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GEOLOGY AND MINERALOGY OF THE CALLIHAM
URANIUM-VANADIUM MINE, SAGE PLAINS,
SOUTHEASTERN, UTAH

by

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of the Requirements for the Degree of
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GEOLOGY AND MINERALOGY OF THE CALLIHAM
URANIUM-VANADIUM MINE SAGE PLAINS,
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ABSTRACT

The Calliham mine, located near the Utah-Colorado border in the Sage Plains district of southeastern Utah, is currently producing uranium and vanadium from the Salt Wash member of the Jurassic Morrison formation. Integrated mine, mineralogic, chemical, and radiometric studies were initiated to delineate the characteristics of the mine's ores, guides to ore, and a model for the origin of the deposit.

In contrast to the vast majority of other uranium deposits of the Colorado Plateau the mines on the Sage Plains are not spatially associated with a structural uplift. Rather, the mines are producing from undeformed, unfaulted, very gently dipping, Salt Wash sandstones.

Peneconcordant mineralization occurs in a laterally extensive, but vertically restricted zone in the uppermost 20 meters of the Salt Wash member. Ore zones appear as discontinuous stringers, lenses, and pods in fine-grained, well-sorted, medium-bedded, trough crossbedded to tabular sandstones. Thin zones of mineralization are found along bedding planes and along contacts between sand bodies because of the higher porosity of these sandstones along the hydrologic paths of least resistance in the rock mass.

Mineralized sands vary from gray to greenish-gray and black depending on the amount and character of the chlorites which they contain.

The ore minerals are authigenic vanadium-chlorite and carnotite which occupy the interstices of the sand grains. Chlorite occurs as blades forming tufts and rosettes infilling the pore spaces with carnotite crystallites 1 u to 3 u in diameter randomly scattered among the chlorite blades and along quartz grain boundaries.

Detrital quartz grains invariably exhibit microfractures, undulatory extinction, and ubiquitous quartz overgrowths. The occurrence of undeformed silica overgrowths suggests that the grains were deformed at some earlier time and later were subject to pressure solution at the grain contacts forming the secondary silica.

The paragenetic sequence is quartz overgrowths, chlorite, carnotite, quartz infilling the interstices of detrital quartz grains and carbon grains. Other minerals observed in minor amounts in which the paragenetic relationships are not known or are unclear are pyrite, kaolinite, barite, clausthalite, zircon, ilmenite(?), and montroseite(?).

It is probable that the Uranium and Vanadium minerals present today are the result of the oxidation of uraninite, roscoelite, montroseite, and coffinite(?) by oxidizing, slightly alkaline groundwaters. Secondary migration of Uranium appears to be on the scale of millimeters. The age of mineralization can only be bracketed between the age of the sandstones and the present.

INTRODUCTION

ACKNOWLEDGEMENTS

This study was made possible by a grant from ATLAS MINERALS of Moab, Utah who had selected the Calliham for geologic study. I'd especially like to thank Preston Niesen the Senior Geologist at ATLAS MINERALS who initiated the study and without whom this project would never have occurred and Dr. David I. Norman without whose advice and assistance this project would never have been completed. I am much indebted to Mike Hollingshead the mine foreman, Bill Edgington the mine geologist, and all the miners who helped me so much in the mine. I would like to thank the New Mexico Bureau of Mines and Mineral Resources for allowing me the use of their rock crushing equipment and x-ray diffractometer, Dr. L. Murr chairman of the Department of Metallurgical and Materials Science for the services of Andrew L. Rosenthal who is responsible for all of the S.E.M. images contained herein, and Dr. K.C. Condie of the New Mexico Institute of Mining and Technology for arranging the irradiation of my Lexan prints in Sandia Laboratory's reactor.

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PURPOSE OF THE STUDY

Located in the relatively young Sage Plains district of southeastern Utah, the Calliham mine is currently producing vanadium and uranium from the Salt Wash member of the Morrison formation. Owned and operated by ATLAS MINERALS of Moab, Utah the mine came on line in 1973 and current production averages 10,000 s.t./month of ore with a cut-off grade of 0.10% U_3O_8 . Several other mines in the district are also producing from the Salt Wash member and like the Calliham mine trend to the east-northeast.

The Calliham mine and the other mines in the district exhibited many similarities to other Salt Wash sandstone deposits in the area and for that and several other considerations was selected by ATLAS' exploration staff for intensive geologic investigation.

Therefore, mine, mineralogic, chemical, and radiometric studies were initiated to 1) determine the sedimentary structures present and establish the environment(s) of deposition for the ore bearing sandstones, 2) determine the ore mineralogy by x-ray diffraction and scanning electron microscopy, 3) describe the ore zones and their relationship to the sedimentary features, 4) map any observable oxidation-reduction interfaces, and 5) originate a model for the origin of the deposit and the location(s) of new Salt Wash deposits in the area.

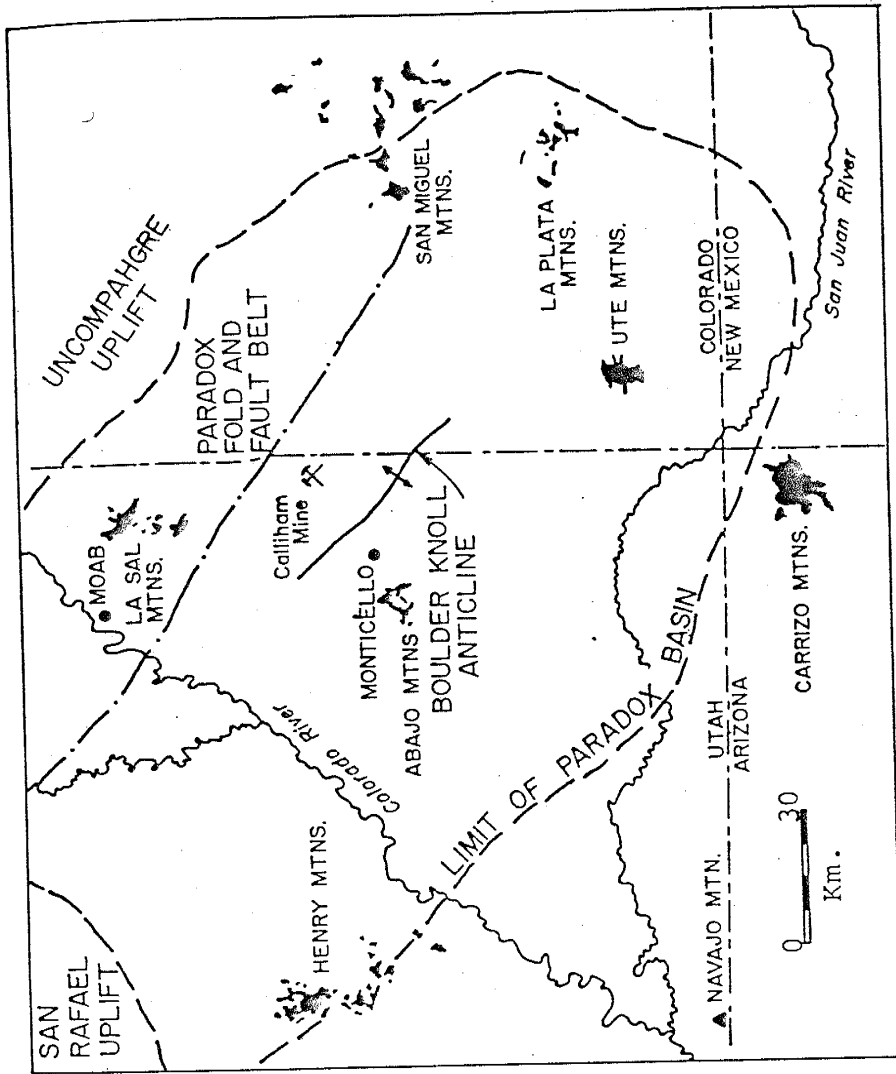
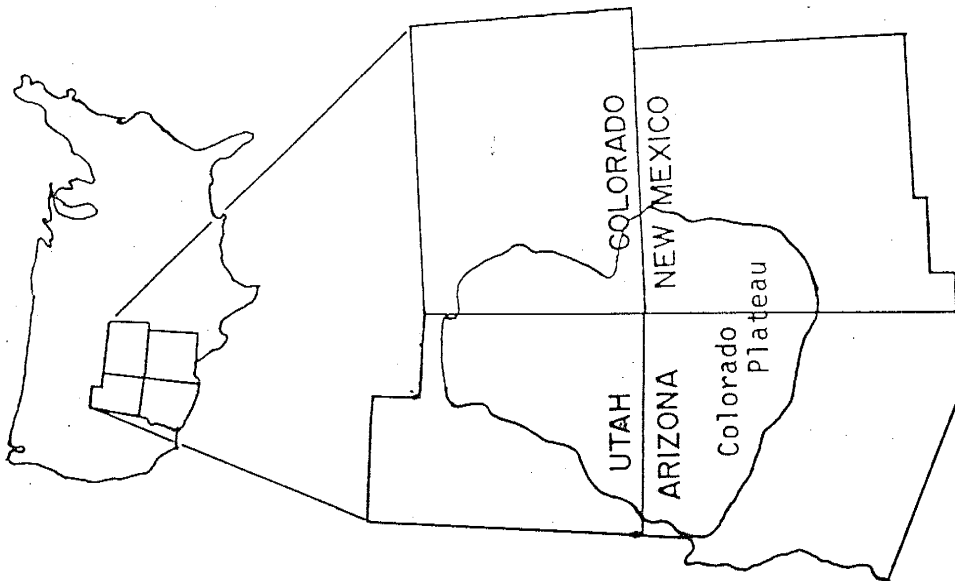
GEOLOGIC SETTING

TECTONICS AND SEDIMENTATION OF THE COLORADO PLATEAU

The Colorado Plateau is a structurally isolated province principally composed of continental and marine, flat lying sediments of Paleozoic to Cenozoic age which are generally undeformed. However, local deformation of these strata has occurred over salt diapirs, around the periphery of several Tertiary laccoliths, and other structural uplifts (see fig. 1)

From Cambrian until Pennsylvannian time the area was part of a foreland shelf of the Cordilleran geosyncline. In late Pennsylvannian and early Mississippian time this stable shelf changed to a subsiding environment forming thick evaporite sequences in basins adjacent to highlands lying to the east. Further sedimentation occurred by erosion of the highlands and deposition in the now rapidly subsiding basins. It is believed that most of the folding and piercement of sediments overlying the Hermosa formation by salt diapirs occurred before the Triassic. By the end of the Jurassic age salt flowage had ceased completely and the salt anticlines were buried by Jurassic sediments. During the Cretaceous period the Paradox Basin was infilled by another 2000 to 2700 meters of continental and marine

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Figure 1. Location map and selected structural features of the Paradox Basin.
(after Kelly (1958))

sandstones and shales.

With the onset of the Laramide orogeny folding and faulting once again occurred forming the San Rafael Swell, the Monument Upwarp and the southern Uinta Basin.

Beginning about 27 to 24 million years (m.y.) ago the entire Colorado Plateau began to be epirogenically uplifted approximately 1500 meters to its present position. The timing of this uplift roughly coincides with the intrusion of the Henry, La Sal, Abajo, Carrizo, and Ute mountain laccoliths in the interior of the plateau and the extrusion of voluminous silicic volcanics in four major fields around the periphery of the Colorado Plateau. These laccoliths have intruded as much as 4500 meters of sediments and are syenitic to dioritic in composition.

It is thought that with the advent of uplift and igneous activity wide-scale heating and circulation of groundwaters began allowing dissolution of the salt domes and collapse of adjacent and overlying strata.

PREVIOUS WORK IN THE AREA

While scattered mining and exploration activity date back to the 1890's, the first large scale research efforts began in the 1940's when the United States Atomic Energy Commission in conjunction with the U.S. Geological Survey launched a program to locate and assess uranium deposits of economic proportions.

These early studies were designed to delineate the extent, lithofacies, sedimentary structures, thickness, and petrology of the Morrison formation and other known uraniferous formations. Craig (1955) measured and sampled over fifty stratigraphic sections in Utah and Colorado and described two separate source areas for the Salt Wash and Recapture members. Boardmann et al (1955) studied the relationship of sedimentary structures to the ore-sands and described mineralization occupying festoon cross-laminations, ripple and current lineations, along with regular crossbedding. Phoenix (1955) analysed 900 samples from Outlaw Mesa in Colorado and ascertained that the permeability of these rocks was a function of lithologic character both at the time of deposition and after the subsequent effects of diagenesis. Dodd (1955) compiled a study of uranium deposits in the Morrison formation concentrating on regional structures, sedimentary structures, mineralogy and alteration. Barton (1958) was

the first to synthesize carnotite crystals large enough for single crystal x-ray study and concluded it was "difficult if not impossible" to avoid precipitation of carnotite in a solution containing potassium, hexavalent uranium, and pentavalent vanadium.

Weeks et al (1959) summarized the ore mineralogy of the Colorado Plateau and divided the deposits into four groups based on the presence or absence of vanadium and the oxidation states of U and V. They suggested that carnotite ores were the result of the progressive oxidation of earlier primary ores. Foster (1959) studied the chemistry of vanadiferous clays and was able to show that mineralized and unmineralized clays were of very similar composition except for the substitution of vanadium into the lattice at the expense of aluminum and (indirectly) silicon. Hathaway (1959) examined the vanadiferous clays by x-ray diffraction and found a striking similarity between the structures of roscoelite and chlorite. Archbold (1959) semiquantitatively determined the calcite content in mineralized portions of several Salt Wash sandstone mines in the Slick Rock district and found carbonate rich layers seem to lie above and below mineralized zones separated by several feet of barren sandstone with normal carbonate content.

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The literature concerning the Colorado Plateau is quite voluminous. However, several review papers worthy of consideration are Stokes (1967), Wood (1967), Motica (1967), and Young (1978). The geochemistry of these U-V ores has been studied and discussed by Garrels and Larsen (1959), Hostetler and Garrels (1962), Gableman (1977), Langmuir (1978), Levinthal (1979), and Granger and Warren (1979).

STRATIGRAPHY OF THE SALT WASH MEMBER

Sedimentary rocks in the Sage Plains area range from the marine Pennsylvanian Hermosa group upward through a thick sequence of continental sandstones, siltstones, and shales capped by the Cretaceous Dakota formation.

While nearly every non-marine formation in the area has produced uranium, vanadium, or copper, the basal sandstones of the Triassic Chinle formation and the Salt Wash member of the Jurassic Morrison formation have accounted for the bulk of production (see Table I for a summary of the stratigraphy of the area and type of deposits found).

The Salt Wash member conformably overlies the Summerville formation and is overlain by the Brushy Basin member composing the upper Morrison which is in turn overlain by the Cretaceous Burro Canyon formation. Surface cover in the area is the Cretaceous Dakota sandstone. The aggregate thickness of sediments overlying the Salt Wash member exceeds 200 meters.

The Salt Wash member has been subdivided into three units (rims) separated by two prominent mudstones. Sandstones in the upper Salt Wash member are more permeable and porous than the middle unit which contains a greater percentage of mudstones and intergranular cement. The overlying Brushy Basin member is also a relatively impermeable unit composed of volcanically derived silts and

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clays interbedded with thin discontinuous sandstones. The vast majority of deposits in Salt Wash sandstones are found in the upper 15 to 25 meters of the member.

GENERAL DESCRIPTION OF THE SALT WASH SANDSTONE

With few exceptions, the Salt Wash member is thickest in south-central Utah (180 m) and thins radially to the north and east from a sediment source thought to be the ancestral Mogollon Highland (Craig, 1955).

In outcrop the color of the Salt Wash member ranges from grayish yellow to very pale orange and white, it is fine to medium-grained, moderately to well rounded, moderately to well sorted, containing lenses of conglomerate. Detrital quartz grains are variably cemented by silica, carbonate, clays, and rarely gypsum.

The shapes of the sandstone bodies vary from lensoidal to planar with transitional to sharply scoured channel bases. Reddish brown to red and greenish gray mudstones separate successive channel sands with a cumulative mudstone/sandstone ratio varying from 0.6 to 4.0. Where the sands are highly lenticular, trough crossbedded sandstones predominate and individual beds are not laterally extensive. However, with more planar bedding, a single sand bed may extend from 100 to 500 meters. Salt Wash sandstone distributaries have been described exceeding five kilometers in width (Young, 1978).

Carbonaceous material is nearly ubiquitous in and around mineralized sandstones ranging in size from tree trunks to sand size grains. It has been noted that the long

axes of fossil logs and the trends of ore bodies tend to lie subparallel with the general trend of the sand bodies (Shawe et al, 1968). While it has never been established that carbon is a control on mineralization it certainly does show a strong spatial association with uranium ores throughout the area (Stokes, 1967).

MODE OF DEPOSITION-DISCUSSION

It is now generally agreed that the Salt Wash member is composed of a maze of stacked, superimposed, channel sands interbedded with or completely enclosed in mudstones that were deposited on a large alluvial plain and lowland (Craig, 1955, Mullens and Freeman, 1957, Shawe, 1968, Young, 1978). However, some controversy does exist as to the exact mode of deposition for the Salt Wash member.

Craig et al (1955) concluded that the Salt Wash sandstones were deposited by a braided stream system superimposed on a large alluvial fan system. Mullens and Freeman (1957) described both stream deposits (crossbedded sandstones with no clays) and floodplain deposits (with planar bedding and significant clay content). Smith (1970) noted that the lower Morrison sediments were deposited on a floodplain of low relief from sluggish meandering streams.

Ethridge et al (1980) have presented evidence from detailed measured sections in the Slick Rock district that the Salt Wash sandstones were deposited by a fine-grained meandering stream system aggrading on large alluvial plain and lowland.

Experimental flume studies by Schumm (1977) illustrated the influence sediment load and slope has on both channel morphology and sediment transport. With increasing sediment load and slope it was found the channel pattern evolved from

sand waves on straight channels to alternate bars through a meandering thalweg with point bars and point bar-braided channels to a truly braided system (see Schumm, 1977, p. 115). This point bar-braided pattern occurs when the stream's power is in transition between a meandering thalweg and a braided channel. During times of normal flow streams actively erode their outer banks and deposit sediment on point or alternate bars on the inner bends of the channel producing a meandering channel pattern. During periods of high flow and flood the stream reaches a point where the existing (meandering) channel does not significantly influence water flow or sediment transport allowing the stream to braid. It is interesting to note that Schumm found a thin layer of kaolinite was sufficient to armour the point bar sequences thus stabilizing the channel and possibly preserving the bars from subsequent catastrophic events.

Young (1978) has suggested that the streams depositing the Salt Wash sandstones were braided when they first entered the alluvial plain and carried a large amount of fine sand. Further downstream the competence of the stream would be higher thus creating entrenched meandering channels.

STRUCTURE

The mines of the Sage Plains district are producing from undeformed, unfaulted, very gently dipping sediments in a block forming the Sage Plains. In contrast to the other uranium districts of the Colorado Plateau the mines are not spatially associated with the margin of a salt anticline, laccolithic intrusion, or other structural uplift. The Sage Plains block is rectangular in plan view and elongate N 45 W between the Boulder Knoll anticline on the southwest and the Paradox Fold and Fault Belt on the northeast (fig. 1).

GEOLOGY OF THE CALLIHAM MINE

SEDIMENTARY STRUCTURES

Sandstones of the Calliham mine exhibit bed forms spanning the entire range of flow regimes from current ripples and small scale trough stratification, through sand waves, tabular cross strata, and dunes, to large scale trough and flat bedded strata. Gray, green, and black mudstones occur at the base of channels and as thicker overbank deposits in shallow ephemeral ponds. These preserved bed forms indicate flow velocities of the Salt Wash streams varied from 20 to 100 cm/sec and flow depths of 20 to 100 cm (see Harms, 1979, p. 228). These bedforms also indicate that the extant slope varied from less than 1.2% to 1.5%.

Point bar sequences can be recognized in two forms; 1) a sequence containing abundant clay galls (fig. 2) overlying an older, tabular, unmineralized, channel sand, or 2) thicker steeply truncated crossbedded sandstones with minor clay content and carbonaceous debris again overlying a tabular or crossbedded, unmineralized sandstone (fig. 3). This carbonaceous debris is composed of sticks and that have been thoroughly carbonized to coal and graphite.

Well developed channels can be seen throughout the mine (fig.4). Due to the high degree of sorting and fine grain size successive channel sands are differentiated by the mudstones separating the individual sand bodies in both the

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crossbedded and tabular sand units (fig. 5). Grain size of the sandstones is usually fine ranging from 3.0 to 2.0 ϕ (phi) units and when an intervening mudstone is not present successive sandstone units can be quite difficult to distinguish.

Figure 6 illustrates a cross sectional view across the toe of a large roll front defined by chlorite. The roll front has apparently migrated from right to left. Note how the mineralization in the upper part of the face is concordant while the roll itself cuts across the bedding and how bedding planes can be traced from the barren core through the mineralized front.

Figure 7 illustrates a sectional view through the margin of a shallow ephemeral pond. Note the thin overbank deposits of clay intercalated with thinly bedded, discontinuous sandstones. Note also how the sandstones and mudstones pinch out against the bank.

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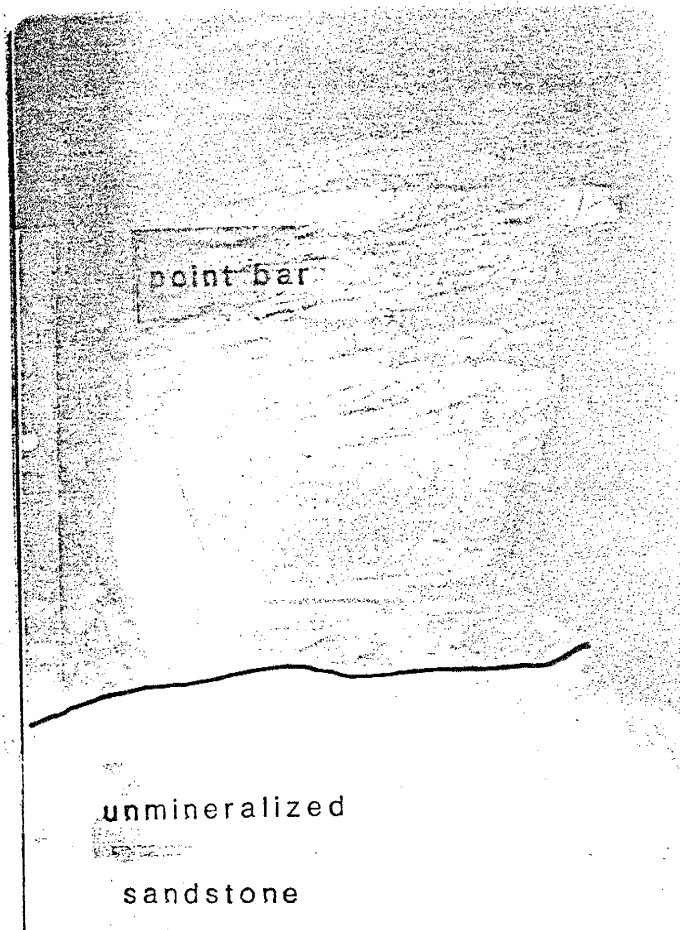


Figure 2. Point bar
sequence with abundant
concretions overlying a
finely bedded, unmineral-
ized, sandstone.
Scale is about 80 cm long.

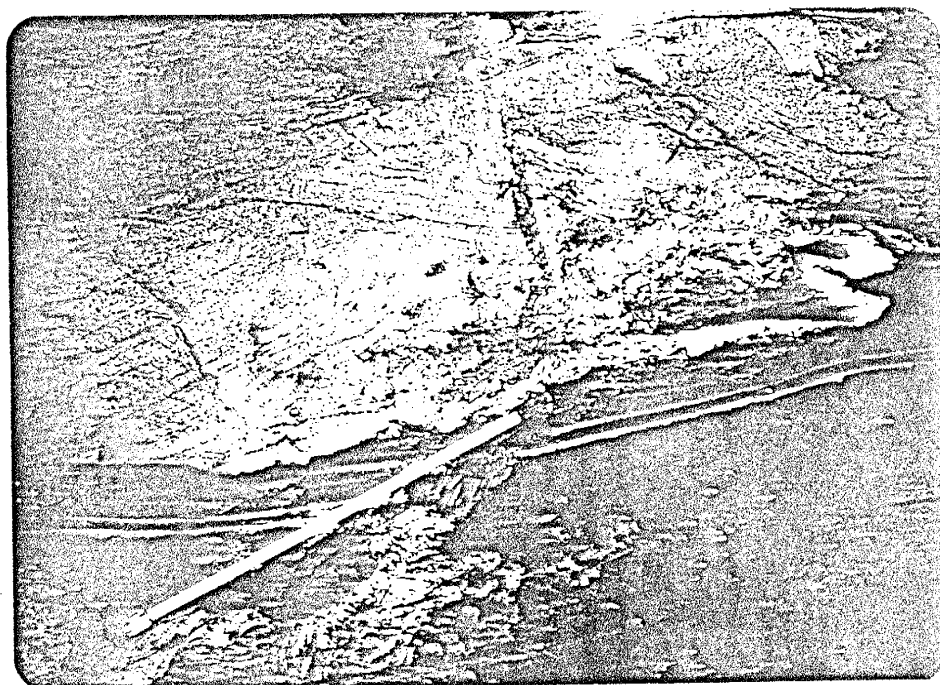


Figure 3. Carbonaceous debris lying semiconcordantly
in mineralized, crossbedded, sandstone.
Scale is about 80 cm long.

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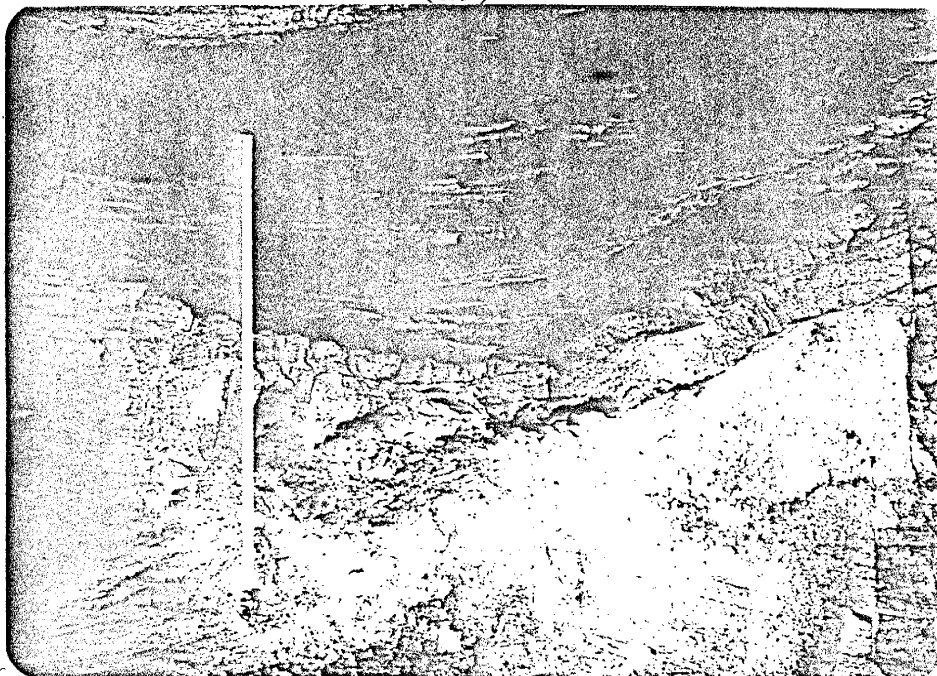


Figure 4. Channel scour infilled with alternating sandstone and mudstone. Scale is 1 m long.

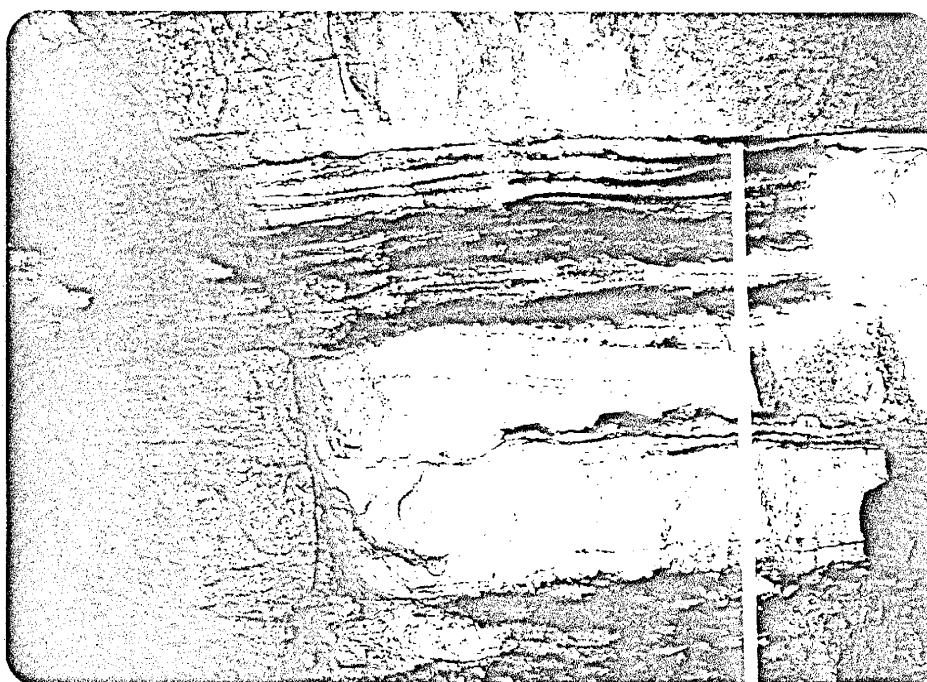


Figure 5. Tabular (planar) sandstone beds intercalated with black mudstones. Scale is 95 cm long.

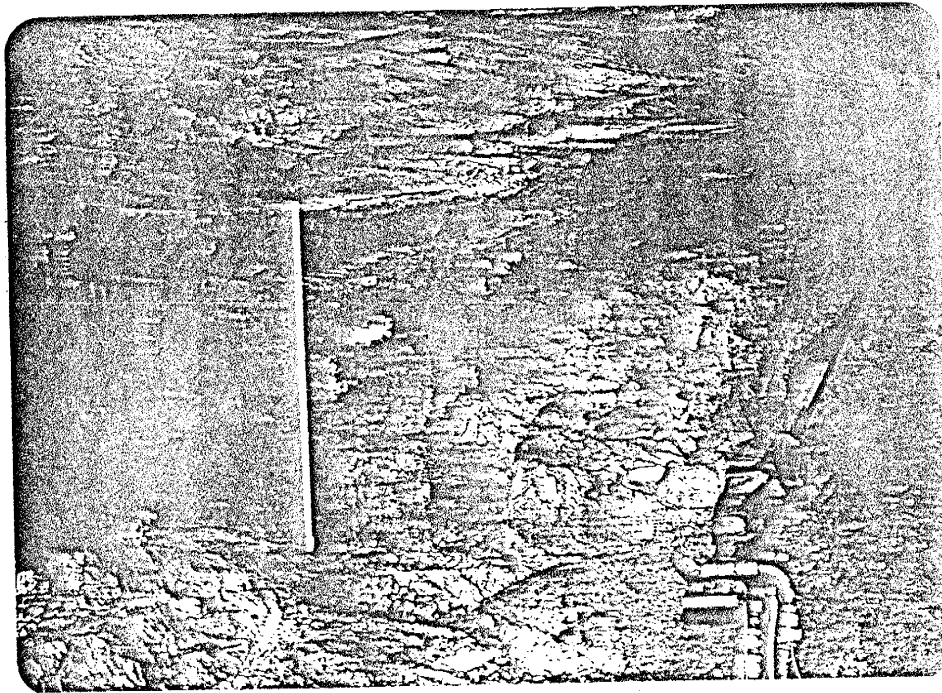


Figure 6. Cross sectional view across the toe of a large roll front. Scale is 1.25 m long.

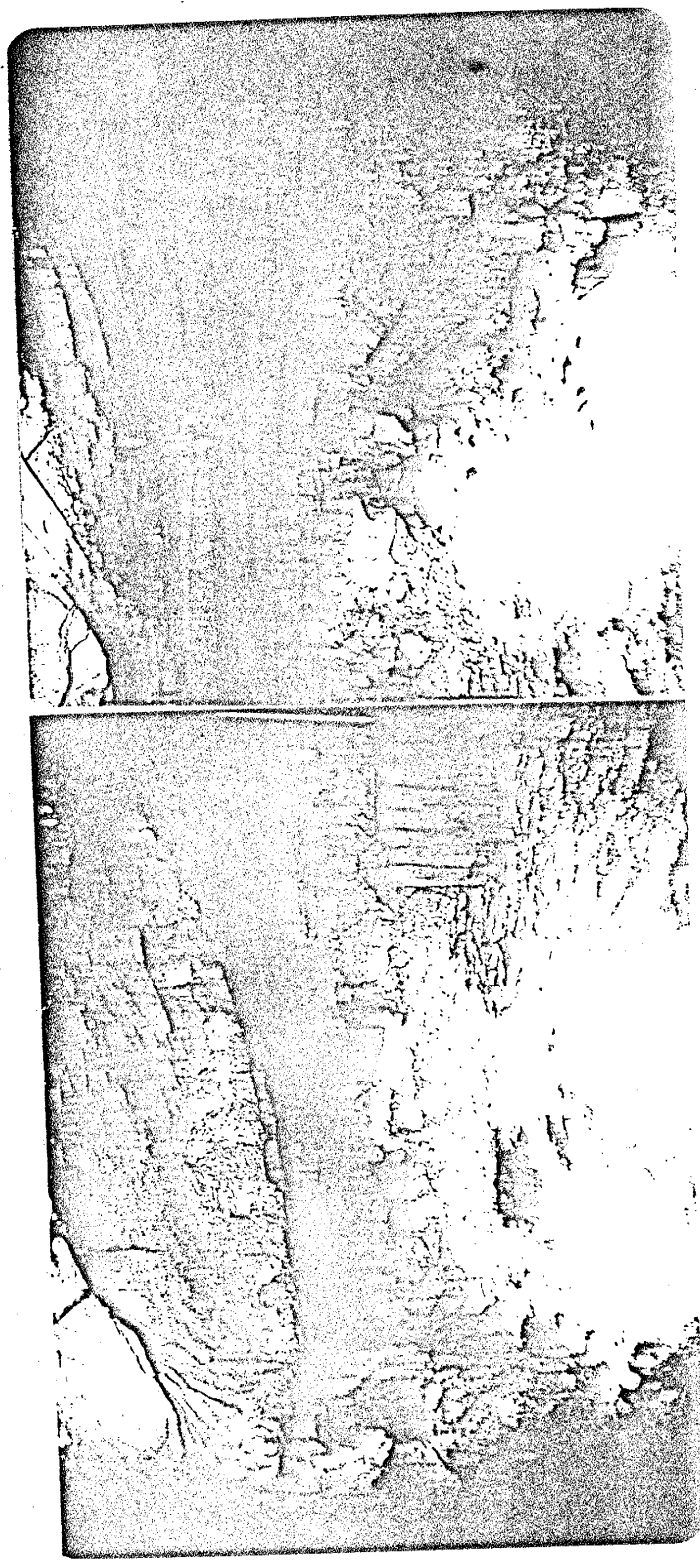


Figure 7. Margin of a shallow ephemeral pond that has been infilled by overbank and splay deposits. Scale is 1.5 meters long. The curvature is an illusion created by circular barrel of the wide-angle lens.

MINERALIZATION

Mineralization in the Calliham mine occurs as peneconcordant stringers, lenses, and pods in the uppermost sandstones of the Salt Wash member. Mineralized sandstones are gray, greenish-gray, and black depending on carbon content, character of the vanadium minerals, and intensity of mineralization. Two generations of chlorite can be distinguished in the mine (fig. 8). Here the black chlorite is concordant while the green chlorite crosscuts the bedding in a vertically restricted zone in the central part of the sand body. In other parts of the mine black and green chlorite can be distinguished across solution fronts.

Unmineralized sandstones between ore bodies are generally light gray to tan and white with abundant pseudomorphic kaolinite after feldspar thus giving rise to the term "bleached zones".

Uranium is always found with vanadium but the opposite is not true. When found together the vanadium seems to be zoned around the concentrations of uranium. This relationship is brought out especially well on ribs exposed to atmospheric oxygen forming the yellow bloom of carnotite and orange bloom of vanadium oxide (fig. 9).

While all types of sedimentary features in the mine are variably mineralized the higher grade ores are associated with the point bar sequences on the large bends in the

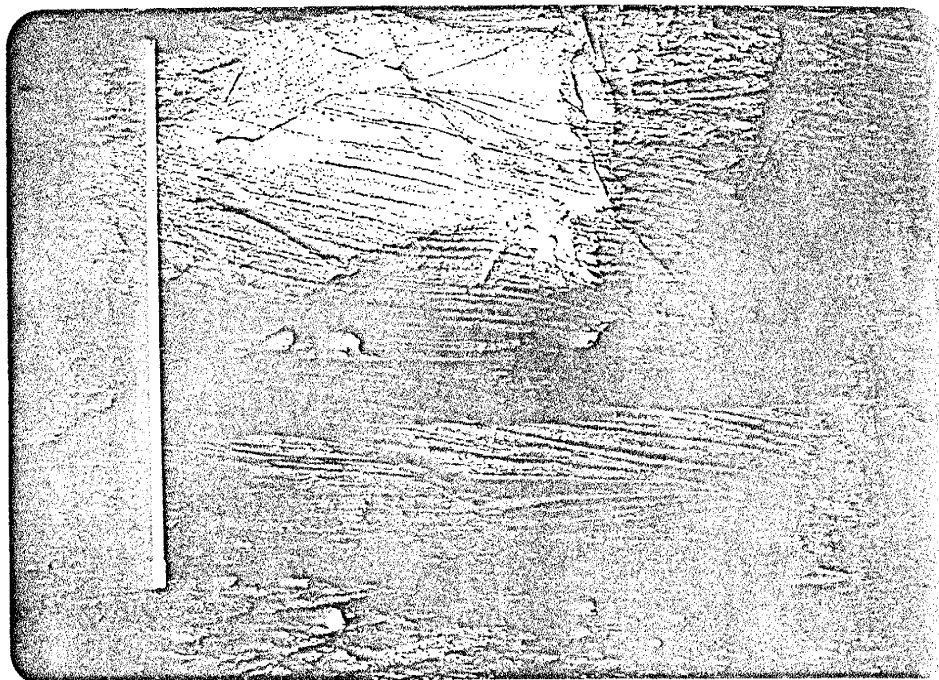


Figure 8. Two generations of chlorite. The black chlorite is essentially concordant while the green chlorite crosscuts the bedding planes. Scale is slightly longer than 1 meter.



Figure 9. Bloom of orange vanadium oxide forming a halo around a pod of high grade uranium ore. Scale is about 40 cm long.

stream channel (fig. 2).

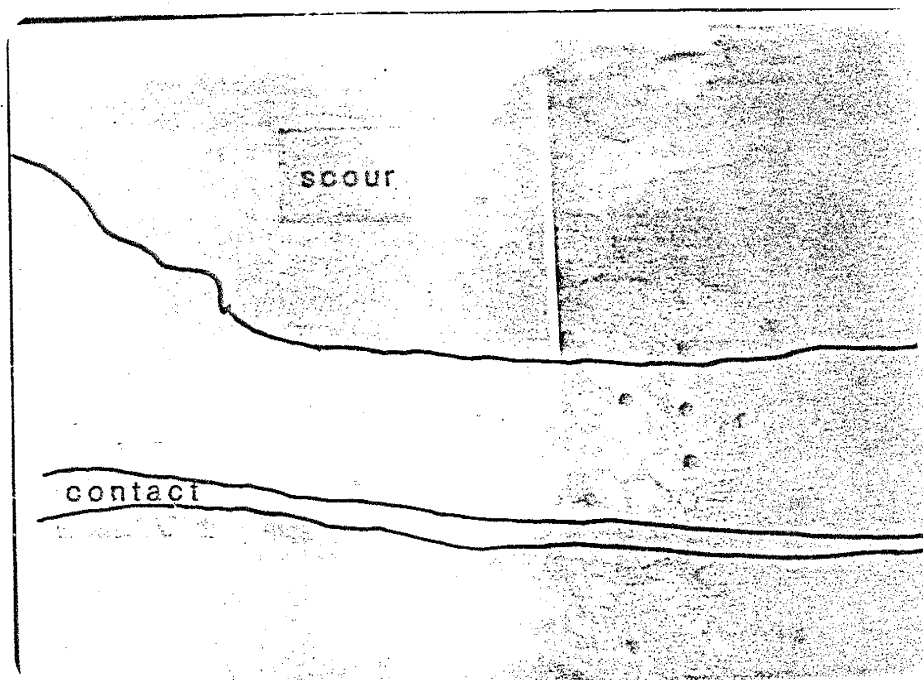
Mineralization can also be seen concentrated in infilled channel scours (without a mudstone split) and along the contacts between sand bodies (fig. 10).

Stringer, podiform, and lensoidal ore bodies can be found in quite close proximity. In Figure 11 a strongly mineralized zone at the base grades upward into a small pod of ore that is overlain by stringers of mineralization following the bedding planes.

Infilled channels underlain by mudstones can be the sites of ore exceeding 2% U₃O₈ (fig. 12).

Small roll fronts occur rarely (fig. 13). The fronts are defined by a ring of vanadium chlorite surrounding an inner core of barren, lowgrade sand. Ranging from 30 cm to 1 m from top to bottom these features are exceptional but do show the effects of solution activity.

Carbonaceous material is nearly ubiquitous in and around the ore zones as grains 64 μ to 250 μ (microns) in diameter (fig. 14). However, carbonized twigs large enough to be visible can be found lying semiconcordantly in crossbedded sandstones (fig. 3).



Figu

sand bodies. Scale is about 1 meter long. veen

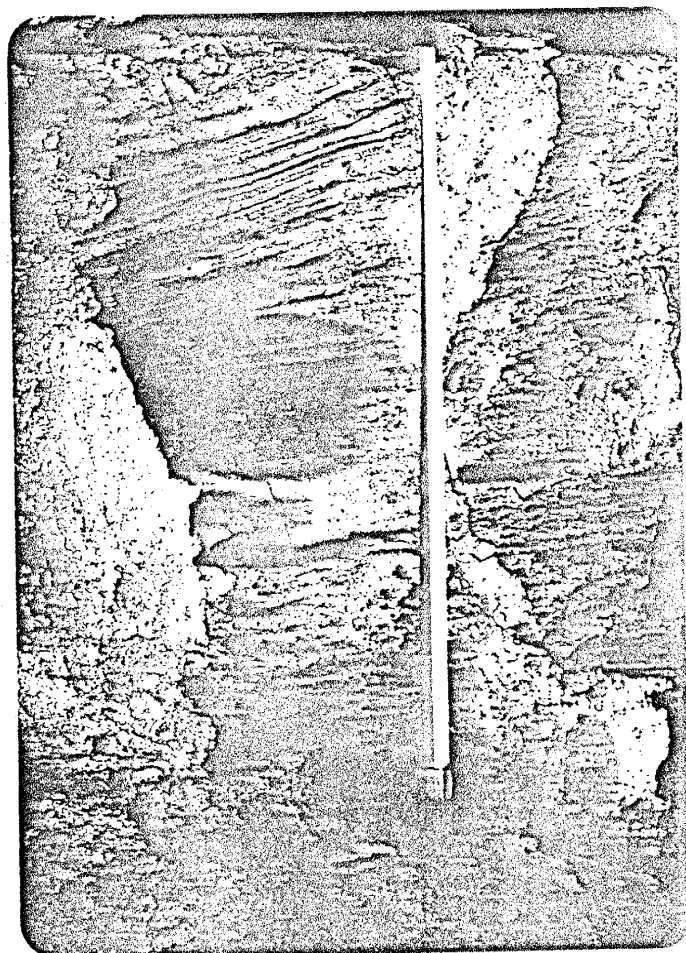


Figure 11. (From top to

bottom) stringer, podiform, and massive ore. Note the sequence of strong mineralization at the base grading upwards into a small pod of ore and at the very top are stringers of mineralization concordant with the bedding. Note also the black mudstone overlying the ores. Scale is 0.95 m long.

(26)

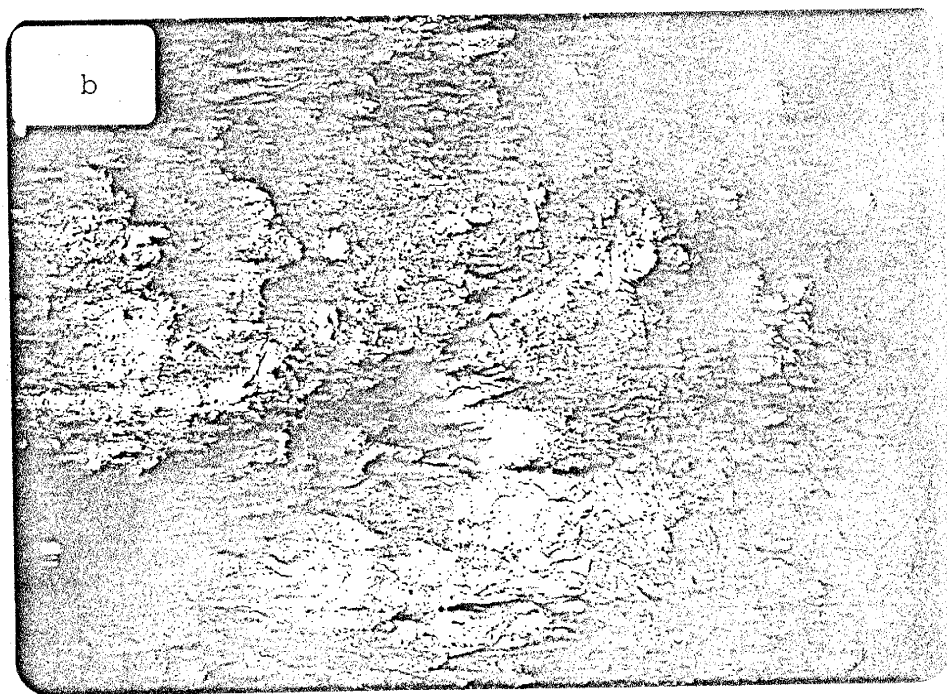
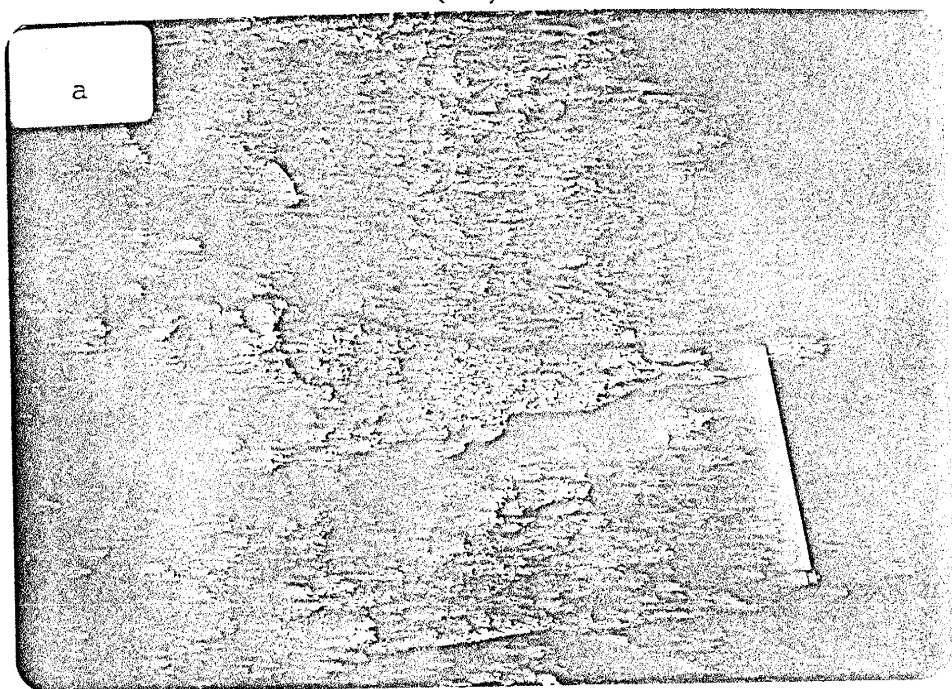


Figure 12. a & b) Heavily mineralized base of a channel margin underlain by a thin black mudstone. Scale is about 80 cm long.

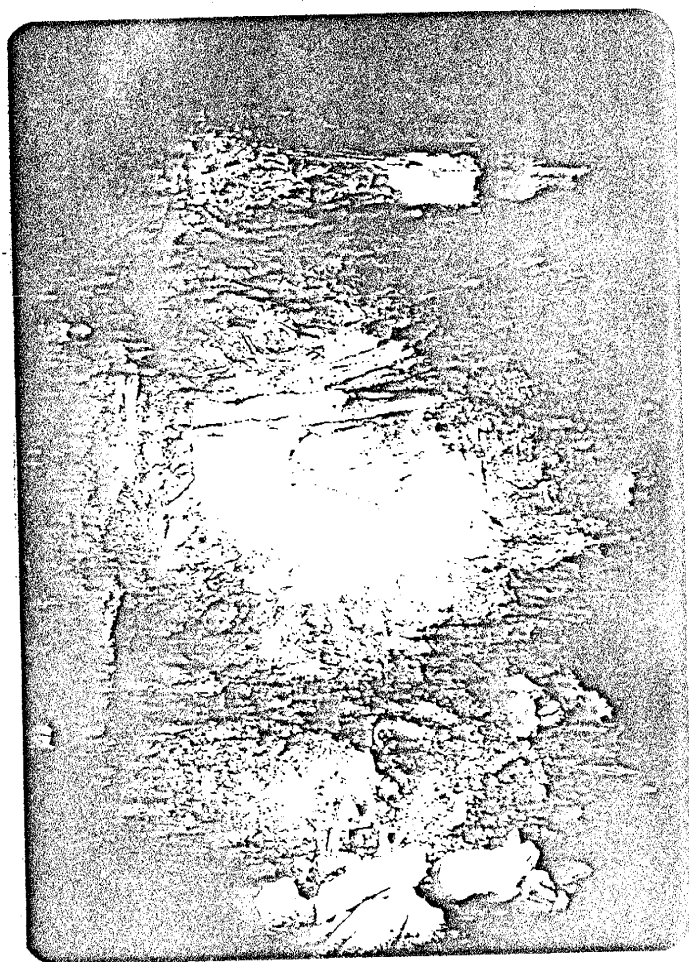


Figure 13. Mineralized crossbeds and small roll front defined by chlorite. Small roll front is approximately 15 cm from top to bottom.

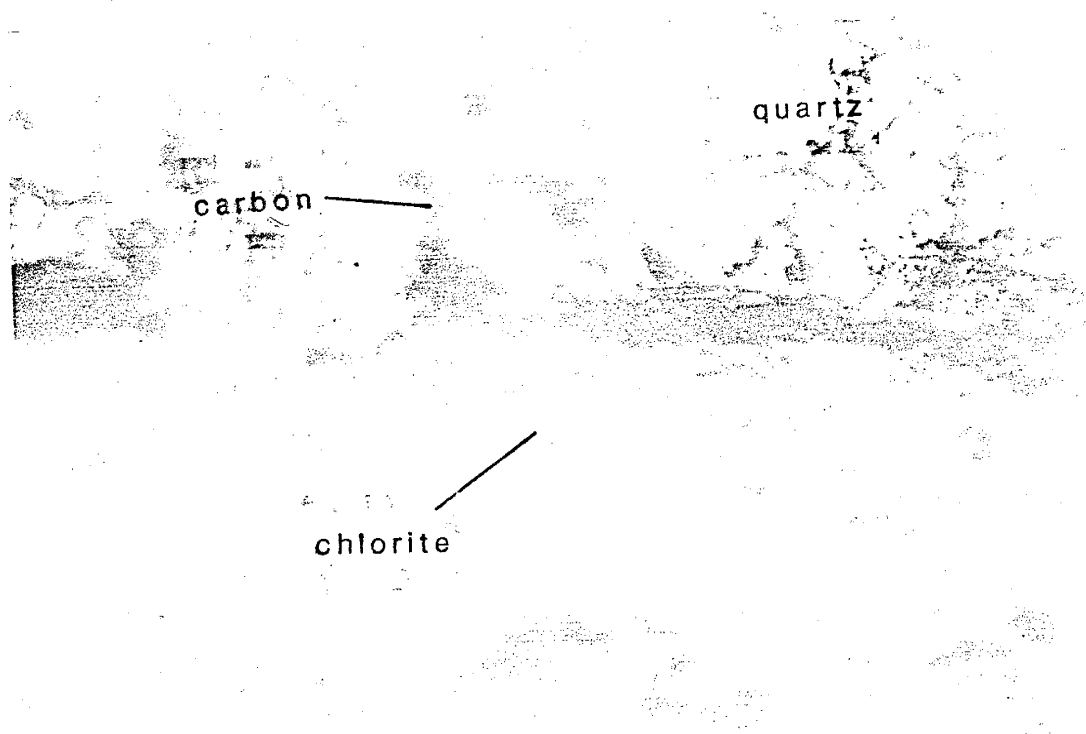


Figure 14. Photomicrograph of quartz, chlorite, and carbon. 32X.

Fission Track Analysis With Lexan Plastic.

To further delineate the relationship of uranium mineralization to bedding planes, carbon concentrations, and grain boundaries a fission track technique utilizing Lexan polycarbonate plastic was utilized (for a detailed explanation of the method used see Appendix II).

Comparison of thin sections to their Lexan prints under a microscope reveal the uranium is concentrated in the pore spaces occupied by chlorite and along quartz grain boundaries. Figures 15 and 16 are 1.5X images of the sections and their respective Lexan prints. Clearly the mineralization is concentrated along the bedding planes (fig. 15) but can also spread out into the sand when a permeable zone is encountered (fig.16).

Carbon grains are also concentrated along the bedding planes suggesting they were entrained as part of the bed load and deposited on the crossbedding slip faces. On the scale of a thin section it would appear that the uranium is associated with concentrations of carbon. To see if the uranium is associated with carbonaceous material a thin section containing significant carbon was examined on the S.E.M. After scanning the carbon grain and counting the x-rays for an extended period of time (35,000 counts) there were no recognizable peaks (fig.17). No radioactive halo could be discerned around the periphery of the carbon grains.

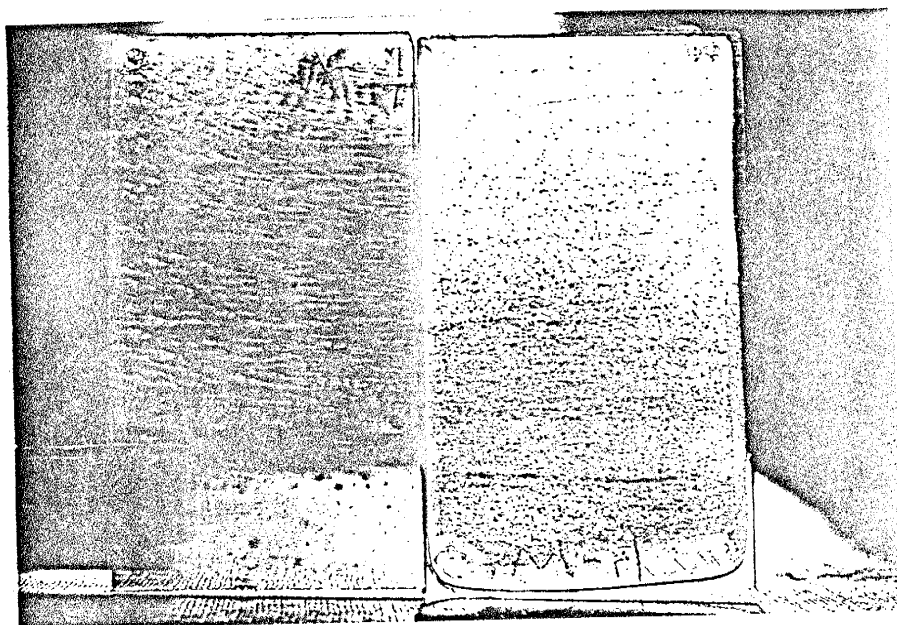


Figure 15. Thin section and Lexan print illustrating carbon grains and uranium mineralization concentrated along the bedding planes. 1.5X.

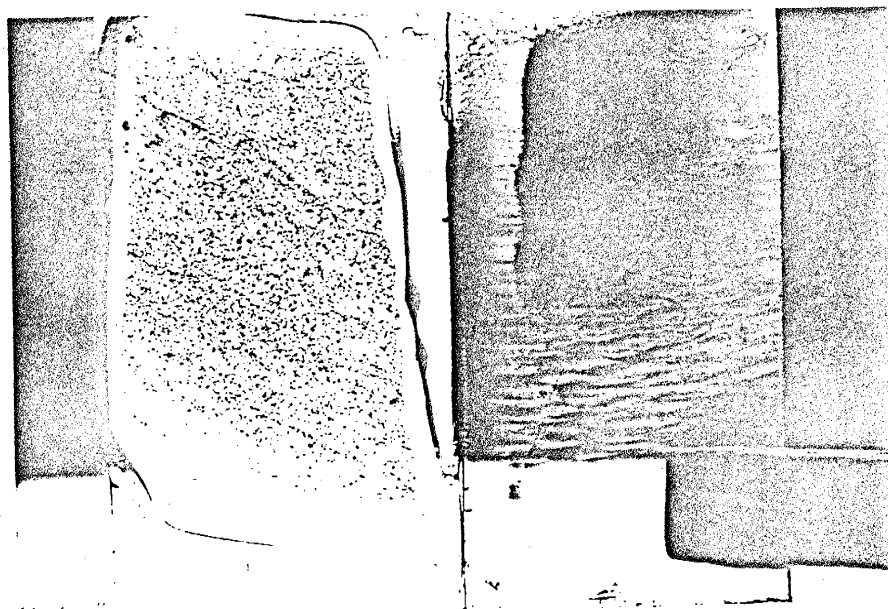


Figure 16. Heavily mineralized thin section and Lexan print. 1.5X.

(31)

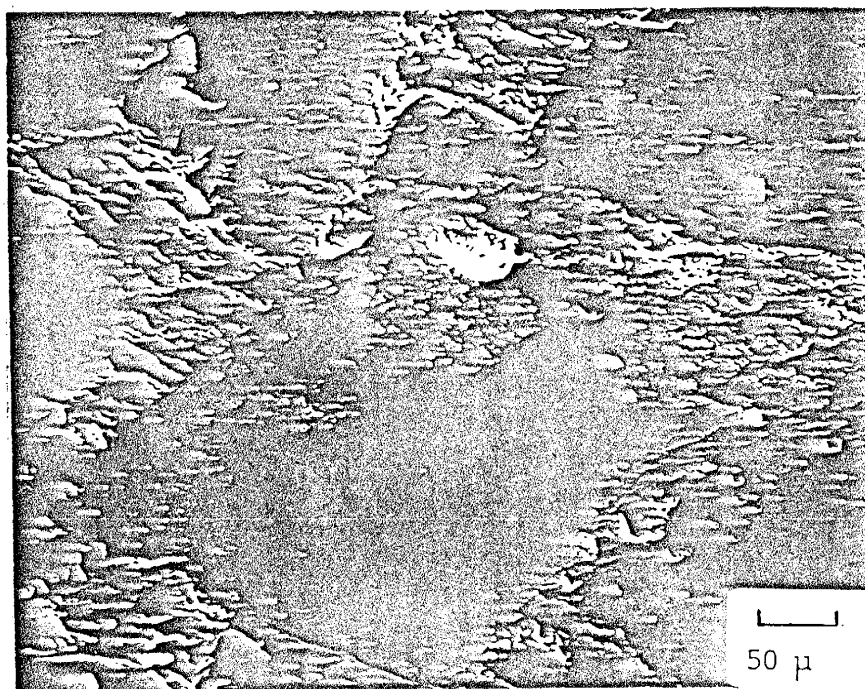


Figure 17. Carbon grain and resultant clean scan after 35,000 counts (the elements lighter than Na do not produce x-rays of sufficient energy to be detected). 200X.

Figure 18 summarizes the important locations of mineralization in the Calliham mine. These are 1) high grade zones in channel scour sandstones, 2) along contacts between sand bodies, 3) along individual bedding planes, and 4) other high porosity zones. The effects of low temperature solution activity are plainly evident in any of the sandstone type uranium-vanadium mines in the area. Equally clear is the loci of mineralization coincide with the most permeable and porous portions of the rock mass. The point bars are more permeable and porous due to their poorer sorting and abundant bedding planes.

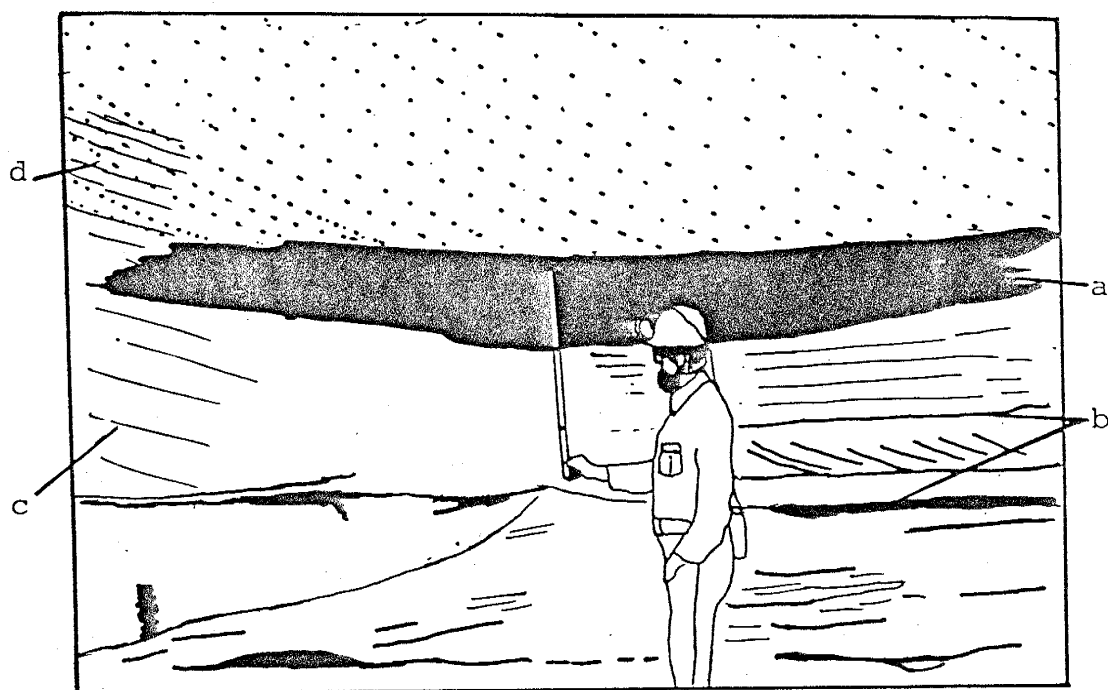
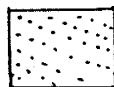


Figure 18. Typical loci of mineralization.
Scale is 0.75 m long.



High grade U-V ore occupying a) infilled scours, b) along contacts between sand bodies, c) along individual bedding planes, and d) along other high porosity zones.



Crossbedded, variably mineralized, sandstone.



Tabular bedded, unmineralized to slightly mineralized, sandstone.

MINERALOGY AND PARAGENESIS

The sandstones of the upper Salt Wash member are composed of detrital quartz and carbon grains with the interstices variably infilled by the authigenic clays chlorite, montmorillonite, kaolinite, and mixed layer hydromicas.

Detrital quartz grains range from less than 125 μ to greater than 250 μ in diameter (3.0 to 2.0 phi units) are well sorted, and subangular to subrounded. The sands vary from well cemented by secondary silica, carbonate, and clays to completely incohesive.

The data indicate a paragenetic sequence of quartz overgrowths-chlorite-carnotite-late quartz (fig. 19).

SEDIMENTARY PETROLOGY

The samples examined in thin section were taken from in or near ore zones and exhibited a fairly simple mineralogy which includes the assemblages quartz+carbon+calcite (fig. 20 a & b) and quartz+carbon+vanadium-chlorite (fig. 21a & b).

Calcite and chlorite do not occur together suggesting they were deposited by separate events. Uranium mineralization is associated with the chlorite rich zones while the calcite-rich rocks are usually barren or weakly mineralized at best.

The data indicate a paragenetic sequence of
quartz overgrowths-chlorite-carnotite-late quartz

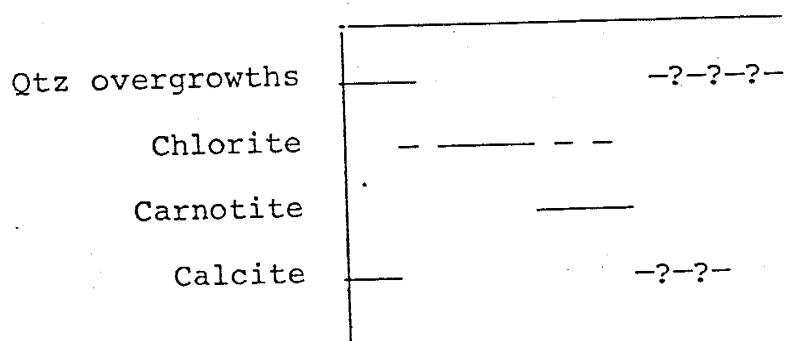
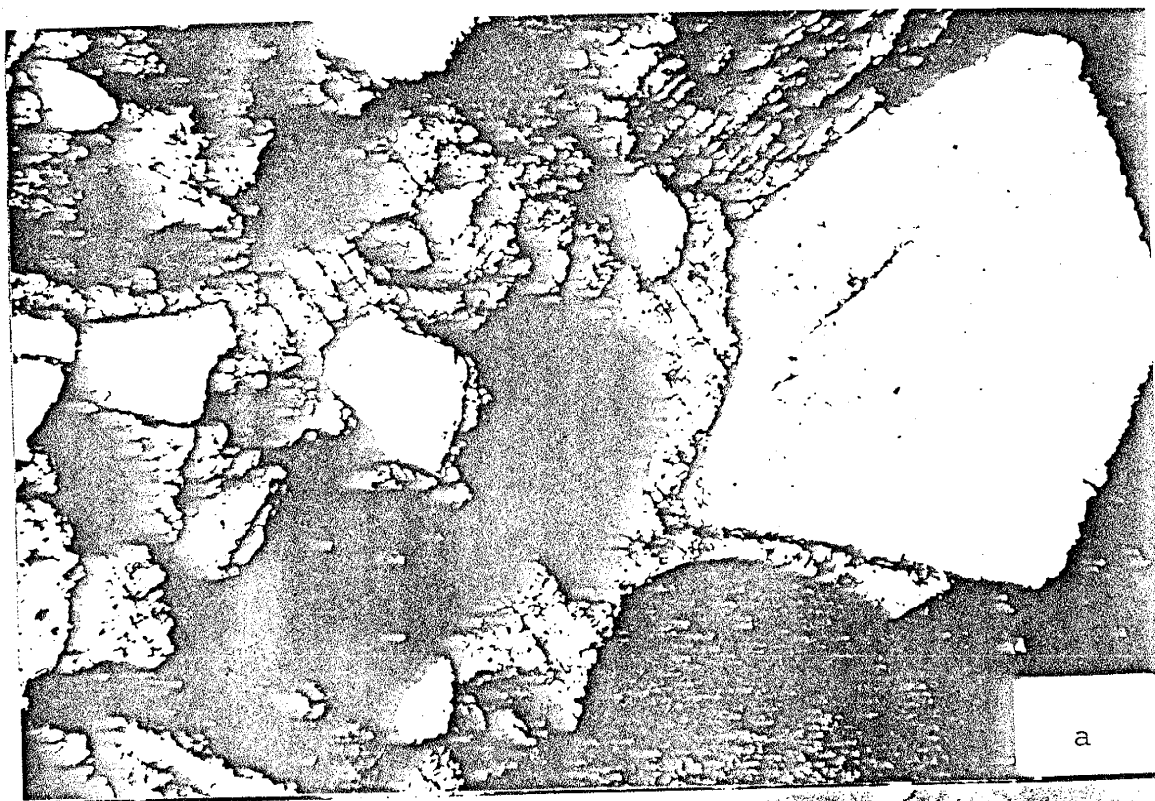


Figure 19. Paragenetic sequence of the interstitial, epigenetic minerals.



a

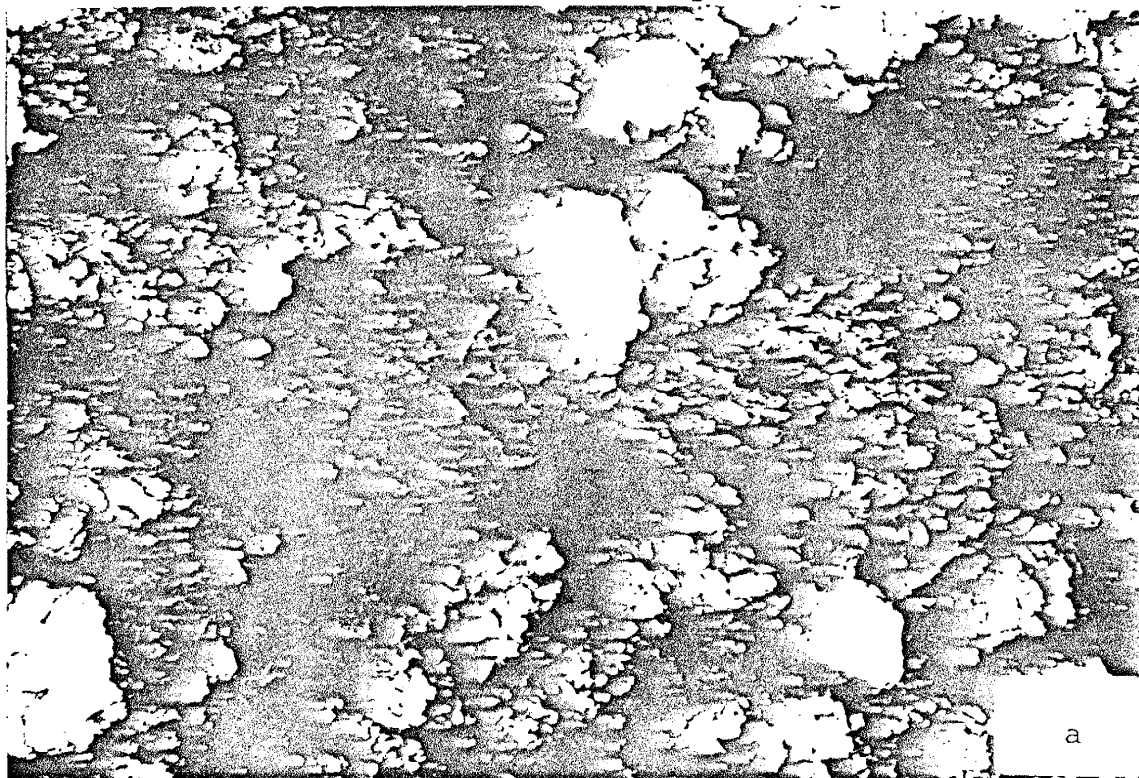
carbon

quartz

calcite

Figure 20. a) Photomicrograph of quartz, carbon, and calcite. 32X.
b) View of a) with uncrossed nicols.

(37)



chlorite

quartz

carbon

chlorite. 32X.

b) View of a) with uncrossed nicols.

Detrital quartz grains exhibit uneven to long concavo-convex sutured boundaries between the individual grains and mild to pronounced undulatory extinction. Invariably the quartz grains exhibit some degree of microfracturing and later cementation of these fractures by secondary silica or chlorite (fig. 22).

Figure 23 is a view under parallel light illustrating the contrast between detrital quartz, quartz overgrowths, carbon, and chlorite. Note the angularity of the carbon grains contained in both chlorite and quartz overgrowths suggesting that the quartz and carbon grains were deposited contemporaneously.

Secondary silica is nearly ubiquitous as quartz overgrowths. These overgrowths are found embaying and cementing detrital quartz (fig. 23) and trapping carnotite in the cement along grain boundaries (figs. 24 & 25). Detrital quartz grains and most overgrowths were in optical continuity and could not be readily distinguished. However, in some sections detrital quartz was separated from its overgrowth by a layer of trapped chlorite (fig. 26 b.)

Figures 26 a and b are of a thin section that has undergone irradiation by thermal neutrons to expose a Lexan print. Note the iron oxide(?) staining of the chlorites. Sand grains have been almost entirely cemented by secondary silica variably in optical continuity with detrital quartz grains.

(39)

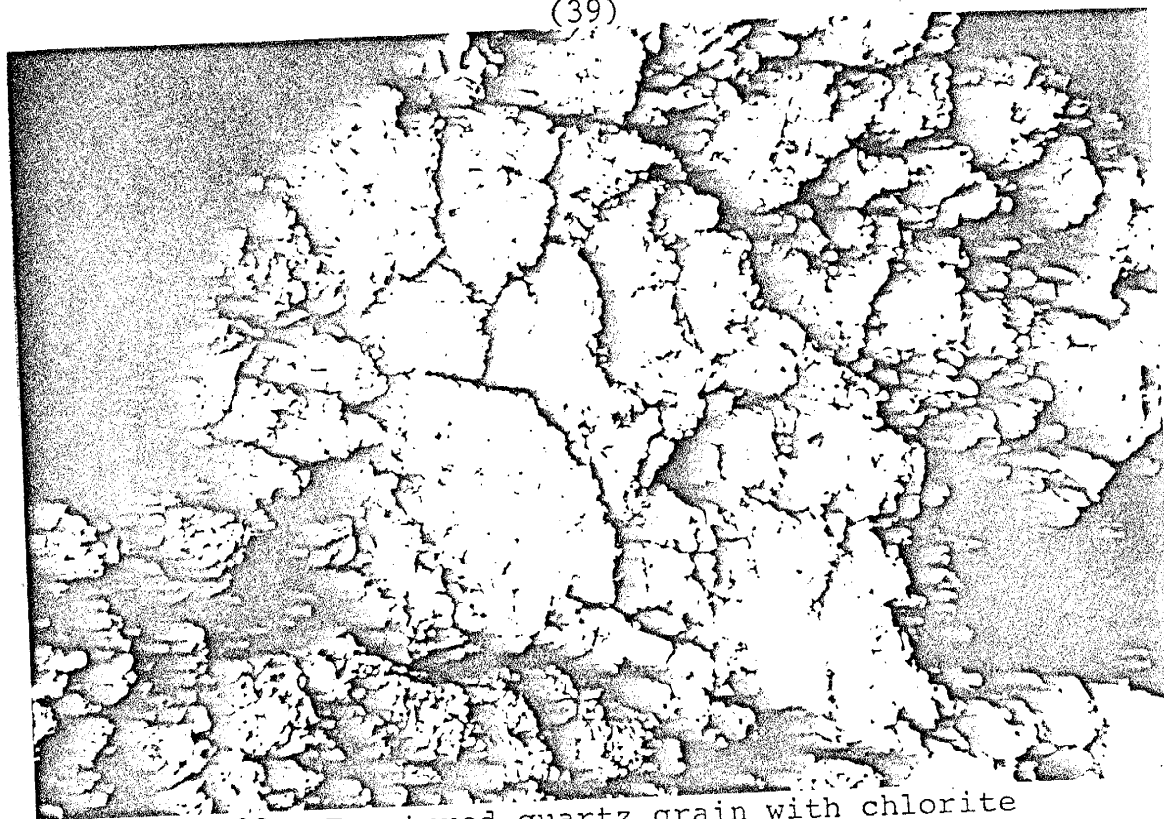


Figure 22. Fractured quartz grain with chlorite infilling the microfractures. 100X.



Figure 23. Secondary silica (white), and chlorite (brown) enveloping carbon grains. Detrital quartz appears dull gray. 32X.

(40)

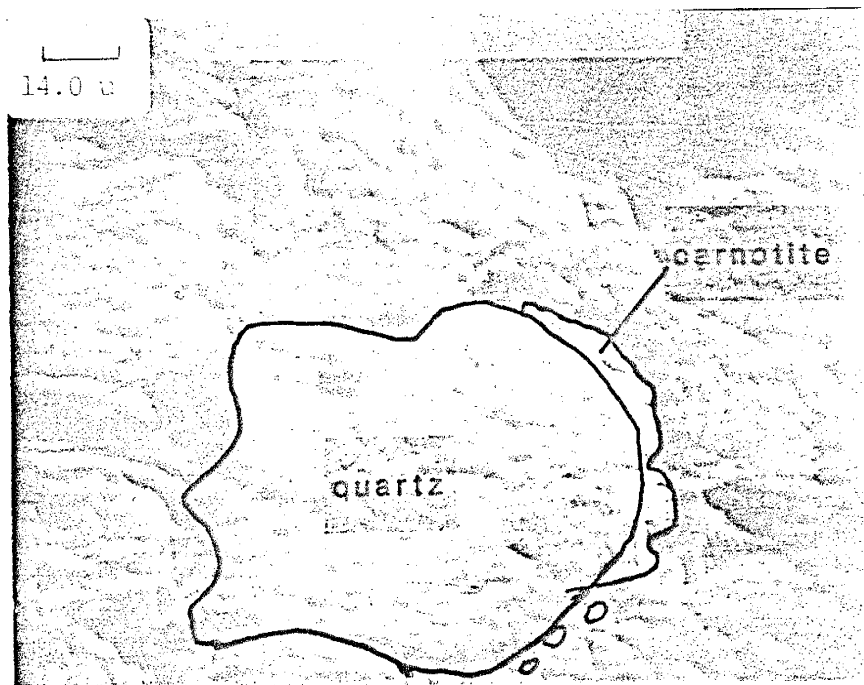


Figure 24. Quartz grain along most of its perimeter by secondary silica trapping carnotite. 700X.

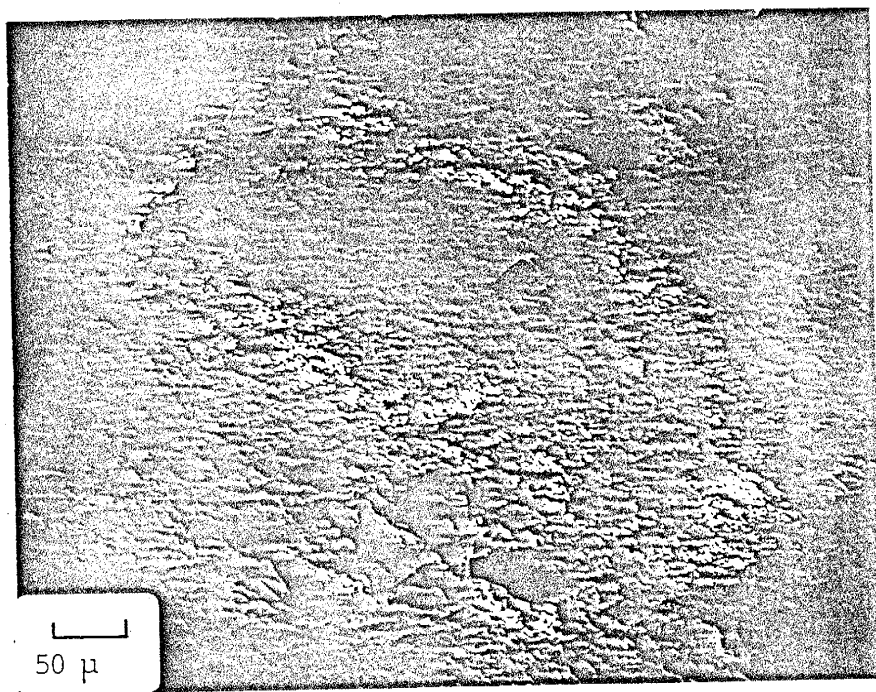


Figure 25. Completely sutured oblong grain. Note how the secondary silica completely encloses carnotite. 200X.

(41)

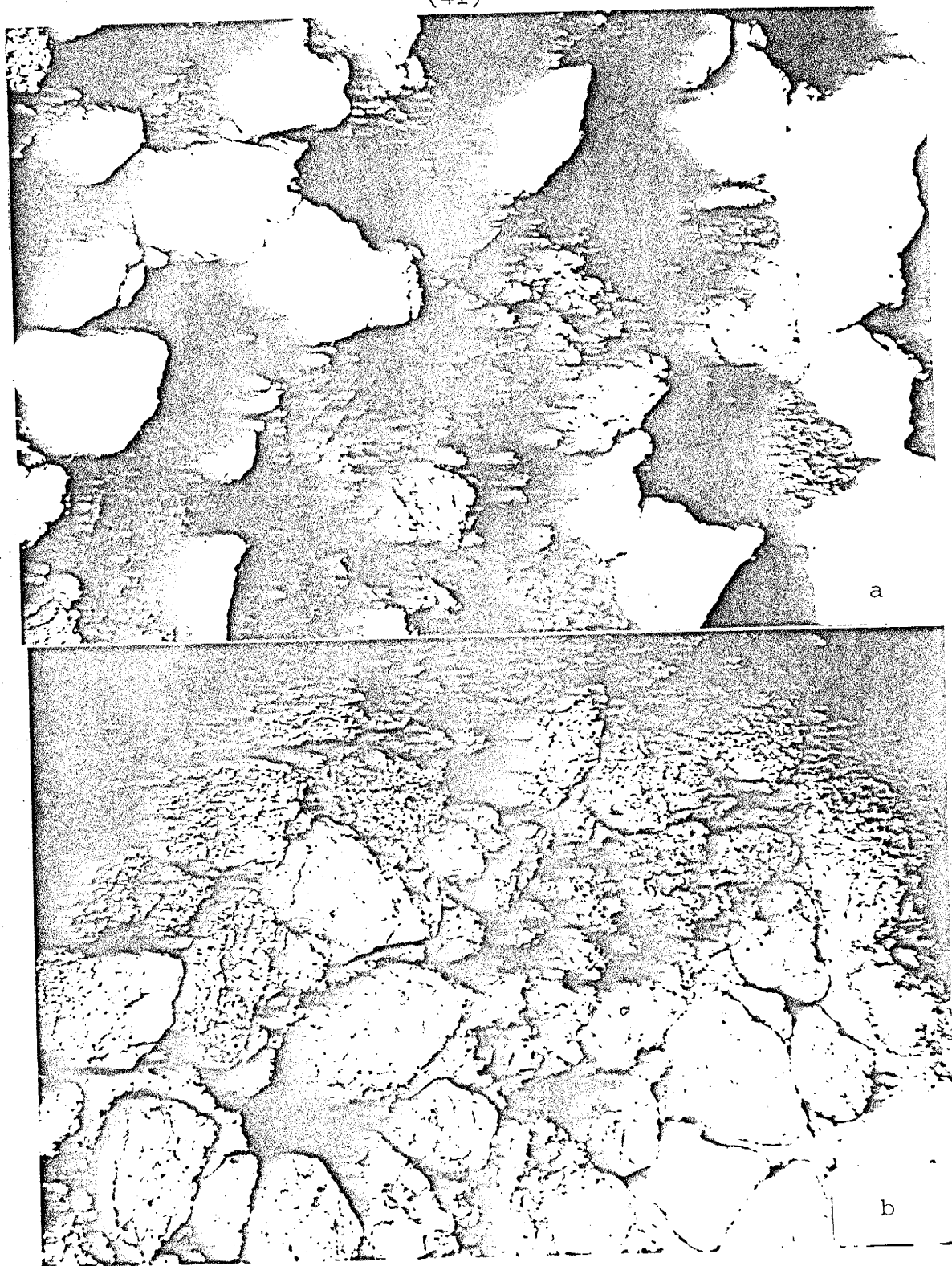


Figure 26. a) Thin section after irradiation to expose a Lexan print. Note the iron oxide staining of the chlorites-probably due to irradiation. 32X.
b) View of a) with uncrossed nicols.

SCANNING ELECTRON MICROSCOPY

Under the S.E.M. the sandstones appear as in figure 27 which shows the carbon grains completely enclosed by secondary silica. The rough surfaced rectangular area in the upper center portion of the image is probably a mixed layer chlorite-montmorillonite (see fig. 32 in this section for a close up view of the area).

In the ore zones clay minerals virtually fill the pore spaces (fig. 28). Figure 29 is a closeup view of one of the pore spaces in fig. 28 illustrating the typical mode of occurrence, crystal morphology, and major element composition of vanadium chlorite.

Under the normal operating mode of the S.E.M. the uranium bearing phases could not be distinguished (fig. 30 a). Therefore a technique using the backscattered electron yield was employed enhancing the phases with the higher average atomic weight. Under this mode carnotite appears as bright, white, crystallites against a dull gray background of chlorite (fig. 30 b). As a check to see that these crystallites were the uranium bearing phase a 100,000X scan was performed on the crystallite in the upper center portion of figure 30 b (fig. 31a) producing the uranium map (fig. 31 b). While the entire area contains variable amounts of uranium, it is clear that uranium is concentrated in the crystallite.

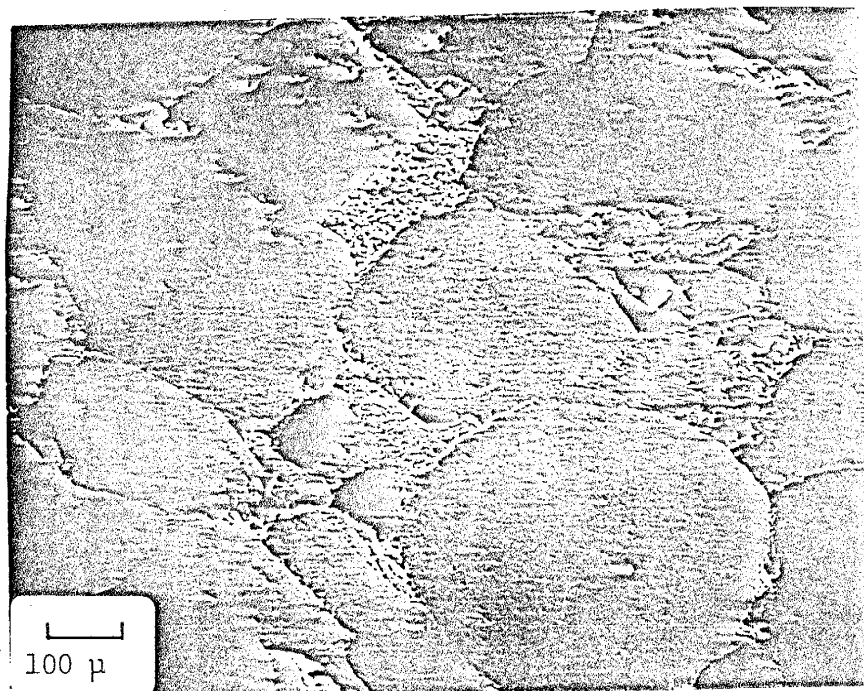


Figure 27. S.E.M. photomicrograph of a tightly cemented sandstone with almost no remaining pore space. Black grains in the center are carbon and the irregular, pitted surface near the top-center is thought to be a mixed layer chl-mont clay. 100X.

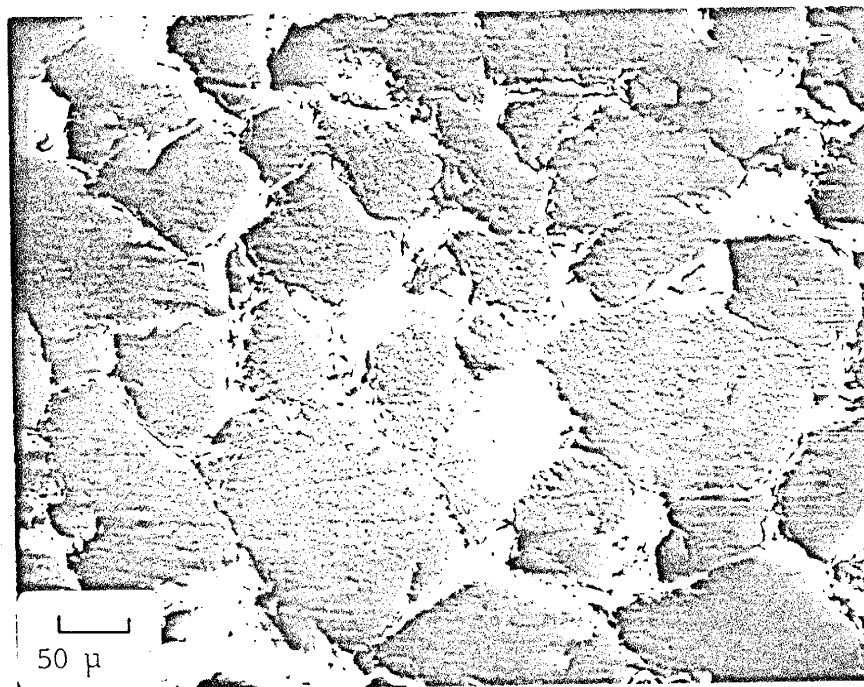


Figure 28. Vanadium-chlorites infilling the pore spaces of the sand grains. 200X.

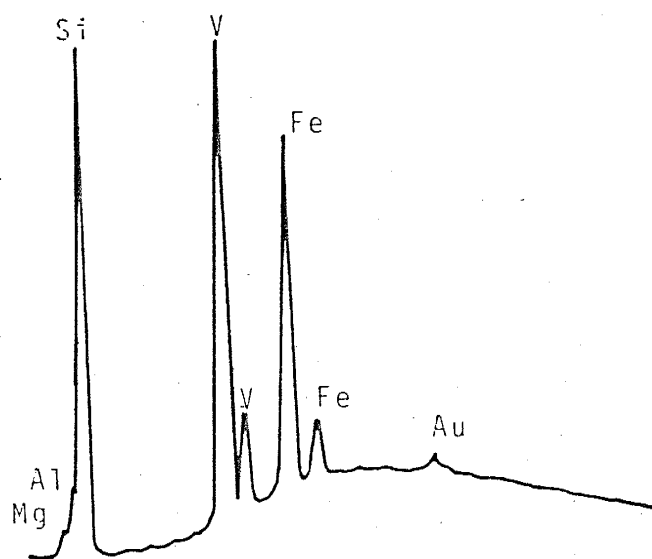


Figure 29. Typical mode of occurrence, crystal morphology, and major element composition of vanadium-chlorite. 3000X.

(45)

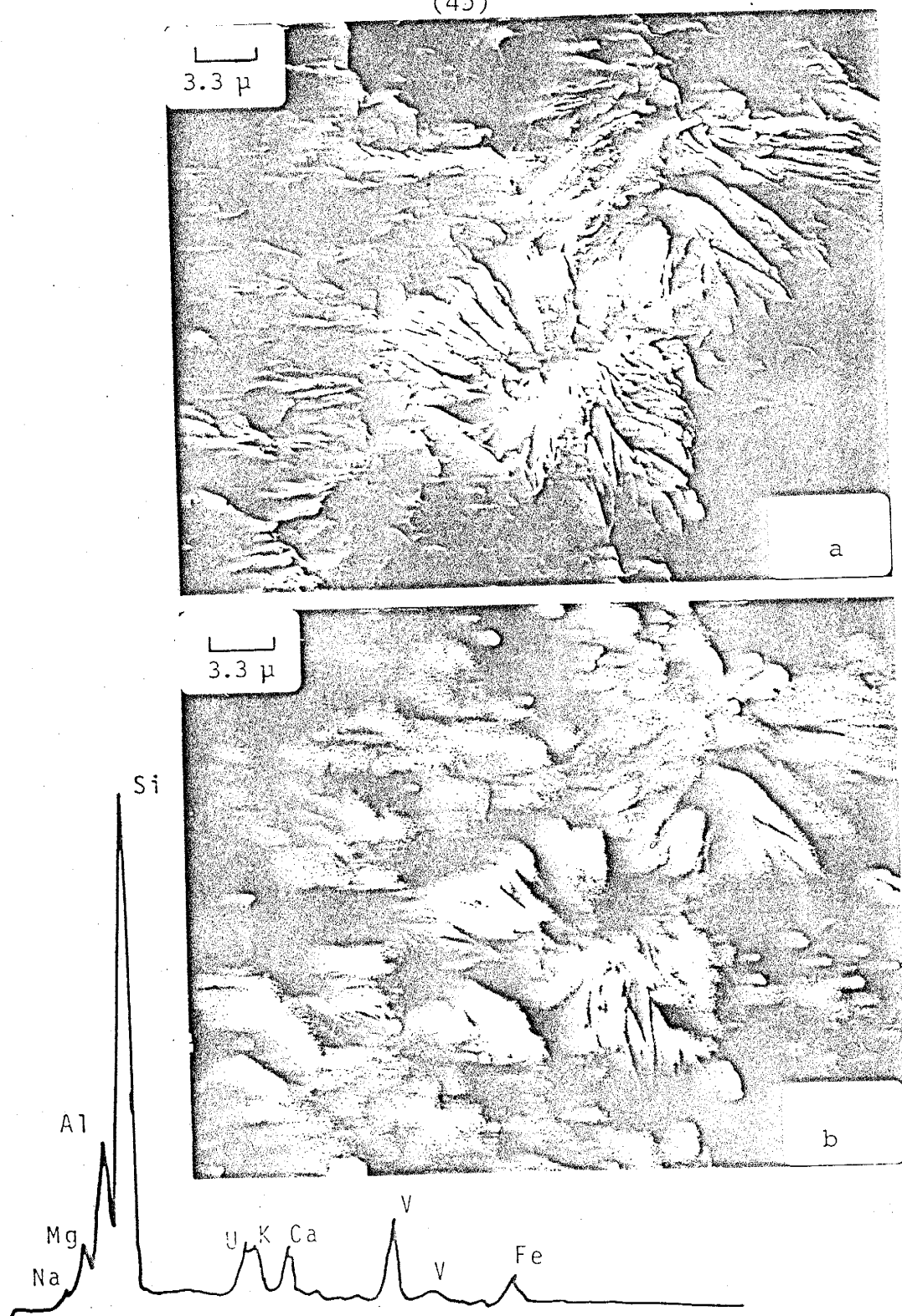


Figure 30. a) Rosette of vanadium chlorite.

b) Backscattered image of a. Carnotite appears as bright, crystallites randomly scattered among the chlorite blades.

3000X

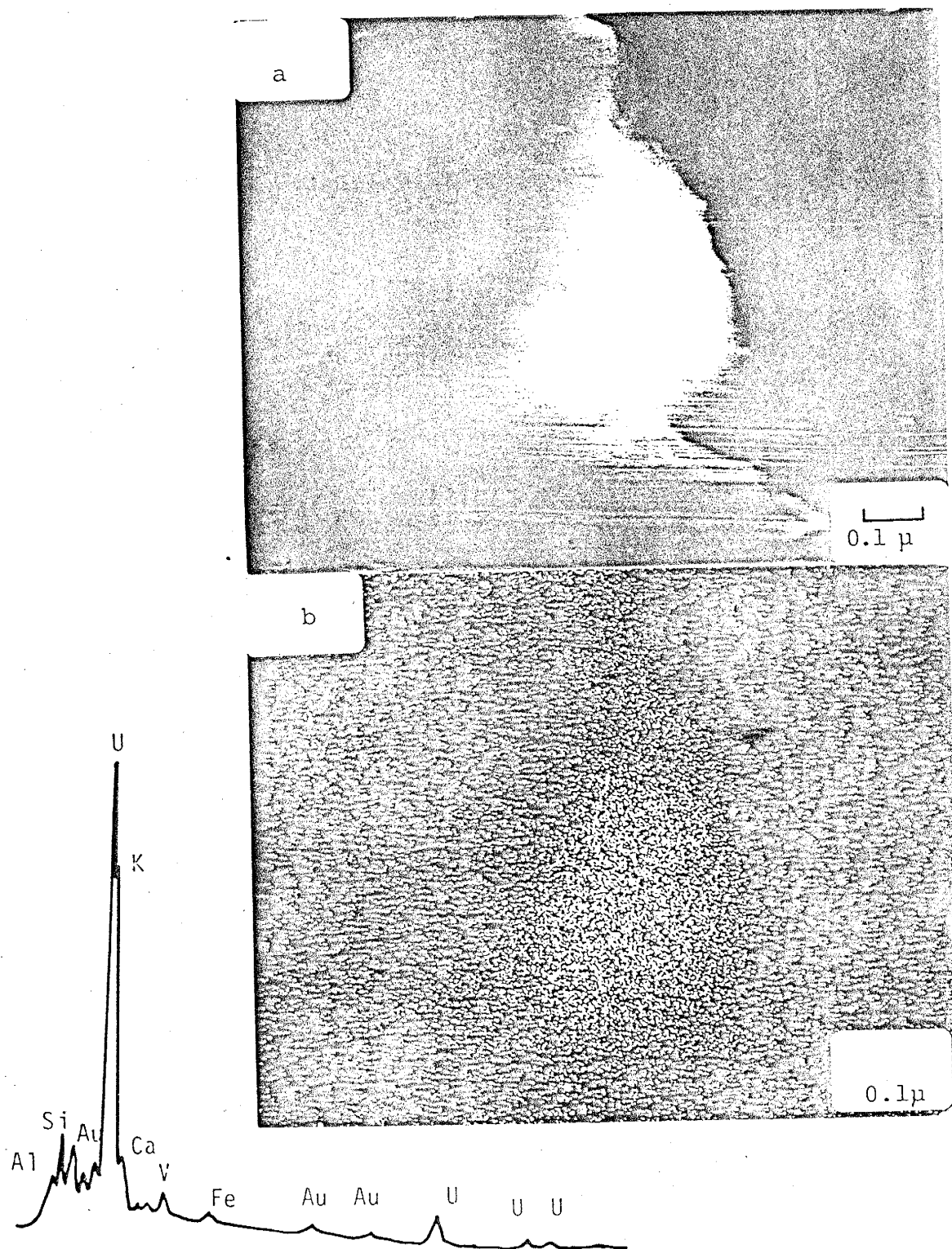


Figure 31. a) Close-up of a carnotite crystallite from fig. 30b. 100,000X.
b) Uranium map and x-ray spectra for 31a.

The late episode of quartz overgrowth formation trapped some of the carnotite in the secondary cement (fig. 24). Complete enclosure of carnotite as the pore space(s) were totally infilled by secondary silica can be seen in figure 25.

Other minerals observed in minor amounts but whose paragenetic relations are unknown or unclear were mixed layer chlorite-montmorillonite (fig. 32), kaolinite (fig. 33), pyrite (fig. 34), clausthalite (fig. 35), zircon (fig. 36), illmenite(?) (fig. 37), and montroseite(?) (fig. 38).

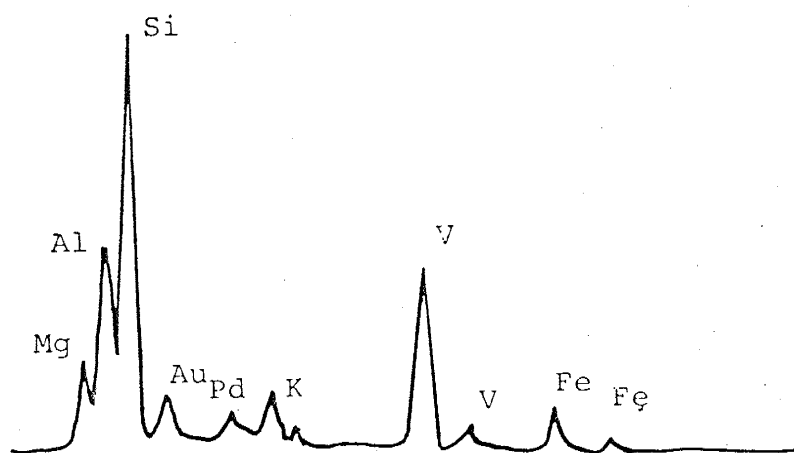
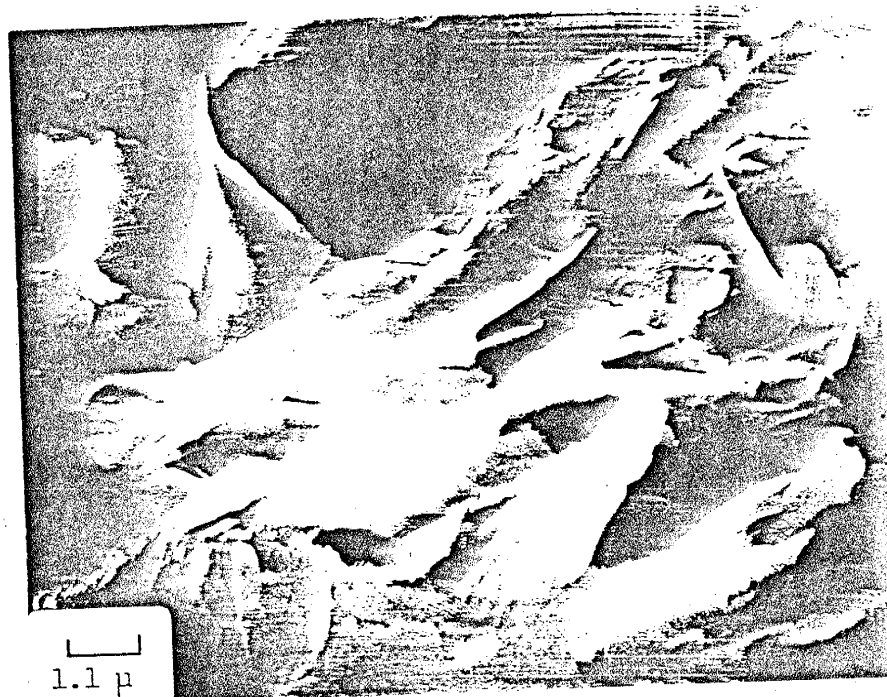


Figure 32. Mixed layer chlorite-montmorillonite.
9000X

(49)

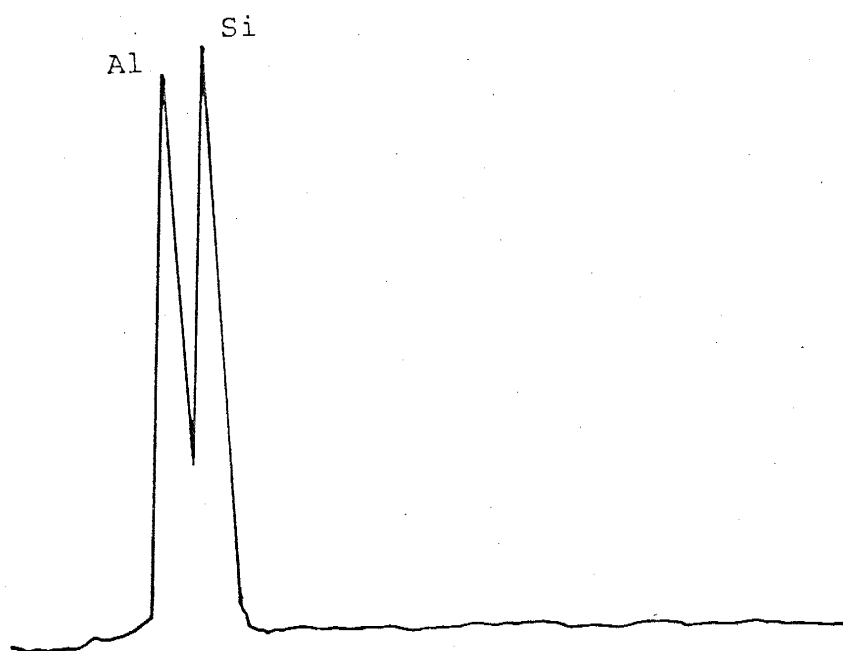
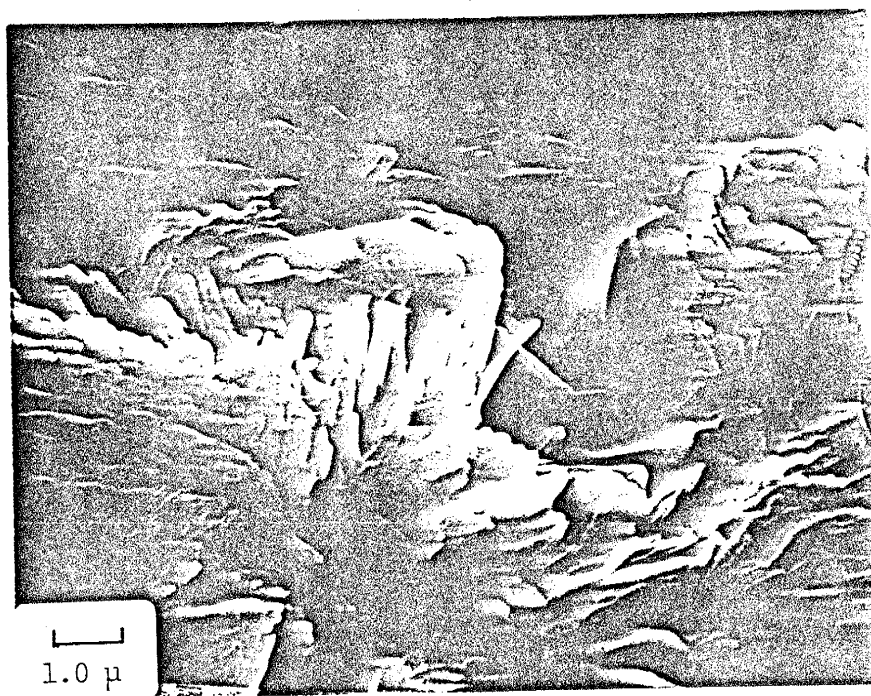


Figure 33. Kaolinite.
10,000X

(50)

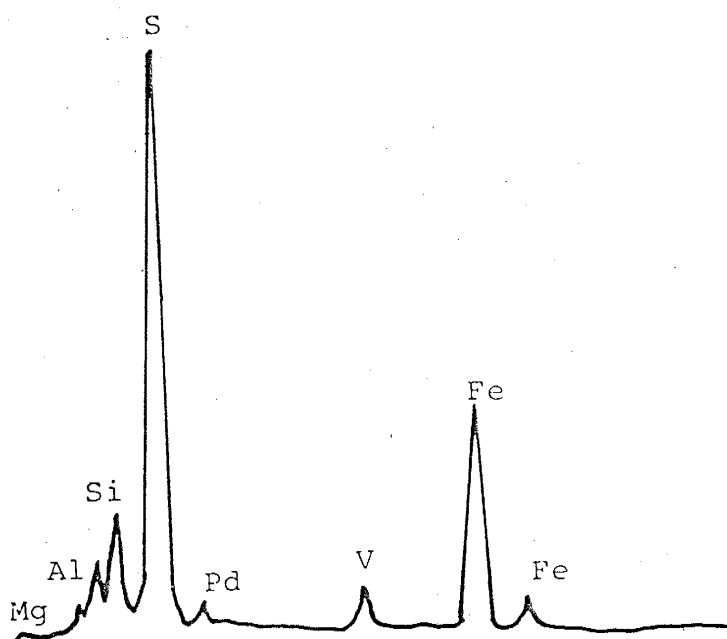
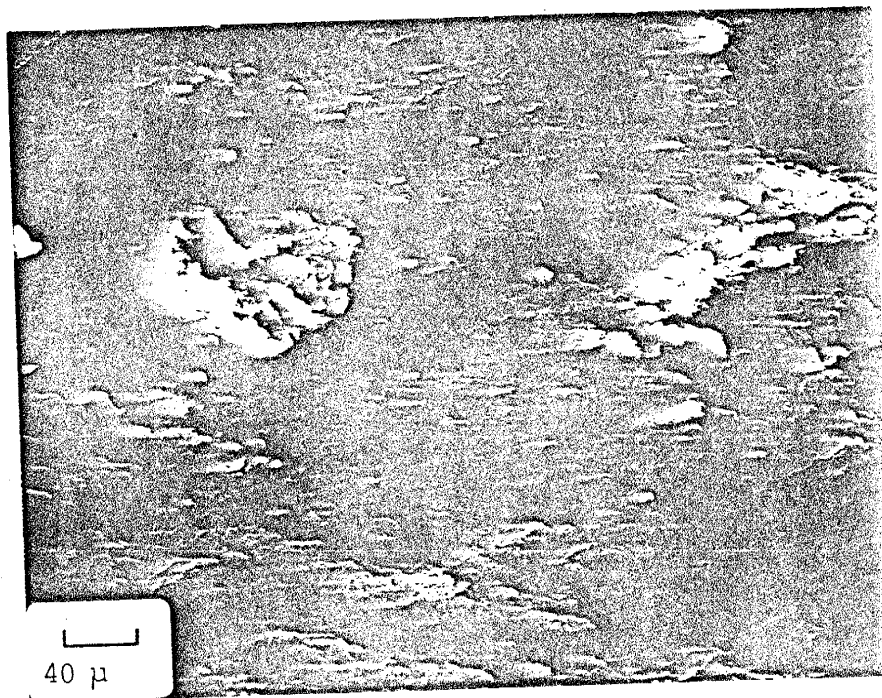


Figure 34. Pyrite grain. 2000X.

(51)

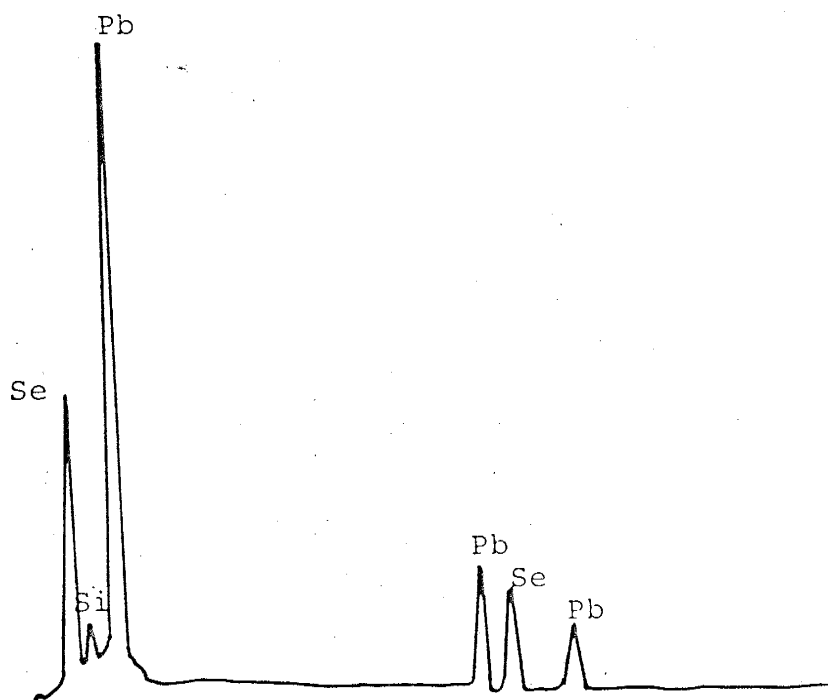
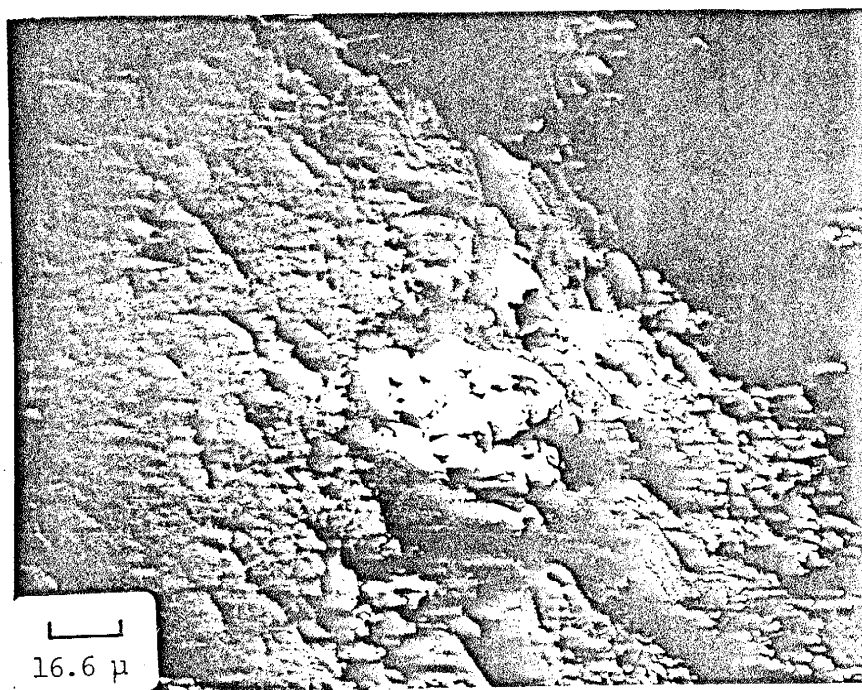


Figure 35. Clausenthalite (PbSe) under the backscattered mode. 600X.

(52)

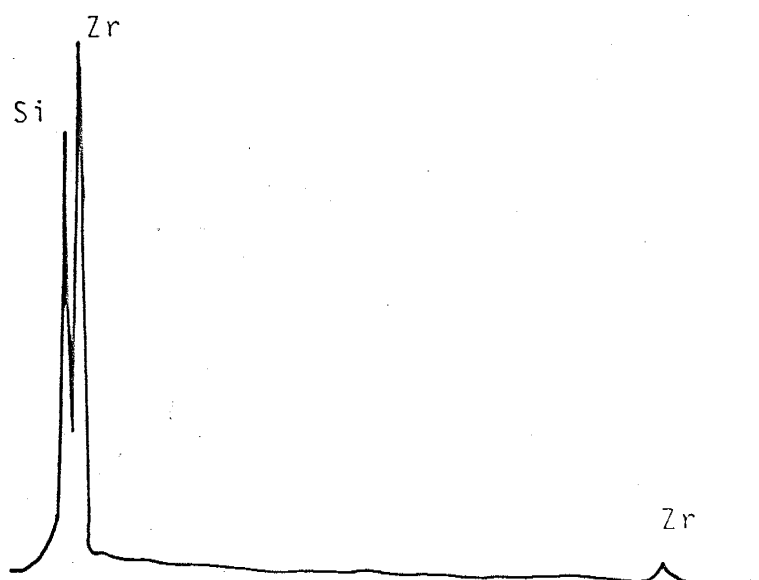
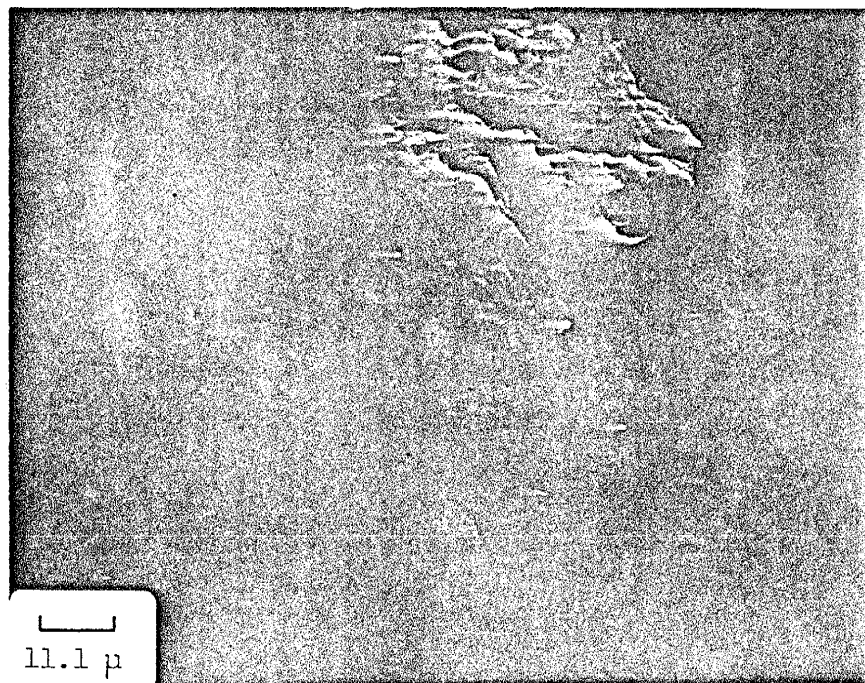


Figure 36. Detrital zircon grain. 900X.

(53)

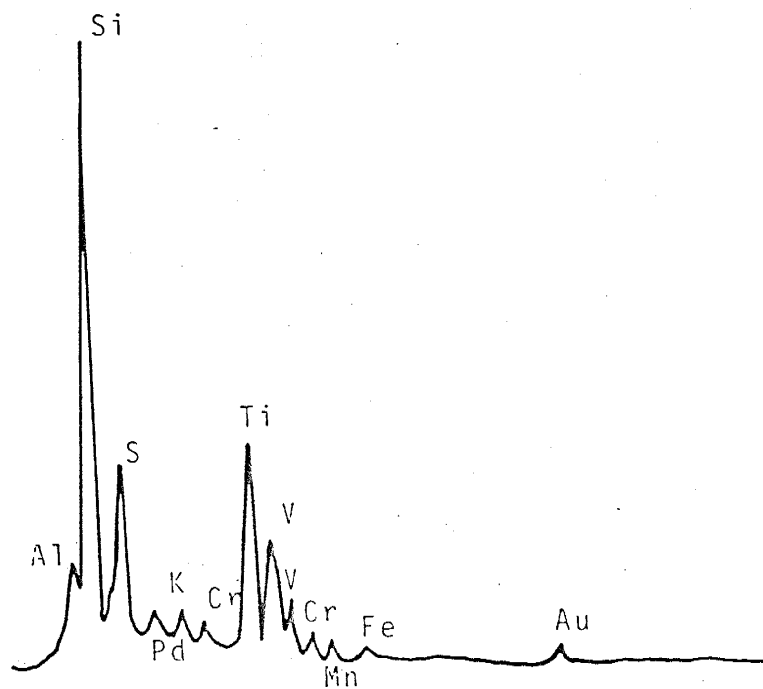
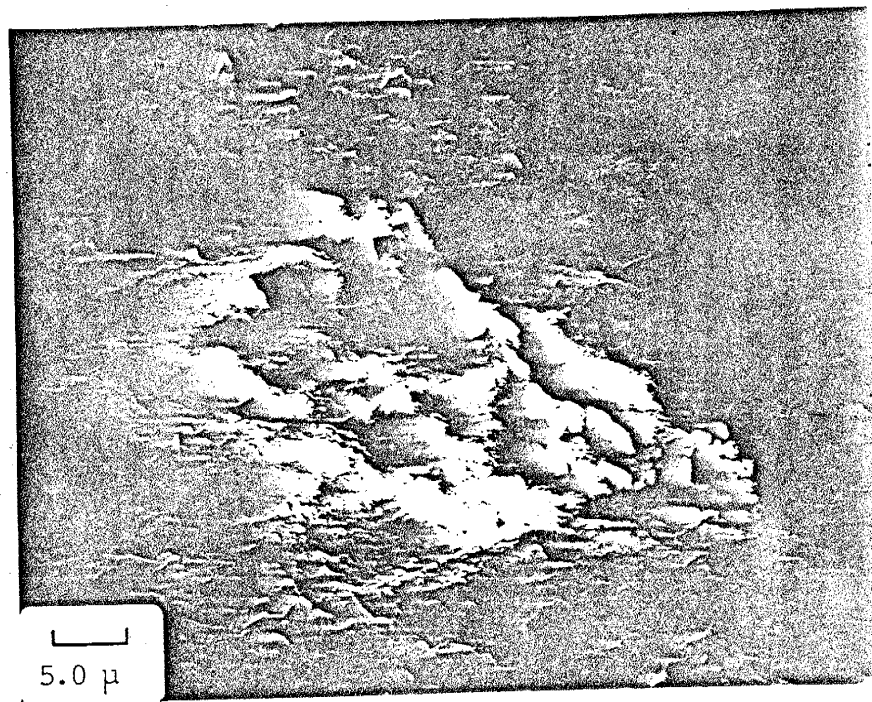


Figure 37. Detrital ilmenite(?). 2000X.

(54)

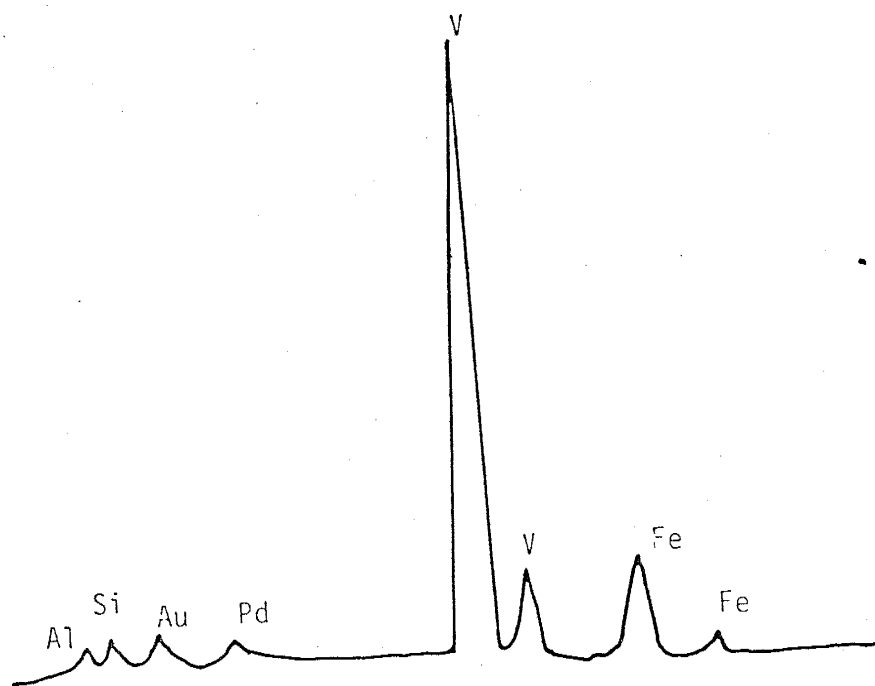
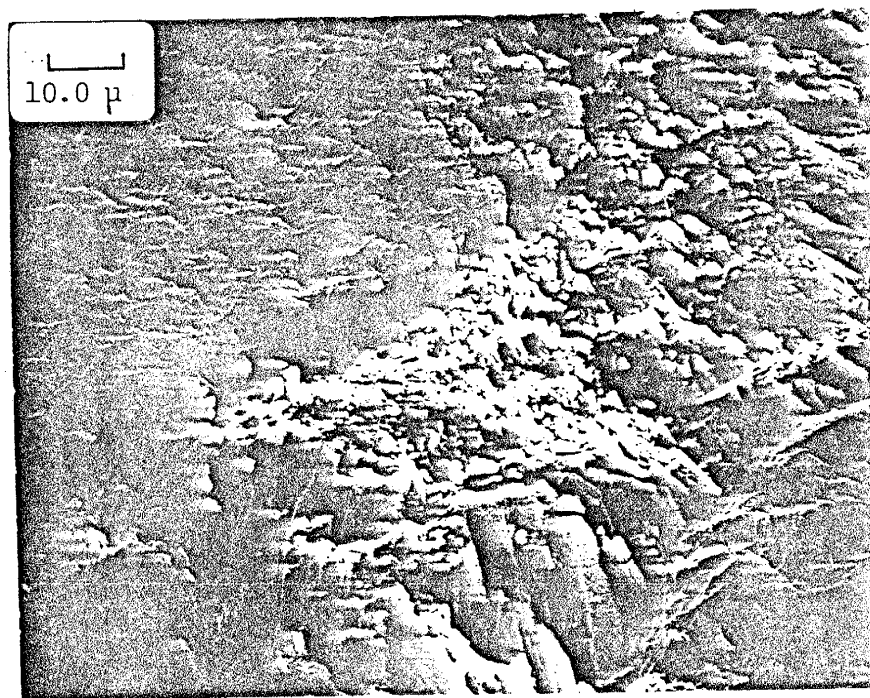


Figure 38. Vanadium-iron mineral (probably montroseite
VO-OH with Fe substitution).

1000X

CLAY MINERALOGY

Most of the clays analysed by x-ray diffraction can be classed as chlorites. However, they exhibit subdued but persistent roscoelite peaks at about 10.5 and 3.36 angstroms and varying development of the 005 planes. The clay minerals identified are in Table II at the end of this section.

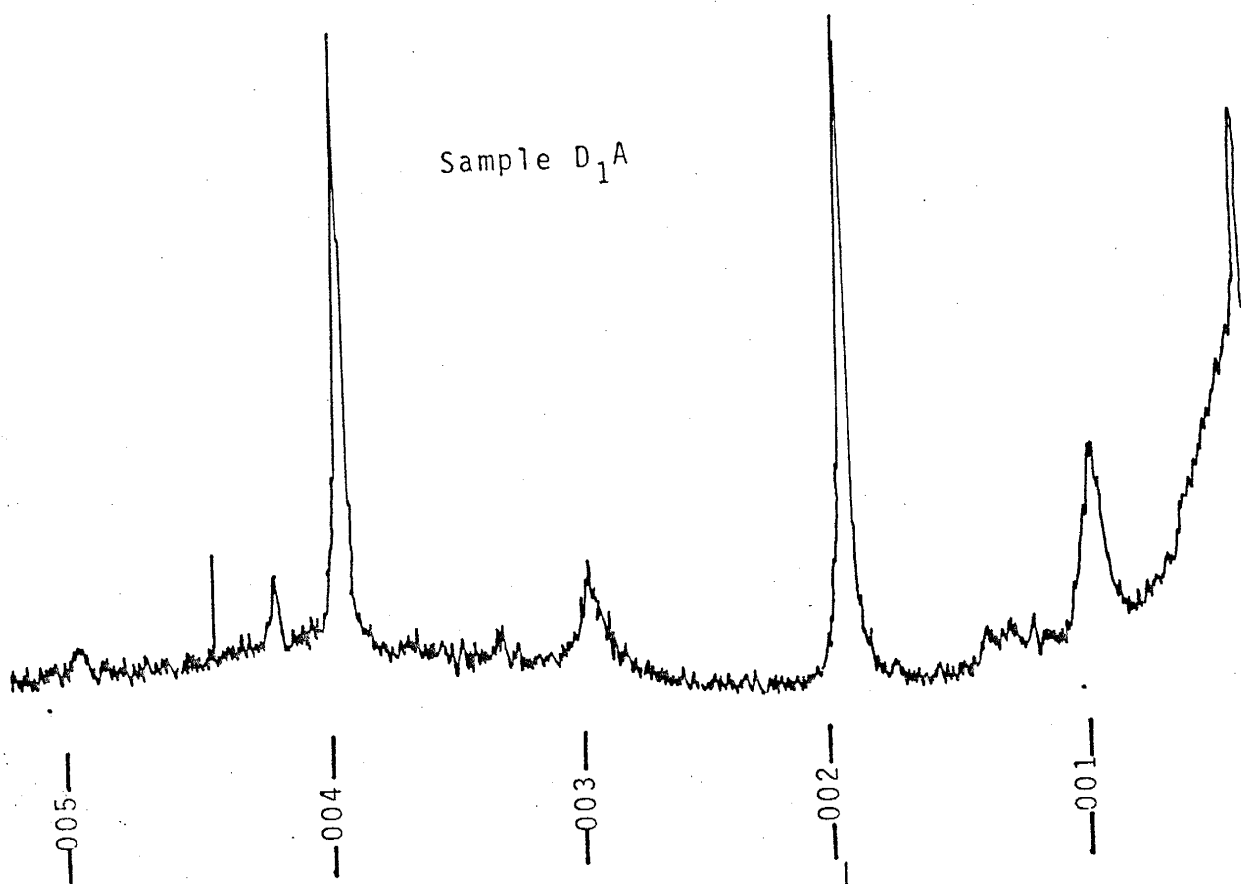
Light olive green chlorite (D1A) overlying and zone of black chlorite (D1B) were taken in a single hand specimen in the N 785 E drift. X-ray analysis of these chlorites show a pronounced variation in peak heights. The 002 and 004 peaks are essentially unchanged. The 001 peak is diminished and the 003 peak is virtually nonexistent. In both samples the 005 peak for chlorite is barely discernable (see fig. 39).

Samples E-1 and X-1 both have well defined chlorite peaks along with a significant roscoelite component (fig. 40). In sample X-1 the peak of greatest intensity is a roscoelite peak.

In samples 3,1 and #6 (fig. 41) the x-ray pattern for well-developed chlorite can be seen. Although #6 does show a roscoelite component the chlorite peaks are all sharp and intense indicating that the clay is well-crystallized. In sample 3,1 the roscoelite peak is insignificant and even the 005 peak for chlorite can be distinguished. The best

(56)

Sample D₁A



Sample D₁B

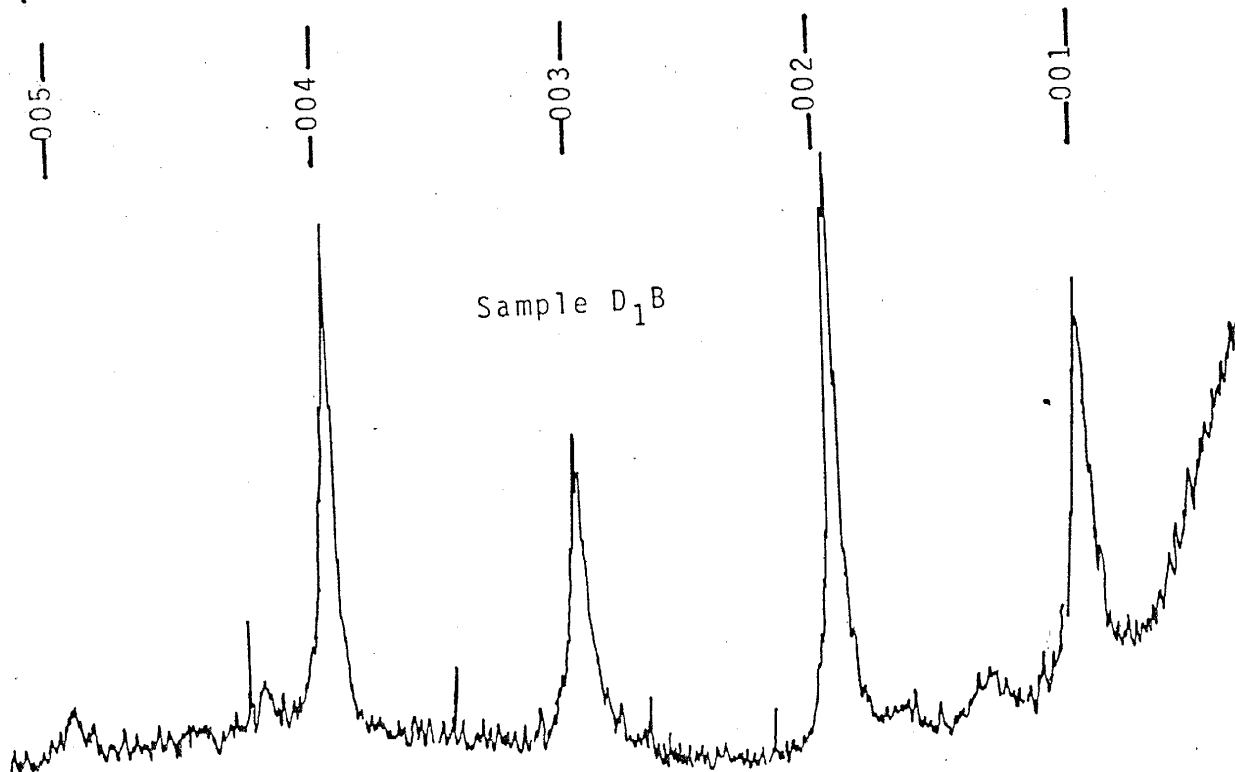
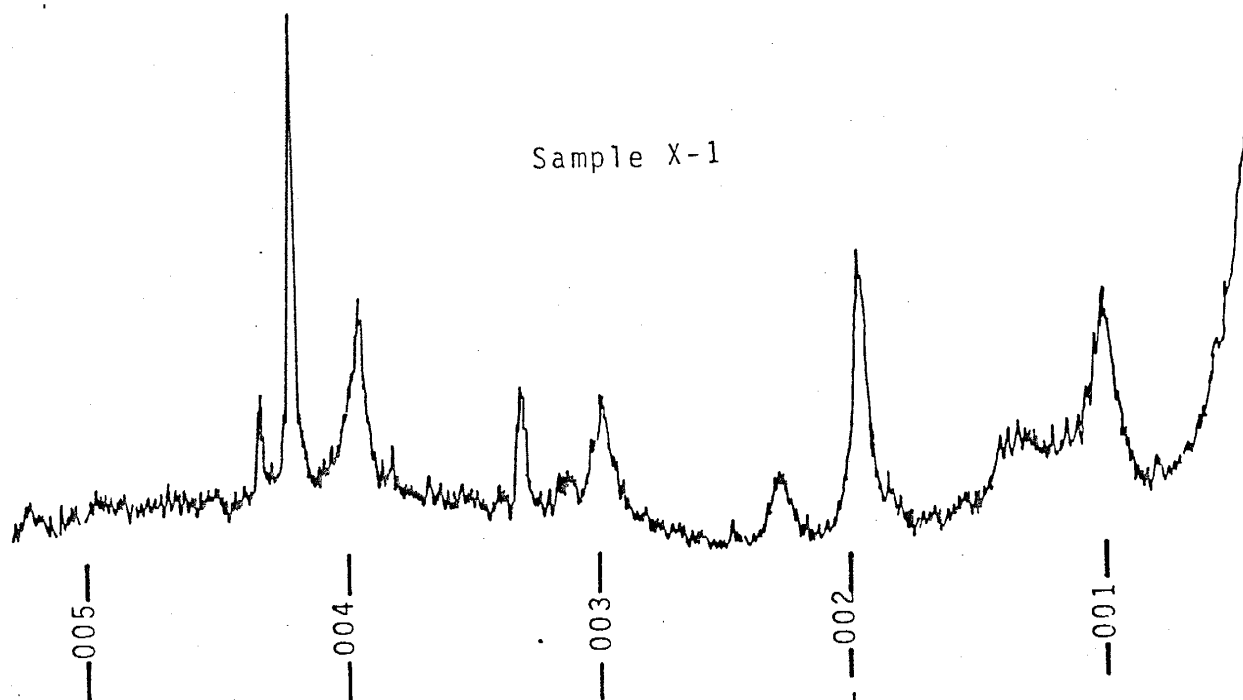


Figure 39. Comparison of green (D₁A) and black (D₁B) chlorites (mixed layer chlorite-roscoelite.)¹ These two samples are from the same hand specimen. Miller indices are for chlorite.

(57)

Sample X-1



Sample E-1

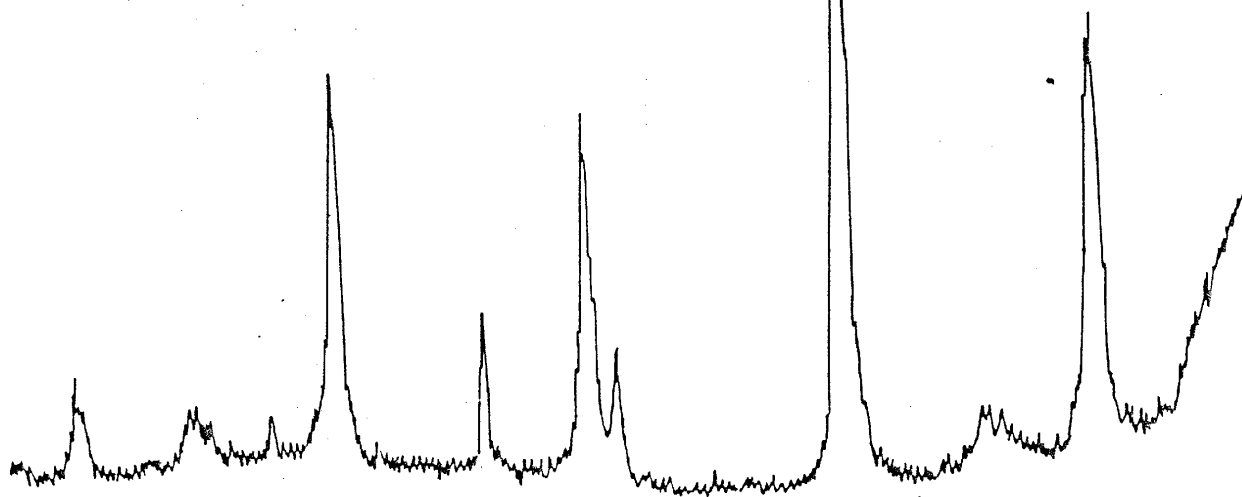
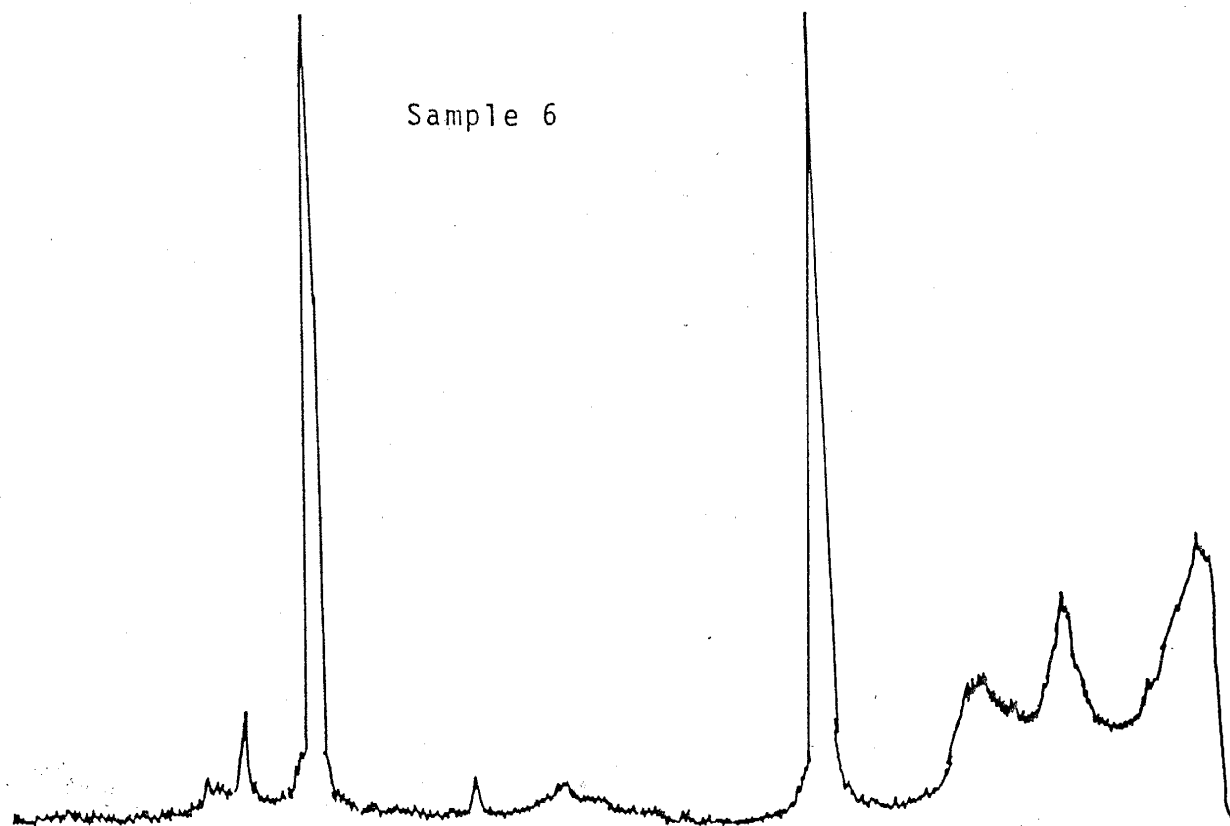


Figure 40. Mixed layer chlorite-roscoelite from a high grade uranium zone. Note from sample X-1 the very well developed 3.36 angstrom peak just to the left of the 004 peak of chlorite.

Sample 6



Sample 3,1

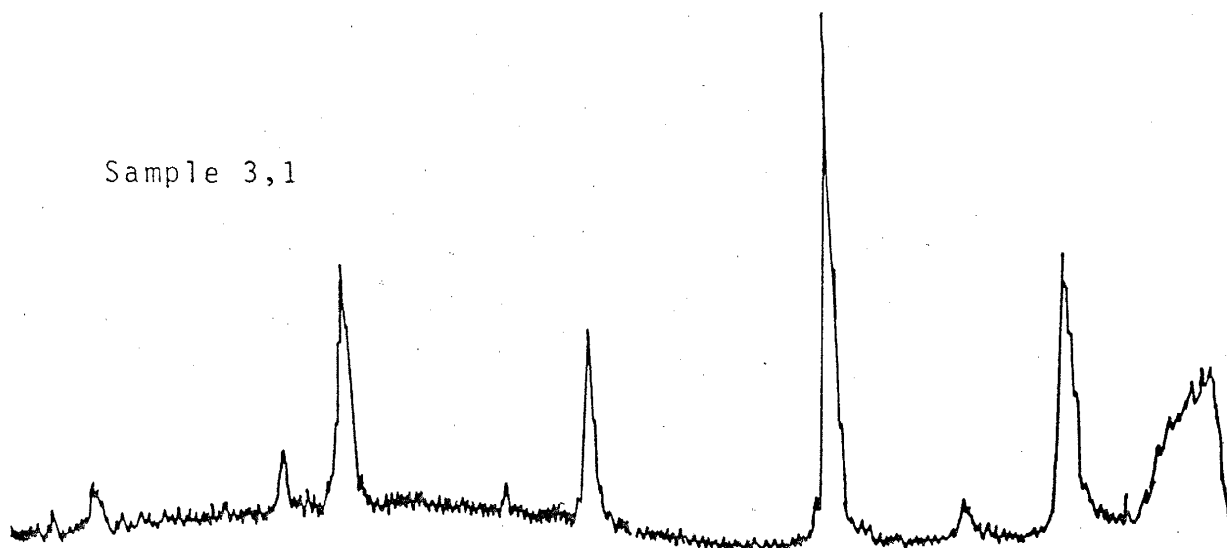


Figure 41. Well crystallized chlorites with subdued roscelite peaks.

crystallized chlorite x-rayed is sample #12 taken from the N 785 E drift (fig. 42).

The sample location for CHGP-1 is unknown because it was taken as a grab sample from the high grade ore pad to insure taking a sample with significant uranium. The samples with the best uranium values always exhibited a significant roscoelite component (compare analyses and x-ray diffractograms for CHGP-1, X-1, and E-1 in Appendix III and fig. 40).

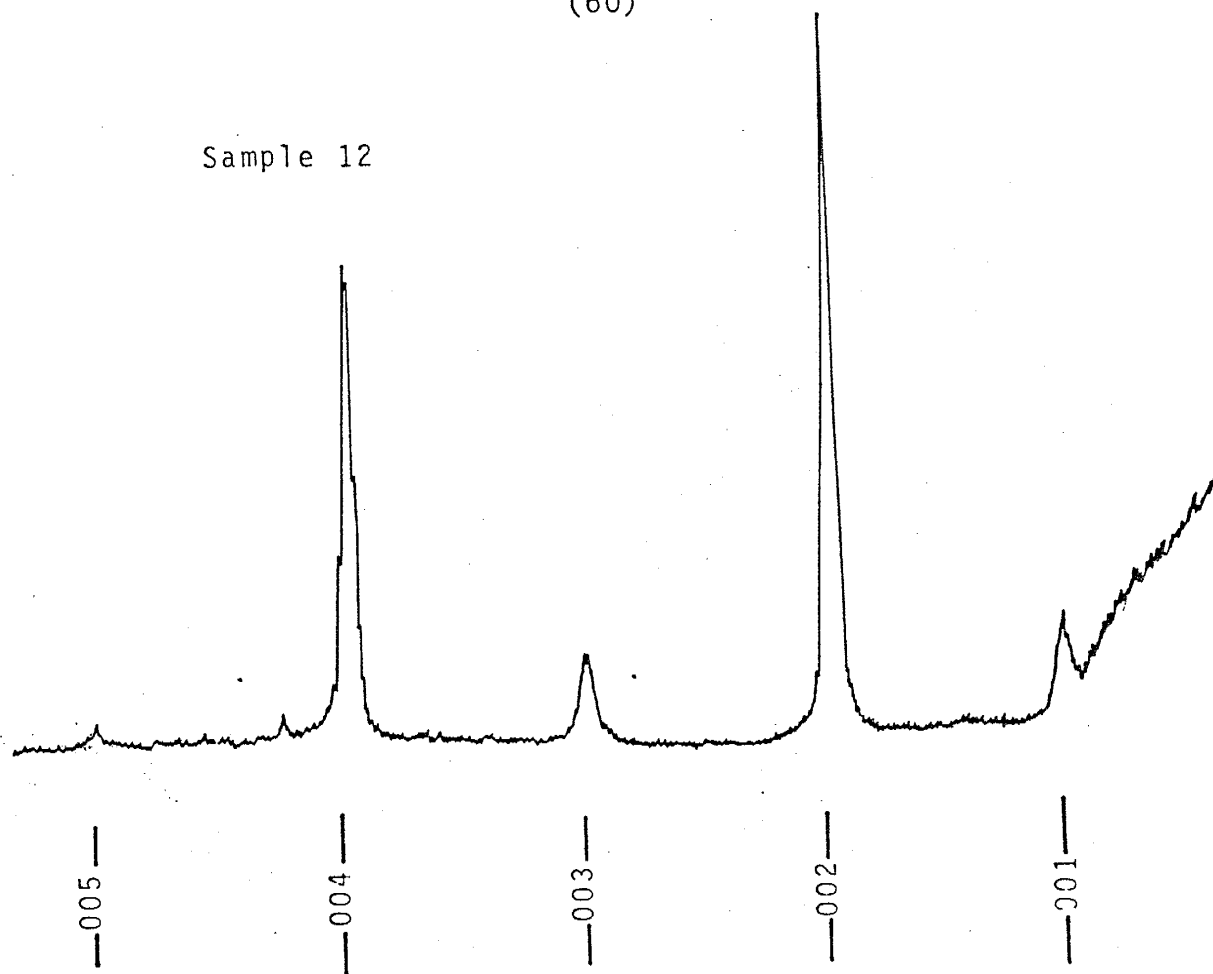
Sample 3,3 is a possible mixed layer montmorillonite-roscoelite-chlorite (fig. 43). Both the chlorite and roscoelite peaks are sharp and intense while the montmorillonite peak is not well preserved.

An attempt was made to identify the clay component(s) in a green mudstone. Although the parameters of the x-ray diffractometer were kept as constant as possible the mudstone revealed only one subdued peak at about $10 \text{ \AA}$ suggesting the clay belongs to the smectite group (fig 43).

To verify and crosscheck that the chlorites contained vanadium in their crystal lattices several "oriented" x-ray diffraction samples were run on the S.E.M. (figs 44 a & b). Note the recurring almost monotonous occurrence of Na, Mg, Al, Si, U, K, Ca, V, and Fe.

(60)

Sample 12



Sample CHGP-1

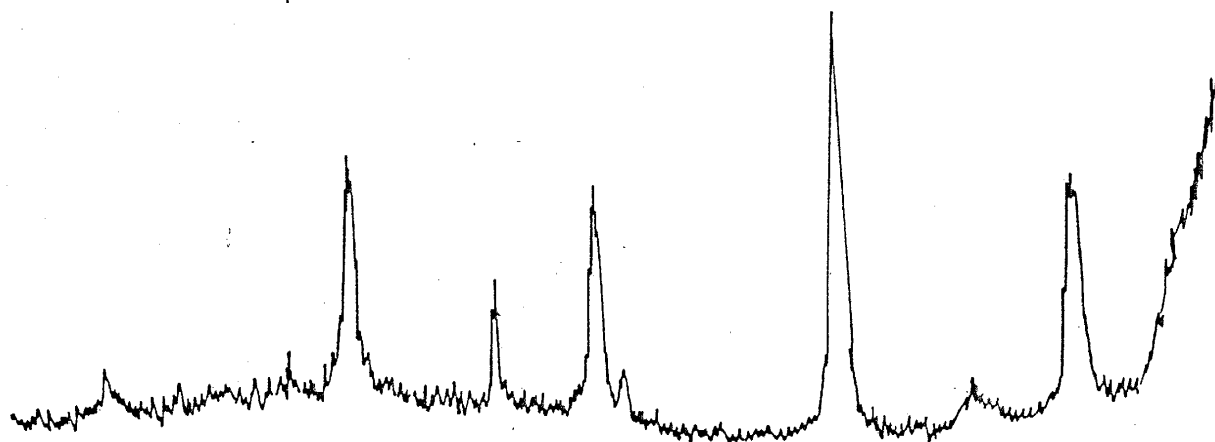
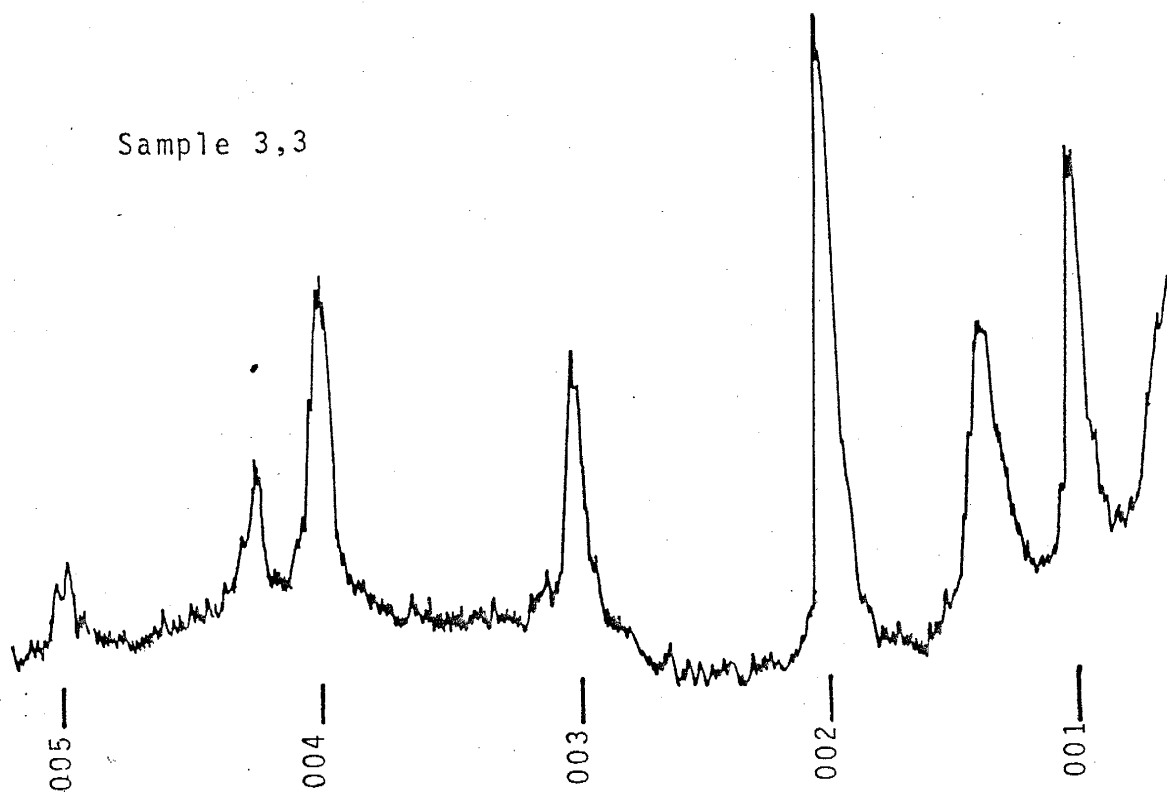


Figure 42. Comparison of well crystallized chlorite and a complex mixed layer chlorite-roscoelite-? from high grade ore samples.

(61)

Sample 3,3



Green Mudstone

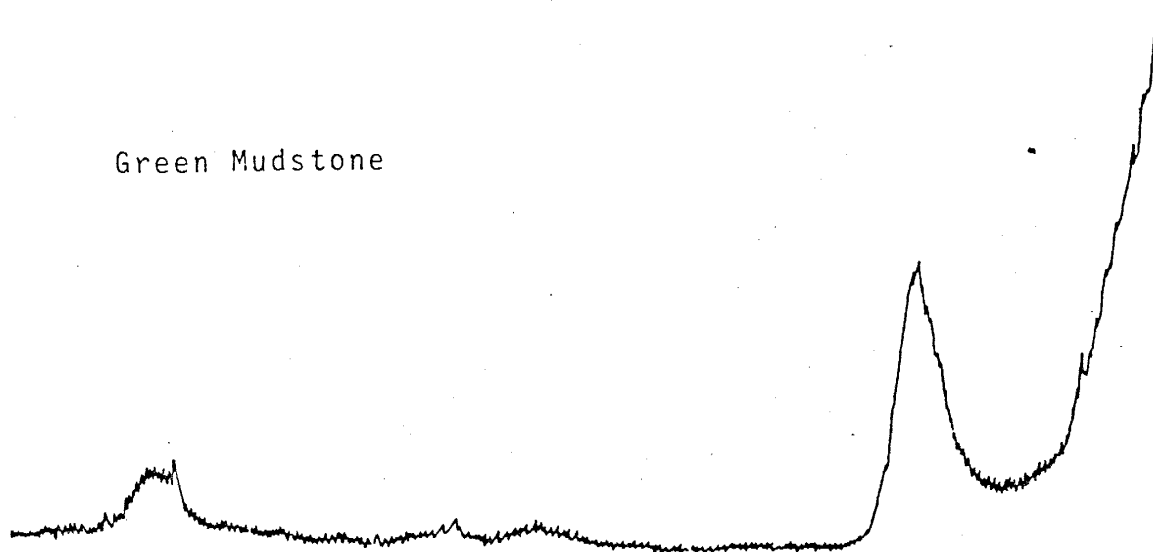


Figure 43. Comparison of well crystallized chlorite-roscoelite-montmorillonite(?) and green mudstone.

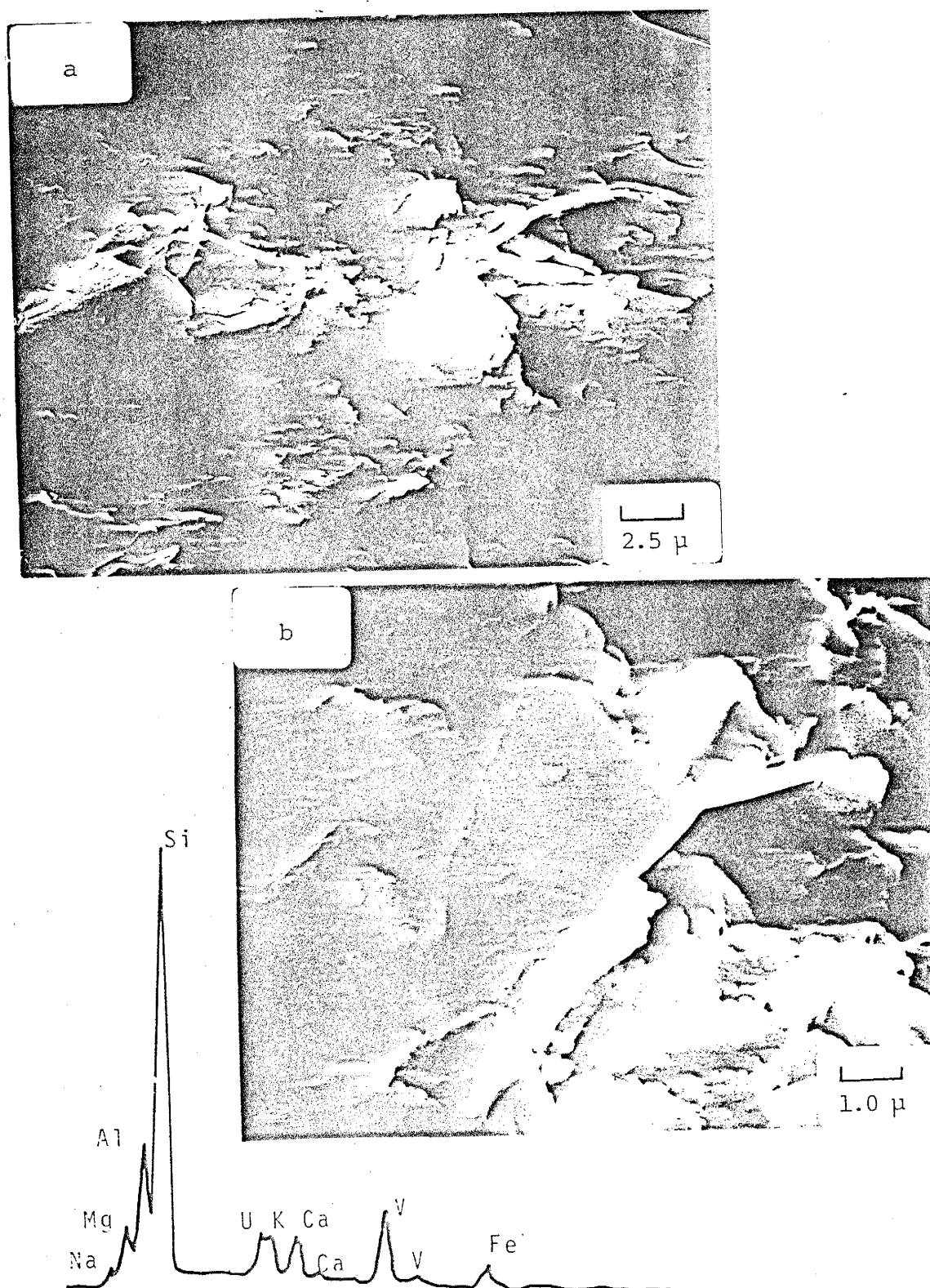


Figure 44. a) Oriented x-ray diffraction sample. 4000X.
 b) Oriented x-ray diffraction sample and x-ray spectra. Mg, Fe, V, and Si are tied up in chlorite while Na, K, V, and U are in carnotite. 10,000X.

Mineral(s)

<u>Sample #</u>	<u>001</u>	<u>002</u>	<u>003</u>	<u>004</u>	<u>005</u>	
D ₁ A	14.61 ₃₈	7.20 _x	4.76 ₁₈	3.57 _x 3.36 ₁₉	----	Chl-Ros
D ₁ B	14.24 ₇₈	-- 7.13 _x	4.72 ₅₅	3.56 ₁₇	2.84	Chl-Ros
X-1	14.26 _x	10.79 ₅₄ 7.21 ₈₂	4.79 ₅₅	3.57 ₁₇ 3.36 ₆₃	2.85 ₁₉	Chl-Ros
E-1	14.52 ₅₈	10.41 ₁₀ 7.27 _x 4.97 ₁₈	4.76 ₄₃	4.19 ₂₃ 3.57 ₅₂	2.86 ₇	Chl-Ros
#6	14.42 ₁₃	----- 7.21 _x	4.76 ₅	----- 3.59 _x 3.36 ₁₈	-----	Chl-Ros
3,1	14.42 ₅₅	-- 7.13 _x	4.74 ₄₂	-- 3.55 ₅₅ 3.34 ₁₈	2.84 ₁₄	Chl
#12	14.42 ₁₈	7.21 _x	4.76 ₁₃	3.58 ₆₃ 3.34 ₄	-----	Chl
CHGP-1	14.47 ₆₂	10.15 ₁₆ 7.17 _x	4.79 ₆₀	4.19 ₃₈ 3.56 ₆₉	2.85 ₂₀	Chl-Ros

3,3	15.71 ₈₀	11.06 ₅₄ 7.43 _x	4.88 ₅₀	3.65 ₆₂ 3.40 ₃₆	2.89 ₁₉	Mont-Chl

Table II. $d(\text{\AA})$ spacings and relative peak heights of x-rayed clay fractions. Miller indices are for chlorite.

GEOCHEMISTRY OF THE CALLIHAM MINE

Whole rock analysis and S.E.M. spectra show the sediments of the Calliham mine to be composed of Na, Mg, Al, Si, Ca, K, Fe, U, and V. Vanadium/uranium ratios in uraniferous ores vary from 1.8/1 to >10.3/1. The lowgrade ores exhibited a wide range of ratios varying from 3.2/1 to 43.0/1 while the bulk average for the mine at the millhead is ~8/1.

By linear regression analysis correlation coefficients were calculated for uranium and vanadium versus the oxides and metals (see Table III). For interpretation of these data a high correlation coefficient and a positive slope were taken as criteria that the element in question was introduced during the mineralization process. Conversely, a low coefficient with a negative slope would suggest depletion during mineralization. Ambiguous values with intermediate coefficients and very low slopes indicate the oxide or metal remained essentially unchanged during the mineralization process.

The correlation coefficient for vanadium vs. uranium was very high at 0.95 (fig. 45) and therefore their respective coefficients versus the oxides and metals are not significantly different. Statistically it appears that Al,

TABLE III

Correlation Coefficients and Slopes for U and V vs Oxides
and Metals

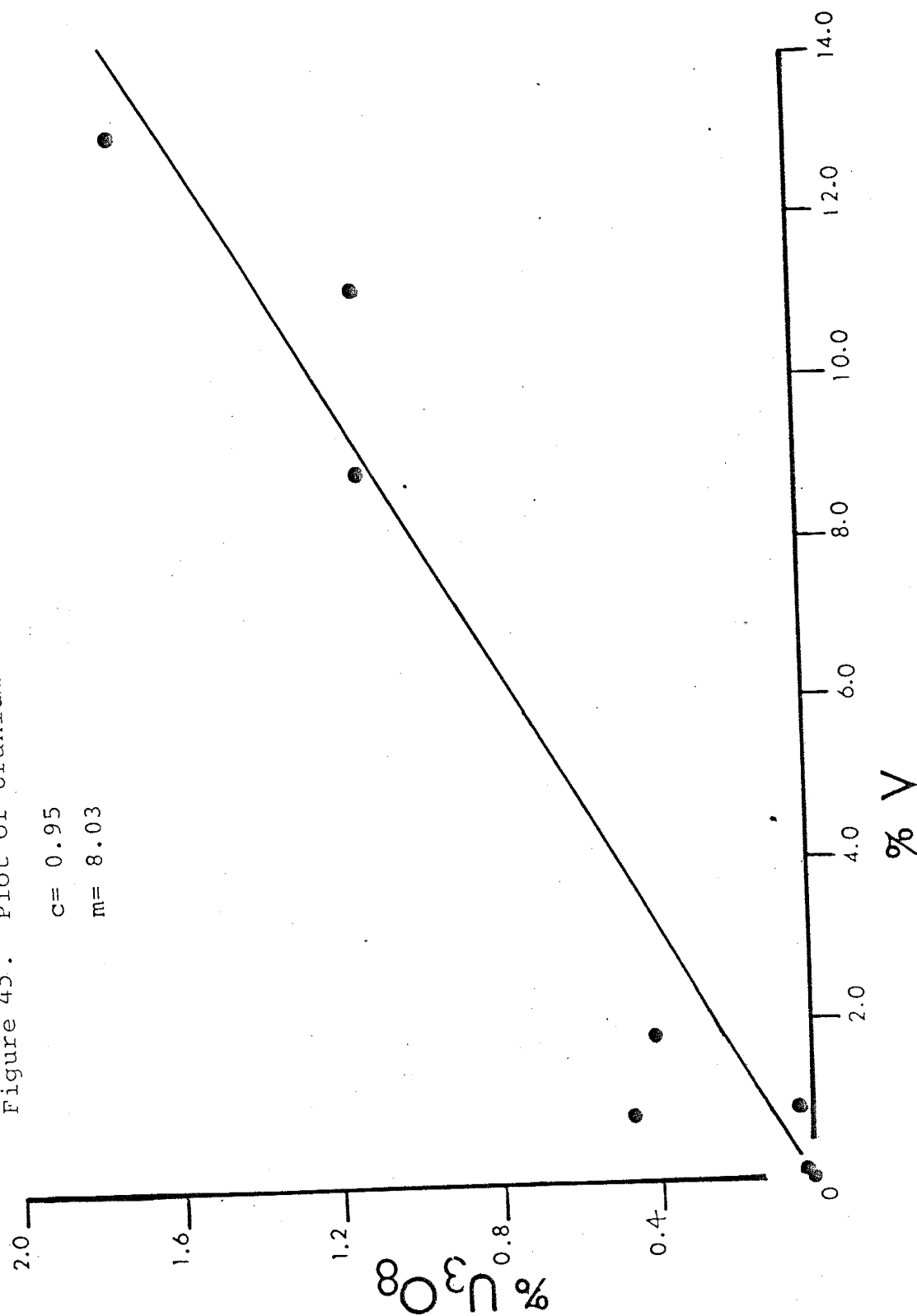
%	Uranium	Vanadium
SiO ₂	0.88 (-)	0.93 (-)
Al ₂ O ₃	0.75 (+)	0.74 (+)
Fe ₂ O ₃	0.92 (+)	0.95 (+)
CaO	0.45 (-)	0.46 (-)
MgO	0.47 (+)	0.45 (+)
Na ₂ O	0.73 (+)	0.69 (+)
K ₂ O	0.77 (-)	0.70 (-)
TiO ₂	0.23 (+)	0.41 (-)
MnO	0.35 (-)	0.41 (+)
P ₂ O ₅	0.94 (+)	0.84 (+)
LOI	0.44 (-)	0.40 (-)
p.p.m		
Cr	0.94 (+)	0.93 (+)
Cd	0.32 (+)	0.33 (+)
Co	0.73 (+)	0.74 (+)
Cu	0.22 (+)	0.25 (+)
Mo	0.31 (+)	0.12 (+)
Ni	0.29 (+)	0.17 (+)
Pb	0.47 (+)	0.35 (+)
Sb	0.95 (+)	0.98 (+)
V	0.95 (+)	-----
Zn	0.84 (+)	0.79 (+)

(64)

Figure 45. Plot of Uranium versus Vanadium

$C = 0.95$

$m = 8.03$



Fe, Mg, P, Cr, Co, Sb, V, and Zn are all enriched during mineralization while Si, Ca, K, and LOI are depleted. The ambiguous metals are Na, Ti, Mn, Cd, Cu, Mo, Ni, and Pb. Due to the low number of data points (9) these statistics can in no way be considered definitive and are only suggestive of the processes involved. However, the chemical data obtained in this study are in good agreement with data published by Foster (1959), Shawe and Archbold (1959), Garrels et al (1959), Motica (1968), and Brooks and Campbell (1976).

Beta minus gamma data from this and other studies (see Shawe et al, 1959, Garrels et al, 1959, and Brooks and Campbell, 1976) indicate that uranium has not been significantly remobilized.

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DISCUSSION BY SUBJECT

Sedimentary Features

In the Calliham mine point bars and other features attributable to a meandering stream system are evident. The thicker mudstones of the Calliham mine indicate an entrenched meandering channel existed forming overbank and splay deposits in marginal ephemeral ponds. However, longitudinal bars and anastomosing channels are also present suggesting some of the sands were deposited by a braided system.

It is proposed that the flow regimes responsible for the deposition of the uppermost Salt Wash varied from the lower regime (producing ripples and dunes), through the transition flow regime (with washed out beds and flat beds), to the upper, generally turbulent flow regime (where only planar beds are preserved.)

Deposition by a point bar-braided system seems to fit the Salt Wash sandstones of the Calliham mine best. The thicker mudstones found in the mine imply the existence of entrenched channels periodically overflowing or breaching the natural levees while the thinner mudstones are the result of the suspended load sediment settling out during periods of slack water.

Relation of Mineralization to Sedimentary Features.

The highest grade ores are crossbedded sandstones of the point bar sequences and infilled channel scours underlain by an impermeable mudstone.

In the case of the ephemeral ponds of the upper Salt Wash sandstones, it appears that in some ore bodies the mineralizing solutions "ponded up" in a series of perched water tables precipitating ore minerals in a stagnant environment above an impermeable base, and below the lip containing the "pond". This is most clearly seen in infilled channels underlain by impermeable mudstones.

Roll fronts defined by chlorite can be discerned throughout the mine. However, it must be stressed that these discordant rolls are only a geologic oddity because the best and most frequently mined ores in the mine are stringers, pods, and lenses of various thicknesses.

Sedimentary Petrology

Invariably, detrital quartz grains in thin section exhibit uneven to long concavo-convex boundaries sutured by secondary silica, a feature commonly found in sandstones of all ages. The quartz grains also commonly exhibit a mild to pronounced undulatory extinction. Connally (1965) proposed that sand grains exhibiting undulatory extinction indicated that they had undergone plastic (irreversible) deformation sometime in their history. In the Salt Wash member's case it is probable that the grains were deformed before being eroded and transported (Smith personal communication 1981).

Pittman (1979) surveyed the available literature and compiled no less than ten possible sources of silica cement in sandstones. Of these ten the most likely and geologically reasonable is pressure solution of the quartz grains at the point of contact with other grains.

Pressure solution of quartz grains has been accomplished in the laboratory by Renton, Heald, and Cecil (1969), and Sprunt and Nur (1976). Bathhurst (1975) suggested that dissolution took place at the point where two grains and the pore liquid meet. de Boer (1977) convincingly demonstrated through thermodynamic arguments that the quartz grains dissolve inside the grain-grain contacts. Silica in solution then diffuses through a thin adsorbed water layer and precipitates in a low pressure area in the pore space. By calculating the chemical potential of a stressed grain boundary he was able to show that the

solubility of silica may be increased 1.5 times normal and therefore the only reasonable site for the supersaturation of silica is along these grain-grain contacts. The quartz grains undergoing pressure solution would show only a faint residual deformation.

Water is a requisite for pressure solution and is also enhanced by the presence of smectitic clays between grains. It has been found that pressure solution in carbonate rocks is severely hampered when clay minerals are absent. Apparently the composition of the pore waters has little effect on pressure solution.

It is interesting to note that de Boer (1977) proposed that during plastic deformation part of the mechanical work done on the system is released as heat. This heat source could be partially responsible for the elevated temperatures during burial required for the breakdown of uranyl carbonates and uranyl organic complexes to form the "primary" uranium deposits of the Colorado Plateau.

The most likely source for the ubiquitous carbon grains and stringers (fig. 21) has been proposed by Button's (1979) example on the Sabi river of Rhodesia where colonies of algae were observed being entrained by the migrating sands and trapped along the foreset beds. In the Calliham mine carbon grains are concentrated along bedding planes and several lines of evidence from this study suggest the quartz and carbon grains were deposited contemporaneously.

Geochemistry

It is known that the groundwaters of the Colorado Plateau are alkali rich carbonate fluids of neutral to slightly alkaline composition [Phoenix (1959)] containing significant amounts of vanadium as VO_4 [Kopp and Kroner (1967)]. With the abundance of calcite present in the mine it is not unreasonable to assume that the system has been buffered by the carbonate ions' equilibria producing near neutral pH's.

The geometry of the ore zones suggest that laterally migrating solutions were responsible for the transport and deposition of the ore metals.

Hostetler and Garrels (1962) investigated the stability relations of uranium and vanadium in aqueous systems at 25 degrees C. Among their conclusions were 1) pure water does not transport uranium very well unless the pH is 5 or less, 2) by adding CO_2 to the system carnotite solubility is increased enormously and the uranyl carbonate complexes are stable enough to coordinate considerable amount of uranium. Therefore, uranium is most likely transported as uranyl dicarbonate (UDC) and uranyl tricarbonatate (UTC) complexes. 3) Carnotite precipitation is critically controlled by the activities of U, V, and CO_2 in solution and is the only phase that is insoluble under oxidizing conditions, 4) U and V are soluble under mildly reducing conditions containing

abundant CO₂, 5) with increasingly oxidizing conditions carnotite forms and with increasing reducing conditions uraninite and montrosite form, 6) to electrostatically balance the groundwater system Na, Ca, and Mg are probably transported along in solution, 7) corroded quartz grains and secondary overgrowths imply the existence of a liquid that at some time hovered around quartz saturation values, and 9) if the temperature of the (buried) rocks rose above 120 degrees C the UDC and UTC complexes could have broken down allowing the formation of primary deposits.

Garrels and Christ (1965) show chlorite to be stable at pH's from 7 to 9 and log [K+] from 10⁻¹ to 10⁻⁴ M and log [Mg+2] from 10⁻² to 10⁻³ M. Certainly these concentrations are not beyond the scope of actively circulating groundwaters. Under such condition chlorite (V-hydromica) could coexist with uraninite and coffinite and several authors have described such a mineral assemblage (see Weeks, 1955, 1959, Evans, 1959, Foster, 1959, Adler and Sharp, 1967, and Motica, 1968).

Gableman (1977) studied the process of uranium mineralization by distinguishing which metals had been introduced into the sands. It has long been realized that the effects of alteration on the sands are so subtle that some problem exists in identifying diagenetic cement from epigenetic alteration products. Nevertheless, samples were taken to establish suites for barren, distantly altered,

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proximally altered, protore, ore and high grade ore from five host sandstones on the Colorado Plateau. The samples were all disaggregated and sieved and all size fractions were analysed. Gableman concluded the major elements introduced during mineralization are Ca, Fe, Mg, Ti, Ba, Mn, Sr, U, V, Mo, Se, and F. This family of metals is distinctive and suggests an affinity with element suites of typical mantle derivatives such as volatile rich carbonatites and alkaline magmas.

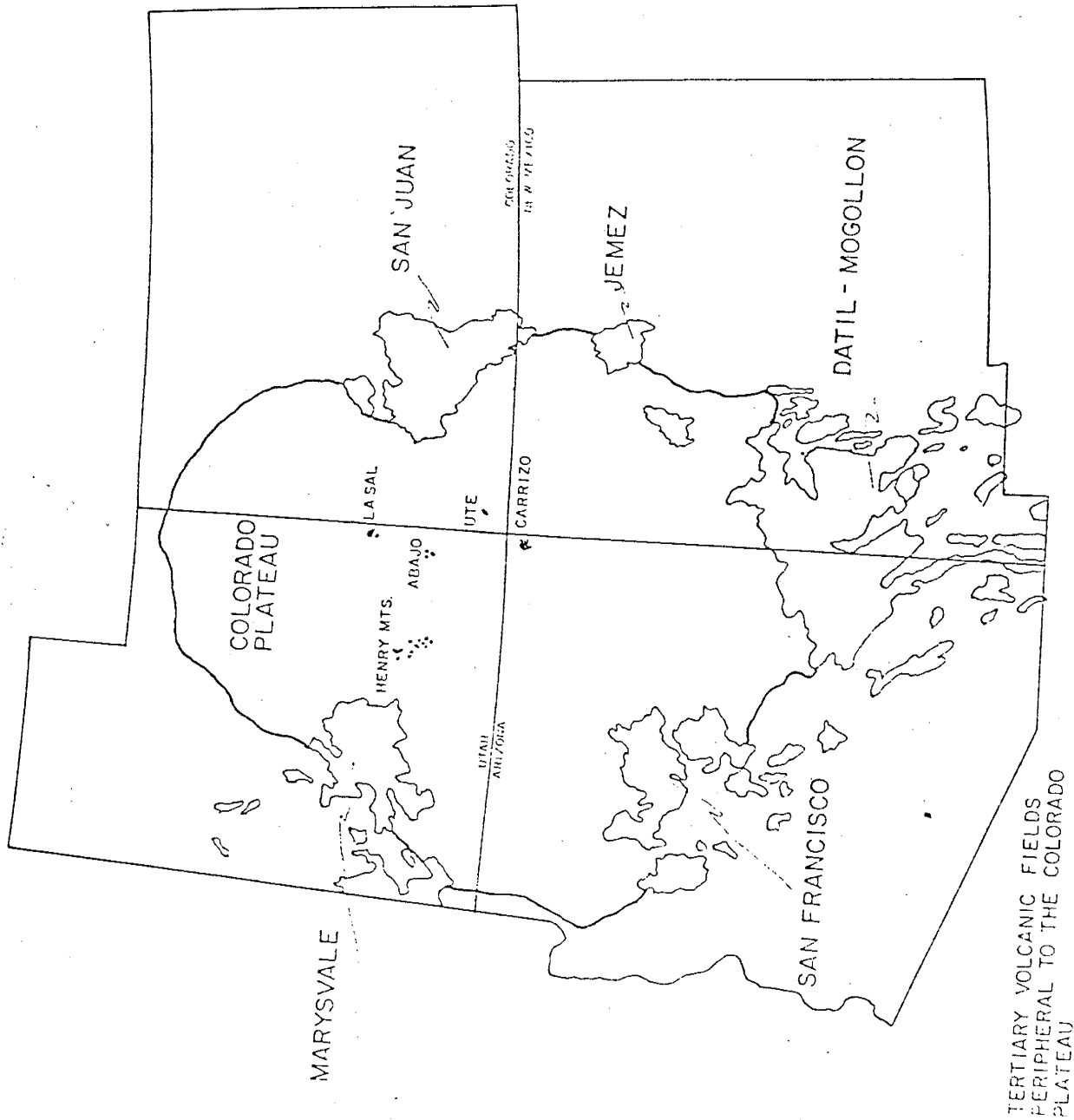
MODEL FOR THE ORIGIN OF THE DEPOSIT

It is clear that the ore metals of the Calliham mine are in the oxidized state. It is probable that the ore minerals present today are the result of the oxidation of uraninite, montroseite, roscoelite, and coffinite by oxidizing, slightly alkaline, groundwaters.

By the end of Cretaceous time the Salt Wash member could have been overlain by more than 3000 meters of sediments. At this depth the ground-waters are depleted in oxygen and uranium is most likely transported as uranyl dicarbonate and uranyl tricarbonat (Langmuir 1978). By some mechanism primary ores were formed and preserved before the uplift and canyon cutting episode of the Colorado Plateau.

Beginning about 24 million years (m.y.) ago the Colorado Plateau began to be epirogenically uplifted. At this same time eight alkalic laccoliths were emplaced in the interior of the plateau and along the periphery intense silicic volcanism was occurring in four major volcanic fields (fig. 46). As a result of this uplift the rocks in the area have undergone an extensive period of erosion and canyon cutting. This igneous activity and uplift has allowed oxidizing possibly heated meteoric waters to circulate through the rock mass and extant ore bodies above the water table.

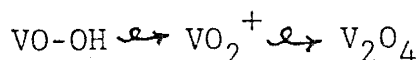
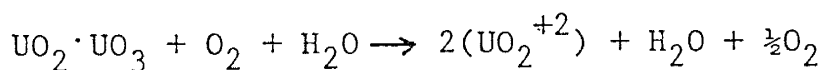
Sufficient carbonate is present in the Salt Wash member that it is likely the system has been buffered by the



TERTIARY VOLCANIC FIELDS
PERIPHERAL TO THE COLORADO
PLATEAU

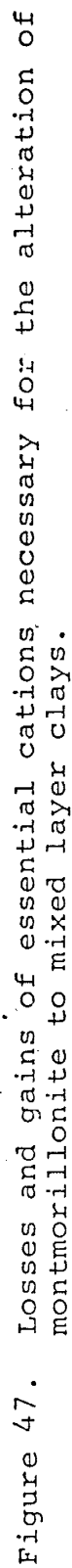
Figure 46.

carbonate ions' equilibria producing near neutral pH values. With the introduction of neutral to slightly alkaline groundwaters of varying major element composition the pre-existing primary ore minerals would be altered and dissolved putting U into solution as $(\text{UO}_2)^{+2}$ or a complexed ion. In the absence of K and V the reaction would proceed by:



(after Weeks (1959), Hostetler and Garrels (1962), Grandstaff (1976))

Barton (1959) found "difficult if not impossible" to prevent carnotite precipitation when uranium is present in solution with sufficient amount of vanadium and potassium. Therefore it is proposed that carnotite precipitated as colloidal particles from the pore space solutions as sufficient amounts of U, K, and V became available from the dissolution of uraninite, coffinite, and montrosite (after Weeks et al (1959)). Contemporaneously or perhaps slightly earlier, roscoelite began altering to chlorite by the release of K and addition of Mg and Fe into the lattice (fig. 47). Carnotite is the least soluble uranium bearing phase at low CO_2 pressures and from pH's of 5.5 to 7.5. Groundwaters in equilibrium with carnotite would contain less than 1 p.p.b dissolved uranium (Langmuir, 1978) and therefore these oxidized deposits would be preserved for long periods of geologic time.



SUMMARY AND CONCLUSIONS

The sandstones of the Calliham mine exhibit bed forms and sedimentary structures spanning the entire spectrum of flow regimes which include current ripples and small scale trough stratification, sand waves, tabular cross strata, and dunes, to large scale trough and flat bedded strata. Schumm's (1977) point bar-braided environment seems to fit the preserved sandstones of the Calliham mine best.

Mineralization in the Calliham mine occurs as peneconcordant stringers, lenses, and pods in the uppermost portion of the Salt Wash member. The ore minerals are carnotite and vanadiferous chlorites. Carbonaceous material is nearly ubiquitous in and around the ore zones as grains 64 to 250 μ in size are intimately mixed with the quartz grains. Uranium mineralization always occurs with vanadium mineralization but the opposite is not true suggesting U and V are not syngenetic. While all types of sedimentary features in the mine are variably mineralized, the higher grade ores seem to be associated with the point bar sequences of the large bends in the stream channel system.

The loci of mineralization coincide with the most porous and permeable portions of the rock mass i.e. sandstones in infilled channel scours, along contacts between sand bodies, along individual bedding planes, and other higher porosity zones above impermeable mudstones in the rock mass.

Thin section mineralogy varies from quartz-carbon-calcite to quartz-carbon-chlorite. Calcite and chlorite occur exclusive of one another suggesting they too were formed by separate events. The data indicate a paragenetic sequence of;

quartz overgrowths-chlorite-carnotite-late quartz.

The clays of the Calliham mine can be classed as chlorites with subdued but persistent roscoelite peaks indicating the clays now present altered from an earlier suite of clay minerals possibly including montmorillonite.

The chemical system of the Calliham is dominated by; Na, Mg, Al, Si, Ca, K, Fe, U, and V. Which is similar to the dissolved solid content of normal groundwaters. The metals showing the highest correlation with uranium mineralization are Cr, Sb, V, and Zn.

It is probable that the uranium and vanadium minerals present today are the result of the oxidation and alteration of roscoelite, montroseite, and coffinite by oxidizing, slightly alkaline groundwaters. Secondary migration of uranium appears to be on the scale of millimeters.

The absolute age of the mineralization can only be bracketed between the age of the sandstones and the present.

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APPENDICES

Appendix I

THEORY OF BACKSCATTERED ELECTRONS

by

ANDREW L. ROSENTHAL

S.E.M. Operator

Electrons accelerated into a specimen in an S.E.M. are called primary electrons. Upon interaction with the specimen two kinds of electrons are ejected, a) low energy secondary electrons, and b) high energy, primary, backscattered electrons. The secondary electrons originally belonged to the atoms of the specimen but were knocked out of their orbitals by collisions with the primary electrons. The backscattered electrons were originally in the primary beam but after having undergone very few collisions and little energy loss are deflected out of the specimen.

The electron yield from a specimen is dependent upon two factors a) surface topography, and b) average atomic number of the specimen. For flat specimens topographic influence is constant. Areas with a higher average atomic number on a specimen will be seen as a bright area. Therefore, in two zones of different composition the zone with the higher average Z will appear the brighter of the two. This phenomenon is known as atomic number contrast.

TABLE OF DETERMINATIVE X-RAY ENERGIES USED BY THE S.E.M.

(in Kilo electron volts)

Name	Atomic #	K alpha 1	K alpha 2	K beta 1	K beta 2
Magnesium	12	1.245		1.297	
Aluminum	13	1.487	1.486	1.553	
Silicon	14	1.740	1.793	1.832	
Sulphur	16	2.308	2.306	2.464	
Chlorine	17	2.622	2.621	2.815	
Potassium	19	3.313	3.310	3.589	
Calcium	20	3.691	3.688	4.012	
Vanadium	23	4.952	4.944	5.427	
Manganese	25	5.898	5.887	6.490	
Iron	26	6.403	6.390	7.057	
Selenium	34	11.221	11.181	12.495	12.615
Zirconium	40	16.614	16.520	18.621	18.951
		L alpha 1	L alpha 2	L beta 1	L beta 2
Molybdenum	42	2.293	2.290	2.395	2.518
Palladium					
Barium	56	4.467	4.451	4.828	5.156
Platinum	78	9.441	9.360	11.069	11.249
Gold	79	9.711	9.625	11.439	11.582
Uranium	92	13.613	13.438	17.218	16.425

APPENDIX II

ANALYTICAL PROCEDURES

During the summer of 1978 the ribs in the Calliham mine were mapped on a scale of 1"=10'. Features mapped in the mine included sedimentary structures, bedding thickness, color, clay splits, and mineralization. Concurrent with mapping the ore zones were sampled and later samples were taken from throughout the mine on a 50' grid.

In the lab the samples were scanned with a geiger counter and grouped according to uranium content as ore, subore, or barren. Representatives from each group were selected and four slabs cut from each sample for a thin section, S.E.M. chip, x-ray diffraction slide, and a sample to be crushed for chemical analyses. For the thin sections and S.E.M. chips it was necessary to impregnate the rock samples with Petropoxy before any further treatment could be augmented.

X-RAY DIFFRACTION

For x-ray analysis the sandstones were partially disaggregated (but not ground) in a ceramic mortar and pestle. The sample was then mixed in a beaker with 100 mls of distilled, deionized water and placed in an ultrasonic cleaner to propel the clay fraction into suspension. The samples were then let stand for fifteen to twenty minutes

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allowing the oversize fraction to settle. The uppermost portion was then pipetted onto a petrographic slide and let dry overnight at room temperature. All slides were then x-rayed on a Philips diffractometer from 2 to 36 deg 2 θ .

SCANNING ELECTRON MICROSCOPY (S.E.M.)

Rock slabs for the S.E.M. were ground smooth on a thin section machine but left about 2 mm thick to facilitate breaking off pieces for mounting on aluminum studs. The samples had to be as smooth as possible so the backscattered x-rays emanating from the sample would not be absorbed by "rough topography" in route to the x-ray detector. The last step before analysis was sputter coating the sample to make it conductive. Initially this was done with a Au-Pd sputter coating. However, it was found that the peaks of these two metals overlapped with the peaks of the metals of interest in the sample and a carbon coating was then used. The performance of the carbon was very good in that the specimens appeared just as conductive and carbon is too light to produce x-rays of sufficient energy to be detected. The lower detection limit for the S.E.M. was approximately 2%. Positive/negative Polaroid images were taken as well as maps of selected metals. For clarity most of the images are of relatively low magnification (200 to 3000 power) since at magnifications above 20,000 power resolution fell off drastically. Higher magnifications were used for analytical scans only. Conveniently, at 1000X one centimeter on the field of view is equal to 10 microns (μ) on the sample.

To perform qualitative analytical scans the S.E.M. would detect the x-rays resulting from the primary electron beam displacing electrons of the sample. X-rays were

counted from 0.5 to 20.0 KeV (kilo electron volts) and fed into a multichannel analyser which printed the counts per second data as peak height vs. KeV on 8 1/2 x 11 inch paper.

Under normal operating conditions the uranium bearing phases could not be distinguished from the other materials present (fig. 30a). To locate these heavier phases a technique using the backscattered electrons was utilized to produce images like fig. 30b.

WHOLE ROCK ANALYSES

Ten samples of varying uranium contents were selected and crushed to -400 mesh on the New Mexico Bureau of Mine's and Mineral Resources "hockey puck" mill. A sample contributed by Dr. J. R. Robertson that had been previously analysed several times was included as a control. This sample set was sent to Technical Services Laboratories in Toronto Canada for analysis by Plasma Emission Spectroscopy. Two channel samples were also analysed by Tom Smith of New Mexico Institute of Mining and Technology for U, V, and CO₂. The analyses are compiled in Table form in Appendix III.

FISSION TRACK TECHNIQUE USING LEXAN POLYCARBONATE PLASTIC

This technique involves gluing thin section size strips of Lexan plastic onto a petrographic thin section. These sandwiches were then bombarded by thermal neutrons in Sandia Lab's reactor for one hour causing a significant portion of the U²³⁵ in the sample to fission and create fission tracks in the adjacent sheet of Lexan. The fission tracks were

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then etched by preferentially removing the damaged polycarbonate plastic by immersion in 6M NaOH at 70 deg. C for four to five minutes. Side by side comparison of the two slides produces a reversed image of the sites U235 occupied in the sample.

APPENDIX III

WHOLE ROCK ANALYSES FROM TECHNICAL SERVICES LABORATORIES
OF TORONTO, CANADA, AND ASSAYS FROM TOM SMITH OF NEW
MEXICO INSTITUTE OF MINING AND TECHNOLOGY.

SAMPLE	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	LOI	Total (%)
CHGP	64.34	4.01	4.22	0.26	1.79	0.11	0.30	0.08	0.01	0.31	0.53	75.94
X-1	65.93	3.91	4.13	0.24	1.77	0.12	0.28	0.08	0.01	0.18	2.02	78.67
E-1	66.57	5.57	3.54	0.29	2.87	0.10	0.39	0.14	0.01	0.22	3.06	82.76
2,3-7	84.27	3.21	1.39	1.36	1.35	0.12	0.42	0.99	0.03	0.17	2.60	95.92
4,2-16	85.19	2.96	1.06	0.75	1.74	0.05	0.55	0.17	0.02	0.04	2.40	94.93
W-1B	91.00	2.73	0.53	0.75	0.36	0.05	0.78	0.11	0.01	0.06	1.59	97.97
W-1G	85.42	2.52	0.40	0.16	0.55	0.06	0.97	0.12	0.00	0.00	1.58	94.78
2,1 AZ	78.97	2.77	1.67	5.15	2.35	0.06	0.51	0.32	0.06	0.01	7.49	99.38
BLU	31.81	3.47	4.81	0.97	1.00	0.25	0.58	0.13	0.01	0.25	3.57	46.86

Whole rock analysis from Technical Services Laboratory.

SAMPLE	Uranium Oxide (U ₃ O ₈) %	Vanadium (V) %	Ferrous Iron (Fe) %	Sulphur (S) %	Chloride (Cl) %	Fluoride (F) ppm
CHGP	1.75	12.63	---	---	---	---
X-1	1.10	11.38	---	---	---	---
E-1	1.10	8.83	---	---	---	---
4,2-16	0.46	0.84	1.72	0.08	0.09	325
2,3-7	0.41	1.89	3.00	0.22	0.04	350
ore						
W-1B	0.04	0.13	0.46	0.08	0.09	305
W-1G	0.021	0.91	1.21	0.05	0.10	310
2,1 AZ	0.009	0.06	1.11	0.06	0.03	375
non-ore						

Uranium and vanadium assays from Technical Services Laboratory.

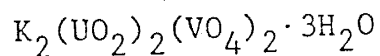
Tom Smith's assays of two channel samples.

SAMPLE NUMBER	Uranium Oxide		Vanadium (ppm)	Carbonate (%CO ₂)
	Fluorometric (%U ₃ O ₈)	Radiometric (eU ₃ O ₈)		
463	0.051	0.059	1100	0.1
464	0.180	0.150	2200	0.1
465	0.130	0.115	1500	0.1
466	0.750	0.770	18,000	0.1
467	6.10	6.90	35,000	0.1
468	0.053	0.054	500	0.1
469	0.065	0.060	500	1.1
470	0.470	0.390	20,000	0.9
471	1.70	1.81	81,000	1.1
472	0.21	0.24	1,600	2.6

APPENDIX IV

COMPOSITION AND CRYSTAL STRUCTURES OF CARNOTITE, CHLORITE
AND ROSCOELITE.

The structural formula for carnotite is

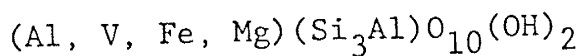


The water of carnotite is partly zeolitic and varies with the humidity. At ordinary temperatures the fully hydrated species has three waters of hydration. Small amounts of Ca, Ba, Mg, Fe, and Na have been reported as substituting into the carnotite lattice. The crystal structure consists of a layered pattern resulting from the strong bonds between UO_2 groups and the V_2O_8 polyhedra. The layers are held together by hydroxyl-hydrogen bonds of the water molecules and also by K, Ca, and Ba occupying the interlayer sites.

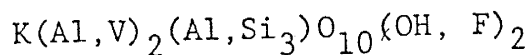
Chlorite is a complex monoclinic clay composed of alternating talc and brucite layers. The layers are stacked in the c direction with basal cleavage between successive layers. The talc layer is electrically imbalanced by substitution of +3 cations for Si^{+4} . The charge in the clay is balanced by either the brucite sheet substituting Al^{+3} for Mg^{+2} or the assimilation of higher valence cations. In the case of the Callihan this was accomplished by taking in

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V+5 at the expense of Al+3 and indirectly Si+4. The structural formula for chlorite is



Roscoelite is a relative simple monoclinic clay with much the same major element chemistry of chlorite but composed of only one layer. The structural formula for roscoelite is:



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