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**BULK MINERALOGY, MICROMINERALOGY, AND AUTHIGENIC  
MINERALS IN THE MEADE PEAK PHOSPHATIC SHALE MEMBER OF THE  
PHOSPHORIA FORMATION, SOUTHEASTERN IDAHO**

By

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## ABSTRACT

Authigenic minerals including quartz, buddingtonite-K-feldspar solid solution, and albite are significant constituents of mudstones in the middle waste unit that lies between the two phosphate ore zones of the Meade Peak Phosphatic Shale Member of the Phosphoria Formation in southeastern Idaho. Quantitative X-ray diffraction analysis of channel samples shows that the authigenic feldspars in the middle waste mudstones together may amount to as much as 35 weight percent of the mineral fraction. Orthoclase in the mudstones is of detrital origin and commonly has buddingtonite-K-feldspar solid solution overgrowths, whereas sparse detrital orthoclase in the dolomites has no overgrowths. Albite is mostly authigenic, but traces of detrital albite may be present. Some quartz is authigenic and may have delicate subhedral to euhedral crystals, but some authigenic quartz overgrown on detrital quartz is anhedral. Muscovite appears to be detrital. Although some samples contain sparse kaolinite, we think that most of the original detrital clay minerals were dissolved during diagenesis. If detrital Ca-bearing plagioclases were originally present, they likely were dissolved in these organic-rich muds. Essentially all of the calcium in the diagenetic pore water was precipitated as carbonate fluorapatite, calcite, or dolomite, although calcite is very sparse or absent in the mudstones. Apatite in the mudstones appears to have crystallized later than calcite because some calcite grains display thin rims of apatite. Remains of microfossils were replaced by calcite. Pyrite occurs between detrital K-feldspar and buddingtonite-K-feldspar solid solution overgrowths. The timing of authigenic feldspar and quartz growth is uncertain. Dolomite beds have calcite dispersed as tiny grains throughout dolomite crystals, indicating that calcite was the primary carbonate mineral before dolomitization.

## INTRODUCTION

### BACKGROUND

The U.S. Geological Survey (USGS) has studied the Permian Phosphoria Formation in southeastern Idaho and the Western U.S. Phosphate Field throughout much of the twentieth century. In response to a request by the U.S. Bureau of Land Management (BLM), a new series of resource and geoenvironmental studies was initiated by the USGS in 1998. Present studies consist of (1) integrated, multidisciplinary research directed toward resource and reserve estimates of phosphate in selected 7.5-minute quadrangles; (2) element residence, mineralogical and petrochemical characteristics; (3) mobilization and reaction pathways, transport, and disposition of potentially toxic elements associated with the occurrence, development, and use of phosphate; (4) geophysical signatures; and (5) improving understanding of the depositional environment. To carry out these studies, the USGS formed collaborative research with BLM and U.S. Forest Service (USFS), which are responsible for land management and resource conservation on public lands; and with five private companies currently leasing or developing phosphate resources in southeastern Idaho: Agrium U.S. inc. (Rasmussen Ridge mine), Astaris LLC (Dry valley mine), Rhodia Inc. (Wooley Valley mine-inactive), J.R. Simplot Company (Smoky Canyon mine), and Monsanto, Inc. (Enoch Valley mine). Because raw data acquired during the project will require time to interpret, the data are released in open-file reports

for prompt availability to other workers. The open-file reports associated with this series of resource and geoenvironmental studies are submitted to each of the Federal and industry collaborators for comment; however, the USGS is solely responsible for the contents of the reports.

## **GEOLOGIC SETTING**

The Meade Peak Phosphatic Shale Member of the Phosphoria Formation in southeastern Idaho consists of four main types of beds: 1) major phosphorite, 2) minor carbonate, 3) major siltstone/mudstone, and 4) minor carbon-rich beds. Organic carbon is present in both phosphorite and siltstone/mudstone but sparse in the carbonate-rich beds. Phosphorite beds are composed predominantly of carbonate-fluorapatite, as are phosphate nodules that occur in many of the mudstones. Carbonate-rich beds are dominantly dolomite. Mudstone consists chiefly of: 1) major amounts of detrital quartz, 2) major or minor amounts of authigenic albite and buddingtonite-K-feldspar solid solution (BD-KFss), 3) major or minor amounts of carbonate-fluorapatite, 4) minor dolomite, muscovite, illite, and pyrite, 5) trace or minor amounts of kaolinite, and 6) traces of detrital zircon, rutile, and monazite. The grain size of silicates and quartz in the mudstones is generally less than 0.050 mm. Organic-rich “carbon seams” have X-ray diffraction (XRD) maxima of poorly crystalline graphite that resulted from burial metamorphism.

The potential influence of thermal alteration due to hydrothermal fluids moving along high-angle basin-range faults during the Tertiary and the possible influence of late Pliocene or Pleistocene basalt intrusions on the Meade Peak strata are not known. However, it seems that Tertiary thermal alteration of these strata in southeastern Idaho was regionally minor.

The paucity of faunal remains and minimal faunal diversity of the Meade Peak in southeastern Idaho has been attributed to high salinity conditions on the seafloor (e.g. Hiatt, 1997) by some workers. The chemical and mineralogical characteristics of the mudstones are consistent with slight alkalinity during diagenesis that resulted in the authigenic growth of silicates and quartz.

## **MINERALOGY OF LESS-WEATHERED STRATA**

Mineralogy of channel samples (continuous composite samples) from 28 lithologic units in measured section WPSB (western US phosphate stratigraphic section B) (Tysdal and others, 1999) of the Meade Peak was determined using quantitative X-ray diffraction (XRD) methods (Knudsen and others, 2000). This measured and channel-sampled section at the Monsanto Company’s Enoch Valley mine (fig. 1), is less oxidized than section WPSA that was about 100 feet nearer the land surface (Tysdal and others, 1999; Herring and others, 1999). The quantitative XRD data of Knudsen and others (2000) shows the amounts of apatite, quartz, muscovite, illite, albite, orthoclase, buddingtonite, kaolinite, dolomite, and calcite in weight percent (Table 1). Use of the term percent here refers to weight percent unless otherwise indicated. These mineral assemblages were used to aid in interpretation of the chemical and physical conditions that may have led to their crystallization. The middle waste interval of section WPSB is 74.5 feet (22.7 m) thick and contains a 9-foot (2.74 m) thick dolomitic phosphate bed at the base, in turn,

overlain by an impure dolomite bed 1.5 feet (0.45 m) thick. The rest of the middle waste is mudstone, except for two 1-foot thick (0.3 m) phosphorite beds near the middle of the waste interval (Tysdal and others, 1999; Herring and others, 1999).

As used in the measured sections, the term mudstone is a field name for rocks that contain differing amounts of clay-size and silt-size particles. Much of the rock so named is fine- to coarse-grained siltstone. The term mudstone used here refers to those beds with less than 50 percent apatite, and less than 50 percent dolomite, and with quartz, muscovite, and feldspars composing more than 50 percent of the rock. The aggregate thickness of the mudstones in the middle waste of section WPSB is about 62 feet (18.9 m) so that they represent about 44 percent of the Meade Peak measured and sampled in the section. In Table 1 the middle waste extends from 059C through 117C (59 to 177 ft, or 18 to 54 m, above the base of the Meade Peak of the measured section). All eight mudstone beds contain apatite, feldspars (albite, orthoclase, and buddingtonite), angular quartz, muscovite, detrital zircon (Herring and others 1999, table 2), and organic matter. They may or may not contain small amounts of dolomite or calcite. Mineral grain sizes of quartz and feldspars are in the range of <0.010 to 0.100 mm; according to Carroll and others (1998), the grain size of the Meade Peak mostly averages between 0.030 to 0.050 mm. Ovoid-shaped phosphate nodules up to several cm in length occur in some mudstone beds; the distortion of adjacent beds above and below, due to differential compaction, indicates the nodules grew and were lithified during early diagenesis.

The eight mudstones in the middle waste (table 1) average 29 percent total feldspar, 17 percent of which is buddingtonite (Fig. 2). The bed-thickness adjusted weighted average ratio of detrital quartz plus muscovite:authigenic feldspars is 7:4; thus, of the quartz plus total silicate fraction, the feldspars constitute 36 percent.

The four dolostones (> 50 % dolomite) in Table 1 average 8 percent total feldspar and 3 percent buddingtonite.

The nine phosphorite beds (table 1) of the upper and lower ore zones average 15.5 percent quartz plus muscovite; however, the total feldspar is only 3.3 percent and the average amount of buddingtonite is two percent.

These differences in the proportions of feldspars in the middle waste mudstone, compared to the phosphate ore and dolostone (Fig. 3) reflect significant differences in both the environment of deposition and diagenesis of these three types of beds.

Piper (1999) reported analytical data for core samples from the Enoch Valley mine and calculated that two mudstones in the middle waste had 26 percent "biogenic", or non-detrital silica (based on his formula that biogenic silica =  $\text{SiO}_2 - 3.5 \times \text{Al}_2\text{O}_3$ ).

Table 1. Weight percent of minerals in 28 lithologic units of the Meade Peak Phosphatic Shale Member of the Phosphoria Formation in measured section WPSB at the Enoch Valley mine. Data from Knudsen and others (2000). [musc = muscovite, orthocl = orthoclase, budding = buddingtonite, feld =feldspar, kaol = kaolinite, dolo = dolomite]

Sample	Interval top, feet	apatite	quartz	musc	illite	albite	orthocl	budding	total kaol	dolo	calcite	
		<u>weight percent</u>										
<b>WPSB</b>												
003C	5	0.8	51	7.4	1.8	0	2.8	0.3	3.1	1.6	33.5	0.3
<b>LOWER ORE</b>												
008C	10	88	7.3	2	0.1	0.1	0.1	0.8	1	0	0.4	0
018C	24.5	91	5	2.1	0.2	0.1	0.6	0.1	0.8	0	0	0
025C	25.5	11.6	9.4	3.2	0.1	0.1	4.4	2.6	7.1	2	66.7	0
026C	27	72	17.3	3	0.1	0.1	1.5	0.1	1.7	0.6	3.7	0
027C	28	9.9	5.4	4	0.1	0	3.1	0.5	3.6	1.2	75	0.1
033C	37.5	82	9.8	3	0.1	0.2	2	1.4	3.6	0.3	1.1	0
038C	40	4.4	10.1	0.1	0.1	3.4	1.9	1	6.3	0	79	0
047C	55	56	22.3	4	0.1	2.3	1.6	4	7.9	0.5	8.4	0
059C	64	50	10.9	5	0.1	0.6	0.1	9.2	9.9	0.6	21.7	1.6
<b>MIDDLE WASTE</b>												
65C	65.5	1.2	6.7	0.7	0.1	4.9	1.3	7.8	14	0.2	71.1	6
070C	75	37	21.6	9	0	0.4	0.1	27	27.5	0.9	1.4	1.7
080C	82.5	14.9	34.3	7.6	0.1	15.7	5.5	20.4	41.6	1.2	0.1	0
084C	85	34	20.3	13	0.1	6.2	0.3	21.2	27.7	0.5	3.3	1.3
087C	90.5	43	23.6	14	0	3	1.7	12.9	17.6	0	2	0
091C	91.5	58	17.1	11	0.1	1.3	1	11	13.3	0	0	0
095C	97	10.9	40.3	9.7	0.1	10.3	4.3	17	31.6	0.4	8.7	1.3
097C	98	74	15.3	5	0.1	1.3	0.3	3.1	4.7	0	0	0
100C	105	22.1	53	1.6	0.1	5.5	6.2	10.1	21.8	1.3	0	0
107C	108	5.9	41.3	5	0.1	16.7	7.2	22	45.9	1.7	0.1	0
117C	129.5	21.7	33.7	11	0.1	8.4	1.6	10.9	20.9	0.4	6.6	0.2
<b>UPPER ORE</b>												
131C	132	80	8.3	9	2	0.1	0.1	0.1	0.3	0	0	0
133C	134	83	8.8	6	0.1	0.1	0.1	1.7	1.9	0.4	0.1	0
134C	135	20.2	49.1	9.3	1.9	10.1	4.9	2.6	17.6	1.7	0	0.1
136C	137	88	7.8	3	0.1	0.2	0.1	0.1	0.4	0	0	0
137C	137.5	2	44	5.9	2	44	2	2	48	0	0	0
139C	140	93	3.8	2.4	0.1	0.1	0.1	0.1	0.3	0	0	0
<b>UPPER WASTE</b>												
145C	151	4.8	61	10.4	1.9	8.4	9.6	2.7	20.7	0.6	0	0
157C	159	10.2	49	17	5.4	4.7	1.4	2.5	8.6	0.3	2	0.4

#### AUTHIGENIC FELDSPARS IN THE MIDDLE WASTE

Gulbrandsen (1974) recognized that buddingtonite was an authigenic mineral developed chiefly in the “middle mudstone” and that the composition in the solid solution buddingtonite-K-feldspar series shows a “range of  $Bd_{82}KF_{18}$  to  $Bd_{13}KF_{87}$ , and

compositions of  $Bd_{72}KF_{28}$  to  $Bd_{50}KF_{50}$  may be the most common.” He also stated that the predominant silicate mineral suite consisted of buddingtonite-albite-illite, and that the buddingtonite-K-feldspar solid solution (Bd-KFss) mineral formed from the dissolution of volcanic glass in the presence of  $NH_4^+$ -rich fluids derived from decomposition of abundant organic matter. Gulbrandsen (1974) did not recognize the presence of minor orthoclase (table 1). Many prior studies of authigenic feldspars in sedimentary rocks show that orthoclase and albite may form in saline lakes due to alteration of volcanic glass. Gulbrandsen (1974) also recognized that low temperature varieties of these two feldspars occur in oil shales (Smith and Milton, 1966; Iijima and Hay, 1968; Surdam and Parker, 1972; Brobst and Tucker, 1973) of the Eocene Green River Formation (of Colorado, Utah, and Wyoming) that contains no associated tuffaceous rocks. The authigenic feldspars in Green River Formation oil shales are typically very small ( $< 0.005$ - $0.010$  mm) and are relatively high purity end members; the albites are of intermediate structural state, and the orthoclases are disordered (Desborough, 1975). A significant argument against the volcanic ash association for the Mead Peak Phosphatic Shale Member of the Phosphoria is the lack of euhedral zircon; rounded zircon and monazite are sparse but common constituents in the mudstones.

Buddingtonite has been found by Loughnan and Roberts (1983) in the Condor oil shale of Tertiary age in Queensland, Australia, where it constitutes up to 16 percent and averages nearly 10 percent of the strata and is associated with abundant montmorillonite, siderite, and quartz. It is of relatively high purity and occurs throughout an interval 600 m thick in which faunal remains are absent; these strata are essentially devoid of other feldspars. This occurrence confirms that buddingtonite can form at low temperatures; the environment of deposition is inferred to be a shallow, saline, euxinic lake or marine bay.

More recently, Ramseyer and others (1993) reported an authigenic K- $NH_4$  feldspar in arkosic sandstones where it forms microfracture fillings and overgrowths on detrital feldspar grains. The composition varies between the buddingtonite and K-feldspar end members. These authors note a low temperature of precipitation from pore waters with the same Sr signature as sea water at the time of deposition, under anoxic conditions in the zone of methanogenesis.

## SCANNING ELECTRON MICROSCOPE STUDIES OF MUDSTONES

The siltstones (field term: mudstones) are so fine grained that XRD diffractometer scans of polished thin sections are adequate to determine the major and minor minerals. However, in rocks for which apatite constitutes several percent of the constituent grains, interferences of x-ray diffraction reflections prohibit pyrite identification. In spite of this, we find that pyrite is present in all polished sections of unoxidized organic-bearing siltstones. Hence, we undertook a preliminary study of such rocks that combined scanning electron microscopy (SEM), energy dispersive X-ray fluorescence (EDXRF) microanalysis, and SEM cathode luminescence (CL) of the textural and chemical relations in the mudstones. Only a few samples were studied due to the time-consuming nature of the microanalysis and electron imaging techniques.

An SEM with EDXRF was used for *in situ* chemical analysis of mineral grains using back-scattered electron (BSE) sample images. In addition, a cathode luminescence (CL) detector was used to examine mineral-luminescence emissions. Simultaneous BSE and

EDXRF could not be used with the CL detector in the imaging (photo) mode; the CL images were done separately for the analyzed areas. Each phase identified was done on the basis of BSE, CL, and EDXRF analysis.

Enoch Valley mine sample WPSB062T This unoxidized siltstone sample is from the channel-sampled interval represented by WPSB065C (Table 1). XRD analysis of the polished thin section studied by SEM methods has more than 10 percent each of quartz, apatite, calcite, dolomite, BD-KFss, and montmorillonite. Combined BSE and CL images obtained by SEM studies of a single area about 150 X 190 micrometers ( $\mu\text{m}$ ) are shown on Figure 4A and 4B, respectively. A bright gray aggregate of porous apatite (ap) on Figure 4 appears left of center, and a large detrital K-feldspar (dKf) near and right of center is overgrown by BD-KFss (b).

We interpret the relations of CL emission images as follows. Several trace or minor elements cause cathode luminescence in minerals due to elemental substitutions or extremely small (sub- $\mu\text{m}$ ) crystalline inclusions (Marshall, 1988). For instance, the CL emissions of apatite are probably due to rare earth elements, which are significant trace elements in these carbonate fluorapatites. Minerals such as quartz and feldspar formed by high temperature crystallization in igneous or metamorphic environments incorporate foreign (non-crystal-structure essential) elements such as Ba or Sr, or tiny mineral crystallite inclusions such as  $\text{TiO}_2$  that may cause luminescence emissions generated by the electron beam. In contrast, authigenic silicate minerals and quartz crystallized in the pore water of marine or lacustrine sediments at temperatures less than about  $25^\circ\text{C}$  tend to be of higher purity than those formed in igneous, metamorphic, or hydrothermal environments (Marshall, 1988). Hence, the authigenic silicates and quartz formed in marine and lacustrine environments of near-neutral pH generally show little or no luminescence (Seyedolali and others, 1997). CL of carbonates such as calcite and dolomite may be caused by substitutions by such elements as Sr, Ba, and others. Some minerals that contain CL-emitting elements may also have CL emission absorbers that might suppress or eliminate CL emissions.

On the basis of these certainly limited CL relations of silicates formed at “high-temperature” versus those formed at “low-temperature”, we offer the following working hypothesis for the Meade Peak silicates and quartz:

- 1.) The most intense CL-emitting grains are of detrital igneous (or metamorphic) origin.
- 2.) The least intense CL-emitting grains are of authigenic origin.
- 3.) Some quartz grains that show minimal or no luminescence may be of detrital origin.

The most persuasive evidence for these conclusions is the fact that the strongest K-feldspar and quartz CL emitters considered to be of detrital origin display overgrowths of: 1. Non- or minimal CL-emitting BD-KFss, 2. Non- or minimal CL-emitting quartz, and 3. Rarely albite grains emit measurable CL, but most do not. Other evidence of authigenic growth of both quartz and albite is their occurrence as tiny crystals in the samples, as shown by BSE photographs. In another aspect, EDXRF analysis shows that the detrital feldspars contain greater amounts of Ca and Na in the K-feldspars, and greater amounts of K and Ca in albite. The CL-emitting detrital K-feldspars commonly contain 0.5 weight percent of CaO and/or  $\text{Na}_2\text{O}$  and the sparse CL-emitting detrital albites contain as much as 0.5 weight percent of CaO and  $\text{K}_2\text{O}$ , respectively.

Dry valley mine sample 220-2. This unoxidized siltstone sample from the Dry Valley mine (fig. 1) was previously studied by Desborough and others (1999) in regard to bulk mineralogy, chemistry, selenium in pyrite, and selenium solubility in passive laboratory tests. Apatite, orthoclase, albite, quartz, muscovite, dolomite, and pyrite were identified by XRD. XRD of the polished section studied here showed quartz, albite, buddingtonite, pyrite, and only trace amounts of muscovite. Based on bulk chemical analysis of this sample including total C, and allocating all K to orthoclase, all Na to albite, all P to apatite, and all Fe to pyrite yields (in weight percent): quartz-34, orthoclase-20, albite-18, pyrite-6, organic carbon-6, apatite-4, and loss on ignition-12. Buddingtonite could not be computed because, even if nitrogen was analyzed for the sample, an unknown amount of nitrogen is present in the organic material. Thus, the computed amount of orthoclase is the minimum amount of BD-KFss present.

Figure 5 is a BSE photo showing mineral grains that were analyzed by EDXRF using the SEM. The photo represents an area of 130 X 130  $\mu\text{m}$  and was viewed in CL mode, which showed the detrital K-feldspar (dKf) to be highly luminescent and the detrital quartz (dq) to be moderately luminescent. The albite (a) aggregate near right center of the photo has delicate crystallites on grain margins, clear evidence of an authigenic origin. A thin (1-4  $\mu\text{m}$ ) overgrowth of BD-KFss (b) on the right side of the large detrital feldspar (dKf) grain is conspicuous in Figure 5. Discrete BD-KFss grains are up to about 15  $\mu\text{m}$  in their largest dimension. None of the BD-KFss (b), albite (a), or authigenic quartz (aq) in this photo show detectable CL emissions. Grain margins of quartz and albite are straight crystal faces in the size range of about 2-6  $\mu\text{m}$ .

Figure 6 shows a BSE image in A and a CL image in B of an area 80 X 80  $\mu\text{m}$  on sample 220-2. The longest dimension of the detrital K-feldspar (dKf) is 25  $\mu\text{m}$ , and it is completely overgrown by BD-KFss. Pyrite occurs between the detrital K-feldspar and BD-Kfss overgrowth, indicating pyrite formation before BD-Kfss growth. The detrital quartz (dq) margin is conspicuous in the CL image and it is overgrown by authigenic quartz (aq).

Figure 7 shows a BSE image (A) and a CL image (B) of an area 60 X 60  $\mu\text{m}$  on sample 220-2. Detrital K-feldspar (dKf) is surrounded by BD-KFss (b). Detrital quartz (dq), with a maximum dimension of 40  $\mu\text{m}$ , has an attached growth of authigenic quartz (aq) on the left side. Highly luminescent detrital albite (da) is present.

Figures 8a, 8b, and 8c show BSE images of what appear to be microfossils that were replaced by calcite (or recrystallized) or apatite in core sample WPSJ061.3T from the Enoch Valley mine. Figure 8d shows a BSE image of a microfossil, from the same core, that was replaced by calcite. The fossil was tentatively identified as a foraminifer of the genus *Scherochorella*, an arenaceous form suggestive of a depositional environment seaward of a shelf edge (Kristin McDougall, USGS, written commun., 11/20/00). This interpretation is consistent with a basinal depositional setting interpreted for the host strata at this locality.

Eight other polished thin sections from the Enoch Valley mine were studied but show mineralogical and textural characteristics like those shown in SEM photos of Figures 4-8.

A dolomite-rich sample (WPSB065T) from the middle waste unit at the Enoch Valley mine was examined by SEM-CL methods to determine the detrital minerals present. Sparse grains of highly luminescent K-feldspar and strongly luminescent quartz were

found but neither Bd-KFss nor albite are present. This is interpreted as evidence that Bd-KFss and albite are not detrital minerals.

In a study of detrital feldspars in the Oligocene Frio Formation of south Texas, Milliken (1992) found that near-end member albite is more stable (less soluble) in mudrocks than more Ca-rich plagioclases (e.g., oligoclase, etc.). Similarly, the more pure K-feldspars are less soluble in mudrocks than those with substituted Na and Ca (Milliken, 1992). Also, she found that authigenic albite forms during or after dissolution of plagioclases. These observations are consistent with our findings that the only detrital feldspars now present in the mudstones of the middle waste unit of the Meade Peak Phosphatic Shale Member are mostly end-member albites and K-feldspars.

## DISCUSSION

Recent studies of quartz in Devonian mudstones by Schieber and others (2000), using CL and oxygen isotope analysis, emphasized the recognition of *in situ* authigenic quartz, which is inferred to be derived from dissolution of opaline skeletons of planktonic organisms such as radiolarians and diatoms. They inferred that large amounts of quartz in mudstones is of *in situ* authigenic origin, rather than of chiefly detrital origin as previously assumed. In an earlier study, Schieber (1996) emphasized the occurrence of abundant silica-filled *Tasmanites* cysts in Devonian black shales of the midcontinent USA and referred to the silica as chalcedony, microquartz, and megaquartz. These Devonian strata have not been exposed to deep burial or elevated temperatures ( $>90^{\circ}\text{C}$ ) according to conodont alteration index of  $\text{CAI} = <1.5$  (Harris, 1979).

The Meade Peak Phosphatic Shale Member studied here was exposed to burial depths between 6 and 7 km, which caused oil generation prior to Cretaceous thrusting (Claypool and others, 1978). We do not know what the deep burial thermal alteration and the associated water plus oil migration through these strata may have had on the diagenetic mineralogy. Thermal alteration in the area based on CAI values varies widely for Permian strata in our study area ( $\text{CAI} = 2-4$ ) indicating temperatures in the range of  $90-200^{\circ}\text{C}$  (Harris and others, 1980). It is probable that the authigenic aluminosilicates remained stable under these conditions. However, silica polymorphs such as opal CT and other cryptocrystalline silica phases may have been converted to quartz during migration of aqueous fluids at burial temperatures of  $100^{\circ}\text{C}$  or higher. We therefore infer that under these burial thermal and chemical conditions, many of the fossil remains may have been exposed to chemical and mineralogical alterations, as shown in Figure 8.

The presence of authigenic albite and BD-KFss demonstrates that significant amounts of Na, K, Al, and Si were present in the pore water of the organic-rich mud that was a precursor of the mudstones and siltstones of the Meade Peak Phosphatic Shale Member. The presence of authigenic quartz confirms that silica polymorphs or dissolved, complexed silicon was relatively important during diagenesis or catagenesis (petroleum generation) as confirmed by the presence of euhedral quartz and quartz overgrowths on detrital quartz that is highly cathode luminescent (figs. 6 and 7).

## REFERENCES CITED

- Brobst, D.A., and Tucker, J.D., 1973, X-ray mineralogy of the Parachute Creek Member, Green River Formation, in the Northern Piceance Creek Basin, Colorado: U.S. Geological

- Survey Professional Paper 803, 53 p.
- Carroll, A.R., Stephens, N.P., Hendrix, M.S., and Glenn, C.R. 1998, Eolian-derived siltstone in the upper Permian Phosphoria Formation: implications for marine upwelling: *Geology*, v. 26, p. 1023-1026.
- Claypool, G.E., Love, A.H., and Maughan, E.K., 1978, Organic geochemistry, incipient metamorphism, and oil generation in black shale members of Phosphoria Formation, western interior United States: *American Association of Petroleum Geologists Bulletin*, v. 62, p. 98-120.
- Desborough, G.A., 1975, Authigenic albite and potassium feldspar in the Green River Formation, Colorado and Utah: *American Mineralogist*, v. 60, p.235-239.
- Desborough, G.A., DeWitt, E., Jones, J. Meier, A., and Meeker, G., 1999, Preliminary mineralogical and chemical studies related to the potential mobility of selenium and associated elements in Phosphoria Formation strata, southeastern Idaho: U.S. Geological Survey Open-File Report 99-129, 20 p.
- Gulbrandsen, R.A., 1974, Buddingtonite, ammonium feldspar, in the Phosphoria Formation, Southeastern Idaho: *U.S. Geological Survey Journal of Research*, v. 2, p. 693-697.
- Harris, A.G., 1979, Conodont color alteration, an organo-mineral metamorphic index, and its application to Appalachian basin geology: *in* Scholle, P.A., and Schloger, P.R., eds., *Aspects of Diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication 26*, p. 3-16.
- Harris, A.G., Wardlaw, B.R., Rust, C.C., and Merrill, G.K., 1980, Maps for assessing thermal maturity (conodont color alteration index maps) in Ordovician through Triassic rocks in Nevada and Utah and adjacent parts of Idaho and California: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1249.
- Herring, J.R., Desborough, G.A., Wilson, S.A., Tysdal, R.G., Grauch, R.I., and Gunter, M.E., 1999, Chemical Composition of weathered and unweathered strata of the Meade Peak Phosphatic Shale Member of the Permian Phosphoria Formation A. Measured Sections A and B, Central part of Rasmussen Ridge, Caribou County, Idaho: U.S. Geological Survey Open-File Report 99-147-A, 10 p.
- Hiatt, E.E., 1997, A paleoceanographic model for oceanic upwelling in a late Paleozoic epicontinental sea: A chemostratigraphic analysis of the Permian Phosphoria Formation [Ph.D. thesis]: Boulder, University of Colorado, 300 p.
- Iijima, A. and Hay, R.L., 1968, Analcime composition in tuffs of the Green River Formation of Wyoming: *American Mineralogist*, v. 53, p 184-200.
- Knudsen, A.C., Gunter, M.E., and Herring, J.R., 2000, Preliminary mineralogical characterization of weathered and less-weathered strata of the Meade Peak Phosphatic Shale member of the Permian Phosphoria Formation: Measured sections A and B, Central part of Rasmussen Ridge, Caribou County, Idaho: U.S. Geological Survey Open-File Report 00-116, 74 p.
- Loughnan, F.C., and Roberts, F.I., 1983, Buddingtonite (NH<sub>4</sub>-feldspar) in the Condor oilshale deposit, Queensland, Australia: *Mineralogical Magazine*, v. 47, p. 327-334.
- Marshall, D.J., 1988, *Cathodoluminescence of Geological Materials*, Uniwin Hyman, Boston, 137 p.
- Milliken, K.L., 1992, Chemical behavior of detrital feldspars in mudrocks versus sandstones, Frio Formation (Oligocene), south Texas: *Journal of Sedimentary Petrology*, v. 62, p. 790-801.
- Piper, D.Z., 1999, Trace elements and major-element oxides in the Phosphoria Formation at Enoch Valley, Idaho—Permian sources and current reactivities: U.S. Geological Survey Open-File Report 99-163, 66 p.
- Ramseyer, K., and Boles, J.R., 1993, Authigenic K-NH<sub>4</sub>-feldspar in sandstones: a fingerprint for organic-inorganic reactions under anoxic conditions: *in* *Abstracts with Programs*,

- Geological Society of America Annual meeting, Boston Massachusetts, October 25-28, 1993, p. 202.
- Schieber, J., 1996, Early diagenetic silica deposition in algal cysts and spores: a source of sand in Black shales?: *Journal of Sedimentary Research*, v. 66, p. 175-183.
- Schieber, J., Krinsley, D., and Riciputi, L., 2000, Diagenetic origin of quartz silt in mudstones And implications for silica cycling: *Nature*, v. 406, p. 981-985.
- Seyedolali, A., Krinsley, D.H., Boggs, S., O'Hara, P.F., Dypvik, H., and Goles, G.G., 1997, Provenance interpretation of quartz by scanning electron microscope-Cathodoluminescence fabric analysis: *Geology*, V. 25, p.787-790.
- Smith, J.W., and Milton C., 1966, Dawsonite in the Green River Formation of Colorado: *Economic Geology*, v. 61, p. 1029-1042.
- Surdam, R.C., and Parker, R.D., 1972, Authigenic aluminosilicate minerals in the tuffaceous rocks of the Green River Formation, Wyoming: *Geological Society of America Bulletin*, v. 83, p. 689-700.
- Tysdal, R.R., Johnson, E.A., Herring, J.R., and Desborough, G.A., 1999, Stratigraphic sections and equivalent uranium (eU), Meade Peak Phosphatic Shale Member of Permian Phosphoria Formation, central part of Rasmussen Ridge, Caribou County, Idaho: U.S., Geological Survey Open File Report 99-20, 1 plate.

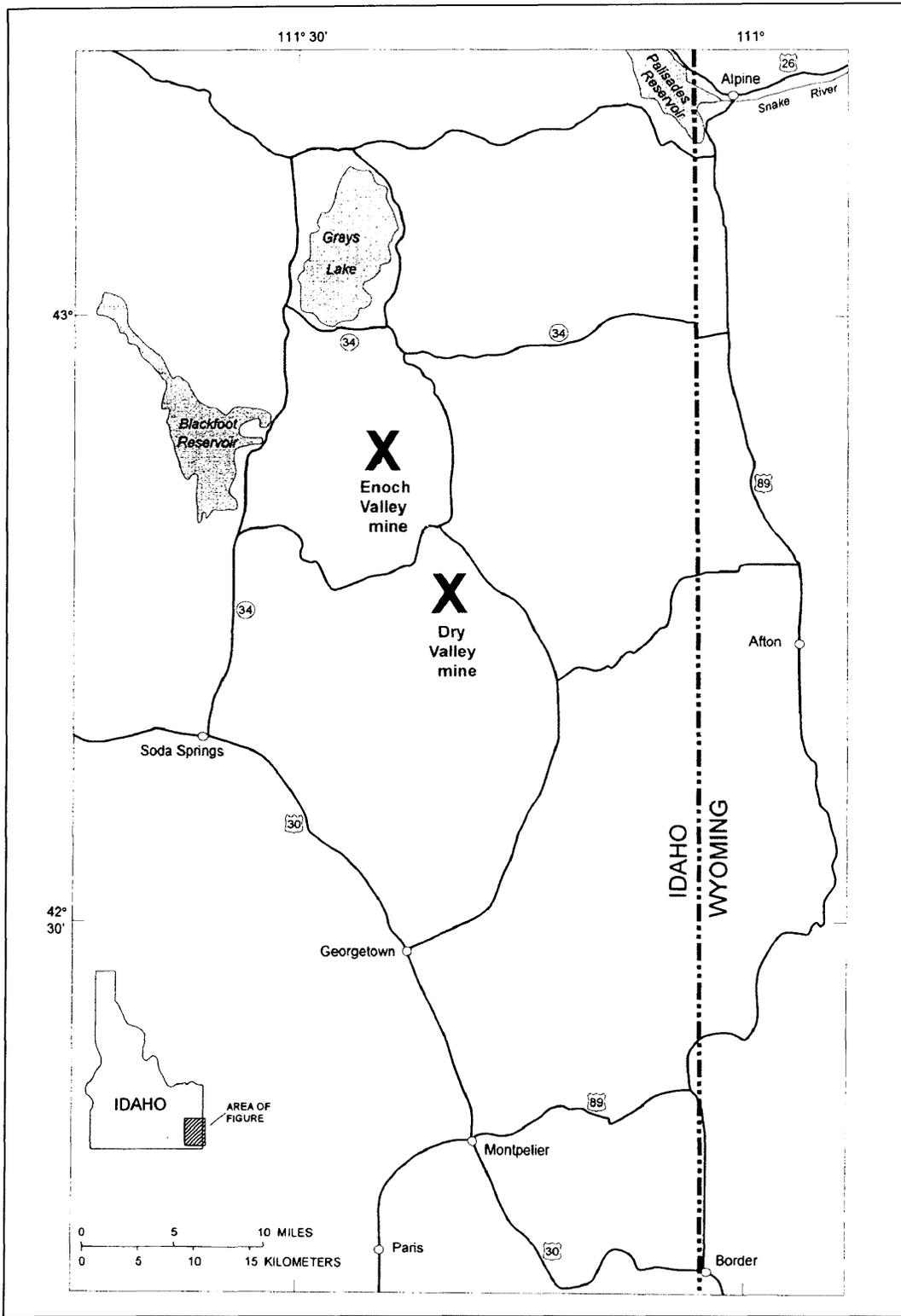


Figure 1. Locations of Enoch Valley mine and Dry Valley mine in Idaho.

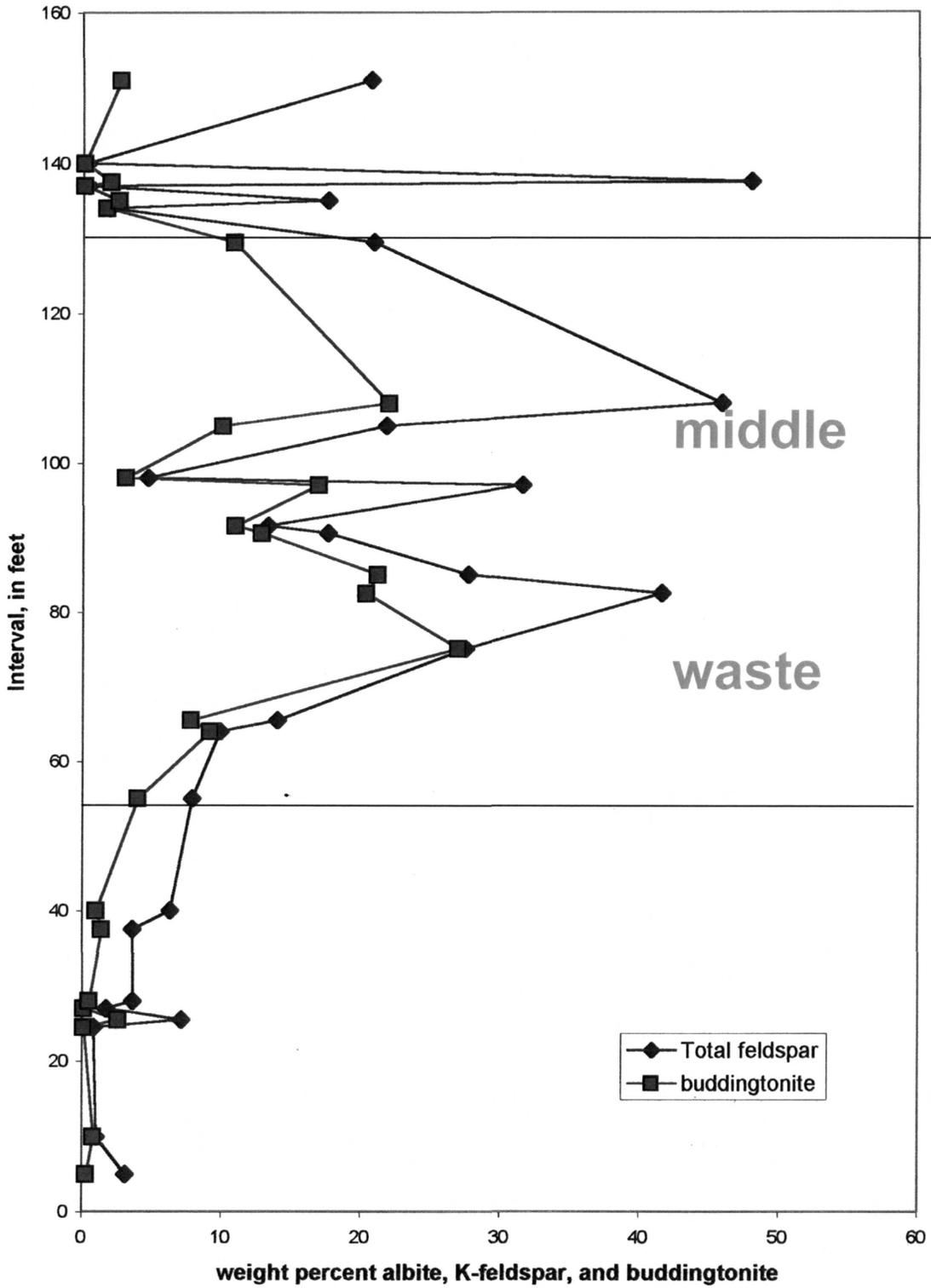


Figure 2. Total feldspars including buddingtonite in the Meade Peak Phosphatic Shale Member in section WPSB at the Enoch Valley phosphate mine.

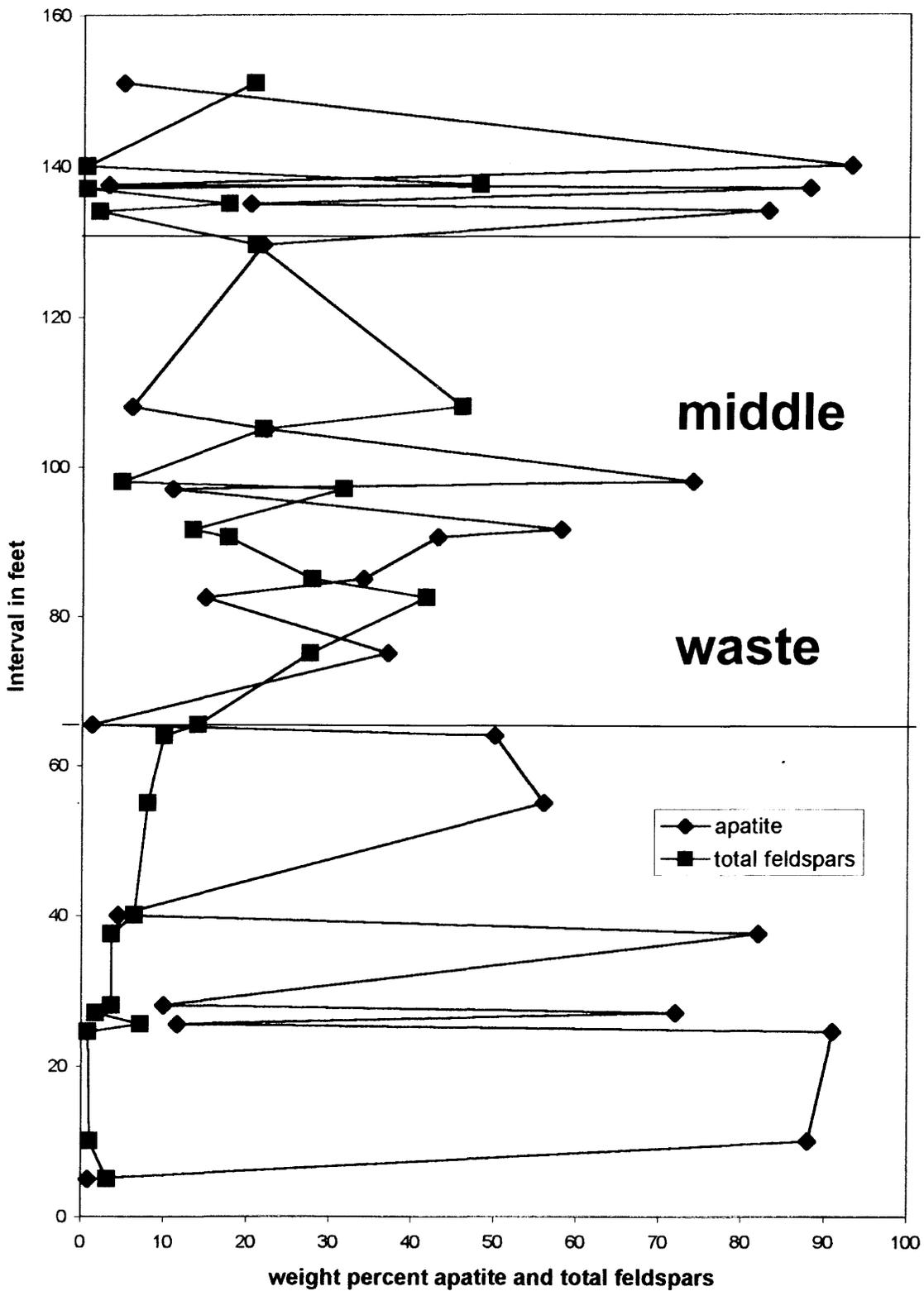


Figure 3. Abundances of apatite and total feldspars in the Meade Peak Phosphatic Shale Member in section WPSB at the Enoch Valley phosphate mine.

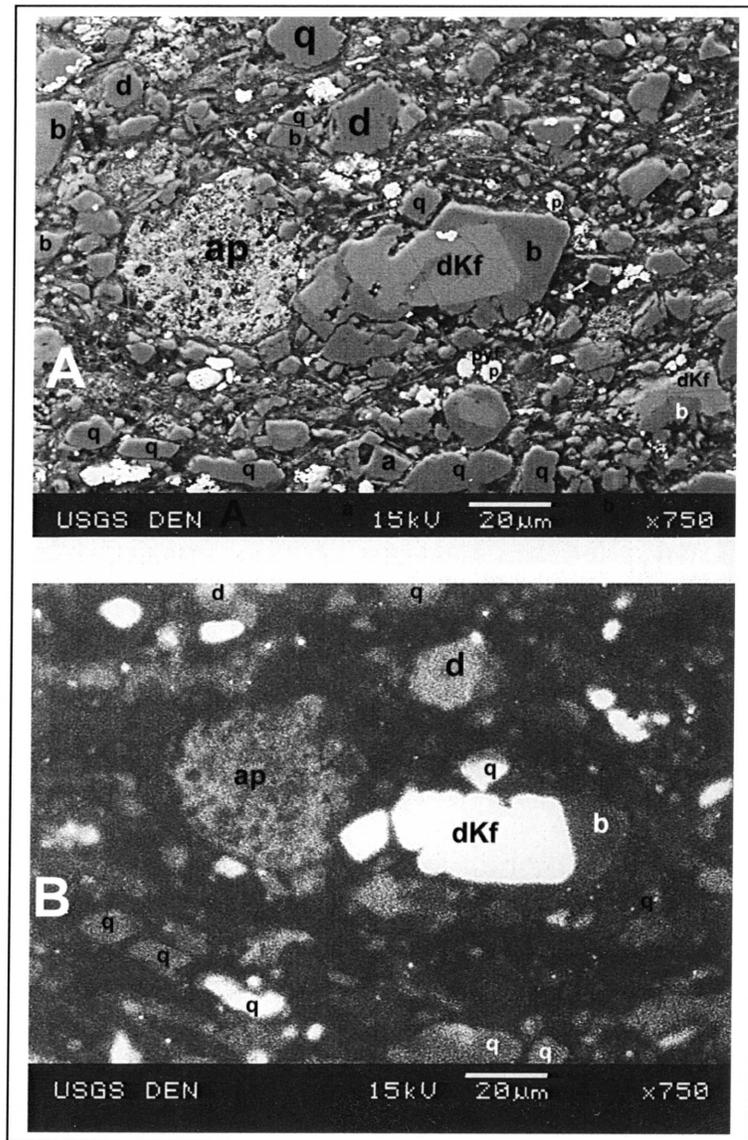


Figure 4. Back-scattered electron (BSE) photo A and cathode luminescence (CL) photo B of an area about 150 X 190 µm on polished thin section WPSB062T of a mudstone sample. Bright white grains in BSE photo A are mostly pyrite, but some may be detrital zircon or monazite. a = albite, ap = apatite, b = BD-KFss, d = dolomite, dKf = detrital feldspar, p = pyrite, and q = quartz.

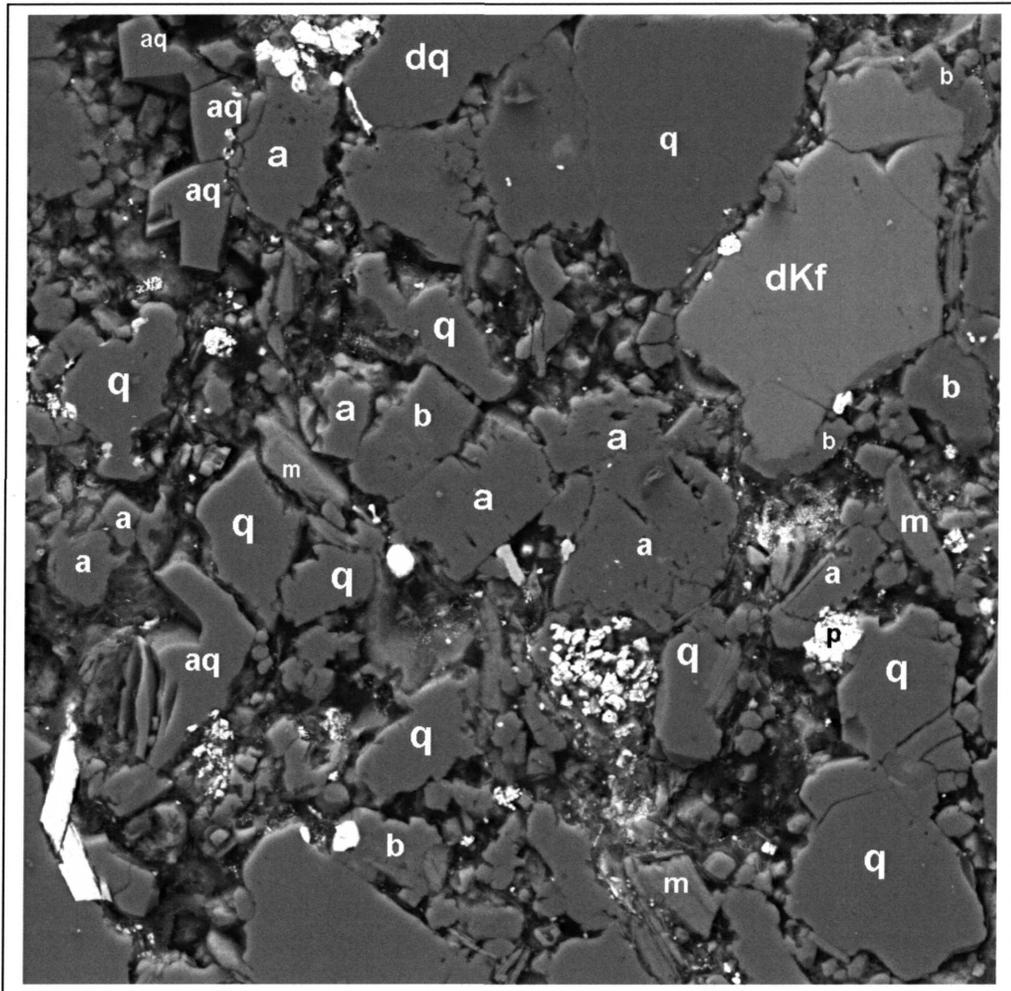


Figure 5. Back-scattered electron (BSE) image of a 130 X130  $\mu\text{m}$  area of analyzed mineral grains in mudstone sample 220-2 from the middle waste of the Dry Valley mine. Bright white grains are chiefly pyrite. The largest quartz grain (q) in the upper right quadrant of the photo has a maximum dimension of 40  $\mu\text{m}$ . a = albite, aq = authigenic quartz, b = BD-KFss, dKf = detrital K-feldspar, m = mica, p = pyrite, q = quartz.

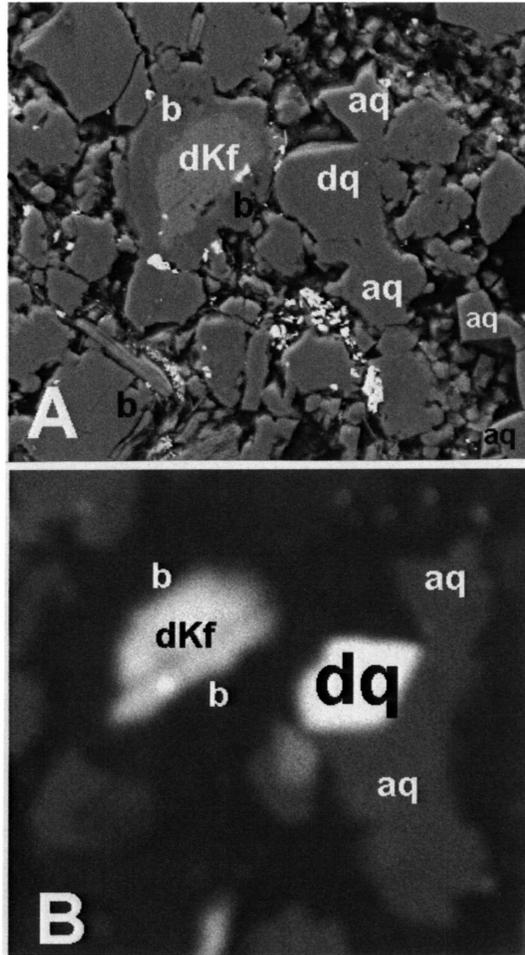


Figure 6. Back-scattered electron (BSE) image A and cathode luminescence image B for an 80 X 80  $\mu\text{m}$  area of mudstone sample 220-2. The longest dimension of the detrital K-feldspar is 25  $\mu\text{m}$ . Bright white is pyrite. aq = authigenic quartz, b = BD-KFss, dKf = detrital K feldspar, dq = detrital quartz.

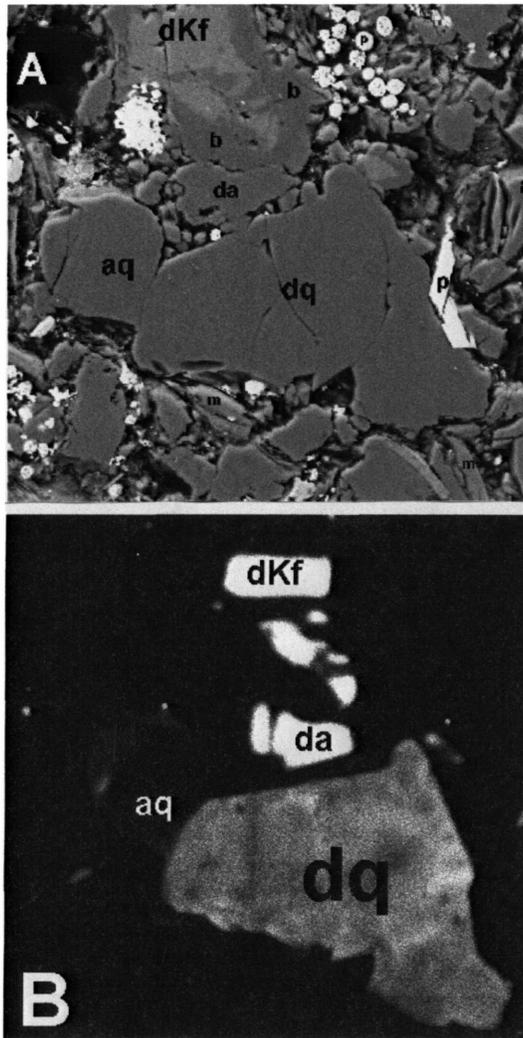


Figure 7. Back-scattered electron (BSE) image A, and a cathode luminescence (CL) image B, of an area of 60 X 60 μm on mudstone sample 220-2. The maximum dimension of the large detrital quartz (dq) grain is 40 μm. aq = authigenic quartz, b = BD-KFss, da = detrital albite, dq =, detrital quartz, m = mica, p = pyrite.

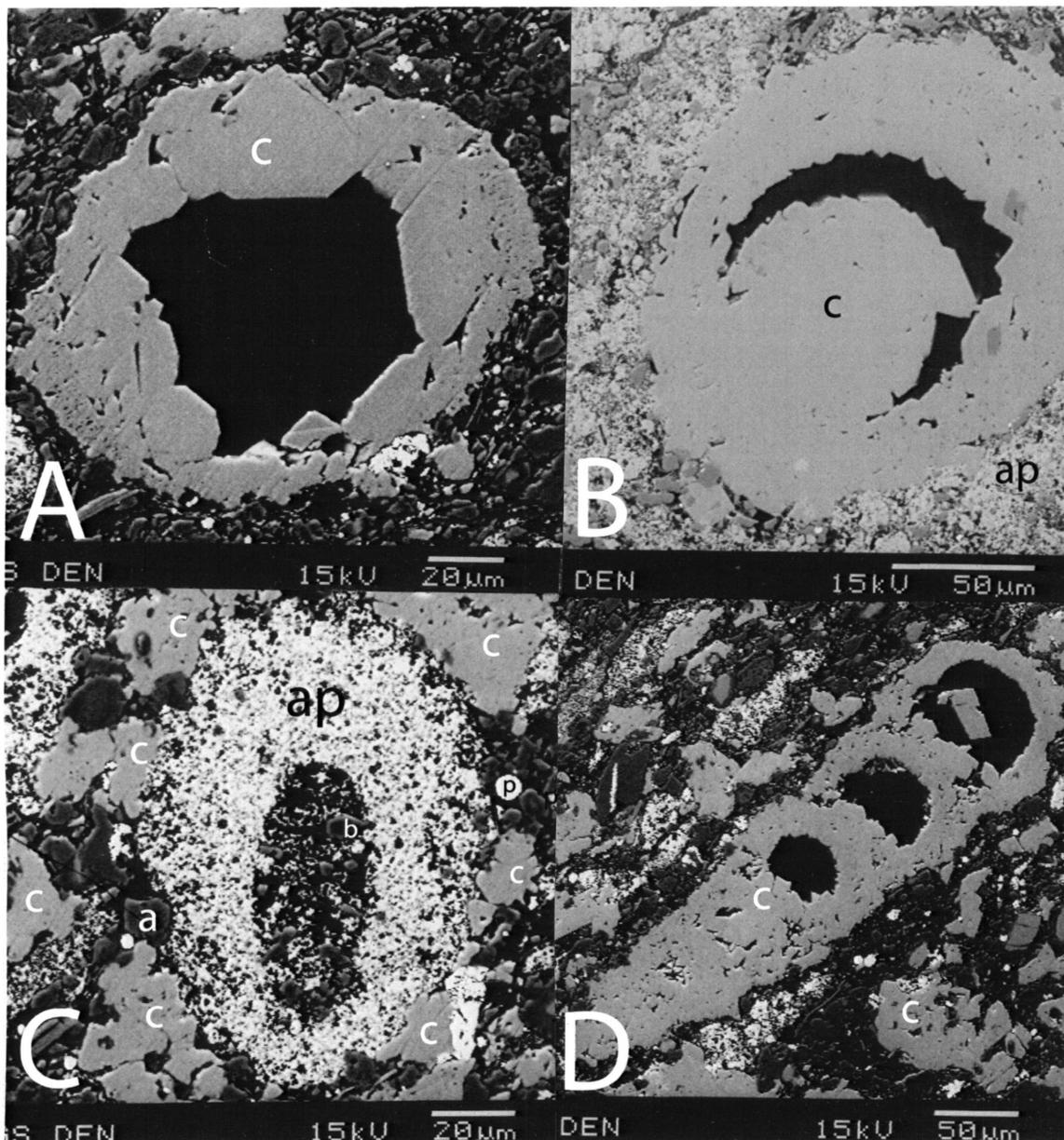


Figure 8. Scanning electron microscope back-scattered electron photos of polished thin section WPSJ061.3T drill core. A. Calcite (c) microfossil filled with organic material and some calcite surrounded by fine-grained silicates (<20  $\mu\text{m}$ ) in an organic-rich matrix. B. Calcite (c) microfossil filled with calcite and organic material and surrounded by a mixture of fine-grained (<20  $\mu\text{m}$ ) apatite (ap, bright gray), silicates (dark gray), and sparse calcite. C. Very fine-grained apatite (ap, white) and calcite (c). Cavity in apatite contains detrital quartz and BD-KF<sub>ss</sub> (b). a = authigenic albite, p = pyrite. D. Calcite (c) foraminifer with voids filled with organic material and some calcite. Surrounding grains are calcite (c), fine-grained silicates (black), organic material (black), and fine-grained apatite (white). Foraminifer tentatively identified by Kristin McDougall (USGS, written commun., 11/20/00) as the genus *Scherchorella*. See text.