

## BURIAL DIAGENESIS IN TWO MONTANA TERTIARY BASINS

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**Abstract**—Samples from initially smectite-rich Tertiary continental volcanoclastic sediment from the Deer Lodge and Big Hole basins of southwestern Montana show a general decrease in illite/smectite (I/S) expandability with increasing burial depth. The mineralogical trends in cuttings from seven wells are interrupted by discontinuities in which I/S expandability abruptly decreases by 30 to 80%. These discontinuities coincide with stratigraphic unconformities in four wells in which the stratigraphy is known. Core samples show a wide range of I/S expandabilities over short stratigraphic intervals, possibly due to composition, porosity, and permeability variations. Sericite coexists with I/S in the deep core samples. A core sample from 7958 ft (2425 m) contains an R3-ordered I/S having a nearly ideal 3:1 illite : smectite ratio, similar to the mineral tarasovite. The structure of this I/S is dominated by stacks of four 2:1-layer fundamental illite particles and small proportions of thicker particles randomly interstratified among the four-layer particles.

**Key Words**—Diagenesis, Illite, Illite/smectite, Smectite, Tarasovite, Volcanoclastic.

### INTRODUCTION

Low-grade metamorphic (diagenetic) clay mineral reactions are well documented in deeply buried, clay-rich, marine sedimentary basins (e.g., Burst, 1959; Dunoyer de Segonzac, 1970; Hower *et al.*, 1976; Pearson *et al.*, 1981; Jennings and Thompson, 1986). Most commonly, the reactions involve the progression illitization of smectite along with the disappearance of K-feldspar and kaolinite and the appearance of chlorite with increasing depth and temperature. Few detailed studies, however, have been made to date of clay mineral reactions in deeply buried *non-marine* basins filled with volcanoclastic sediments.

The mineral and chemical composition controls both path and rate of clay mineral reactions in burial diagenetic sequences (Boles and Franks, 1979; Howard, 1987; Eberl and Hower, 1976; Whitney and Northrop, 1988; Huang, 1988). Dutta and Suttner (1986) showed that climate plays an important role in authigenic clay mineral growth in the pore space of near-surface, non-marine sandstones. Schultz (1978) reported a similarity between mixed-layer clay in marine and non-marine rocks of similar bulk mineralogy in the Pierre Shale Group of the northern Great Plains. Schultz noted, however, more K<sup>+</sup> and tetrahedral Al<sup>3+</sup> in the clays in non-marine rocks than in marine rocks. Variations in salinity within a single marine environment does not appear to influence the rate of the illitization reaction (Środoń, 1984a). Compositional differences between interstitial waters in marine and non-marine sediment and effects of climate and depositional environment in non-marine basins, however, may result in mineralogical differences between non-marine and marine sediment during diagenesis. In the present paper the clay mineralogy and petrology of two Tertiary, volcano-

clastic-rich non-marine basins in southwestern Montana are described, and the clay diagenetic trends are compared with those of marine basins.

### GEOLOGIC SETTING

Several large southwest Montana basins filled with sediment as they developed in response to Tertiary tectonic activity. The dominant sediments of the Deer Lodge and Big Hole basins (Figure 1) occur in the Renova and overlying Sixmile Creek Formations, which range in age from late Eocene to latest Miocene. Both units contain volcanoclastic sediment initially rich in rhyolitic ash, gravels derived from the immediately adjacent mountain ranges, and organic-rich lake and swamp deposits. The Renova Formation unconformably overlies the clay-rich Lowland Creek Volcanics. In the Deer Lodge basin, the Lowland Creek unit unconformably overlies late Cretaceous black shales of the Colorado Group (Figure 2).

The Sixmile Creek and Renova Formations are commonly separated by an erosional unconformity, which in some localities is an angular unconformity (Fields *et al.*, 1985). The high organic content in the lacustrine and swamp facies of the Renova Formation and burial depths in excess of 3000 m, have made these Tertiary basins targets for petroleum exploration during the past 10 years.

### ANALYTICAL METHODS

#### *Sampling*

Samples were taken from cuttings and cores collected by AMOCO Production Company from two exploratory wells in the Big Hole Valley and from five wells in the Deer Lodge Valley (Figure 1). Cuttings samples

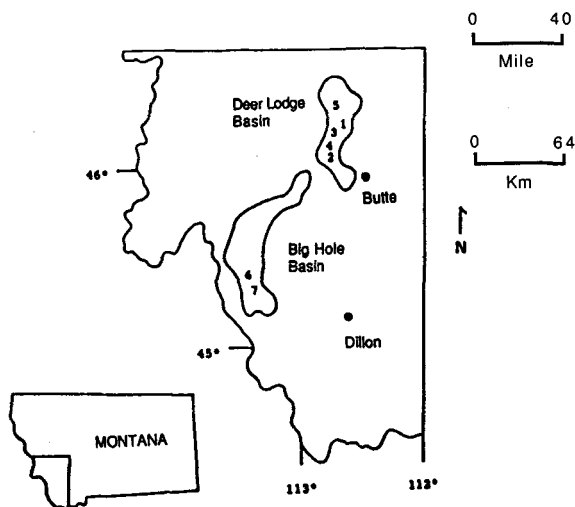


Figure 1. Deer Lodge and Big Hole Valleys of southwestern Montana, showing well locations: 1 = Benson well; 2 = Arco well; 3 = Lewis Johnson well; 4 = Jacobson well; 5 = Montana State Prison well; 6 = Hirshey #1 well; 7 = Hirshey #2 well.

were collected at 100–200-ft<sup>1</sup> intervals from each of the five Deer Lodge Valley wells, and at 30-ft intervals from the two Big Hole Valley wells. Samples were also taken from cored sections in the Big Hole Valley.

#### Sample treatment

All samples were washed in deionized water to remove drilling mud contamination. Samples were crushed in a glazed porcelain mortar and disaggregated in deionized water with an ultrasonic probe. In the cuttings samples, <0.5- $\mu\text{m}$  (equivalent spherical diameter) size fractions were separated from <2.0- $\mu\text{m}$  size-fraction suspensions for X-ray powder diffraction (XRD) analysis by centrifugation. In the core samples from the Hirshey #2 well in the Big Hole Valley the <0.03- to <0.1- $\mu\text{m}$  size fractions were separated from <2.0- $\mu\text{m}$  clay suspensions by centrifugation.

All clay samples were saturated with strontium to eliminate variations in ethylene glycol thickness caused by large monovalent cations (Eberl *et al.*, 1986). The samples were subsequently washed to remove excess electrolyte.

#### X-ray powder diffraction analysis

Oriented samples of the various size fractions were prepared for XRD analysis by a filter-membrane peel technique (Pollastro, 1982). XRD analyses were made of all oriented samples from 2° to 50°2 $\theta$ , and for selected samples from 2° to 90°2 $\theta$  on a Philips X-ray diffractometer equipped with a digital step counter, using

<sup>1</sup> The original depths of samples in feet, as received from AMOCO, are used throughout this report to avoid artifacts that might be introduced by converting to meters.

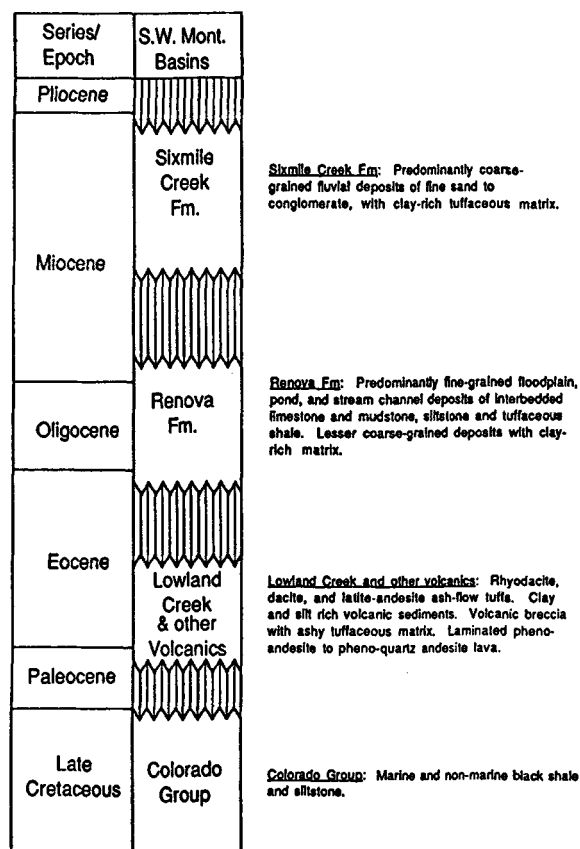


Figure 2. Composite stratigraphy of southwest Montana basins (Fields *et al.*, 1985; Jagmin, 1972; Ehinger *et al.*, 1965; McLeod, 1987). All units shown are in unconformable contact with adjacent units.

CuK $\alpha$  radiation and a graphite monochromator. Some samples were analyzed with an automated Siemens D500 diffractometer.

All oriented samples were analyzed by XRD after ethylene glycol solvation in a heated solvation chamber for 24 hr. Selected oriented samples were heat treated at 600°C for 1 hr and then analyzed by XRD to determine the presence of kaolinite and chlorite (Carroll, 1970).

Illite/smectite (I/S) identifications were made using techniques of Środoń (1980, 1981, 1984b), Reynolds and Hower (1970), and the NEWMOD computer program (Reynolds, 1985). Sericite was identified by sharp 10-Å and integral higher-order reflections in diffractograms.

#### Scanning electron microscope analysis (SEM)

Chips from selected Hirshey #2 core samples were cemented onto aluminum mounts and sputter-coated with Au-Pd alloy or carbon. The mounted samples were examined with a Cambridge Stereoscan 250 MK2 SEM at 20 kV for textural indications of authigenic clay growth. The identification of clay minerals was

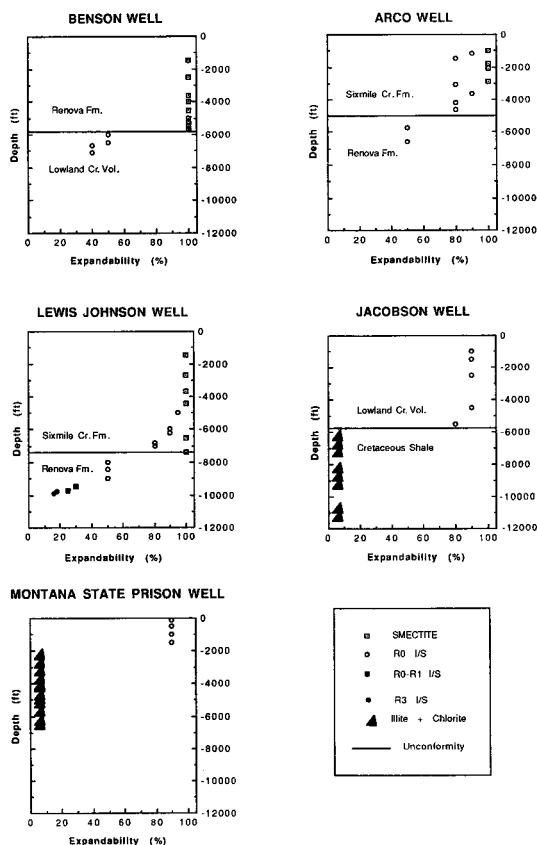


Figure 3. Percent expandability and ordering of illite/smectite compared with depth for  $<0.5\text{-}\mu\text{m}$  size fraction from drill cuttings in Deer Lodge Valley wells.

aided by a spot-specific, energy-dispersive X-ray (EDX) analyzer.

#### Optical microscopy

Standard thin sections were cut from selected core samples from the Hirshey #2 well and examined under an optical microscope to observe whole rock textural characteristics and replacement textures.

## RESULTS

#### Mineralogical results

The dominant mineral in the clay-size fraction of the cuttings and core samples from all seven wells was I/S. The expandabilities of I/S from the seven wells are plotted against depth in Figures 3 and 4 to show the mineralogical trends.

#### Cuttings samples

The Benson well samples (Figure 3) contained smectite from 1500 to 6000 ft and R0-I/S from 6000 to 6700 ft, at which depth the expandability was about 50%. Most of the samples also contained discrete illite and chlorite or kaolinite.

The Arco well (Figure 3) contained smectite and R0-

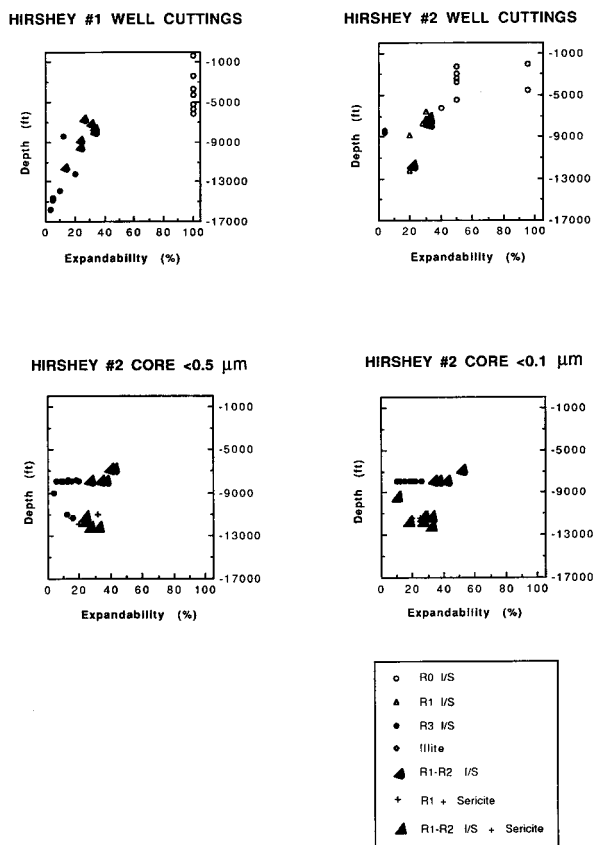


Figure 4. Percent expandability and ordering of illite/smectite compared with depth for  $<0.5\text{-}$  and  $<0.1\text{-}\mu\text{m}$  size fractions from drill cuttings and core samples from Big Hole Valley wells.

I/S. The I/S expandability varied erratically with depth, but was  $>80\%$  to 5700 ft, where it abruptly decreased to 50%. At depths  $>2900$  ft, discrete illite and chlorite or kaolinite were also identified.

In the Lewis Johnson well (Figure 3), smectite and highly expandable R0-I/S was noted to a depth of 7400 ft. The I/S from 8000 to 9000 ft was about 50% expandable and showed an apparent transition from R0 to R1 ordering with decreasing expandability. At depths  $<9500$  ft, R1- and R3-I/S were identified, and expandability decreased to 16% at 9900 ft. Chlorite or kaolinite and discrete illite coexisted with I/S in most samples.

In the Jacobson well (Figure 3), highly expandable R0-I/S was identified from 1000 to 5500 ft. An abrupt mineralogical discontinuity occurred at 6000 ft. Below this depth, all samples were found to contain illite having no measurable expandability and chlorite.

In the Montana State Prison well (Figure 3), a discontinuity between highly expandable R0-I/S and illite, similar to that in the Jacobson well, was noted at a depth of 2000 ft. Discrete illite was present in all R0-I/S samples.

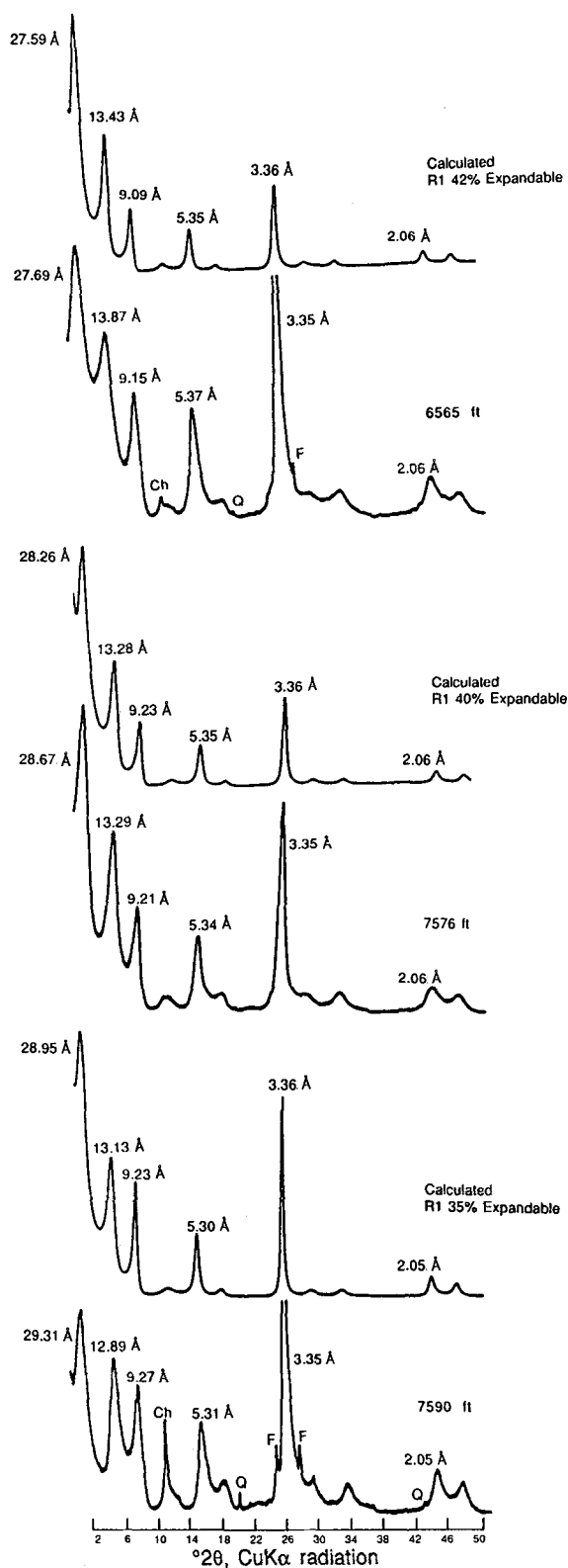


Figure 5. Experimental X-ray powder diffraction patterns from 6565-, 7576-, and 7590-ft core samples from the Hirshey #2 well compared with calculated illite/smectite (I/S) patterns

In the Hirshey #1 well (Figure 4), >90% expandable R0-I/S coexisted with discrete illite and chlorite from 300 to 6140 ft. A mineralogical discontinuity was recognized between 6140 and 6560 ft. From 6560 to 15,790 ft the I/S expandability decreased from 32% to nearly 0%. From 6560 to 11,440 ft, the ordering of most samples was intermediate between R1 and R2 (designated R1-R2). R1-R2-I/S ordering was identified on the basis of XRD reflections between 20 and 37 Å and criteria described by Środoń (1980, 1981, 1984b). R3-ordering began at 13,960 ft and persists to the bottom of the hole at 15,790 ft.

In the Hirshey #2 well (Figure 4), I/S expandability generally decreased from >90% to 10% from 2000 to 13,000 ft. The ordering of I/S was R0 from 2000 to 6200 ft. I/S ordering of the R1-R2, R1, and R3 types occurred without a trend from 6000 to 13,000 ft. Chlorite was identified as an accessory mineral in all samples from 4500 ft to the bottom of the hole.

#### Core samples

The clay mineralogy of 32 core samples from the Hirshey #2 well was determined in the interval 6564 to 11,883 ft. The core was not continuous over this interval; no core was available between 9049 and 10,982 ft. Mineralogical profiles of the <0.5- and <0.1- $\mu\text{m}$  size fractions are shown in Figure 4.

In the <0.5- $\mu\text{m}$  core samples from the Hirshey #2 well (Figure 4), expandability decreased irregularly from 40% to 5% from 6564 to 7958 ft. Most of the expandability decrease occurred over a range of about 300 ft. Ordering of the I/S is R1-R2 from 6564 to 7590 ft; chlorite was identified in all samples within this interval. At 7889 ft, R3-ordered I/S was noted; this material persisted to 9049 ft.

At 10,982 ft, the mineralogy of the core changed significantly. In the XRD patterns of samples from 10,982 ft to the bottom of the hole, sharp 10-Å and integral higher-order reflections were superimposed on I/S peaks. This 10-Å phase is herein referred to as sericite. Random powder analyses of the 11,873- and 11,874-ft core samples, which contained sericite, showed a mixture of  $1M$  and  $2M_1$  polytypes. Expandability of the I/S varied in an irregular manner throughout this interval, but was generally higher than in the interval above, where no sericite was present. Expandabilities were as high as 30% for R1-R2-ordered I/S, and as low as 12% for R3-I/S. R1, R1-R2, and R3

←  
from NEWMOD (Reynolds, 1985). All experimental patterns are from <0.1- $\mu\text{m}$  size fraction. R1 42% expandable and R1 40% expandable I/S patterns were calculated with a mean defect-free distance of six 2:1 layers. R1 35% expandable I/S patterns were calculated with a mean defect-free distance of ten 2:1 layers. I/S from the three experimental samples is R1-R2 ordered, based on parameters outlined by Środoń (1980, 1984b). Ch = chlorite, Q = quartz, F = feldspar.

ordering of I/S was noted in this interval. Chlorite and feldspar were identified in all samples from 10,982 to 11,883 ft.

The  $<0.1\text{-}\mu\text{m}$  core samples from the Hirshey #2 well (Figure 4) showed a similar profile to that of the  $<0.5\text{-}\mu\text{m}$  samples. The major difference was that I/S expandabilities averaged 5% higher in the  $<0.1\text{-}\mu\text{m}$  size fraction.

Figure 5 shows three XRD patterns and corresponding NEWMOD (Reynolds, 1985) calculated patterns, which are typical of the R1-R2 interval in the core samples from 6565 to 7590 ft. Figure 6 shows three typical XRD patterns and corresponding NEWMOD (Reynolds, 1985) patterns from the 7889- to 7958-ft interval. Two of the samples are R3 ordered, one is R1-R2 ordered.

XRD patterns from the 7958-ft sample (Figure 7) indicate that the R3-I/S had a nearly ideal I:S ratio of 3:1, based on the presence of a 47-Å and higher order reflections. This type of I/S has been called "tarasovite" by previous workers (Lazarenko, 1949, 1965; Lazarenko and Korolev, 1970; Brindley and Suzuki, 1983).

I/S samples from 10,982 to 11,883 ft ranged from 16 to 30% expandable. All samples from 9049 to 11,883 ft contained sericite. Ordering of the I/S in this interval was dominantly R1-R2, but R3- and R1-I/S were also identified. Three XRD patterns from this interval are shown in Figure 8, along with corresponding NEWMOD (Reynolds, 1985) calculated patterns. The I/S peaks are more intense relative to sericite in the  $<0.1\text{-}\mu\text{m}$  fraction than in the larger size fraction.

#### *I/S expandability of different size fractions from single samples*

The I/S expandability and ordering for different size fractions from the 11,000-, 10,982-, and 11,872-ft core samples from the Hirshey #2 well are shown in Table 1. I/S expandability consistently increases with decreasing size fraction, with the exception of the  $<0.03\text{-}\mu\text{m}$  size fraction from the 11,000-ft sample.

#### *Scanning electron microscopy (SEM)*

Figure 9 shows typical authigenic mineral textures observed with SEM. Mineral identification was based on morphology and chemical composition from EDX analysis. Interpretations of authigenesis were based on euhedral morphologies and textures.

#### *Optical microscopy*

Figure 9 shows typical rock fabric and replacement textures, including sericite replacement of sediment grains, in core samples from the Hirshey #2 well.

## DISCUSSION

Marine sediments generally exhibit a regular decrease in I/S expandability and an increase in ordering with increasing burial depth and temperature (see, e.g.,

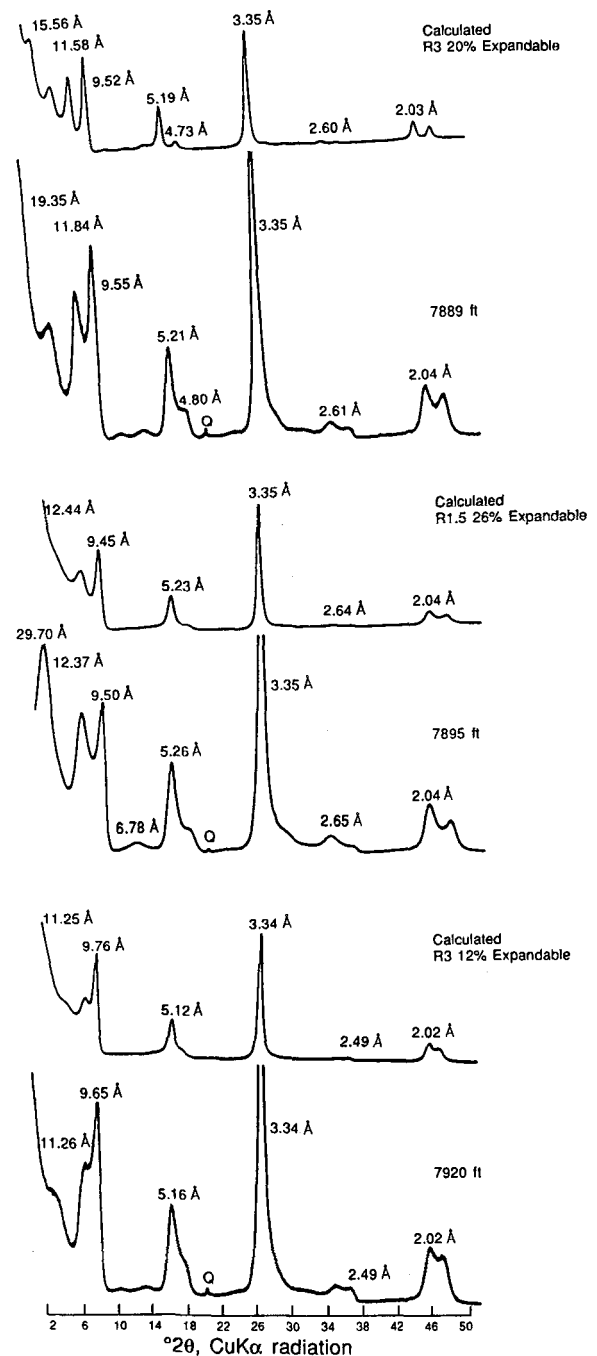


Figure 6. Experimental X-ray diffraction patterns from 7889-, 7895-, and 7920-ft core samples from the Hirshey #2 well compared with calculated illite/smectite (I/S) patterns from NEWMOD (Reynolds, 1985). All experimental patterns are from the  $<0.1\text{-}\mu\text{m}$  size fraction. All NEWMOD patterns were calculated using a mean defect-free distance of eight 2:1 layers. I/S from the 7889- and 7920-ft samples is R3 ordered; I/S from the 7895-ft sample is R1-R2 ordered (similar to R1.5 of NEWMOD calculations), based on parameters outlined by Srodon (1980, 1984b). Q = quartz.

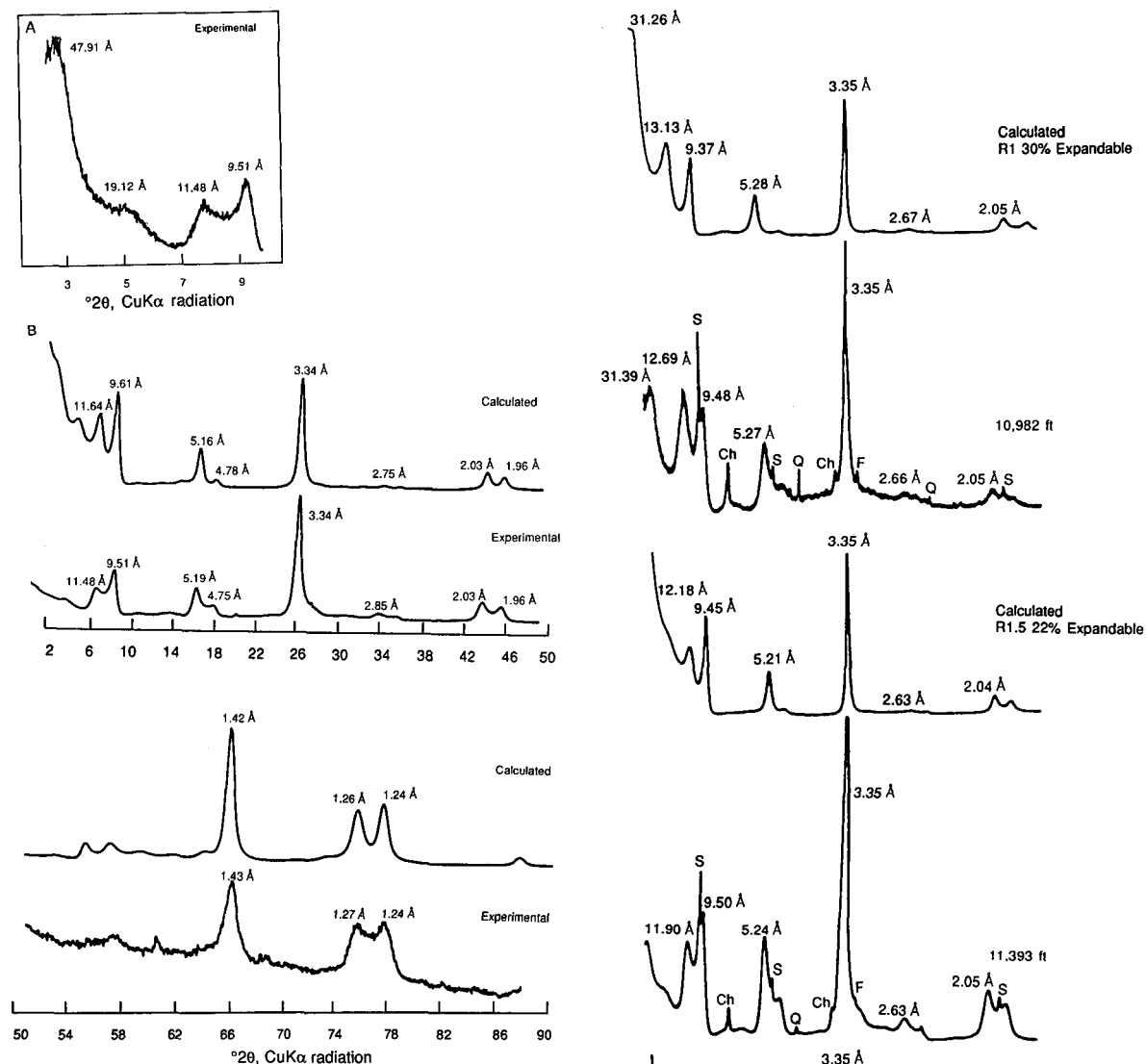
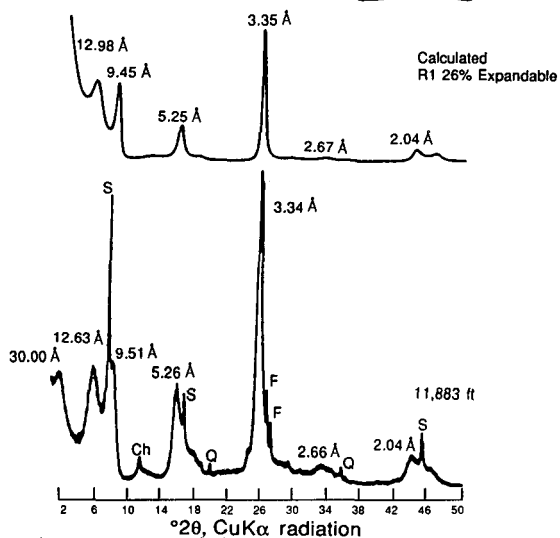


Figure 7. (A) High-angle X-ray powder diffraction (XRD) pattern, run with  $0.1^\circ$  slits, for  $<0.1\text{-}\mu\text{m}$  size fraction of the 7958-ft core sample from the Hirshey #2 well. (B) Experimental XRD pattern for the  $<0.1\text{-}\mu\text{m}$  size fraction of the 7958-ft core sample from the Hirshey #2 well, compared with NEWMOD (Reynolds, 1985) calculated pattern for R3-ordered, 18% expandable illite/smectite. NEWMOD pattern was calculated using a mean defect-free distance of seven 2:1 layers.

Figure 8. Experimental X-ray powder diffraction patterns of 10,982-, 11,393-, and 11,883-ft core samples from the Hirshey #2 well compared with calculated illite/smectite (I/S) patterns from NEWMOD (Reynolds, 1985). All experimental patterns are from the  $<0.1\text{-}\mu\text{m}$  size fraction. NEWMOD patterns for R1, 30% expandable and R1, 26% expandable I/S were calculated using a mean defect-free distance of eight 2:1 layers. The R1.5, 22% expandable I/S pattern was calculated using a mean defect-free distance of ten 2:1 layers. Experimental patterns show that I/S coexists with sericite. The sericite 001, 002, and 005 peaks are labeled. I/S phases in the experimental samples are R1-R2 ordered, based on param-



eters outlined by Środoń (1980, 1984b). Ch = chlorite, Q = quartz, F = feldspar, S = sericite.

Hower *et al.*, 1976; Jennings and Thompson, 1986; Velde *et al.*, 1986). These trends were noted in the cuttings samples from the Deer Lodge and Big Hole Valley wells; however, the trends were interrupted by discontinuities in which the I/S expandability abruptly changed from 30% to 80%.

Core samples from the Hirshey #2 well showed wide variations in I/S expandability over short stratigraphic distances and an increase in I/S expandability below 10,982 ft. Below 10,982 ft, the I/S coexisted with authigenic sericite.

#### Cuttings samples

Unconformities have been well documented in the Tertiary sedimentary section of southwest Montana (Kuenzi and Fields, 1971; Robinson, 1967; Fields *et al.*, 1985). In his study of the Deer Lodge basin, McLeod (1987) correlated stratigraphy between the Lewis Johnson, Benson, Arco, and Jacobson wells based on dipmeter logs, changes in the electrical properties of the rocks, paleontology, and seismic reflection data. The mineralogical discontinuities described in the present study coincide with unconformities in all four wells in which the unconformities have been identified (Figure 3).

Two types of mineralogical discontinuities were noted in the Tertiary basins of southwestern Montana: (1) an abrupt transition from smectite or highly expandable RO-I/S to pure illite coexisting with chlorite, and (2) an abrupt transition from highly expandable I/S to I/S of low expandability.

The first type of discontinuity, found in the Jacobson well, coincides with the boundary between the Tertiary Lowland Creek volcanics and Cretaceous Colorado Group shale. The Lowland Creek volcanics were initially rich in rhyolitic ash, tuffs, and clay-rich volcanogenic sediments (Iagmin, 1972). The Colorado Group shale in the Deer Lodge Basin is rich in illite and chlorite that may be detrital and derived from the Precambrian shales of the Belt supergroup presently exposed in the adjacent mountain ranges (Ehinger *et al.*, 1965). The identical discontinuity seen in the Montana State Prison well, where the stratigraphy is not known, may be due to a similar Tertiary-Cretaceous contact. In three of the remaining five wells, the mineralogical discontinuities coincide with unconformities between the Sixmile Creek Formation and the Renova Formation or the Renova and Lowland Creek volcanics (Figure 3). In the other two wells the depths of those unconformities are unknown, but the similar mineralogical discontinuities suggest that the unconformities are indeed present.

Bulk chemical and mineral composition can enhance or inhibit the illitization process (see e.g., Eberl and Hower, 1976; Whitney and Northrop, 1988; Huang, 1988). Permeability variations control migration of interstitial fluids and modify system composition, there-

Table 1. Core samples, Hirshey #2 well, southwestern Montana.

Illite/smectite ordering and expandability <sup>1</sup>	
11,000 ft	
Size fraction ( $\mu\text{m}$ )	
<2.0	ser. + R1 10%
<1.0	ser. + R1 7%
<0.1	R1 17%
<0.05	R1-R2 30%
<0.03	R1-R2 25%
Bracketed size fraction ( $\mu\text{m}$ )	
1.0-2.0	ser. + R1 7%
0.5-1.0	ser. + R1 7%
0.1-0.5	ser. + R3 12%
0.05-0.1	R1-R2 25%
0.03-0.05	R1-R2 32%
10,982 ft	
Size fraction ( $\mu\text{m}$ )	
<0.5	ser. + R1-R2 22%
<0.1	ser. + R1-R2 30%
<0.05	ser. + R1-R2 32%
11,874 ft	
<0.5	ser. + R1-R2 30%
<0.1	ser. + R1-R2 30%
<0.05	ser. + R1-R2 40%

<sup>1</sup> X-ray powder diffraction results of different size fractions from single samples. ser. = sericite.

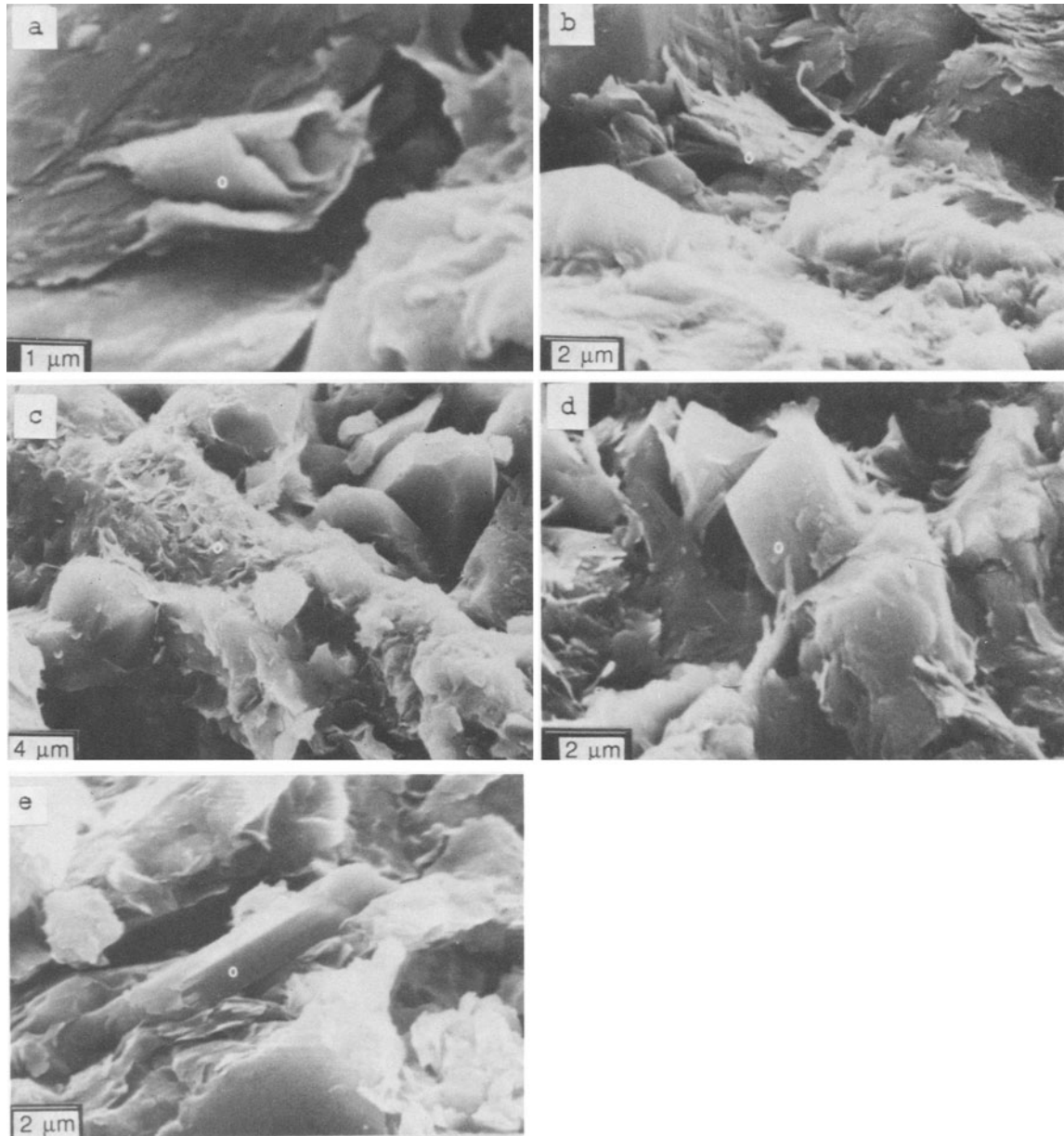
by affecting the rate and extent of illitization (Boles and Franks, 1979; Howard, 1987). Thus, the coincidence between the I/S discontinuities and the stratigraphic unconformities suggests five possible explanations:

1. System composition differences resulting from a change in provenance of the sediments above and below the unconformities may have caused the mineralogical discontinuities by changing bulk mineral composition (Eberl and Hower, 1976; Whitney and Northrop, 1988; Huang, 1988).

2. Compositional differences in interstitial water, resulting from different permeabilities above and below the unconformities, could have differentially affected the illitization process and produced the I/S discontinuities (Howard, 1987; Boles and Franks, 1979; Fields *et al.*, 1985).

3. Climatic differences during the deposition of the sediments above and below the unconformities may have produced geochemical differences, which caused the discontinuities (Dutta and Suttner, 1986; Thompson *et al.*, 1982).

4. The discontinuities may have resulted from basin subsidence and sedimentation, interrupted by uplift and erosion followed by renewed subsidence and deposition. In this scenario, partial illitization of smectite would have occurred in lower Renova sediments during latest Eocene through middle Miocene time as the Renova Formation thickened. In late-middle Miocene time, the Tertiary basins of southwest Montana un-



**Figure 9.** Scanning electron micrographs showing authigenic mineral textures from Hirshey #2 core samples. Figure 9a is from 10,982 ft; Figures 9b, 9c, and 9d are from 7902 ft; Figure 9e is from 11,393 ft. The delicate curled texture of the illite in Figure 9a suggests authigenic growth. Figure 9b shows illite laths on the surfaces of authigenic quartz crystals. Figure 9c shows a mat of illite and authigenic quartz crystals. Figure 9d shows authigenic quartz coated with authigenic clay. Figure 9e shows authigenic K-feldspar.

derwent a period of uplift and erosion, which removed an unknown thickness of upper Renova sediment prior to resumption of sedimentation (Fields *et al.*, 1985). Cooling accompanying the erosion caused cessation or slowing of the illitization reaction (Jennings and Thompson, 1986). In late Miocene time, the smectite-rich Sixmile Creek Formation accumulated on top of the remaining Renova Formation. As the Sixmile Creek Formation thickened due to continued deposition, il-

lite formation in the reburied Renova sediments may have recommenced, beginning anew in the lower Six-mile Creek sediments, resulting in the mineralogical discontinuity.

5. A combination of uplift, erosion, and interrupted deposition with compositional variations described in 1–3 may be the best explanation for the mineralogical discontinuities.

Changes in provenance and sediment composition,



permeability variations, climatic changes, and a complex tectonic and sedimentation history, are all known to have affected the sedimentary and burial history of the Tertiary basins of southwestern Montana. All of these factors may have combined to produce the mineralogical trends and discontinuities now seen in the basins.

#### Core samples

Mineralogical trends with increasing depth in the <0.5- and <0.1- $\mu\text{m}$  fractions (Figure 4) from the Hirshey #2 core were significantly different from the progressive illitization seen in the cuttings samples. Although the Hirshey #2 core samples showed progressive illitization with depth, they also showed wide variations in I/S expandabilities over short stratigraphic distances, as reported by Boles and Franks (1979), Pearson *et al.*, (1981), and Howard (1987). The core samples also had higher I/S expandability from 9049 ft to the bottom of the hole than at shallower depths; the deeper samples contained sericite, as well.

The <0.1- $\mu\text{m}$  fraction of the core samples showed three distinct mineralogic intervals. Between 6564 and 7590 ft, R1-R2-I/S having expandabilities of 50% to 32% was identified (Figure 5). From 7889 to 7958 ft, the samples consisted of R3-I/S having 26 to 10% expandability (Figure 6). From 9049 ft to the bottom of the hole at 11,883 ft, R1-R2-ordered I/S having 8% to 30% expandability was identified coexisting with sericite (Figure 8). In core samples from the Hirshey #2 well, sericite was identified on the basis of sharp 10- $\text{\AA}$  and integral higher-order reflections, indicating nearly 0% expandability (Eberl *et al.*, 1987).

The paragenesis of the sericite and coexisting I/S in these samples is not known. Possibly, the sericite was the product of illitization, as shown in the cuttings samples, or it may have crystallized from solution in a process unrelated to the illitization of smectite. If the sericite is the product of illitization, the coexisting I/S may have nucleated independently to form a separate population of small fundamental particles (Eberl and Šrodoň, 1988).

The <0.5- $\mu\text{m}$  fraction from the 11,873- and 11,874-ft samples contained sericite and a mixture of  $1M$ - and  $2M_1$ -polytypes. The exact temperatures governing the stability of mica polytypes has not been determined because compositional variations affect the structure (Radoslovich and Norrish, 1962; Velde, 1965; Güven 1971). The  $1M \rightarrow 2M_1$  reaction, however, seems to occur between 200° and 350°C under hydrothermal conditions (Yoder and Eugster, 1955; Velde, 1965). The presence of the  $2M_1$  polytype in the sericite interval implies elevated temperatures. Perhaps the migration of hot fluids during tectonic development of the basin produced the sericite. If hot fluids are responsible for the sericite, they may also explain the coexisting I/S, if a population of small illite particles

nucleated from the fluids, or if the previous population of I/S fundamental particles underwent partial dissolution during the process of Ostwald ripening (Eberl and Šrodoň, 1988).

Sufficient data are not available to determine genesis of the sericite and I/S in this interval. Expandable I/S and sericite should not be compatible unless metastability, fundamental particle theory, and the Ostwald ripening process are considered.

The core samples ranged widely in I/S expandability over short stratigraphic distances, (e.g., 7889 to 7958 ft, in which <0.5- $\mu\text{m}$  fraction samples ranged from 5 to 20% expandability; see Figure 4). The variation in I/S expandability may have resulted from compositional differences of interstitial fluids, controlled by variations in lithology and/or permeability over small stratigraphic distances (Howard, 1987; Pearson *et al.*, 1981; Boles and Franks, 1979).

#### Tarasovite

I/S from the 7958-ft core sample from the Hirshey #2 well showed a nearly ideal 3:1 I:S ratio and was R3 ordered (Figure 7). This type of I/S has been called "tarasovite" (Lazarenko, 1949, 1965; Lazarenko and Korolev, 1970; Brindley and Suzuki, 1983). A 47- $\text{\AA}$  reflection and near-integral higher order reflections were present in the XRD pattern. Peaks between 10° and 15°2 $\theta$  and several distinctive reflections between 50° and 90°2 $\theta$  were particularly diagnostic of tarasovite.

In a MacEwan crystallite model (Moore and Reynolds, 1989), in which I/S is a sequence of interlayers within a single crystallite, I/S having an exact 3:1 I:S ratio should be 25% expandable, if the crystallite were infinitely thick. If the thickness of the crystallite is limited, however, as in Figure 11, expandability should be only 18%. Brindley and Suzuki (1983) reported the expandability of tarasovite to be about 20% and attributed the lower expandability relative to an exact 3:1 I:S ratio to the random addition of illite layers in MacEwan crystallites of the mineral sample.

The tarasovite structure can also be described by a fundamental particle model (Nadeau *et al.*, 1984a, 1984b), in which fundamental illite particles four 2:1 layers thick are arranged in stacks with expandable interfaces separating the stacks (Figure 12). The expandability of sample 7958 was 18%, lower than the ideal expandability of perfect tarasovite. In fundamental particle theory, the addition of a few thicker fundamental particles in a stack dominated by four 2:1 layer particles could account for the less-than-ideal 25% expandability, because fewer expandable interfaces would be present in the stack (Figure 12).

Calculations with NEWMOD (not shown) indicate that if all of the fundamental particles were exactly four silicate layers thick, as in perfect tarasovite, the XRD peaks would be very sharp and narrow, more so than in the XRD pattern from sample 7958. A few thicker

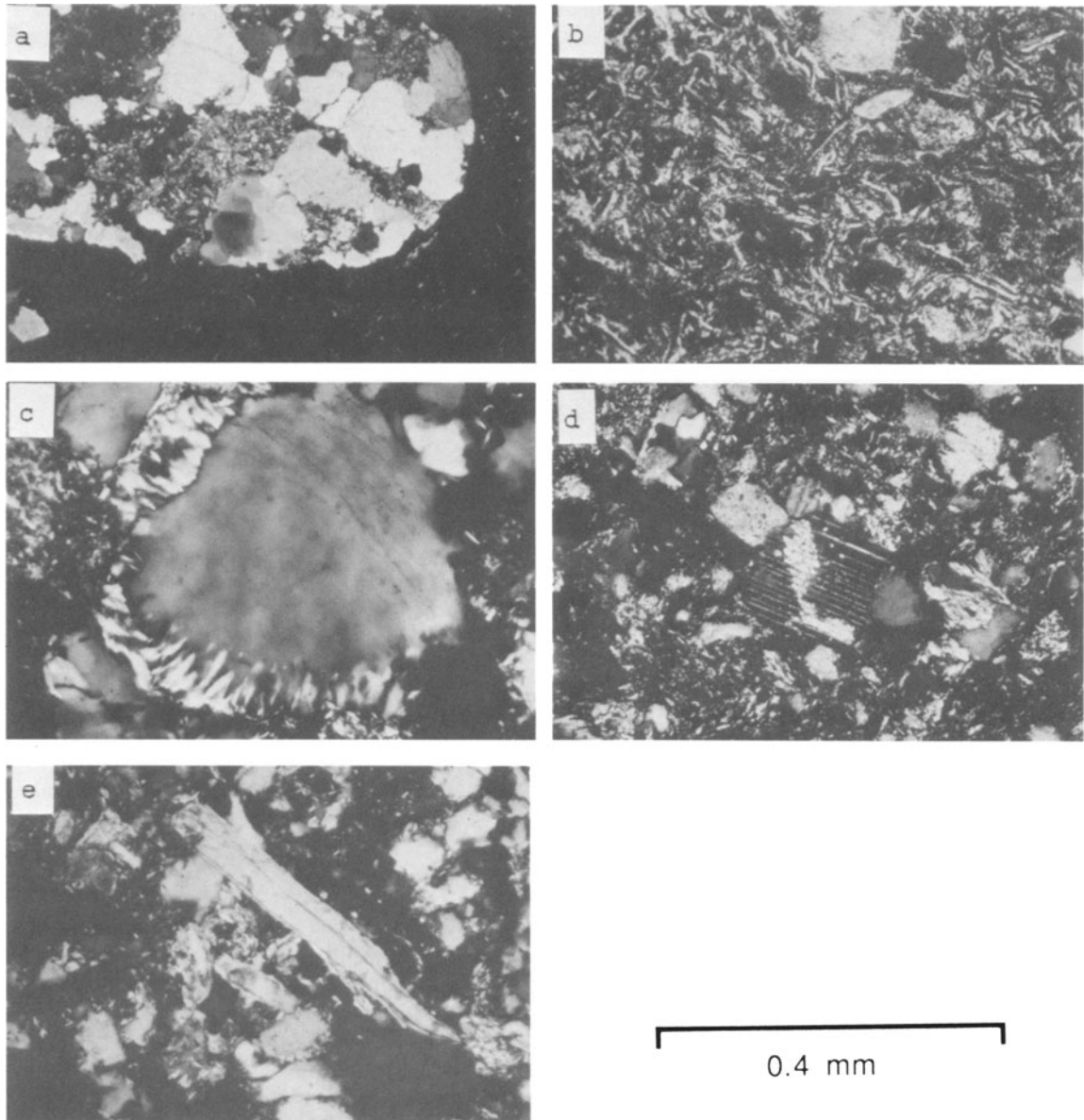


Figure 10. Cross-polar photomicrographs showing lithology and replacement textures from Hirshey #2 core samples. Figure 10a is from 6565 ft; Figure 10b is from 7890 ft; Figures 10c, 10d, and 10e are from 11,363 ft samples. Figure 10a shows a sedimentary rock fragment from the 6565-ft level, with minor carbonate alteration in a matrix of unaltered tuffaceous material. Figure 10b shows tuffaceous clay from the 7890-ft level, with a few clasts and little or no replacement texture. Figure 10c shows sericite from a depth of 11,363 ft replacing quartz and growing outward from the quartz grain. Figure 10d, from 11,363-ft depth, shows birefringent sericite replacing clastic grains and tuffaceous matrix and carbonate replacement of a plagioclase grain. Figure 10e, from 11,363-ft depth, shows sericite replacement of clastic grains and matrix, with a large grain of white mica that may be authigenic or detrital.

particles, as shown in Figure 12, would broaden the peaks to be similar to those of sample 7958.

The limited peak broadening and the 47-Å and higher-order reflections in the XRD patterns of sample 7958 imply that the sample contains numerous four-layer illite particles and a few fundamental particles of greater and lesser thicknesses (Figure 12).

#### *Further evidence of interparticle diffraction from fundamental particles*

Table 1 shows XRD results from successively smaller size fractions from the Hirshey #2 11,000-, 10,982-, and 11,874-ft core samples. Expandability of 1/S increased with a decrease in particle size. More

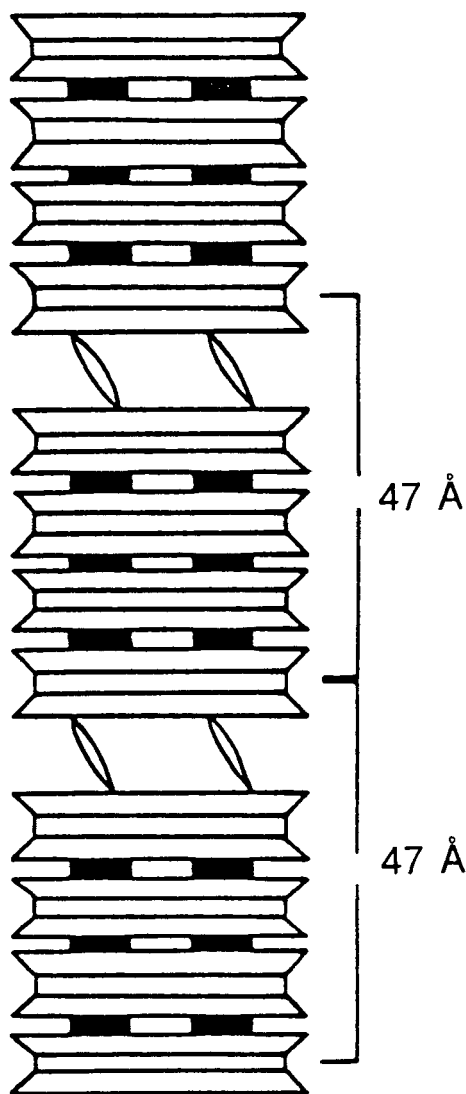


Figure 11. Schematic illustration of a stack of four 2:1 layer fundamental particles expanded with ethylene glycol.

small fundamental particles should produce more expanding interfaces if particle stack on XRD slide preparations (Nadeau *et al.*, 1984a, 1984b; Eberl *et al.*, 1987). Therefore, the fact that successively smaller size fractions showed successively greater expandabilities indicates that fundamental particles were separated by size in a centrifuge.

The smallest size fraction analyzed from the 11,000-ft sample,  $<0.03 \mu\text{m}$ , was slightly less expandable than the next larger size fraction,  $<0.05 \mu\text{m}$ , possibly due to the thin concentration of the clay suspension used to make the XRD slide. The thin clay concentration may have produced shorter stacks of fundamental particles, containing fewer expanding interfaces (see Eberl *et al.*, 1987).

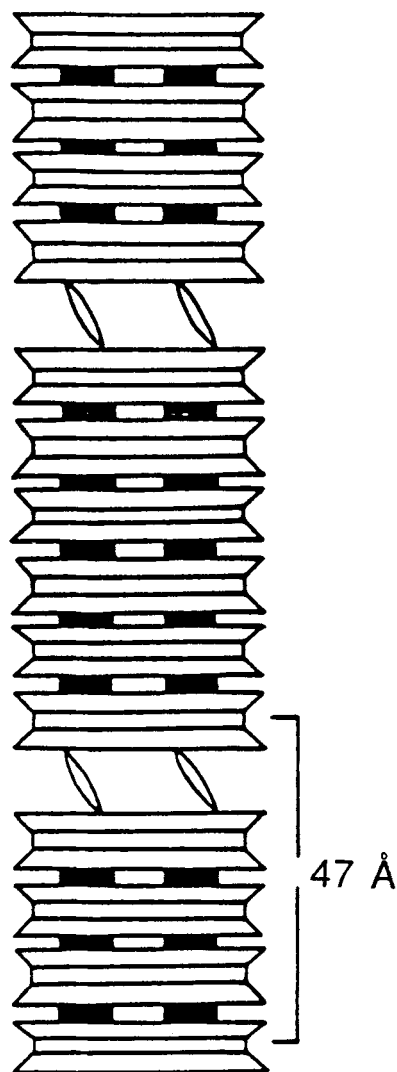


Figure 12. Schematic illustration of four 2:1 layer fundamental particles in a stack with a thicker fundamental particle expanded with ethylene glycol.

#### *Authigenic mineral growth*

The delicate textures of the clays growing on euhedral quartz and feldspar seen by SEM indicates authigenic crystal growth (Figures 9a-9c). EDX analysis of these clays indicate that the crystals had a high potassium content and were therefore illite or sericite. Authigenic sericite growth was also documented from thin sections (Figure 10).

Figures 9d and 9e show euhedral quartz and K-feldspar, respectively; based on EDX analyses that show a high Si and no K content in Figure 9d, and a high K content in Figure 9e. The size and morphology of these crystals, along with feldspar peaks in the XRD patterns of the  $<0.1\text{-}\mu\text{m}$  size fractions from this stratigraphic interval (e.g., Figure 8), suggest the growth of authigenic K-feldspar and quartz. The growth of K-feldspar

contrasts with samples from the Gulf Coast and Colorado River delta in which K-feldspar appears to have been consumed at increasing depth (Hower *et al.*, 1976; Jennings and Thompson, 1986).

### SUMMARY AND CONCLUSIONS

I/S expandability trends in cuttings samples in the Tertiary non-marine sediments of southwestern Montana showed abrupt discontinuities coincident with stratigraphic unconformities. These discontinuities may have resulted from: (1) system composition differences due to differences in sediment types above and below the unconformities, (2) differences in interstitial water compositions resulting from permeability variations above and below the unconformities, (3) differences in climatic conditions during the deposition of the sediments above and below the unconformities, (4) a two-stage burial event interrupted by uplift and erosion or (5) a combination of these models.

In the core samples, I/S expandabilities ranged widely within short stratigraphic intervals. This variation may have been due to differences in rock and fluid compositions and/or fluid-composition differences resulting from permeability variations.

Sericite, coexisting with I/S in the deep portions of the Hirshey #2 well may represent the end product of progressive illitization of I/S, or the I/S may have grown during a separate nucleation. Alternatively, the sericite may have formed independent and unrelated to progressive illitization, possibly from a hydrothermal-tectonic event.

The expandability of I/S one samples increased with a decrease in particle size, indicating that fundamental particles can be separated by size fractionation.

Mineral assemblages and diagenetic trends in cuttings samples were significantly different from those observed in core samples. The coexistence of sericite and I/S was not recognized in cuttings, whereas the two phases were both present in core samples from the same depth. Core samples depicted the mineralogy of narrow stratigraphic horizons, in contrast to cuttings samples, which represented an average mineralogy for a relatively broad stratigraphic range.

Diagenesis in non-marine basins differs from diagenesis in marine basins, such as the Gulf Coast (Hower, 1976) and Colorado River delta (Jennings and Thompson, 1986), which show a regular decrease in I/S expandability and consumption of K-feldspar with depth. The non-marine basins in the present study have discontinuities in I/S expandability and show an increase in I/S expandability in deep samples containing sericite and the growth of K-feldspar in deep samples. The growth of sericite and K-feldspar was consistent with a higher K<sup>+</sup> ion activity in non-marine rocks.

The 7958-ft core sample contained R3-ordered I/S having a nearly ideal 3:1 illite:smectite ratio, similar to the mineral tarasovite. The structure of this I/S is

consistent with a sample dominated by stacks of four 2:1 layer illite particles with small proportions of thicker and thinner particles randomly interstratified among the four-layer particles.

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