably

rise stratigraphically to the north, our mapping has shown that a very significant proportion of those in the Section 23 mine descend stratigraphically to the north.

The ore layers commonly split into several layers in a complex manner along roll axes, so it becomes difficult locally to ascertain which among the several splits is the main limb extending laterally from the roll axis. Figure 6 shows our interpretation of the configuration of one complex roll in the Section 23 mine.

In some ways the humate layers have the appearance of a blanket supported, locally, by discontinuous sedimentary features such as scours, diastems, and thin mudstone lenses between which the humate layers drape, somewhat irregularly, across more uniform sandstone. Splits, branches, and holes in the blanket, however, tend to cloud and confuse this generally simple analogy.

Based on observations of rolls in the Section 23 mine, company geologists (Gould and others, 1963) developed a hypothesis that S-rolls typically occur at regular intervals of about 34 m (110 ft) with a poorly developed or minor roll at 17 m (55 ft). We have had no opportunity to test this idea thoroughly but can see no reason why such regularity should occur. Our investigations in other mines and discussions with other mine geologists indicate that such precise regularity must have been unique to the area in which the hypothesis was formulated.

Once the humate layers were deposited they seem to have been quite stable until oxidizing conditions affected some portions of them in relatively recent time. There is, however, some evidence for at least minor early redistribution and partial destruction of a humate layer in a few places in the Section 23 mine. Figure 7 illustrates a typical 1-meter (3-ft)-thick

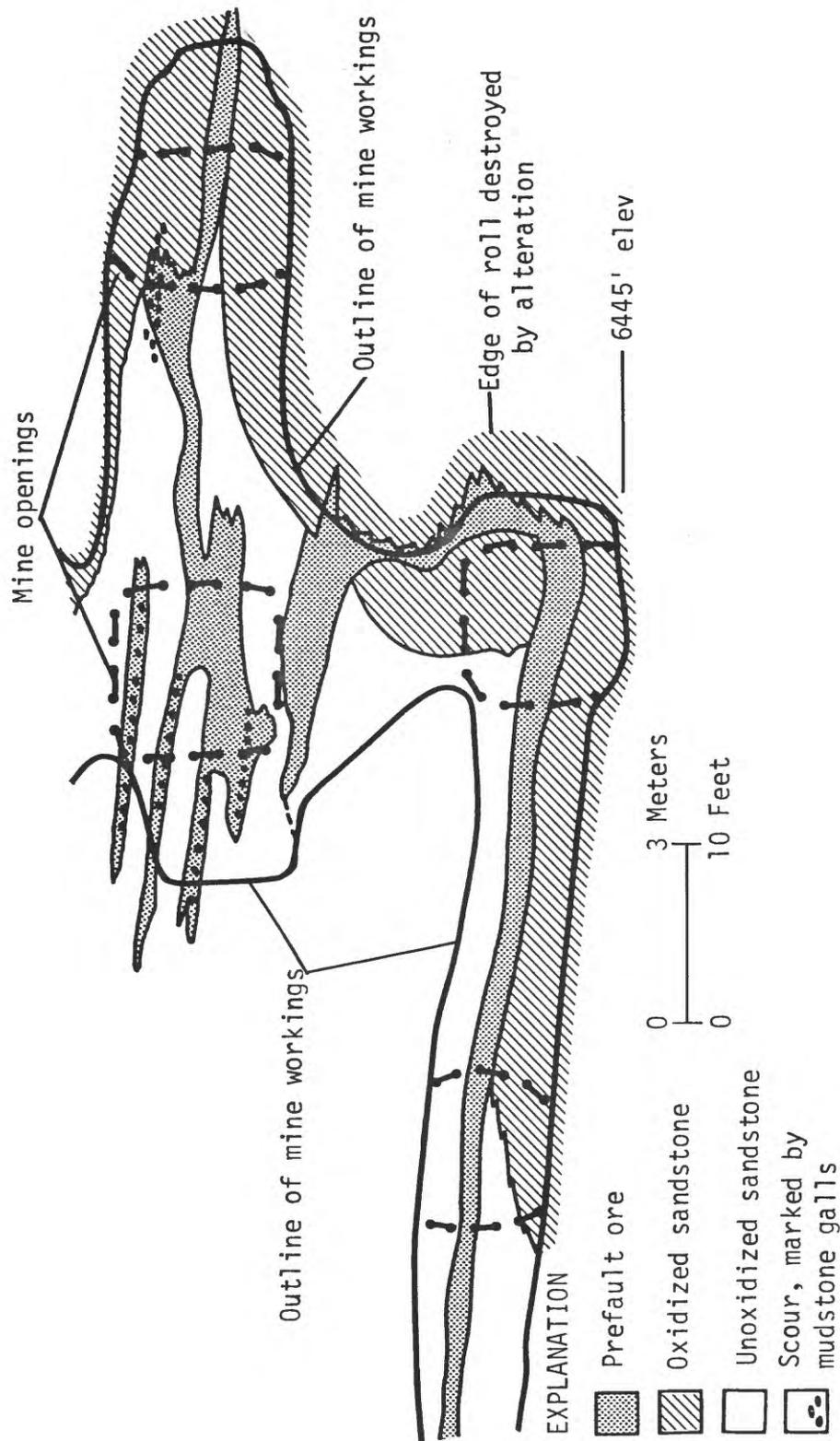


Figure 6.--Roll in prefault ore layer. This highly irregular undulation in the ore layer was enclosed originally by reduced rock. Oxidation occurred much later and is genetically unrelated to this ore

uraniferous humate layer that has been thinned and redistributed without any oxidation or any significant change in general chemical composition or Pb/U ratio. The distribution of selected elements in two suites of samples from this locality is shown on figures 8 and 9. The distribution suggests that here the redistribution of humate occurred not long after, or perhaps even before, the deposition of uranium.

In the type of redistribution illustrated in Figure 7, it is generally only the upper margin of a humate layer that is displaced, manifested as a depression at the top of a layer. In this instance the displacement was so extreme that the entire layer was moved. The displacement border commonly is marked by one or more narrow dark zones, like diffusion bands, that appear to be concentrations mostly of humate and pyrite. Although no provable explanation for these displacement features can be given, the general appearance suggests a perched subterranean watercourse that flowed on top of the humate layer and, by solution, removed part of it. This water would then become, in effect, an "ore solution" and would be capable of depositing some of the humate elsewhere.

Humate distribution, indicated by organic carbon analyses, is ordinarily symmetrical, with concentrations generally increasing from the top and bottom margins toward the center of a layer. The upper margin commonly is much sharper than the lower one; the upper margin of humate may be abrupt, occupying a zone less than 1 cm wide, whereas the lower margin may appear to be gradational, having a width of several centimeters. The lower boundaries may be as sharp as the upper one in some places in the district, but such a condition is rare in the Section 23 mine.



Figure 7.-- Caption for figure 7 on following page

Figure 7.--Displacement of a pre-fault ore layer (photo courtesy of Ted Rizzi, Homestake-Sapin Partners). The horizontal, 1-m thick, black uraniferous humate layer on the left was deposited in a reaction zone between 2 solutions, and when hydrologic conditions permitted a minor lowering of the solution interface, the humate layer was dissolved and redeposited as a thin curved layer at the lower right, along the new position of the interface. Dissolution and redeposition occurred before the original humate had aged to an insoluble substance. (Note the dark, tongue-shaped stain of humate that evidently "bled" out of the original humate layer after dissolution.) Sample suite 62G61 (fig. 8) was collected across the original humate layer at left; suite 63G61 (fig. 9) was collected across the redistributed humate at right. The similarity of the Pb/U ratios presented in figures 8 and 9 suggests either that both uranium and lead were redistributed with the humate or that uranium was deposited throughout the humate at one time. (If all Pb is radiogenic, an age of about 115 m.y. for both events is indicated)

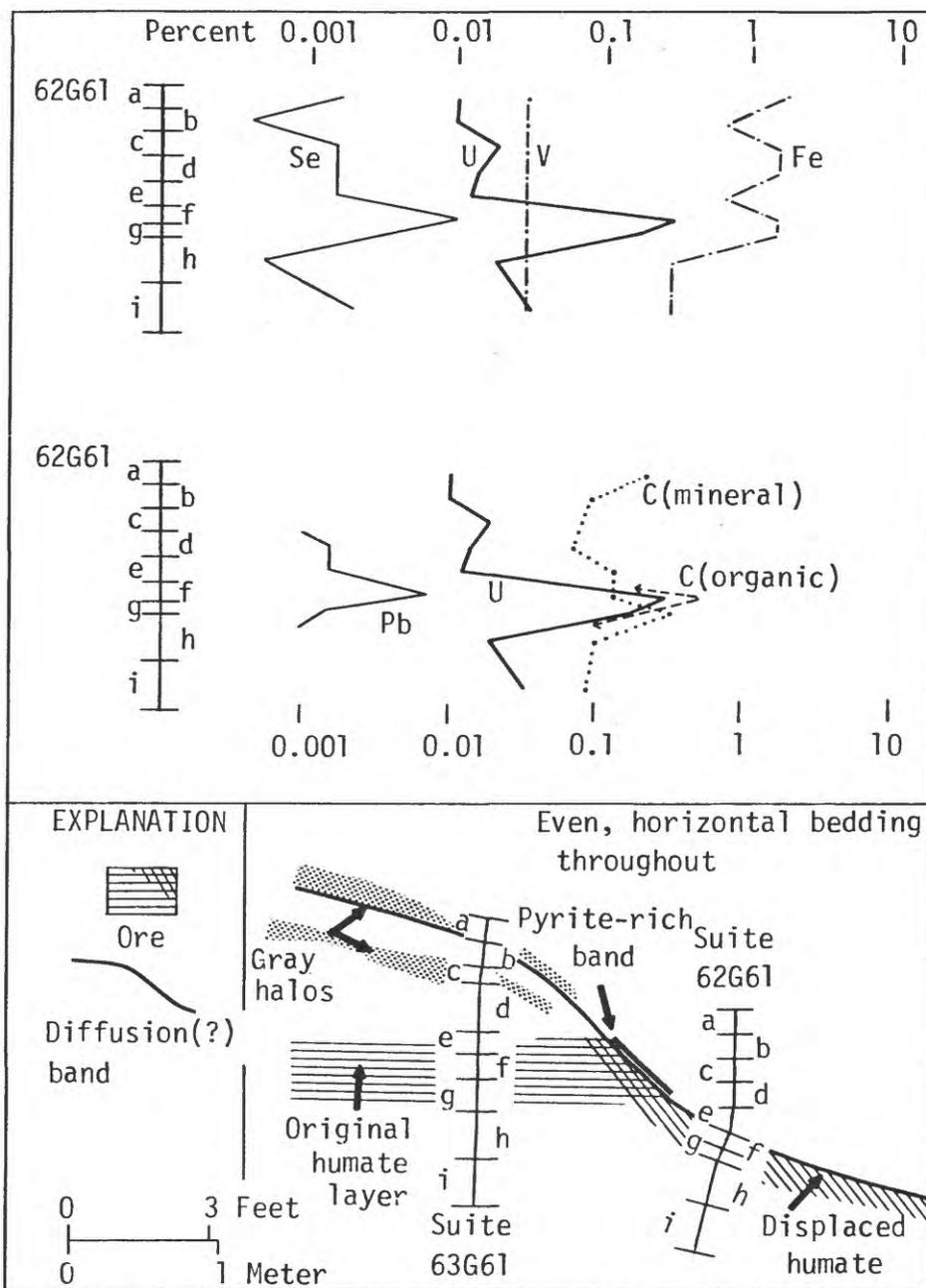


Figure 8.--Distribution of selected elements in sample suite 62G61, collected across original humate layer in Section 23 mine, (see fig. 7 for photo of sample site)

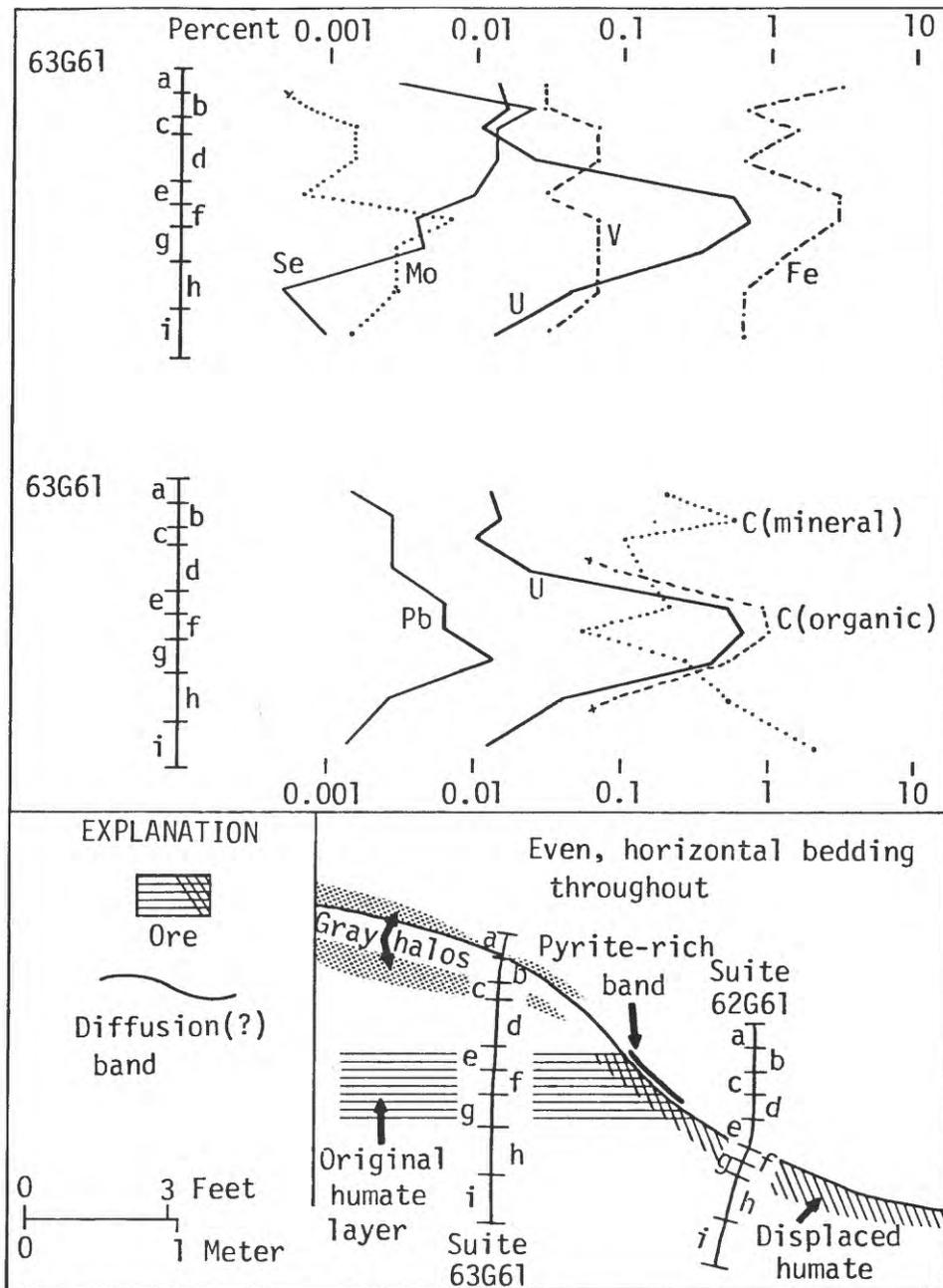


Figure 9.--Distribution of selected elements in sample suite 63G61, collected across redistributed humate zone in Section 23 mine. (See fig. 7 for photo of sample site)

## Mineralogy of pre-fault ores

Although these deposits seem to contain a fairly simple suite of ore minerals, they commonly are very fine grained and not easily studied by optical or X-ray methods. In the following discussion we have 'glossed-over' the possibly complex relation of clay minerals (Granger, 1962; Brookins, 1976) to the ore-forming process and have provided only a cursory description of other ore-stage minerals. Examination of these ores with modern equipment, such as the electron microprobe and the scanning electron microscope, should disclose much information not readily apparent through optical study of thin sections. The following section should, therefore, not be considered an exhaustive study of the ore mineralogy.

Introduced, or extrinsic, minerals in or associated with pre-fault ores are coffinite-bearing humate, jordisite, ferroselite, pyrite, marcasite, calcite, and kaolinite.

The principal mineral component of pre-fault ore is uraniferous humate (figs. 4 and 5). This material is largely amorphous, although all separates yield X-ray diffraction patterns that indicate the presence of coffinite. The coffinite has not been observed even in polished or thin sections under high magnification, so it must be extremely fine-grained and thoroughly dispersed in the humate.

No definite tests have been made to show that all of the uranium in the uraniferous humate is in the form of coffinite, and it is possible that some, if not most, of the uranium may be adsorbed on the humate or in the form of a urano-organic compound, ligand, or chelate. If the humate is capable of holding uranium in this manner, it is probable that some fraction of the other

metals in the ore such as vanadium, molybdenum, and selenium are also fixed by the humate. The capability of natural organic substances to hold metals has been observed by several investigators (Ong and Swanson, 1966).

Prefault ore typically contains more iron, largely in the form of pyrite, than does the surrounding barren rock. Pyrite generally occurs as cubes, some of which are modified by octahedral faces, or as extremely fine-grained, irregularly shaped masses partly filling interstices among sand grains in the ore. Less common are octahedrons, cubes modified by pyritohedrons, and corroded and rounded grains; a few well-formed pyritohedrons were also noted in one sample (8G66b, Granger, 1966a). It seems reasonable to assume that the corroded grains preceded the deposition of uraniferous humate, but even some of the euhedral grains of pyrite are completely enclosed by humate and the paragenetic sequence of deposition is not clear.

Some of the pyrite, both euhedral grains and irregularly shaped aggregates, partly fills voids that remained after the humate deposition. These pyrite forms were clearly emplaced after deposition of the humate, but it cannot necessarily be concluded that they formed later than the uranium.

Marcasite, less than 5 percent as abundant as the pyrite, occurs as fine, well-formed rhombic grains in several prefault ore samples. The grains all seem to occupy pore spaces and none of them are known to be enclosed by the uraniferous humate. The samples in which marcasite was recognized were all collected within a few tens of feet from an oxidized zone, and they are probably related to post-fault processes. It is very doubtful that any marcasite was deposited during the time of humate accumulation.

The occurrence at Ambrosia Lake of jordisite, an amorphous molybdenum disulfide mineral, has been described by Granger and others (1961), Granger (1963), and Granger and Ingram (1966). It was also described and illustrated by Squyres (1963) (see also, Squyres, 1969), who referred to it at that time as "barren material."

Low concentrations of molybdenum are disseminated within the uraniferous humate in many places, but in what form is not known. Molybdenum-organic complexes and jordisite are the most likely possibilities, but these cannot be easily detected by physical means where they are sparsely disseminated because they are nearly black like the humate itself. In thin sections jordisite can appear almost identical to uraniferous humate.

On the other hand, conspicuous accumulations of molybdenum in the form of jordisite in the Ambrosia Lake deposits have been described as follows (Granger and Ingram, 1966): "Much of the jordisite is distributed zonally around unoxidized parts of the primary uranium ore bodies....The distribution is spotty and erratic, but jordisite-rich zones are commonly within 5 feet either above or below a uranium ore layer or within a few tens of feet beyond the lateral termination of an ore layer. In some places, however, jordisite-rich bodies are partly to completely enclosed by primary uranium ore.

"Jordisite in zones outside but near the uranium ore layers in sandstone occurs in two ways: (1) in irregular deposits as streaks and in feathery patterns along cross-laminae, and (2) as deposits with sharp, rounded boundaries in which the rock is completely and uniformly stained. Both types of deposits tend to be elongate subparallel to the stratification. At some places the second type is also completely or partly enclosed by uranium ore."

The jordisite-rich zones are ordinarily nearly black, in contrast to the dark brownish gray of uraniferous humate. Coarse-grained, jordisite-rich sandstones commonly sparkle brightly in the light because of abundant minute triangular faces on quartz overgrowths although these overgrowths may appear to be much less abundant in thin section than in hand specimen.. Fine-grained jordisite-rich sandstones and some jordisite-rich mudstones commonly have a velvety to tarry black appearance.

Jordisite has been observed in thin sections as a coating both on rounded quartz grains and on quartz overgrowths (fig. 10), and also as a dusty layer beneath the quartz overgrowths. Where relations with quartz overgrowths have been noted in thin sections from the Section 23 mine, most of the jordisite(?) is younger.

Jordisite is sparse throughout the Section 23 mine except in a remnant orebody which had been developed in the southeastern workings as of 1966 (fig. 3), and which is completely enclosed by oxidized rock. Considering the ease with which jordisite is destroyed by even mild oxidation, this seems to be a most unlikely place to find it. Its presence here indicates that the remnant ore must have been well shielded from oxidation as the front of the oxidized tongue pushed past the orebody.

Squyres (1963) illustrates an occurrence of jordisite ("black barren material") in the Ann Lee mine, in which it appears that fractures have controlled both deposition and leaching of the jordisite, whereas the adjacent uraniferous humate is little affected by the fracturing. We have observed similar relations in other mines but not in the Section 23 deposits. In the Section 30 mine (fig. 2) jordisite may locally appear to be leached along a fracture or to terminate or extend along a fracture. The same fractures that

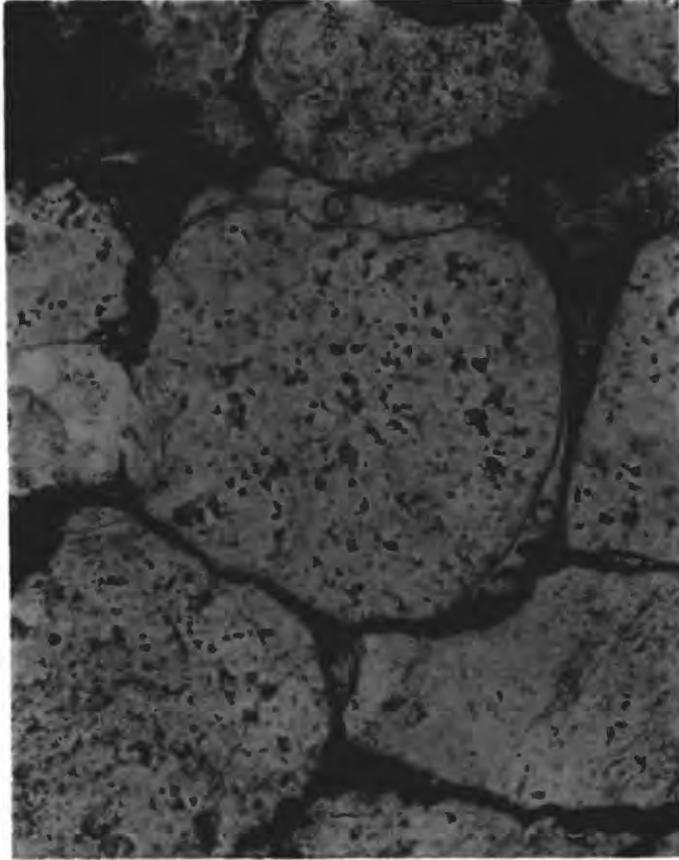


Figure 10.--Photomicrograph showing black jordisite (?) coating sand grains. Quartz overgrowths (O) on the central grain are overlain by jordisite (?), although other works (e.g., Squyres, 1969) describe overgrowths underlain by jordisite. The query (?) expresses the difficulty of unequivocally identifying jordisite in thin section. Plane polarized light; length of field = 0.5 mm

exert this apparent control over the jordisite merely offset the uraniferous humate ore zone immediately below. The uranium ore is not visibly leached or otherwise affected.

Although cogeneration is suggested where there is a consistent association between the uraniferous humate ore and jordisite, the apparently conflicting relations to and control by some fractures suggest a later age for at least some of the jordisite.

Selenium is commonly but not invariably concentrated in the jordisite zones. We have not positively identified the form of the selenium in such occurrences, although S. R. Austin (written communication, 1959) has recognized ferroselite associated with jordisite in one of the other mines in the district. Granger and Ingram (1966) inferred from the analyses of certain molybdenum-rich samples that the Mo occurred as  $\text{MoS}_2$  and that iron occurred principally as pyrite and ferroselite, even though ferroselite was not detected physically.

Whatever the mineral form of selenium, it tends to be concentrated at and near the top of ore layers (fig. 8 or 9). As it has a distribution that is zoned relative to that of uranium and organic carbon and also unlike that of molybdenum, it may have been deposited at a different time.

Although some of the pre-fault ore is calcite rich, much is not, and nearly all observed calcite fills interstices left in the rock after impregnation by humate. The evidence suggests that most calcite is post-fault and was never an intrinsic part of pre-fault ore.

Evidence for early calcite concretions is found in peculiar zones within ore which we call mottled ore and which Squyres (1963) called calcite "shells." These are calcite-rich zones within the ore which are typically rounded and elongate subparallel to the ore layers. These concretion-like

forms contain a multitude of barren spots from a few millimeters to 2 centimeters across. Squyres describes them as follows: "The outer edge of this shell is sharp, abutting against low-grade rock. The inner margin is less distinct, and is gradational through about one foot, from solidly calcite-impregnated sandstone into ore containing spotty, isolated pea-size calcite bodies. There is no ore material on the sand grains enclosed by the calcite of this shell." These zones have the appearance one would expect if a calcite concretion made up of a poikiloblastic or poikilotopic mosaic of calcite crystals were partly replaced by uraniferous humate, the humate having penetrated along calcite grain boundaries and replaced the margins of the crystals, leaving the crystal centers as barren orbs in a mesh of ore. If the process of formation outlined above is what actually occurred, some calcite must have been present before the humate was deposited.

Most calcite in the ore was deposited after the ore minerals. It fills pores that were left after both uraniferous humate and jordisite were deposited. Quartz overgrowths typically preceded the calcite. Calcite locally replaced detrital orthoclase. In some instances an orthoclase grain rimmed by humate or jordisite was partly or completely replaced by calcite leaving a black ring "floating" in a sea of interstitial calcite. More rarely, the feldspar in a detrital grain of granophyre (micrographic quartz-feldspar intergrowth) was completely replaced by calcite, leaving optically oriented cuneiform quartz blebs surrounded by calcite.

The gangue or matrix material is simply the host sandstone, which has retained nearly all of its original characteristics such as texture and mineral composition. The ore and associated extrinsic minerals have merely filled open spaces in the porous fabric of the host rock with only very minor replacement (fig. 4 and 5). The ore contains a higher proportion of chlorite

than the immediately adjacent rocks (Granger, 1962) probably because of conversion of some of the syngenetic montmorillonite. Some highly altered detrital grains are partly replaced by or filled by uraniferous humate.

#### DEEP OXIDATION AND WEATHERING

After early diagenesis, and prior to mid-Tertiary faulting, the Westwater Canyon Sandstone Member throughout most, if not all, of the Ambrosia Lake area must have been chemically reduced, light gray, and pyrite bearing (Granger and others, 1961). In the late Tertiary, when the Westwater Canyon had been exposed by erosion to produce outcrops along the southern margin of the present San Juan basin, oxidizing meteoric waters entered the rocks and moved slowly but persistently downdip as a pervasive flux. The oxidizing waters reacted with pyrite, organic materials, and other reduced components of the rock until the oxidizing potential was spent. Recharge from the outcrop regularly added fresh supplies of oxygenated water to replenish the spent solutions which flowed on through the oxidation "front." Much of the oxidizable material behind the oxidation front, such as pyrite, was converted to metal oxides. The front probably moved through the rocks at a rate several orders of magnitude slower than the flow of groundwater (Granger and Warren, 1978). In both section and plan view, the moving oxidation front must have been quite sinuous, owing to irregularities in permeability.

Fault zones parallel to the dip and transverse to the outcrop augmented the basinward flow of meteoric waters, whereas faults that were nearly parallel to the outcrop and to the strike of the beds tended to retard and divert the flow. Oxidation bordering the San Mateo fault zone (fig. 2) has been described by Rapaport (1963). A broad zone along this fault is oxidized, and ore has been removed and redistributed at least as far north as the

Cliffside mine, whereas rocks just beyond this zone are commonly unoxidized. On the west side of the Ambrosia fault zone the Westwater Canyon Sandstone Member is oxidized over a broad area that extends far northwest of the Ambrosia Lake district, but extensive oxidation extends only a few hundred meters to the east of the fault on the north side of Ambrosia Dome.

Of most importance to this study is a zone of Westwater Canyon Sandstone Member behind that part of the oxidation front that advanced eastward from the Ambrosia fault zone and northward from the outcrop onto the south flank of the Ambrosia dome. This part of the oxidation front defines the irregular limits of an oxidized tongue of Westwater Canyon Sandstone Member within which all but the by-passed remnants of oxidizable materials have been altered or dissolved and removed (fig. 3). For example, pyrite has been converted to hematite or hydrous iron oxides; the sulfur has been removed, probably largely as sulfate in the ground water; organic materials probably have been converted to carbon dioxide and water or to reconstituted humic acids (Granger and others, 1961) and largely removed in solution; and uranium and other metals in orebodies have been oxidized and dissolved.

Within the oxidized tongue the sandstone characteristically is stained red by a pervasive coating of dust-like hematite on all the sand grains. Near the margins of the tongue, adjacent to unoxidized rock, is an irregular border zone stained by hydrous iron oxides (largely goethite?) rather than hematite. This zone, though locally absent, ranges up to several tens of feet thick and forms a sort of discontinuous envelope (fig. 11) separating the hematite zone from the unoxidized pyritic sandstone.

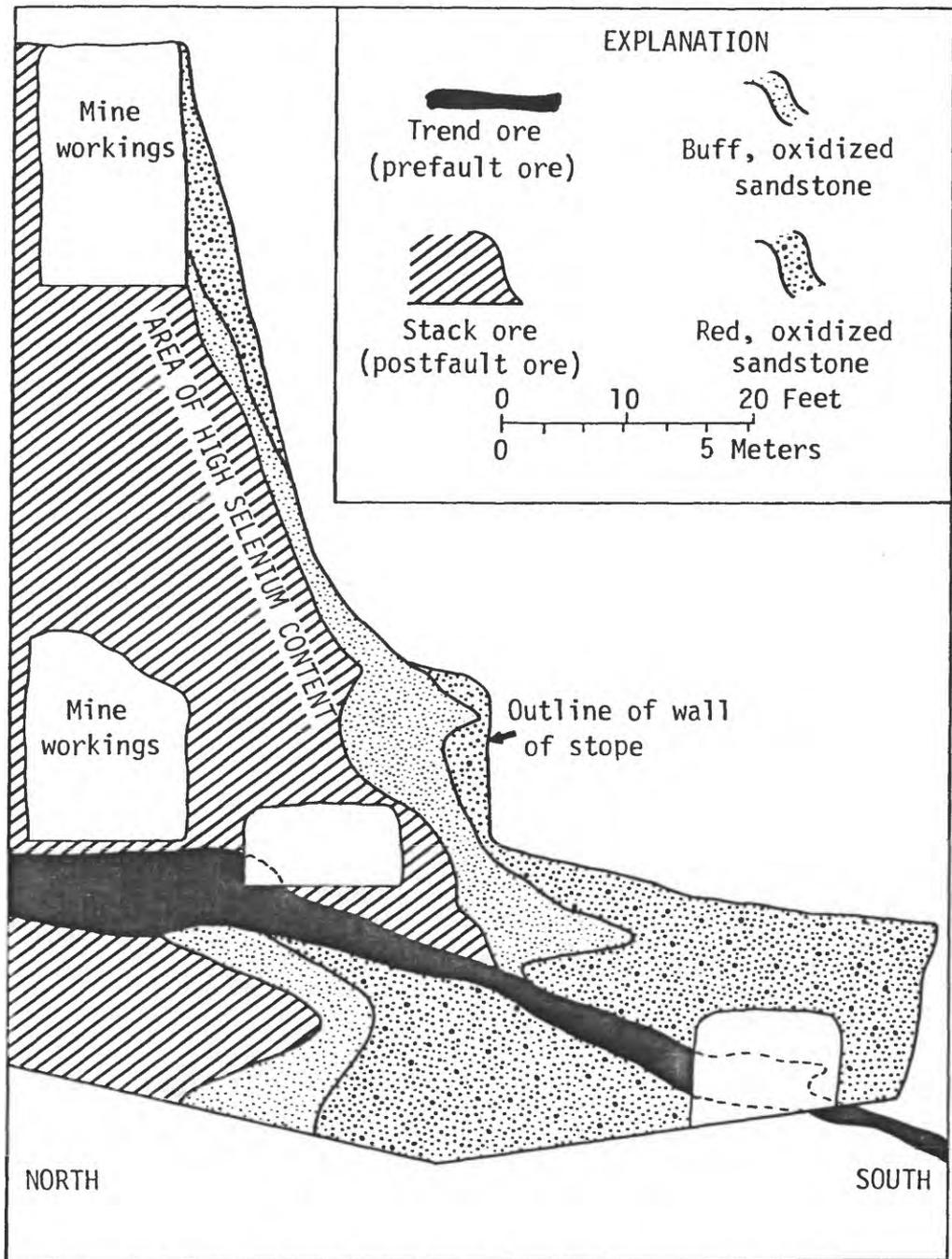


Figure 11.--Roll-type ore at boundry between oxidized and unoxidized sandstone. (Modified from Gould and others, 1963). Note relict prefault ore layer

The front of the tongue of iron-oxide-stained sandstone is very irregular in detail. If the Westwater Canyon Member were a uniform permeable sandstone enclosed between the Brushy Basin and Recapture Members, the front of the tongue, in section could be expected to form a parabolic roll projecting convexly into unoxidized sandstone (Warren and others, 1980). Irregularities in the rock, however, have caused variations in permeability and seem to have had an effect on the symmetry of the leading edge of the tongue. The shape of the oxidized zone is controlled by variations in permeability among units that range from conglomerate to mudstone and by the choking of pores by calcite and clay cements, as well as by disruptions by structural features such as faults, fractures, and joints. Concentrations of oxidizable materials such as pyrite and organic matter tended to control the shape of the front, deflecting it around both sides, and were then slowly oxidized in remnant zones surrounded by oxidized rock.

Although the broken zone surrounding major faults has provided increased transmissivity of the rock, minor faults and fractures have tended locally to decrease the transmissivity, particularly in a direction transverse to the fault plane. Thin layers of gouge and clay filling have restricted the passage of water across these faults.

The process of encroachment by the oxidized tongue took place entirely below the water table. The waters necessarily flowed relatively slowly, not solely because of low transmissivity, but also because all the rocks were saturated basinward. The hydrostatic pressure gradient downdip was not sufficiently abrupt to permit rapid flow of the ground water. As there probably were no large abrupt changes in pressure across such features as faults and joints, a thin filling of clay or gouge would have been effective in impeding and diverting the uniform flow of ground water downdip.

The shape of the front of the oxidized tongue in Figure 3 reflects the subtle control imposed by faults in the vicinity of sec. 23. None of the faults seems to have been a total barrier to the oxidizing solutions, yet the outline of the oxidized tongue conforms in a general way to the fault pattern.

The oxidized tongue is merely an extension of near-surface weathering. For reasons we don't yet completely understand (see ms p. 63), however, oxidation of the pyritic sandstones at the leading edge of the tongue normally has resulted in pale orange coloration; farther back, but still beneath the ground-water table, the oxidized colors of the core of the tongue are reds and browns; and, at the surface, oxidation has produced drab, buff-colored rocks. Most of the sandstones seen at the surface in the Ambrosia Lake area are red and brown; these colors presumably were formed largely by oxidation at depth and are now exposed through erosional processes. Rocks that had been bypassed at depth by the oxidized tongue and subsequently exposed by erosion are colored buff, not red, by near-surface weathering. Such rocks, for example, can be seen in weathered exposures of the Poison Canyon sandstone around the Poison Canyon mine (fig. 2), whereas much of the nearby underlying sandstone in the Westwater Canyon is colored red.

#### Destruction of primary ore

Most of the primary ore layer once present in sec. 23 probably has been destroyed by encroachment of the tongue of oxidized rock described above. Isolated remnants of the original uraniferous humate layer(s) persist at various degrees of preservation within the tongue. These remnants, surrounded by oxidized rock, are more numerous near the front of the tongue. Pale ghosts of the original ore layer can be seen, locally, connecting better preserved, poddy remnants of partly oxidized ore. The ghosts represent almost completely

oxidized and destroyed parts of the humate-rich ore layer. Immediately in front of the oxidized tongue, in unoxidized rock, the primary ore layer has the appearance of being only mildly affected, although analyses indicate that there has been some leaching. Because the front of the oxidized zone is very irregular, with branches and small tongues of oxidized rock extending outward along faults, fractures, and permeable beds, the merging of ore layer and oxidized rock is not geometrically simple.

The effect of oxidation on the element distribution in primary ore has been studied in several mines. Sample suite 122G61, illustrated in figure 12, is typical of these tests and consists of two lines of channel samples across remnant parts of the pre-fault ore layer where it is completely enclosed by oxidized rock a few meters south of the front of the oxidized tongue.

Sample d appears to be relatively unaffected by oxidation. Samples c, e, and l represent parts of the original ore layer that were partly oxidized and leached. Samples k and m represent parts of the original ore layer that have undergone near destruction due to strong oxidation and leaching. The remaining samples are in oxidized, relatively barren host rock adjacent to, and enclosing, the original ore layer.

Composite information from all of the investigations indicates that one of the first effects of oxidation is dissolution and removal of molybdenum, both in the jordisite zones peripheral to ore and within the ore layer itself. Following this, under initial oxidizing conditions, selenium seems to be moved to the interfaces between oxidized rock and relatively unoxidized ore. Although selenium is highly concentrated only at the top of the ore layer prior to oxidation, it may be concentrated at both top and bottom margins of the ore (Granger and others, 1961), and even within the ore, after

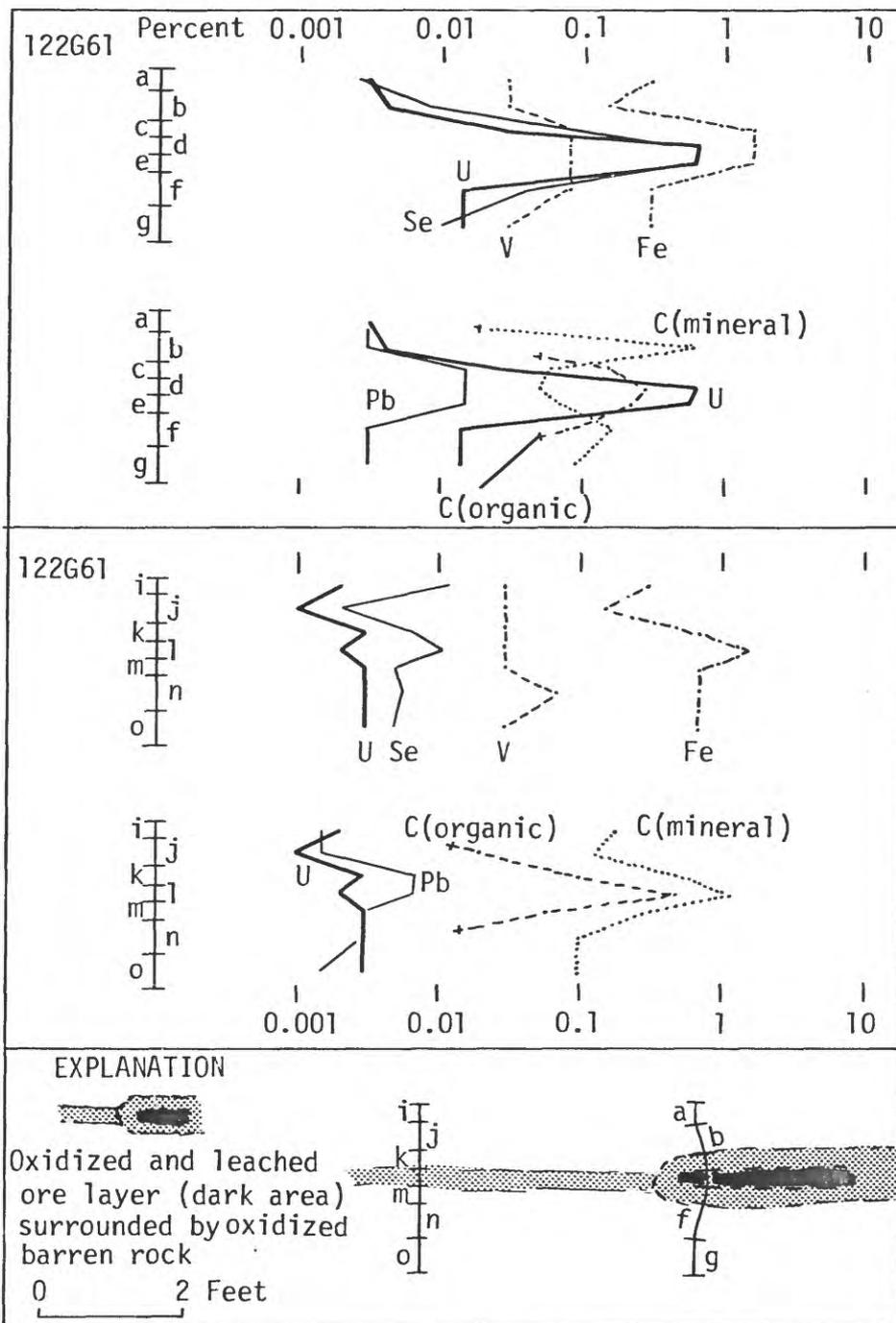


Figure 12.--Distribution of selected elements in sample suite 122G61, collected across (subsamples a-g) and in front of (subsamples (i-o) the oxidized tongue at the Section 23 mine

oxidized rock has enveloped the ore layer. More thorough oxidation, related to removal of uranium and organic carbon, then tends to result in removal of the reconcentrated selenium.

Attempts to detect coffinite in uraniferous humate where it is enclosed by oxidized rock have been unsuccessful. It is inferred that the initial oxidation tends to remove much of the uranium held in the form of coffinite but that uranium held by an organic association may be retained until oxidation is nearly complete. At this stage, the ratio of uranium to organic carbon drops abruptly, and much of the uranium undergoes leaching. Vanadium is leached at this stage, but more slowly than uranium. Lead and organic carbon probably persist the longest, but ultimately they, too, are oxidized and largely removed. Sulfide iron changes to an oxide under oxidizing conditions and is not as readily leached as the other elements.

Immediately in advance of the oxidized tongue the primary ore layer and enclosing rocks may appear much as they do in reduced rock tens of meters away, or they may have certain subtle characteristics that suggest mild alteration, leaching, and redistribution of components of the ore. The edges of the ore layer may be a little less well defined than they are farther from the oxidized zone. The ore layer may be somewhat lighter colored and the uranium content may be more erratic and of lower grade than is usual in reduced deposits farther from the oxidized tongue. In some mines the pre-fault ore layer in advance of the oxidized zone seems to be secondarily enriched in uranium (e.g., the Hogan and Cliffside deposits, fig. 2), but this situation is uncommon in the sec. 23 deposit.

Ore halos may be indicative of mild oxidation and seem to be most common near primary ore in reduced host rocks within about a hundred meters of oxidized sandstone. These halos have a sporadic zonal relation to pre-fault

ore that is similar to that of jordisite. The halos are several centimeters to a meter from either side of an ore layer and are from about 10 cm to a meter or so thick. The rock within the halo is distinctly darker gray than the barren sandstone, but much lighter gray than ore. The halos generally are characterized by a higher pyrite concentration than barren rock and may have various, but small, concentrations of uranium, molybdenum, and vanadium.

Observations of many of these halos have resulted in the impression that they are commonest near oxidized sandstone. That is, they are more abundant and better developed in the transition zone between rocks in which pyrite has been completely oxidized and rocks in which the uraniferous humate shows little evidence of having been affected by weak oxidation, leaching, or redistribution.

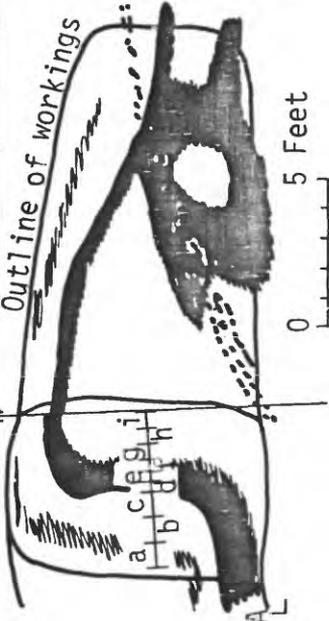
The halo band faithfully parallels the margins of ore, both where the ore is concordant and where it forms S-type rolls (Fig. 13). Although the mechanism of formation is not understood, the appearance of the halos is similar to that which one would expect if some part of the ore were mobilized and moved outward by diffusion to form a vague chromatographic band in the enclosing rocks.

The enclosing barren host rock, in the places where the halos are conspicuous, commonly is light tan or light brown rather than light gray. In some places the feldspars are pale orange, which gives the rock a tan cast. In other places, however, it is difficult to determine why the rock should appear to be tan or light brown. This tint seems to be characteristic of many places just ahead of strongly oxidized rock, and the halos may, therefore, be related to undefined conditions under which pyrite was generally stable but some other ore constituents were mildly oxidized and mobilized.

Plan of workings



1 in. = 30 ft. (9 m)



1 in. = 3 ft. (0.9 m)

-  Medium-grained, cross bedded sandstone
-  Mudgall conglomerate with coarse-to very coarse-grained matrix
-  Dark gray prefault ore showing both sharp and diffuse borders
-  Gray ore halo

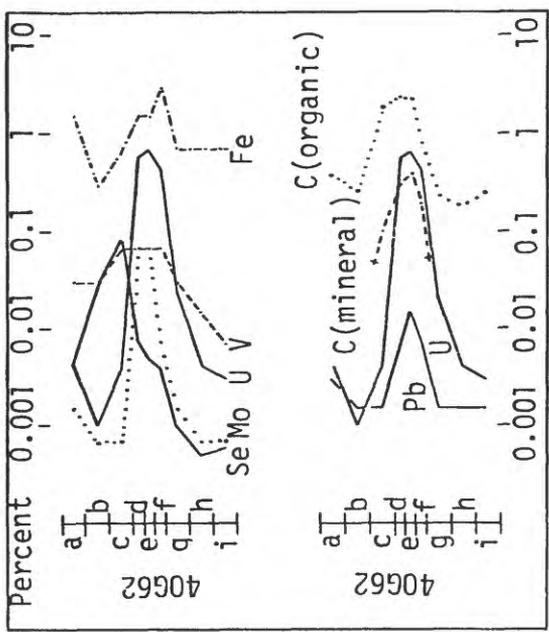


Figure 13.--Distribution of selected elements in sample suite 40G62 and sketch of mine wall at sample site 40G62 showing halo band parallel to a prefault ore layer. (Mine location: 1500 W of 14 N)

## POSTFAULT ORE

Reconcentration, under reducing conditions, of some of the components of oxidized primary ore has resulted in redistributed orebodies (stack ore) which occupy large volumes of rock principally just in advance of the irregularly convex terminal edges of the oxidized tongue (fig. 14). These redistributed orebodies consist of reduced minerals and are similar in many respects to roll-type orebodies such as are found in some of the Tertiary basins of Wyoming (Harshman, 1972; Shawe and Granger, 1965). The Ambrosia Lake deposits, however, differ from the Tertiary basin roll bodies in that they consist of redistributed ore derived from a precursor primary ore layer which has been partly destroyed by encroachment of oxidation. Another conspicuous difference is that the redistributed orebodies at Ambrosia Lake lack the well-defined upper and lower limbs of ore which, in Wyoming, commonly mark the upper and lower boundaries of the oxidized tongue.

Although the principal control of postfault or redistributed ores is the oxidized tongue, the shape of the tongue is so dependent on faults, fractures, joints, and sedimentary structures and textures that these features constitute secondary controls which strongly influence the shape and grade of the postfault ore.

Although the spatial relations of the postfault deposits to the oxidized tongue show many unpredictable vagaries in the Section 23 mine, they are, in general, more regular and easily understood than those in several of the other mines. In some places the complex intermingling of postfault ore and oxidized zones near the terminal edge of the oxidized tongue make a thorough understanding of the three-dimensional relations almost impossible even in the Section 23 mine. The gross geometric pattern is, however, quite clear.

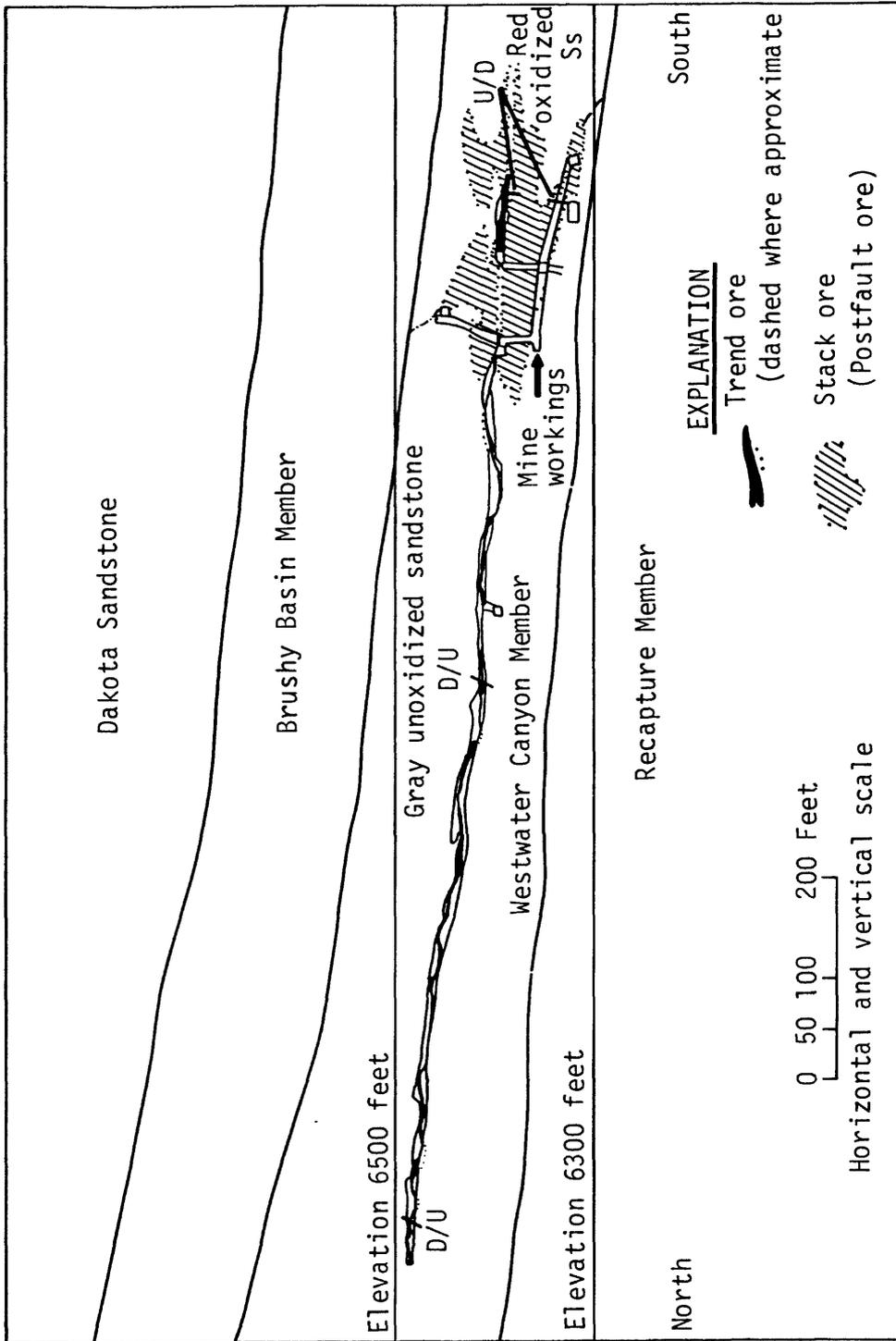


Figure 14.--Cross section fo the Homestake-Sapin Section 23 mine showing relationship of trend and stack ore bodies. (modified from Gould and others, 1963)

West of the major northwestward-trending fault in sec. 23 (fig. 3), the thick, blunt, distal end of the oxidized tongue encroached on the pre-fault ore layer in such a way that the post-fault ore tended to be redistributed just in advance of the tongue. This configuration produced thick zones of redistributed ore, locally as much as 35 m from top to bottom. Immediately in front of the tongue the ore tends to be more continuous vertically than it does farther ahead of the tongue, where northward projecting layers of redistributed ore interfinger with and grade outward into unoxidized barren rock.

The continuity and roll-like symmetry of the redistributed ore is interrupted by irregular fingers of the oxidized rock, which project into the post-fault orebody along fractures and more permeable units of sandstone. The upper and lower parts of the redistributed ore are separated by the primary ore layer, which is essentially continuous to the north beyond the limits of the redistributed ore (fig. 14).

East of the northwest-trending fault, the distal end of the oxidized tongue has projected, wedgelike, beneath the layer of pre-fault ore, and oxidation of the ore layer has taken place mostly near the upper surface of the tongue. Here much of the redistributed ore forms a rather thin manto-like mass above the tongue and mostly overlies the partly to completely oxidized pre-fault ore layer. This mass closely corresponds in shape to so-called "limb ore" in geometrically simpler rolls in Wyoming. Limb ore generally is a thin ore zone at the top or bottom of the oxidized tongue, in contrast to the thick ore that lies in front of the convex termination of the tongue. The eastern part of the sec. 23 deposit differs from typical limb ore, however, in not being localized along the contact with oxidized rock. It is more like a

tongue or manto of postfault ore projecting into unoxidized rock from near the top of the oxidized tongue and tending to be localized by favorable coarse-grained permeable units.

East of the terminal edge of the oxidized tongue, in sec. 24, some of the postfault orebodies are as thick as they are on the west side of sec. 23. This circumstance suggests that the oxidized tongue has directly encroached on the pre-fault ore layer in parts of sec. 24 rather than wedging under it.

#### Mineralogy of postfault ores

As noted in the description of pre-fault ore mineralogy, our mineralogic data is cursory and should not be considered exhaustive. These ores and particularly some of the subtle alteration effects on the host rock are probably much more complex than the following section indicates.

Minerals in or associated with postfault ores are coffinite, montroseite, paramontroseite, haggite, ferroselite, elemental selenium, pyrite, marcasite, calcite, and very minor uraninite.

Coffinite in postfault ore forms aggregates that coat sand grains as a thin film; it also fills small interstices and partly replaces highly altered feldspar(?) and other detrital grains. Some of the coffinite appears in some samples as reddish-brown aggregates when strongly illuminated in thin section. Individual grains generally are less than 0.005 mm long and 0.001 mm across. The tiny grains all seem to be length slow under crossed nicols and have refractive indices near 1.7, which is somewhat less than that for synthetic coffinite. In most samples, however, this reddish brown coffinite is absent, and the coffinite apparently occurs as gray to black opaque accumulations on detrital grain surfaces and within altered grains.

Where quartz overgrowths are present on sand grains in postfault ore, most of the coffinite overlies the overgrowths but, in some instances, sparsely distributed grains of coffinite apparently mark the surface of the original rounded quartz grains. Coffinite commonly is associated with montroseite, but the paragenetic relations generally are ambiguous. In the best examples it appears that montroseite needles are perched on the coffinite aggregates but, in other instances, the bases of the needles are surrounded by coffinite. Although much pyrite in the ore must be earlier than coffinite, in most specimens that have been examined it appears to be later than coffinite.

Paramontroseite probably occurs only as pseudomorphs after montroseite (Evans, 1959), which readily oxidizes to paramontroseite after brief exposure to the atmosphere. Specimens initially identified by X-ray as montroseite have all changed to paramontroseite after a few months' storage in the laboratory. The occurrences of paramontroseite probably are the same as those of montroseite, whose distribution is described below.

Montroseite forms fracture fillings, cement, and disseminations in the ore-bearing sandstones. As fracture fillings it varies in appearance from a firm grayish-black crust to a velvety layer of delicate, black, acicular crystals as much as 1 mm long oriented normal to the fracture planes. The solid crusts of montroseite are rarely more than about 1 mm thick and range from earthy to botryoidal with a distinct, bladed, radiating crystal structure on broken edges. Amorphous-appearing montroseite cements unoxidized sandstone bordering fracture-surface coatings principally near the interface between oxidized and unoxidized rock. It ranges from a film on sand grains to a thorough impregnation of the pore spaces.

A characteristic feature of most postfault ore is the presence of microscopic single acicular crystals or radiating clusters of montroseite perched on sand grains and projecting into interstices. The crystals commonly are about 0.05 mm long and rarely exceed twice this size. Coffinite commonly is associated with these occurrences of interstitial montroseite. Also associated with interstitial montroseite are pyrite, calcite, and kaolinite. Montroseite probably started to crystallize shortly after coffinite and continued crystallizing after coffinite development had ceased. Montroseite is perched on pyrite cubes in a few places and surrounded by calcite in other places. The relations between montroseite and kaolinite generally are not clear, but in most places kaolinite seems to envelope the montroseite in much the same way as calcite. Montroseite generally overlies quartz overgrowths.

Haggite occurs principally perched on sand grains as black stubby crystals a few thousandths of a millimeter across. This nearly equidimensional shape serves to distinguish it from montroseite with which it generally is associated. Haggite also occurs as a black coating on sand grains near oxidized sandstone along joints in a manner which suggests that vanadium was redistributed along the joints under oxidizing conditions and precipitated as haggite near the margin of the oxidized zone.

Spanning the contact between oxidized and reduced rock is a zone from a few centimeters to a meter or so thick that is enriched in selenium (fig. 11). Rocks on the reduced side of this interface contain elemental selenium, particularly within fractures. Fracture surfaces that cut this narrow zone commonly are lined with a "furry" coating of gray selenium fibers that average about 1 mm long and are oriented nearly normal to the fracture surface. Native selenium found on the oxidized side of the interface probably was formed on the reduced side but lagged behind as the interface advanced. Also,

on the oxidized side of the interface, tiny crystals and stellate twins (Granger, 1966a) of ferroselite commonly occur in interstices among the sand grains. These evidently formed in the oxidized rock simultaneously with pyrite oxidation.

Although ferroselite has been identified (ca. 1966) in only a few postfault deposits in the Ambrosia Lake district (Granger, 1963, 1966a), it probably is present in many of the other mines as well. In the Section 15 mine (fig. 2) bright metallic prismatic or rod-shaped crystals of ferroselite also occur in a matrix of claylike material containing calcite crystals. Some of the calcite crystals are coated with aggregates of ferroselite. X-ray patterns of the claylike matrix indicate the presence of major goethite and very minor quartz. In the Section 10 mine ferroselite occurs as overgrowths on marcasite (Santos, 1968).

Postfault pyrite occurs both in joints and in fractures and is disseminated throughout the sandstone host rock. The age of disseminated pyrite may be difficult to determine but, where rocks adjacent to a fracture contain more pyrite than those some distance away, it seems obvious that the pyrite is later than the fracture. The disseminated postfault pyrite seemingly has no distinctive characteristics that distinguish it from pre-fault varieties, although the sparse occurrence of octahedral faces may be a criterion.

In fractures, pyrite generally occurs sporadically as drusy aggregates and porous masses. The grain size rarely exceeds 0.5 mm and the smallest grains are microscopic. Cubes, octahedrons, and combinations of these are the most common crystal forms.

Marcasite has been noted only in fractures, where it generally is associated with pyrite. Locally, however, areas within a fracture are filled with a monominerallic aggregate of marcasite grains.

Pyrite and marcasite seem to be very poor index minerals for determining paragenetic relations, as they evidently formed at several different times in the history of the host rocks. For the most part, pyrite preceded calcite in deposition. Fracture walls commonly are coated with a drusy surface of pyrite, and the remaining space is filled with calcite. Where postfault pyrite is disseminated in the sandstone, it seems to be earlier than montroseite which, in places, is perched on the pyrite grains. Although very obscure, the relation between postfault coffinite and pyrite generally indicates that the coffinite preceded postfault pyrite.

Although generally less abundant than in prefault ore, calcite in postfault ore and in adjacent barren oxidized sandstone occurs in irregular zones as interstitial cement or as fracture fillings. Where it occurs as cement, calcite is later than montroseite and, on fracture surfaces, it is later than most pyrite. Some drusy coatings of calcite in fractures are plated with a fairly smooth shiny film of mixed pyrite and marcasite. When fresh, some of these crystals appear as if they were gold plated. Calcite that occurs in limonitic sandstone was, very likely, deposited after the oxidation. The acid produced during the conversion of pyrite to limonite would have dissolved any calcite that may have been present prior to oxidation.

Uraninite evidently is sparse in the Westwater Canyon host rocks of the Ambrosia Lake district and is probably exclusively a postfault mineral. Near all of the few known occurrences, oxidation has destroyed some pyrite and coffinite. The variety pitchblende occurs in a vug extending along a northwest-trending fracture in the Section 22 mine (Granger, 1963). Although

this occurrence of pitchblende is below the water table, hematite and limonite derived from oxidized pyrite also occur in places at the same level of the mine. X-ray patterns of the nonmetallic fraction of heavy-mineral separates from postfault ores commonly show that sparse uraninite is mixed with the dominant coffinite. It is likely that uraninite was deposited from ground-water solutions during formation of postfault ores by reduction of uranium acquired from the oxidation of coffinite nearby. No vugs containing pitchblende were encountered in the Section 23 mine but we can see no reason why small quantities of pitchblende could not exist there as well as in other postfault deposits in the district.

A large variety of oxidized uranium minerals occur in both near-surface and deep subsurface deposits. Some of these minerals were formed before mining was initiated; others are postmining efflorescent minerals. For a list of these minerals and their modes of occurrence, the reader is referred to Granger (1963).

#### HYDROLOGY

Although no systematic hydrologic study was attempted in section 23, data bearing on the subject were made available to us by mine officials for this and adjacent properties. We obtained some additional data by sampling waters from selected mines in the district. Because these data may provide some insight into ore-forming and redistribution processes, they are included in this report.

## Water Table

Before mining and dewatering commenced in mid-1958, the static water level in the Westwater Canyon Member in section 23 was at an elevation between 1994 and 1999 m (6543-6558 ft). The levels, measured in eight wells, are shown in Table 1. There is some evidence that normal seasonal variations might affect these measurements by 1.5 to 3.0 m (5 to 10 ft). The ground surface is at an elevation of about 2134 m (7000 ft) throughout section 23, placing the static water table at a depth of about 137 m (450 ft). After mid-1958, when dewatering commenced, the water table dropped steadily.

The average static water levels in six holes in section 25 and two holes in section 22 prior to dewatering averaged about the same elevation as that in section 23.

Table 1 --Earliest recorded static water levels in section 23

<u>Hole No.</u>	<u>Date measured</u>	<u>Static water level elevation</u>	
		Feet	Meters
23 H <sub>2</sub> O	September 1956	6,548	1,995.8
23 H <sub>2</sub> O A	April 1957	6,558	1,998.9
23 H <sub>2</sub> O B	May 1957	6,547	1,995.5
23 OB 1	September 1956	6,550	1,996.4
23 OB 2	April 1957	6,556	1,998.3
23 OB 3	May 1957	6,543	1,994.3
23 OB 4	May 1957	6,545	1,994.9
D5-A4	April 1957	6,553	1,997.4

All of the ore mined prior to 1967 in section 23 was below the premining static water level, but because the host strata rise to the north on the flank of the Ambrosia dome, both pre-fault and post-fault orebodies in the adjacent sections 14 and 15 extend above the premining static water level.

#### Ground-water Recharge

Ground-water recharge for the Westwater Canyon Member must come largely from the outcrop and be essentially unrelated to waters in other aquifers in the district. Static water table tests recorded by hydrologists from the U.S. Geological Survey's Albuquerque office indicate that the water table in the overlying Dakota and Mancos Formations of Cretaceous age is at an elevation of a little more than 2073 m (6,800 ft) (written communication, S.W. West, 1965). In the deeply underlying San Andres Limestone of Permian age, the static level piezometric surface is at an elevation of about 1951 m (6,400 ft), which is about 30 m (100 ft) below the static level in the Westwater Canyon Member in section 23.

The Westwater Canyon Member is directly overlain by impermeable montmorillonitic strata of the Brushy Basin Member and underlain by clay- and silt-rich strata of the Recapture Member. It is reasonable to assume, therefore, that there is very little intermixing with waters of the aquifers above and below. Large, through-going faults and fault systems, such as the Ambrosia and San Mateo fault zones, may have provided vertical channelways through the impermeable units along which ground waters have migrated and intermixed, but, owing to the swelling properties of montmorillonite and the presence of clay-rich gouge, it is believed that, in general, the faults were sealed off to such migration.

Present recharge into the uranium host strata must, therefore, be relatively meager because of the generally low rainfall in the region and the fact that much of the host's outcrop is along steep slopes and cliff faces at elevations well above the major drainages. Most of the recharge may be where small drainages breach the outcrop along faults such as the San Mateo fault zone (Thaden and others, 1967). These are the most likely places for major recharge because the host rocks in these drainages are overlain directly by alluvium that must be saturated at times, particularly after rains. Assuming that water would tend to flow downdip along the fault zones, it is probable that much of the recharge would penetrate deep under the static water table before mingling completely with the ground water. The small amount of water that enters the outcrop elsewhere probably percolates slowly downdip until it merges with ground water at the water table. Irregularities such as faulted and jointed zones and flexures, as well as variations in porosity and permeability, probably affect the rate and direction of downward percolation.

#### Porosity and permeability

Table 2 shows the results of porosity and permeability measurements on 17 samples of drill core from the Westwater Canyon Member in sec. 23. Data for this table were obtained from the Homestake-Sapin Partners records of analyses in the late 1950's made by Core Laboratories, Inc. (unpublished data). These data show that permeability ranges from 0.1 to 3,220 millidarcies and porosity ranges from 2.6 to 27.4 percent; each depends, in large part, on the proportion of calcite cement or clay in the rock.

Table 2.--Porosity and permeability of 17 drill core samples from the Westwater Canyon Member in sec. 23, T. 14 N., R. 10 W.  
[gr., grained; med., medium; ss., sandstone]

Sample No.	Description	Hole No.	Sample depth (feet)	Permeability (millidarcies)	Porosity (percent)
PS-1	Coarse gr., light brown ss.	AM23-21	555	1,620	21.2
-2	Fine gr., light greenish-gray ss.	23-21	520	2,910	25.3
-3	Coarse gr., light gray ss.	23-4	546	112	12.2
-4	Fine to med. gr., light gray ss.	23-21	491	815	24.2
-5	Fine gr. ss. and greenish mudstone	23-21	614	650	21.1
-6	Fine to med. gr. ss. and mudstone	23-4	636	815	20.4
-7	Coarse gr., buff to light-gray ss.	23-4	676	197	14.0
-8	Fine gr. ss. and green siltstone	23-52	460	387	25.0
-9	Fine gr., gray ss.	23-52	501	1,750	25.9
-11	Fine to med. gr., light brown ss.	23-52	595	3,220	27.4
-12	Green siltstone	23-46	501	12	6.0
-13	Medium gr., light gray ss.	23-46	550	2,000	25.4
-14	Fine to coarse gr., calcitic ss.	23-46	612	1.6	7.2
-15	Fine gr., light gray ss.	23-46	668	127	26.2
-23	Medium gr., red-stained ss.	23-A	740	0.20	2.6
-24	Med. to coarse gr., red ss. and mudstone	23-A	670	0.60	23.6
-25	Fine gr. ss. and green siltstone	23-A	580	<u>0.10</u>	<u>23.1</u>
			Average	860	19.5

Data from a report by Core Laboratories, Inc., to Sabre-Pinon Corp.

Calcite cement tends to lower both porosity and permeability, whereas mudstone fragments and abundant clay may only lower the permeability without markedly affecting the porosity. The average of these parameters in the 17 samples is 860 millidarcies permeability and 19.5 percent porosity.

For comparison purposes we might cite some data obtained on the adjacent sec. 25 property. In November 1956, pumping and other tests on a water well in sec. 25 were made by C. E. Jacob (unpublished data), ground-water consultant, and reported to the Sabre-Pinon Corp. These tests indicated that the average permeability of sandstone in the Westwater Canyon in the vicinity of the water well was about 780 millidarcies. He reported the average porosity as about 22 percent. These results, therefore, are closely comparable to the measurements on drill core in sec. 23.

#### General classification of ground water

The chemical characteristics of mine waters in the Ambrosia Lake district have been briefly discussed by Corbett and Matthews (1963). They show that the major cations in these waters are  $\text{Na}^+$  and  $\text{Ca}^{++}$  and that the major anions are  $\text{HCO}_3^-$  and  $\text{SO}_4^{--}$ . The few analyses of samples we report in table 3 support the results of these authors. Evaporation of these waters seeping out of the mine walls has resulted in a variety of efflorescent calcium, sodium, magnesium, and uranium sulfates and carbonates (Granger, 1963).

Corbett and Matthews report that the pH of mine waters as measured in the laboratory averages about 8.4 but that the pH at the time of collection was probably somewhat lower. The increase of pH prior to analysis is attributed to loss of  $\text{CO}_2$  from the samples. The pH values we report in table 3 also were measured in the laboratory and average 8.3, in unusually close agreement

Table 3.--Analyses of mine waters, Ambrosia Lake District, New Mexico  
(--, not determined)

Serial No.	pH	Milligrams per liter														F	NO <sub>3</sub>	PO <sub>4</sub>		
		U	SiO <sub>2</sub>	Al	Fe	Mn	Ca	Mg	Na	K	Li	As	Se	HCO <sub>3</sub>	CO <sub>3</sub>				SO <sub>4</sub>	Cl
5115	7.7	.013	22	.23	.10	.00	45	7.2	69	3.2	.09	.00	.04	249	0	88	3.5	.7	.2	.06
5117	7.8	.0021	19	.14	.08	.00	53	13.	252	5.2	.01	.00	.01	209	0	636	8.7	.9	.3	.07
5118	8.2	.0019	14	.18	.00	.00	15	4.9	226	3.7	.07	.00	.01	252	0	322	7.7	.3	.2	.05
5122	7.8	.082	16	.06	.02	.00	32	17.	90	7.4	.05	.00	.00	247	0	136	5.6	1.0	.0	.00
5123	8.0	.055	14	.07	.06	.00	25	9.2	178	6.2	.05	.00	.00	300	0	222	7.9	.6	.2	.00
271495	8.9	.010	--	--	--	--	--	--	--	--	--	--	--	251	18	103	4	--	--	--
271496	8.8	1.26	--	--	--	--	--	--	--	--	--	--	--	239	17	117	4	--	--	--
271497	9.0	.010	--	--	--	--	--	--	--	--	--	--	--	254	20	111	4	--	--	--

Mine	Date Collected	Remarks	Analysts
5115 San Mateo (S.30, T.13N., R.8W.)	4/25/63	Underground sump; Represents total mine drainage	P. K. Roscio Kay Gardner
5117 Cliffside (S.36, T.14N., R.9W.)	4/24/63	Drainage from underground drill hole	do.
5118 Sandstone (S.34, T.14N., R.9W.)	4/24/63	Drainage from underground drill hole	do.
5122 Section 24 (S.24, T.14N., R.10W.)	4/29/63	Drainage from underground drill hole	do.
5123 Section 17 (S.17, T.14N., R.9W.)	4/30/63	Drainage from underground drill hole	do.
271495 Ann Lee (S.28, T.14N., R.9W.)	Mar. 1959	Flow from fracture	D. L. Ferguson, I. C. Frost, H. K. Lipp
271496 Ann Lee	Mar. 1959	Drip from back	do.
271497 Ann Lee	Mar. 1959	Flow from fault	do.

with the figure given by Corbett and Matthews. Mine waters, as they emerged from drill holes and fractures in the mine workings, have been tested in several of the mines by means of pH-sensitive papers. Many of these have yielded pH values near 6.5, supporting the thesis that the underground waters initially have a pH lower than that determined in the laboratory, and that loss of CO<sub>2</sub> quickly results in this increase of pH.

#### Uranium content of ground water

Records are inadequate to report quantitatively on the uranium content of ground water in sec. 23 prior to mining and how it changed as mining and water-table lowering progressed. The following diverse data may be significant.

In 1960, Walton, referring evidently to premining withdrawal of water from the central parts of the district, said, "Water pumped out of the middle of the huge uranium deposit contains no detectable trace (less than 1 ppb) of dissolved uranium." The figure 1 ppb (parts per billion) is equivalent to 0.001 mg/l (milligrams per liter).

In 1958 and 1959, when the deeper deposits mostly were undeveloped and considerable water was being pumped from the shafts and sparse workings, it was reported (oral communications, mine geologists, Phillips Petroleum Co. and Homestake-New Mexico Partners) that all of the uranium being pumped from the mines was in the sediment in the water; the water itself contained no dissolved uranium. Company records for the section 32 mine (sec. 32, T. 14 N., R. 9 W.) show, however, that 14 filtered water samples collected within

the mine in May 1958 contained an average of 1.4 mg/l  $U_3O_8$  (= 1.4 ppm). Solids filtered and settled from these and other water samples contained an average of 0.564 percent  $U_3O_8$ .

In early 1959, three water samples (table 3) were collected in the Ann Lee mine (sec. 28, T. 14 N., R 9 W.) and analyzed in the Survey laboratories in Denver. Water flowing from a fracture and water flowing from a fault each contained 0.01 mg/l U. A sample of water seeping from the back of the workings, however, contained 1.26 mg/l U.

In August and September 1962, thirteen samples of water being fed into a settling pond from the sec. 23 mine were found to contain 6.8-8.3 mg/l  $U_3O_8$ . They averaged 7.5 mg/l (written communication, Homestake-Sapin Partners).

Five mine water samples (table 3) collected by the Survey from five different mines in the district in 1963 contained from 0.0019 to 0.082 mg/l U. No particular pattern was evident from these samples, although the sample with highest uranium content was from a mine containing significant amounts of oxidized rock and postfault ore. None of these samples was from the sec. 23 mine.

The analyses reported by Walton and those reported by the Survey seem generally to be 1 or more orders of magnitude lower than those reported through company records. Since they are not analyses of duplicate samples taken at the same time from the same localities, it is impossible to reconcile the seeming discrepancies. It seems very reasonable to assume, however, that the large-scale mining operation was contributing to a gradual increase in uranium content in the ground waters of the district.

By mid-1964, water pumped from some of the mines was being run through ion exchange columns, and a very significant amount of uranium was being extracted. The mine waters were being enriched by underground leaching of broken low-grade ore and, locally, by washing-down the efflorescent salts that form on the mine walls.

Figure 15 is a chart (from company records) showing the increase in uranium content in waters fed to a surface settling pond from the Sec. 23 mine between August 1964 and January 1966. Experiments to test the practicability of attempts to upgrade the uranium content of the waters were being conducted during this time. Accumulations of efflorescent minerals were washed from the mine walls, and underground sprinkling systems were set up to leach uranium from broken rock in abandoned postfault-ore stopes. These tests produced the irregularities reflected by the graph. Although analyses were made daily during some of this time, only analyses taken at intervals of about a month are shown on the chart. Samples of water taken at selected localities within the mine commonly contained several hundred mg/l  $U_3O_8$  during this experimental program, and the water used to wash efflorescent minerals off the walls contained as much as 700 mg/l  $U_3O_8$  (R. B. Smith, oral communication, 1965).

#### DISCUSSION AND SUMMARY

Much of this paper was prepared in late 1966 and early 1967, and those parts have been retained with only minor changes that reflect subsequent experience. A great deal of study, exploration, and mining in subsequent years, however, therefore, has served to expand greatly our understanding of the Grants mineral belt. Therefore, in this section, we will endeavor to

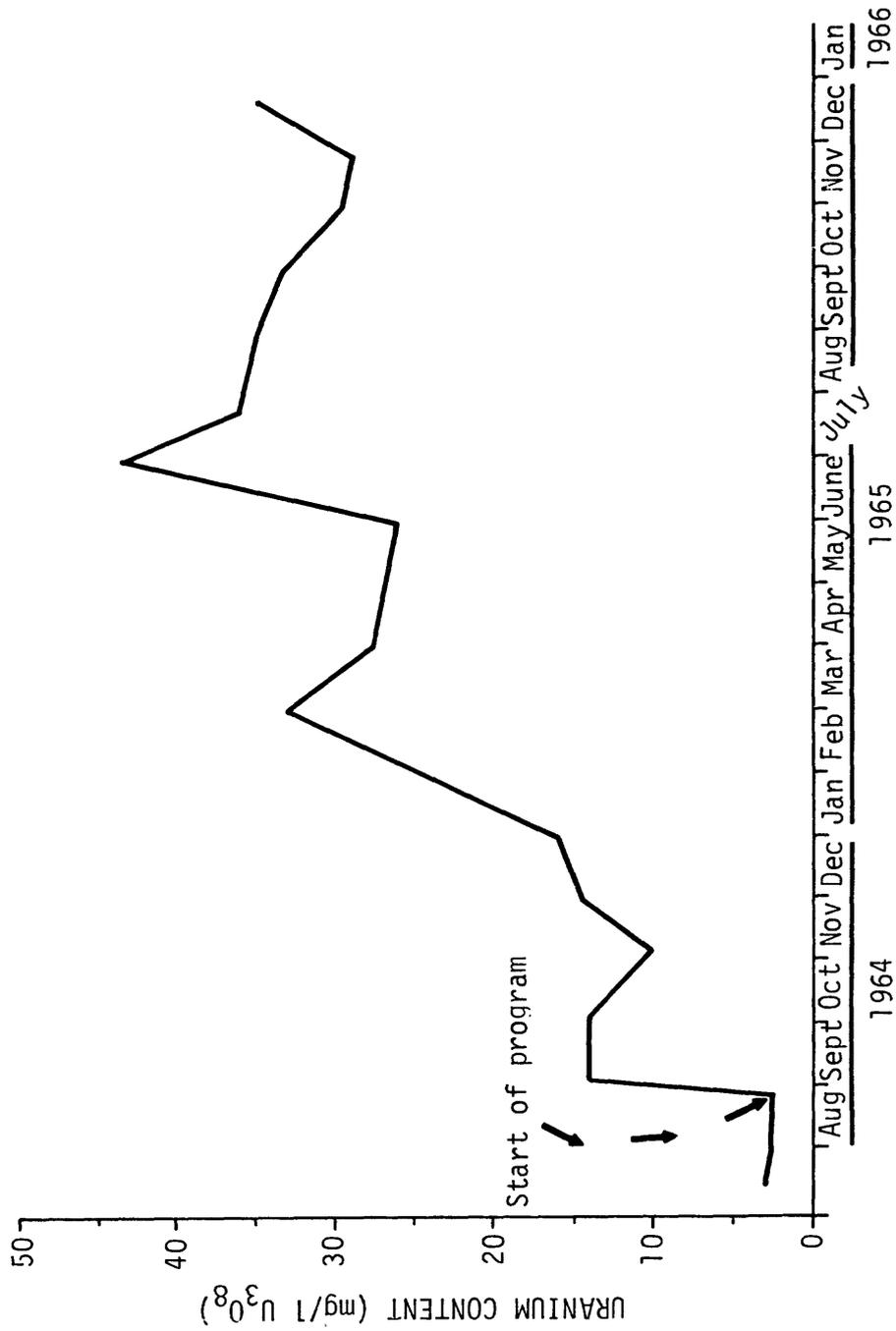


Figure 15.--Change in uranium content of waters being fed to a surface settling pond during experimental underground leaching, Section 23 mine

discuss the Section 23 mine and the Grants mineral belt in the light of present knowledge. We will do this by relating a brief, generalized genetic history for the entire mineral belt.

The Westwater Canyon was laid down in Late Jurassic time, principally by braided streams migrating across a broad featureless fluvial plain. Sandstone units were derived primarily from drab-colored granitic and other debris (similar to present-day braided stream sediments), but the intercalated overbank mudstone units seem to be largely composed of montmorillonite that originated from volcanic ash. In Brushy Basin time the deposition of mudstone dominated over deposition of channel sandstones, and the change from Westwater Canyon to Brushy Basin may have been caused more by a change in the proportions of tractive and suspended loads than by a drastic change in depositional environment or provenance.

During early diagenesis the waterlogged wood fragments incorporated with the wet fluvial sediments were degraded to coalified fossil matter by bacterial action. Some of these bacteria were sulfate-reducers that produced  $H_2S$ . These and other species produced complex organic byproducts such as fulvic and humic acids and simpler organic derivatives such as methane and  $CO_2$ . The diagenetic pore waters, containing dissolved  $H_2S$  and organic acids in the rocks surrounding the degrading plant debris, attacked detrital iron-bearing minerals, partly dissolving them (Adams and others, 1974 and 1978) and converting the iron to disseminated pyrite. The net effect was to produce a light-gray pyritic sandstone derived from the original drab sands wherever adequate degrading organic matter was present. Elsewhere (where not protected by the reducing capacity of abundant organic matter), the drab sands

were oxidized to red hematitic sandstones by red-bed-forming processes (Walker and others, 1978). Presumably, this entire diagenetic alteration phase was essentially completed in Late Jurassic time.

During Early Cretaceous time the southern margin of the San Juan basin was gently uplifted, and the edges of the Morrison were beveled and truncated subaerially, prior to the southward and westward advance of a Cretaceous sea. A swampy, boggy environment that was developed on this subaerial surface produced peaty and lignitic deposits, which later probably dried somewhat and contributed humic acids to the ground water. In this humic environment the exposed surfaces of feldspar-rich Morrison sandstones were extensively kaolinized to depths of as much as 50 m. The present site of the Section 23 mine probably was no less than 30 km from the exposed edges of the Westwater Canyon Member at that time. As these humic acid solutions percolated downdip they presumably lost some of their ability to attack strongly and to kaolinize the feldspars because of changes in pH and the occupation of complexing sites by alumina, silica, and alkali metals. They may, however, have retained some of their ability to reduce and complex iron. We believe that these solutions may have further bleached and altered (by reduction, by selective dissolution of magnetite, etc.) both the red-bed facies and the pyritic, organic facies in the sandstones, considerably enlarging the zones that were originally bleached and reduced by intrinsic diagenetic solutions around degrading plant matter. Virtually all sandstones of the Westwater Canyon sandstones in the Ambrosia Lake district consist of such light-gray facies.

Presumably, at about the same time as magnetite alteration, some of the detrital feldspars downdip from the surface exposures also were being altered but not kaolinized. According to Austin (1963) and Adams and others (1978), the rims of both detrital volcanic sanidines and plagioclases commonly were

replaced or (and) overgrown by albite or K-feldspar (probably adularia). Part of the explanation might be that higher temperature feldspars, consisting of mixed Or-Ab or Ab-An phases were replaced by purer Or and Ab phases, which are more stable under low-temperature, authigenic conditions.

Subsequently, the remaining cores of many of these detrital grains were partly to completely dissolved, leaving the authigenic rims as thin, delicate, remnant shells. Within the rims it is common to find remnants of the original grain and, more rarely, tiny authigenic grains of anatase, pyrite, and calcite. Solution of these feldspar cores, rather than simple alteration to secondary minerals, indicates that alumina, silica, and alkali metals were dissolved and removed. Such a process requires a very specific solution, probably a solution rich in organic acids capable of complexing with and dissolving alumina. Inorganic low temperature solutions probably would be incapable of such efficient dissolution of alumina-silicate minerals.

It would be appealing to think that these same organic-rich solutions may have formed the kaolinite nests seen throughout much of the Westwater, because the solubility of alumina is extremely low in most organic-poor solutions. The paragenetic relations (Austin, 1963; Granger, 1963; Squyres, 1969), however, suggest that the kaolinite nests are much later--perhaps even later than the postfault ore.

Extensive layers of humate were precipitated in the host rocks sometime prior to Dakota deposition (Nash and Kerr, 1966). We have suggested relating the origin of these humate deposits to the humic matter derived from the swamps on the pre-Dakota surface (Granger and others, 1961; Granger, 1968). We also suggested the alternate possibilities that the humate might have been derived either syngenetically from plant matter lining the stream courses in Morrison time or diagenetically from the plant material deposited with the

sandstones. In addition, Peterson and Turner-Peterson (1980) have proposed that the humates might have been derived from humic acids originating within the mudstones and were expelled into the adjacent sandstones during compaction. The origin of the humate has not yet been satisfactorily resolved.

The deposition and localization of the humate is as puzzling as its source. Recognizing that soluble humic acids could be precipitated by an increase in the concentrations of multivalent cations or hydrogen ions (lowering pH), Granger (1968) proposed that humic acid-bearing meteoric solutions percolating generally downdip in the gently basinward-dipping host rocks had deposited the humate wherever they encountered a pore solution in which the humic acids were insoluble. It is assumed that the upper surface of this precipitating solution was essentially an undulant, static watertable surface and that the introduced humic-rich meteoric solutions spread laterally on this surface, depositing the humate at the interface between two solutions. Because of fluctuations of this interface caused by such factors as differential compaction, minor structural movements, and changes in amount of recharge, the humate commonly was deposited in superposed and overlapping layers. Features such as that illustrated in figure 7 suggest that, shortly after deposition, the humate was still soluble in the upper solution but insoluble in the underlying solution. Lowering the interface would then permit the humate layer to dissolve and be redeposited at a lower horizon at the locality shown in figure 7. If this conclusion is valid, humate layers would tend to be preserved by a rising solution interface but destroyed by a dropping interface.

In sec. 23 we were able to identify only one discontinuous humate layer (in 1966), but in adjoining sections (e.g., sec. 14 and 25) humate layers had been found at positions both stratigraphically higher and lower than in sec. 23. Some of the orebodies in these adjacent sections are now known to project into sec. 23 at stratigraphic positions different from that of the dominant layer that we studied in 1966.

The orebody in the extreme north part of sec. 23 is on the projection of a stratigraphically high orebody in sec. 14 (Bucky No. 1 Mine) and is elongate to the east-southeast, as are most of the orebodies in the district. This direction coincides with the general trend of the mineral belt and with the dominant sedimentary trend in the host sandstones as evidenced by crossbedding and sole marks or current lineations on both crossbedded and flat-bedded laminae. The elongation of individual orebodies has not been explained adequately, but it seems probable that it favors directions in which the channel sand sequences in the Westwater Canyon are most continuous, permeable, and transmissive.

Because these deposits are similar in shape and composition to widespread layers of humate deposited at the freshwater-saltwater interface in coastal sands along the western coast of Florida (Swanson and Palacas, 1965), it seems probable that the precipitating solution was brine-like. This concept of a nearly horizontal solution interface seems to explain many of the characteristics of the mineral belt, including its subparallelism to the southern margin of the San Juan Basin. The width of the belt was limited by the intersections of this water table with the upper and lower surfaces of the gently dipping host sandstones (Granger, 1968; Melvin, 1976).

However, subsequent to our initial studies, humate-rich deposits have been found far basinward, to the northeast of Gallup (Rhett, 1980; Clark,

1980). If the concept proposed by Granger (1968), and later modified by Melvin (1976) has any validity, it must accommodate these newer discoveries. According to Galloway (1978, fig. 2), continuous fluvial-channel sandstones, radiating somewhat fanlike from near Gallup, can be traced basinward in the Westwater Canyon. Rhett (1980) and Clark (1980) have described the most basinward of these deposits, presumably within the above-mentioned channel sandstones, as being roll-like in form, being enclosed by reduced sandstone, and having axes oriented northeastward, subparallel to the depositional directions in the host rocks. These characteristics might be compatible with Granger's (1968) hypothesis if tongues of meteoric, humic, acid-bearing waters were able to penetrate the water table and percolate downdip along permeable conduits provided by the channel sands. In this event the humate might have been deposited as roll-shaped layers at the lateral margins of these fingers of meteoric solutions where they contacted the pore waters in which humic acids were insoluble. It should be acknowledged, however, that Rhett (1980) and Clark (1980) believe these ores are re-reduced roll-type deposits, not primary humate-type deposits.

The primary deposition of uranium and its chronologic relation to other geologic events is not entirely clear. The distribution of humate and uranium throughout the mineral belt shows that they are coextensive but does not unequivocally prove that they were deposited simultaneously. Indeed, the many uranium-rich coalified fossil wood fragments within the ore layers must have been mineralized after their deposition. Therefore, some organic matter was present prior to uranium mineralization. If the humate was derived from those fragments of coalified wood scattered throughout the Westwater Canyon, it seems unlikely that uranium would have been present within the humic-rich solutions and would have been deposited simultaneously with the humate. There

seems to be no serious objection either to transport of uranium by an extrinsic solution carrying humic acids or to transport in the (carbonate-bearing?) precipitating pore solutions in which humic acids were insoluble. It might, however, be difficult for the humic solution to carry both uranium and humic acids as complexes in the same proportions as they are found in the orebodies. Humic acids probably are incapable of forming complexes that consist of approximately equal weight ratios of uranium to organic carbon (J.S. Leventhal, oral communication, 1979). Direct precipitation of a urano-organic complex, therefore, seems inadequate to explain the ores. However, the addition of other complexing agents, such as carbonate or, perhaps, fulvic acids, might render the humic acid solution entirely capable of carrying the required amounts of uranium and, at the same time, making reduction of the uranyl ion either kinetically sluggish or thermodynamically impossible until after precipitation.

The geologic relations seem to indicate (Nash and Kerr, 1966) that the ore was deposited prior to Dakota deposition about  $92 \pm 8$  m.y. ago (Brookins, 1980). Lee and Brookins (1980) report that Rb-Sr ages, determined on chlorites they believe to be of the same age as the primary ore, are about  $139 \pm 13$  m.y. Some very preliminary  $^{207}\text{Pb}$ - $^{235}\text{U}$  ratios determined from primary ore in the Ambrosia Lake and Smith Lake districts by K. R. Ludwig (written communication, 1979) are on the order of 115 m.y. These uncertainties prevent us from giving an exact age, but all interpretations seem to be in agreement that the ores were deposited well before the host rocks were deeply buried in Late Cretaceous and early Tertiary (?) time.

Sometime in the late Tertiary the deposits had been brought once again near the surface, and the eroded edges of the Morrison were exposed to weathering and infiltration of meteoric waters. These oxidizing waters,

moving downdip toward the interior of the San Juan basin, formed large tongues of oxidized rock by destroying the disseminated pyrite and forming iron oxides. Wherever the encroaching tongues encountered a primary uraniferous humate deposit, they at least partly destroyed it. The humic substances were largely solubilized and removed, but much of the uranium, vanadium, and certain other elements were merely redistributed along the redox interface by essentially the same processes that have formed roll-type deposits in Tertiary rocks of Wyoming and the Texas Gulf coastal region (Granger and Warren, 1969; Harshman, 1972; Goldhaber, Reynolds, and Rye, 1979). In the Morrison, however, where faulting had affected the host rock, classical, geometrically symmetrical roll shapes did not develop. Rather, they were erratic and unsymmetrical.

The oxidized tongues typically are red and hematitic in the core and are bordered by a relatively narrow zone of buff limonitic rock. Granger and Warren (1974) attributed this relationship to a multiple-stage geochemical process. A possibly better explanation has been offered by Saucier (1979), who attributed the limonitic border to rejuvenation of an earlier (Tertiary) stage of oxidation after a hiatus of indefinite length. He believes that the core is hematitic because of aging and dehydration of iron oxyhydroxides (limonite) formed during the earlier Tertiary oxidizing stage. The border zone, by Saucier's scheme, was formed more recently but has not yet had time to age and to convert to hematite.

The Section 23 mine encompasses the margin or 'front' of a large oxidized tongue near its eastern edge and about 7 km north of the present outcrop of the Westwater Canyon Member. The oxidized tongue is exposed at the outcrop and can be traced in drill logs to the central part of the section. As shown in figure 3, the oxidized tongue on the southern half of the section encloses

many remnant parts of an ore layer that was much more extensive and continuous prior to oxidation. The accumulation of stacked or roll-type postfault ore just in advance of the oxidized tongue is convincing evidence that much of the missing primary ore within the tongue was redeposited along the roll front.

Smith and Peterson (1980) and Peterson (1980) attribute the hematitic oxidized tongue to pre-Dakota oxidation. No ore deposits related genetically to oxidized tongues have yet yielded ages that old, however. K. R. Ludwig (oral communication, 1979) has determined several  $^{207}\text{Pb}$ - $^{235}\text{U}$  ratios for these postfault (roll-type, stacked) ores, and all indicate (preliminary unassessed) ages less than 6 m.y. Granger (1963) also presented total Pb-U data showing that deposition of certain of these ores probably has continued up until the present.

#### CONCLUSION

Problems related to the ore deposits of the Grants mineral belt ranging from resource assessment through genetic history, have not yet been conclusively solved. Concepts, biases, and unanswered questions are even more numerous than the geologists trying to solve the problems. The Grants mineral belt will provide opportunity for study and conjecture for many years, perhaps even after most of the uranium is long gone; extensive mining activity is now in its 30th year in the region and is slated to continue for several more decades.

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