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BURIAL AND CONTACT METAMORPHISM IN THE MANCOS SHALE

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Abstract—Clay samples from shales and bentonites in the Mancos Shale (Cretaceous) and its stratigraphic equivalents in the southern Rocky Mountain and Colorado Plateau have been analyzed by X-ray powder diffraction methods. The major clay in the shales is mixed layered illite/smectite, with 20–60% illite layers. The regional distribution of ordered vs. random interstratification in the illite/smectite is consistent with the concept of burial metamorphism in which smectite interlayers are converted to illite, resulting finally in ordered interstratification. The interstratification data correlate with other geologic information, including rank of coal and Laramide tectonic activity. In addition, contact metamorphism of the shale by Tertiary igneous intrusions produced a similar clay suite. Chemical variation within these shales (particularly the presence or absence of carbonate) affected the clay conversion reactions in the interbedded bentonites and the shale itself during the early stages of transformation. In extreme cases, shales and bentonites from a single outcrop may contain clays that range from pure smectite (calcareous shales) to ordered illite/smectite containing ≥50% illite layers (noncalcareous shales). The use of mixed-layered illite/smectite compositions to infer thermal regimes, therefore, may be misleading unless allowance is made for local chemical controls.

Key Words—Bentonite, Burial metamorphism, Illite, Interstratification, Shale, Smectite, X-ray powder diffraction.

INTRODUCTION

The transformation of clay minerals in pelitic sediments with increasing depths of burial has been observed by several investigators. The loss to absorbed water by smectite and its consequent conversion of illite has been studied in subsurface samples from Tertiary Gulf Coast sediments by Burst (1959), Perry and Hower (1970), and Hower *et al.* (1976). Dunoyer de Sergonzac (1970) reported similar transformations in subsurface samples of Upper Cretaceous shales in the African Cameroun. The lack of smectite in deeply buried sediments was also noted by Powers (1959) and Weaver (1960).

Such transformations in pelitic sediments occur in pre-greenschist facies environments and have been termed burial metamorphism[2] (Hower *et al.*, 1976; Hoffman and Hower, 1979). The major reaction is the transformation of smectite and mixed-layered illite/smectite (hereafter referred to as I/S) of high expandability to I/S of low expandability. Hower *et al.* (1976) formulated the following chemical mechanism for the conversion:

$$\text{smectite (montmorillonite)} + Al^{3+} + K^{+} \rightarrow \text{illite} + Si^{4+}$$

This mechanism has been supported by structural formulae derived from precise chemical analyses (Foscolos and Kodama, 1974), radiometric argon analyses (Perry, 1974; Aronson and Hower, 1976), experimental thermodynamic and kinetic studies (Eberl and Hower, 1976; Eberl, 1977; Eberl, 1978), and oxygen isotope investigations (Yeh and Savin, 1977; Eslinger *et al.*, 1979).

The interpretation of the X-ray powder diffraction (XRD) data of I/S, has been based on the model of Reynolds (1967) and Reynolds and Hower (1970), wherein a typical transformation in Gulf Coast Tertiary sediments commences with shallow sediments containing randomly interstratified I/S, with 20% illite layers. (The percentage of illite layers in the I/S phase is hereafter referred to as percent illite. The designation should not be confused with the content of illite which is common as a discrete phase in these sediments.) The percent illite increases monotonically with depth of burial and culminates in an ordered interstratified I/S phase, allevardite, at depths of 3–4 km. The interstratification is ordered at ≥60% illite a value that corresponds to an inferred temperature of formation of 100°C (Hower *et al.*, 1976).

Similar mineralogic changes have been observed in surface exposures of initially smectitic pelitic sediments, e.g., shales from the Lower Cretaceous Buckinghorse Formation in British Columbia (Foscolos and Kodama, 1974) and Cretaceous shales and bentonites from the disturbed belt in Montana (Schultz, 1978; Hoffman and Hower, 1979). These sediments underwent post-depositional transformation in response to

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[2] Burial metamorphism is defined as low-grade metamorphism without the effects of penetrative deformation (Coombs, 1961; Zen, 1974). Other workers described these clay mineral transformations as diagenetic (Perry and Hower, 1970; Frey, 1970).

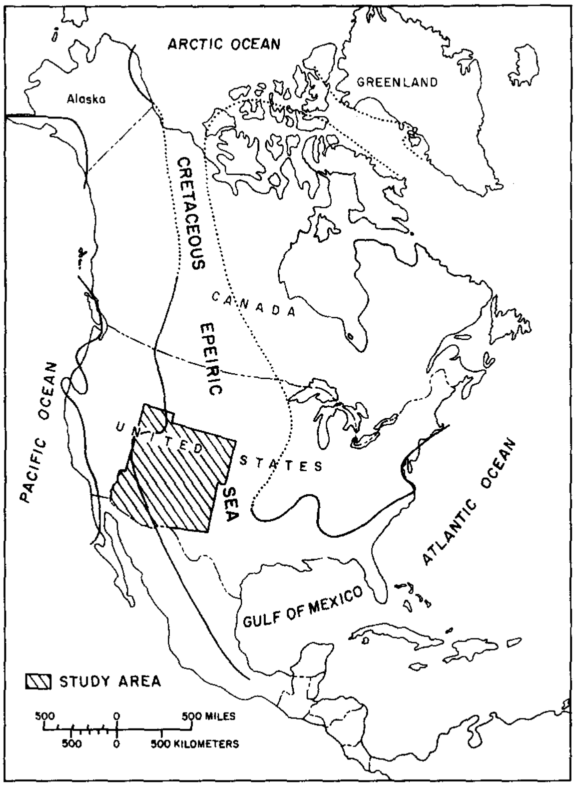

Figure 1. Distribution of Cretaceous marine sediments in North America. (After McGookey, 1972; Kauffman, 1977; Gill and Cobban, 1966.)

elevated temperatures encountered prior to their tectonic uplift and exposure at the surface.

Rationale and purpose of study

The present investigation applied the foregoing concepts of burial metamorphism to the Mancos Shale of the southern Rocky Mountains and the Colorado Plateau. The Mancos Shale, first described by Cross and Purington (1899), includes the interval between the Dakota Sandstone and Mesa Verde Group (Weimer, 1960). The Mancos Shale and its stratigraphic equivalents were selected for study because they are the thickest and most widespread Mesozoic marine shales in the Rocky Mountain region. Consequently, the Mancos Shale represents a wide variety of diagenetic environments. It is also relatively uniform chemically, if calcareous and silty units are disregarded (e.g., 95 of 135 samples reported by Plier and Adams (1962) contain between 1.6 and 2.4% K). Finally, the Mancos Shale contains numerous bentonite beds whose clay fractions are essentially monomineralic smectite or I/S. The presence of discrete illite in the shales compromises the interpretation of the mixed-layered minerals in such rocks.

In portions of the eastern stratigraphic equivalent of the Mancos Shale Gill *et al.* (1972), Tourtelot *et al.* (1960), and Schultz (1978) reported smectite and I/S containing 15–25% illite layers. Schultz (1978) reported primarily randomly interstratified I/S (20–60% illite) in the shales and 100% smectite in the bentonites of the Pierre Shale in the northern Great Plains. The I/S represents 71% of the total clay and 38% of the bulk composition of these shales (Schultz *et al.*, 1980). Therefore, the Cretaceous pelitic sediments have the appropriate initial smectitic random I/S content to undergo transformations in I/S composition.

The present study attempts to: (1) determine the nature and distribution of I/S in the Mancos Shale and associated bentonites, (2) refine the concept of burial metamorphism by investigating the effect of shale chemistry on the conversion reaction, and (3) interpret the results in light of regional geologic/tectonic data.

Geologic setting

The proliferation of epicontinental marine sediments due to a high eustatic stand of sea level during the Cretaceous period has been observed on almost all of the continents (Suess, 1900). The extent of Cretaceous marine sedimentation on the relatively stable interior of the North American craton in response to the high stand of sea level is shown in Figure 1.

The Upper Cretaceous sequence in the southern Rocky Mountains and the Colorado Plateau consists primarily of extensive marine sediments, 60–1500 m thick (Young, 1955). The generalized stratigraphy of this region is shown in Figure 2. Transgressive and regressive cycles caused depositional environments to migrate, mainly in east-west directions (Weimer, 1960; Kauffman, 1969). The initial transgressive cycle produced a sequence in which the basal shale directly above the basal sandstone (generally the Dakota Sandstone) is usually noncalcareous, carbonaceous, and/or siliceous. It is dark grey to black and ranges from a clayey, fissile shale to a massive, silty mudstone; it commonly contains jarosite. This basal shale is overlain by a calcareous shale, somewhat lighter in color, more massive in texture, and containing abundant gypsum and local carbonate concretions. Bentonites from 0.5 cm to 2.5 m thick are present throughout the entire shale section. The period of dominant marine sedimentation in this region terminated at the end of the Cretaceous and was followed by the complex tectonic disturbances and igneous activity of the Laramide orogeny (Tweto, 1975). The Mancos Shale is exposed primarily on the flanks of Laramide basins (Figure 3).

EXPERIMENTAL PROCEDURE

Sample collection

Six hundred ninety samples of Mancos Shale (500–1000 g) and bentonite (5–1000 g) were collected from 154 sites (Figure 3) in the four-state region of Colorado, Utah, Arizona, and New Mexico. Additional samples

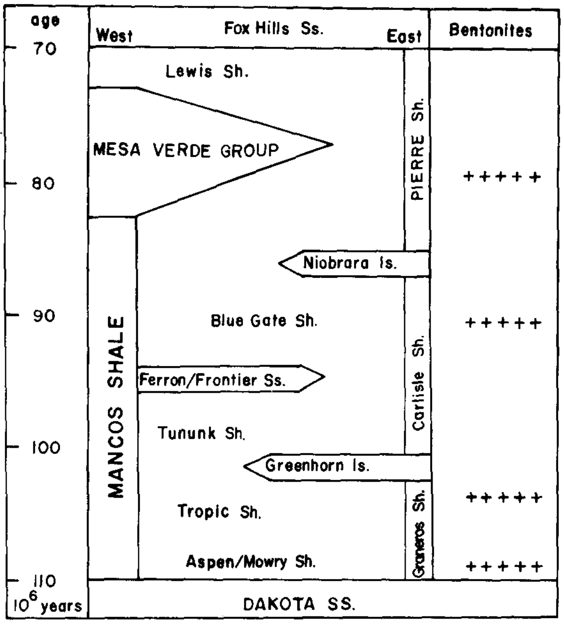

Figure 2. Generalized Cretaceous stratigraphy in the southern Rocky Mountains. (Modified from Cobban and Reeside, 1952; and Cobban, 1972.)

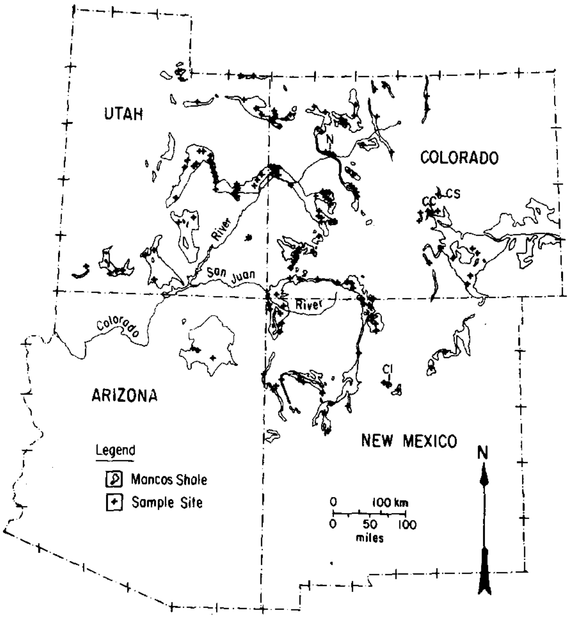

Figure 3. Mancos Shale outcrop and sample site locations, CC = Canon City, CS = Colorado Springs, N = New Castle, CI = Cerrillos.

at appropriate locations allowed the effects of chemical variation within the shale on the conversion of smectite to illite in the bentonites and the effects of contact metamorphism by igneous intrusives to be studied.

Shale samples were collected directly below all sampled bentonites. Efforts were taken to obtain fresh material from the best exposures. Where that was not possible, samples were acquired 15–30 cm below the surface, usually at such a depth that bedding could be identified. The calcareous nature of the shale was determined using 10% HCl.

To determine the effects of carbonate on the clay mineralogy of the shales and bentonites, stratigraphic sections of the lower, noncalcareous Graneros Shale and the overlying calcareous units of the Greenhorn Formation were sampled at Canon City, Colorado Springs, and New Castle, Colorado (Figure 3). Numerous bentonites in both the calcareous and noncalcareous units were sampled at all three sites. Several samples of Greenhorn limestones were also collected to compare the clay mineralogy of their insoluble residues with that of nearby shales and bentonites.

Contact metamorphic effects were determined from samples of shale and bentonite acquired at various distances from an Oligocene monzonite pluton at Cerrillos, New Mexico. Samples near other intrusive bodies were collected at Harmony, Utah, and at Gunnison and Crested Butte, Colorado.

X-Ray powder diffraction analysis

Shale and bentonite samples were prepared for X-ray powder diffraction (XRD) analysis in the following manner. Disaggregation and suspension of the shales was achieved by ultrasonic scrubbing, agitation in a Waring Blendor, or extended periods of agitation in an automatic shaker. HCl (1 N) was employed for carbonate removal. NaCl saturation was employed to achieve homionic saturation of the clays. Bentonites simply required extended periods of agitation for adequate disaggregation. The resulting suspensions of shales and bentonites were then treated with 0.01 N sodium pyrophosphate (a peptizing agent). The <2-μm (equivalent spherical diameter) fraction was obtained by centrifugation; for some samples the <1- and <0.5-μm fractions were also extracted. Oriented samples for XRD analysis were obtained by mounting the clay–water suspensions onto either porous ceramic plates or glass slides.

Five hundred eighty oriented samples were prepared and dried at 95°C, glycolated by the vapor method, and analyzed by XRD methods using CuKα radiation and a GE XRD-5 diffractometer. (For better resolution, a Siemens D-500 diffractometer equipped with a graphite crystal monochrometer was used.) The percent illite in the I/S clay was determined by the position of the illite(002)/smectite(003) reflections for randomly interstratified clays, and the 27-Å superlattice(005)/illite(002) reflections for ordered interstratified clays (Reynolds and Hower, 1970). These reflections occur at 15.8°–17.5°2θ depending on the illite content and the nature of the interstratification. The error in the estimate is generally ±5% but may be much higher for some shale samples due to interference by discrete illite.

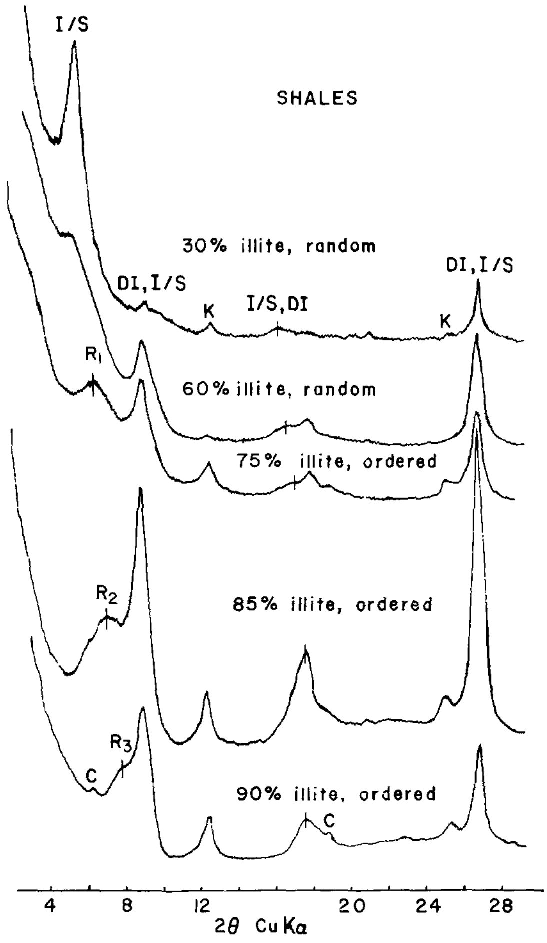

Figure 4. X-ray powder diffraction patterns of clays from shales. I/S = illite/smectite, DI = discrete illite, K = kaolinite, C = chlorite. R_1, R_2, R_3 are degrees of ordering (see text). The vertical line between 16° and 18°2θ indicates the position of the I/S maxima used to determine the percent illite.

RESULTS

X-Ray powder diffraction of clays from shales and bentonites

XRD results for the <2-μm fractions of shales and bentonites show that the dominant clay minerals are I/S and smectite. Representative XRD patterns from shales and bentonites are shown in Figures 4 and 5, respectively. Three types of ordered interstratification of I/S have been observed and generally exhibit higher illite content at higher degrees of ordering. The first is nearest-neighbor ordering composed of IS structural units. I/S exhibiting this type of ordering is referred to as rectorite. The second type is not as common; the structural unit is IIS. The third is referred to as the Kalkberg type and is composed of IIIS structural units (Reynolds and Hower, 1970). These degrees of ordering are also referred to as Reichwite 1, 2, and 3 (R1, R2, R3), respectively (Jadgodzinski, 1949).

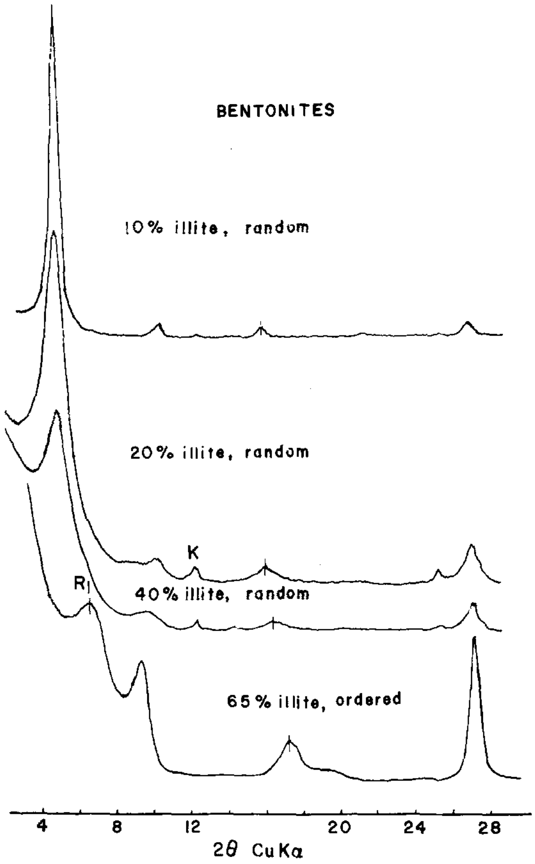

Figure 5. X-ray powder diffraction patterns of I/S from bentonites. K = kaolinite, R_1 indicates the degree of ordering. Vertical line between 16° and 18°2θ indicates position of I/S maxima used to determine the percent illite.

Kaolinite is a common accessory mineral in both bentonites and shales. Rarely it is the primary constituent of some bentonites. Discrete illite is an accessory mineral in most shales; however chlorite is present in relatively few shales, occurring in samples in which the I/S is ordered and highly illitic (≥80%) and as a minor constituent in shales which lack I/S but which contain a dominant, discrete illite phase.

The percentage of illite layers in the I/S in shales is shown in figure 6A. The most abundant clay mineral is random I/S, with 40–55% illite. Ordered interstratification is not present in I/S samples containing <60% illite. From plots of these same data (Figure 6B), two separate groups emerge: calcareous (C) and noncalcareous (N).

The I/S data for bentonites are also shown on Figure 6A. The most abundant clays are smectite and random I/S with <20% illite. Ordered interstratification occurs in I/S which contains ≥50% illite. This value is somewhat smaller than the ≥60% illite in I/S from shales. The correlation between the percent illite in I/S from bentonites and that from immediately underlying shales

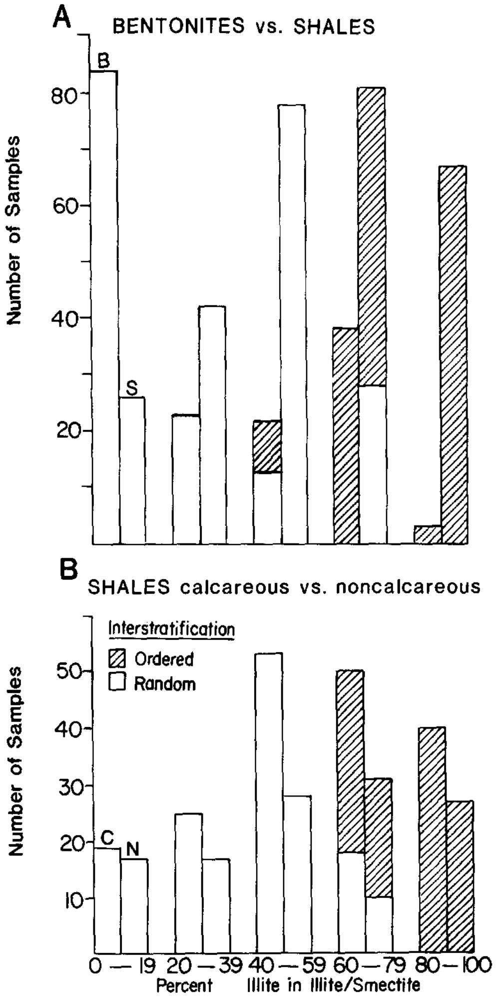

Figure 6. A. Distribution of percent illite and nature of interstratification in I/S from bentonites (B) and shales (S), B. Same data for calcareous (C) and noncalcareous (N) shales.

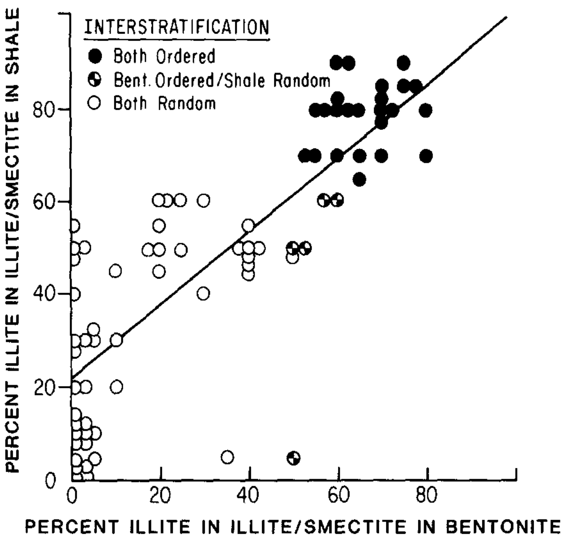

Figure 7. Percent illite in I/S in bentonites vs. percent illite in I/S in subjacent shales.

is shown in Figure 7 as is the nature of interstratification of the sample pairs. Only those sample pairs (77 total) in which the bentonite contains no discrete illite (detrital contaminant) were used for this comparison. Linear regression analysis gives a high correlation coefficient of 0.833 (slope 0.795, intercept = 22), particularly for ordered interstratifications (shaded circles, upper right, Figure 7). The correlation is less marked for random interstratification. The transition from random to ordered interstratification is marked by several sample pairs for which the I/S in the bentonite is ordered, but the I/S in the shale is random (half-shaded circles, Figure 7).

If the relationship depicted in Figure 7 is primarily of metamorphic origin, the figure can be divided into three fields: (1) random I/S, T < 100°C (cf. Perry and Hower, 1970), lower left; (2) a transition zone defined by those sample pairs in which the bentonite contains ordered I/S whereas the shale contains random I/S (T ~ 100°C); and (3) the upper right region that corresponds to ordered interstratification (T > 100°C). Acknowledging that the presence of ordered I/S in the bentonites (≥50% illite) is probably the result of metamorphism, the similarity of the I/S in bentonites and adjacent shales (≥60% illite) confirms that ordered I/S in the shales is also caused by metamorphism.

Detailed XRD and chemical studies of stratigraphic sections

The clay mineralogy of shales and bentonites and the calcareous nature of shales from the Canon City section are summarized on Figure 8. A marked difference exists in the nature of the interstratification of I/S from random to ordered and coincides with the stratigraphic boundary between the calcareous shales of the Greenhorn Formation and the noncalcareous shales of the Graneros Shale.

The bentonites in the Graneros Shale at Canon City are mainly kaolinite. The I/S composition was obtained from the <1-μm or <0.5-μm size fractions. Ordered I/S with 50% illite is not common regionally, but, occurs in the fine size fractions of these bentonites. Most bentonites and all of the shales from the Greenhorn Formation contain smectite and random I/S. Bentonites MB670 and MB671 in the Greenhorn section unexpectedly contain ordered I/S; however, these bentonites have more in common with bentonites in the Graneros Shale than they do with other Greenhorn bentonites in as much as they are intercalated with noncalcareous rather than calcareous shale. The clays in the insoluble residue extracted from a sample of Greenhorn limestone are similar to those from calcareous

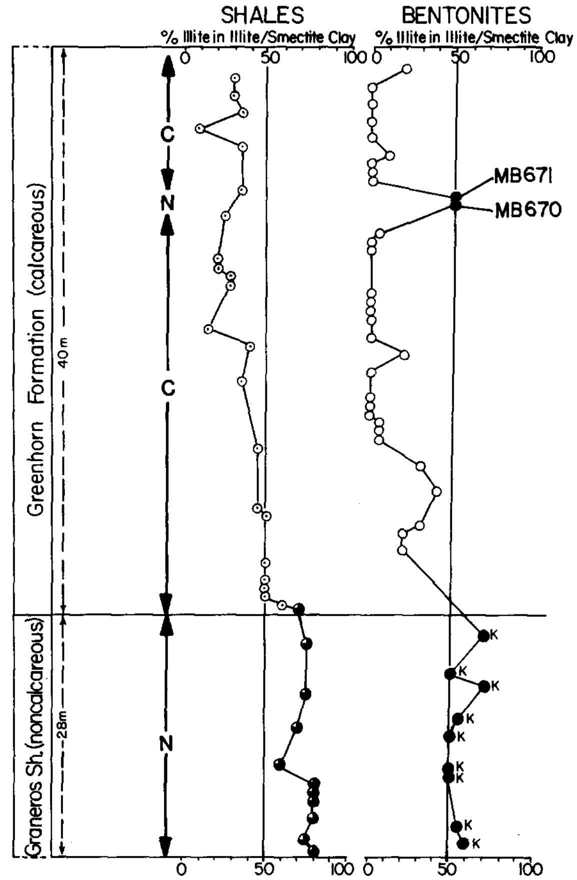

Figure 8. I/S clay mineralogy from stratigraphic section at Canon City, Colorado. Random interstratification is indicated by open circles (with a dot in the middle for shales), and ordered interstratification is indicated by shaded circles (¾ shaded for shales). K indicates that kaolinite is the dominant clay mineral. Calcareous and noncalcareous shales are indicated by (C) and (N), respectively.

shales. The I/S is randomly interstratified, with 55% illite.

The results from the Colorado Springs section are shown in Figure 9A. At this locality the clay mineralogy is relatively uniform, consisting of random I/S in the shales and smectite in the bentonites. In contrast to the assemblages at Canon City, there are no marked differences between calcareous and noncalcareous shale. The results from the New Castle section are shown in Figure 9B. Despite the variable carbonate content of the shales, the clay composition of both shales and bentonites is uniform and characterized by ordered I/S, with ≥55% illite. The clay in the insoluble residue extracted from limestone at this locality is also ordered I/S, with 70% illite.

The effect of the carbonate content of the shales on the conversion of smectite to illite can be evaluated from the data from these three stratigraphic sections. The New Castle section (Figure 9B) demonstrates that, regardless of the carbonate content of the shales, the I/S in both shales and bentonites is ordered, with >50% illite. This represents a metamorphosed clay suite. Additional supporting evidence for uniform burial metamorphism is provided by the presence of ordered I/S in the insoluble clay residue extracted from limestone. The Colorado Springs section (Figure 9A) is unmetamorphosed; the bentonites contain smectite, and the shales have random I/S of low illite content. The Canon City section is transitional because the shales and bentonites exhibit smectite, random I/S, and ordered I/S. The differences in I/S clays are apparently related to variations in the carbonate content of the shale. Such chemical factors would be most effective during the incipient stages of the reaction. The association of kaolinitic bentonites in the noncalcareous shale probably indicates major differences in solution chemistry and mineral equilibria which may be more favorable to the formation of ordered I/S as compared to those conditions in the calcareous shales. The lesser quantity of I/S in kaolinitic bentonites may in itself promote the more rapid and/or lower temperature formation of ordered I/S because less alumina and potassium would be required. The Upper Cretaceous and Paleocene sediments above the Greenhorn Formation in the nearby Florence basin are 2 km thick (Scott, 1977). This thickness represents the possible minimum depth of burial of the Canon City section, and it is in reasonable agreement with the metamorphic interpretation because normal geothermal gradients indicate a temperature of ~80°C for a 2-km depth of burial. A clay-carbonate association similar to Canon City was also found at Acoma, New Mexico.

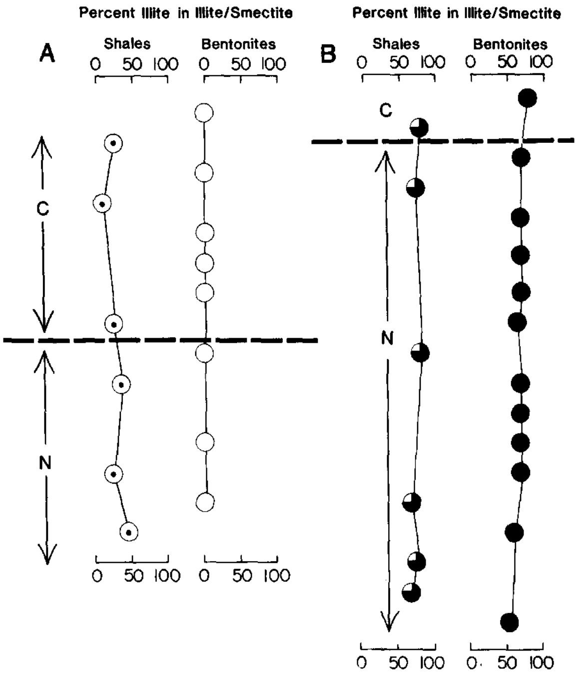

Figure 9. I/S clay mineralogy from stratigraphic section at Colorado Springs, Colorado (A) and New Castle, Colorado (B). Format and symbols are the same as in Figure 8.

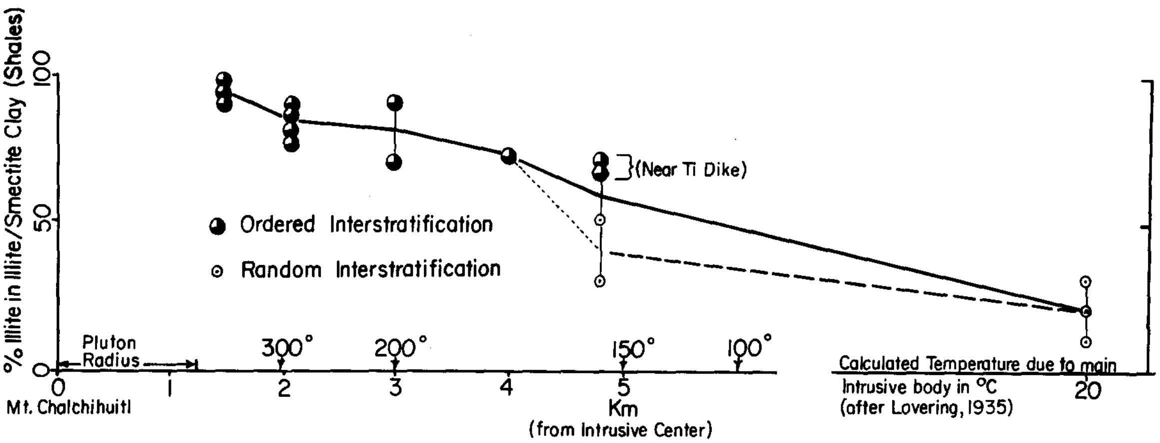

Figure 10. I/S clay mineralogical variation in the Mancos Shale vs. proximity to igneous pluton at Cerrillos, New Mexico.

Effects of proximity to igneous intrusive bodies

Figure 10 summarizes the effects of proximity to an igneous intrusive body (Disbrow and Stoll, 1957) on the I/S clay mineralogy in the shales at Cerillos, New Mexico. The temperature was computed using the equations and assumptions of Lovering (1935). The parameters used are for a cylindrical stock, 2.5 km in diameter, having an initial pluton temperature of 750°C, an initial wall rock temperature of 30°C, and a diffusivity of 0.008.

The I/S in the bentonites is similar to that of enclosing shales. Most of the bentonites at or within the 200°C isotherm have Reichwite 2 ordering; one has Riechwite 3 ordering. The shales within the 200°C isotherm exhibit Reichwite 3 ordering, and many contain chlorite. Samples ~5 km from the intrusive center contain random I/S except for those in close proximity to a Tertiary dike. Shale samples 20 km to the east (Gallisteo, New Mexico) consist of random I/S; the bentonites consist of smectite. The percentage of illite layers in the I/S close to the intrusion is markedly larger. The I/S changes from random to ordered interstratification between the 100° and 150°C isotherm about 5 km from the intrusive center. This temperature range is somewhat higher than the 100°C reported by others for the conversion reaction, and may be due to incorrect parameters used to calculate the isotherms or failure to consider other factors such as hydrothermal fluid flow which would modify the chemical equilibria and/or the heat transfer between the pluton and enclosing sediments.

Samples near other Tertiary igneous intrusions at Crested Butte and Gunnison, Colorado, and Harmony, Utah, contain ordered I/S. Illite/smectites from several shales from Crested Butte have Reichwite 3 ordering and also contain chlorite. This clay mineral assemblage is similar to shale samples collected at or within the 200°C isotherm at Cerrillos.

Regional I/S clay mineralogy

The regional distribution of I/S data from shales and bentonites has been integrated in Figure 11. Randomly interstratified species were grouped with smectite; ordered structures were placed in a single category regardless of their percent illite. Thus, two possible designations represent the limits of inferred metamorphism. Most of the symbols in Figure 11 represent several samples and, in some cases, several sample sites.

Regionally, the interstratification data can be interpreted as delineating regions of metamorphosed, transitional, and unmetamorphosed I/S clay. The metamorphosed areas in Figure 11 include the flanks of the White River Plateau, a northeast-southwest zone across Colorado terminating in the San Juan Mountains, the southern portion of the Raton Basin, and the northern flanks of the San Juan Basin. These areas represent zones of greater depth of burial or higher geothermal gradients. Transitional regions, i.e., those that have undergone incipient stages of metamorphism, include parts of the southern flanks of the Uinta Basin and localized areas of Canon City and in the San Juan and Raton Basins. Also included in this classification are areas where the presence of ordered I/S can be directly attributed to the proximity of the igneous intrusives, including Cerrillos, New Mexico, Harmony, Utah, and Gunnison, Colorado. Unmetamorphosed regions include the flanks of the Uinta Mountains, the North Park Basin, the Colorado Springs region, and, in general, the entire Colorado Plateau, the southern flanks of the San Juan Basin, and the Arkansas River Valley.

The distribution of regions of different metamorphic intensities can be correlated with other geologic data for the southern Rocky Mountains. A correlation between coal rank and I/S types in other sedimentary provinces has been reported by Środoń (1979) and Heroux *et al.* (1979). High ranks of coal are rich in fixed

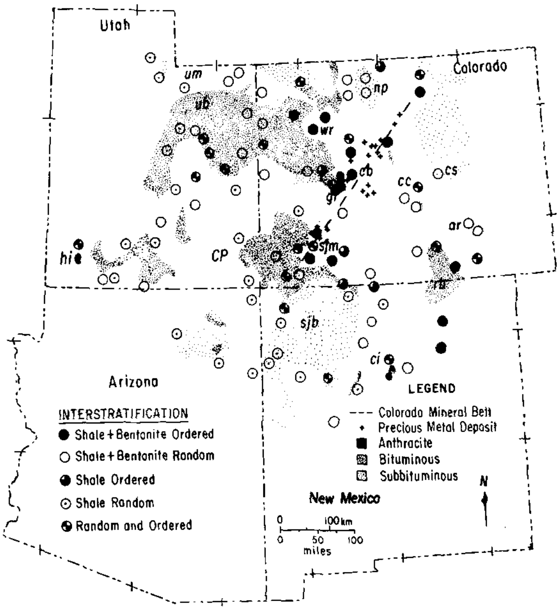

Figure 11. Regional distribution of random and ordered interstratification of I/S within the Mancos Shale and bentonites, and correlation with rank of coal and tectonic features. Localities: ar = Arkansas River Valley, cb = Crested Butte, cc = Canon City, ci = Cerrillos intrusive, cp = Colorado Plateau, cs = Colorado Springs, gi = Gunnison intrusive, hi = Harmony intrusive, np = North Park basin, rb = Raton basin, sjb = San Juan basin, sjm = San Juan Mountains, ub = Uinta basin, um = Uinta Mountains, wr = White River Plateau.

carbon and have low moisture and volatile contents. The increase in coal rank is primarily a response to heat from burial and/or proximity to igneous intrusives with the boundary between subbituminous and bituminous coal being 45% fixed C, and between bituminous and anthracite, 80% fixed C.

The variation in the rank of Cretaceous and Tertiary coals in the southern Rocky Mountains is also shown in Figure 11 (Averitt, 1972). The three anthracite localities are in areas of contact metamorphism (Harmony, Cerrillos, and Crested Butte). At Crested Butte, the I/S from shales is 80–90% illite, even as far as 5 km from the intrusives. This I/S is similar to that found at or within the calculated 200°C isotherm at Cerrillos. The association of this clay mineralogy with anthracite coal is in good agreement with thermal maturation data compiled by Heroux *et al.* (1979). Areas of subbituminous coal are generally those of unmetamorphosed clay, whereas areas of bituminous coal contain both metamorphosed and unmetamorphosed clay suites. The regional relationship is fair, but not overwhelming, partly because the coal-rank data pertain to both Cretaceous and Tertiary coals. Cretaceous coal is mainly bituminous, whereas Tertiary coal, in the southern Rocky Mountains, is mainly subbituminous due, presumably, to its shallower burial depths. Mineralogical data for Cretaceous sediments, particularly at Black Mesa and the Kaiparowitz Plateau, southwestern Utah (Figure 11), indicate that the increase of rank coal from subbituminous to bituminous precedes the transformation from random to ordered I/S, a finding that is in agreement with the thermal maturation indicators compiled by Heroux *et al.* (1979). Tongue Mesa, just northeast of the San Juan Mountains, is the site of a small Cretaceous coal field in a region where the the rank changes markedly over a short distance. Here the coal is subbituminous, whereas Cretaceous coals to the northeast and southwest are bituminous. Tongue Mesa is in the gap in the clay metamorphism of this region (Figure 11).

The northeast-southwest zone of metamorphosed clay across Colorado correlates well with a similar trending zone of Laramide igneous activity and mineral deposits known as the Colorado mineral belt (Figure 12) (Burbank and Lovering, 1933; Vanderwilt *et al.*, 1972; Tweto, 1975). A gap in the igneous activity and mineralization exists along the trend of the Colorado mineral belt northwest of the San Juan Mountains, and correlates with the unmetamorphosed area mentioned above.

The timing of tectonic events may also have controlled the depth of burial of Upper Cretaceous strata. Early Laramide positive tectonic elements, which formed about 65 m.y. ago, may not have accumulated much additional sedimentary thickness over the Cretaceous marine deposits, due to narrow timing constraints (Tweto, 1975). This postulate may explain the differences between the unmetamorphosed nature of I/S along the flanks of the Uinta Mountains and North Park Basin, both early Laramide features, and the metamorphosed nature of I/S along flanks of the White River Plateau, a younger, Eocene, Laramide feature (Poole, 1954; Tweto, 1975).

DISCUSSION AND CONCLUSIONS

Particularly good agreement exists between the nature of interstratification of I/S in bentonites and adjacent shales. For both random and ordered interstratifications, the percent illite in I/S from shales is generally greater than that from bentonites. Ordered interstratification in bentonites occurs prior to, and at a lower illite content (50%) than in shales (60%), confirming the findings of Schultz (1978).

The bulk composition of the shale (calcareous vs. noncalcareous) significantly affects the I/S and associated clay mineral assemblage of the shales as well as of the interbedded bentonites. No clear picture has emerged from bulk chemical analyses of shales from Canon City, New Castle, Colorado Springs, Cerrillos, and other selected sites to explain these results (Nadeau, 1980). Factors which may be of importance include the pH of formation solutions in carbonate-buffered and carbonate-free systems and its effect on mineral equilibria. In addition, the interlayer-cation composition of the smectite may be important (Eberl, 1978).

The anomalous occurrence of kaolinitic bentonites associated with ordered I/S in the noncalcareous section at Canon City suggests that these minerals may be geochemically related. The association of higher illite percentages in the I/S and the dominant presence of kaolinite was observed in the Silesian Coal Basin by Parachoviak and Środoń (1973) who suggested that the illite formed from montmorillonite by sorbtion of potassium released during hydromorphic weathering and kaolinization of glass. Alternatively, kaolinite and I/S may form from smectite in K-poor environments (Eberl, 1971). Kaolinitic bentonites in the Graneros Shale are not always associated with ordered I/S; rarely, they occur with random I/S. Comparison of the bentonites from the noncalcareous section at Colorado Springs (primarily smectite) with the corresponding bentonites from Canon City (primarily kaolinite) indicates that the kaolinite may have formed after the alteration of volcanic ash to smectite. Alternatively, kaolinitic bentonites may represent local, chemically anomalous conditions, which later affected the rate of transformation of smectite to illite. The above arguments, however, are not completely satisfying, and more detailed field and experimental studies are necessary. Kaolinitic bentonites are not common in the Mancos Shale, but have been found elsewhere, e.g., in the Pierre shale (Schultz, 1963).

The assignment of clay mineral assemblages in pre-greenschist facies metasediments to respective metamorphic grade was recently treated by Hoffman and Hower (1979). The results presented here, particularly the I/S data, are in good agreement with those assignments for shales. The first appearance of chlorite, however, is associated with highly illitic, Kalkberg type (R3), or IMII ordering I/S in a high-grade contact environment, and not with the allevardite type (R1) or IM ordering I/S reported by Hoffman and Hower (1979). In addition, the assemblages and associations at Canon City necessitate an adjustment (lowering?) of the temperature for the formation of ordered I/S in carbonate-free systems. This point may be relevant to the Gulf Coast data presented by Hower *et al.* (1976) which show that the formation of ordered I/S with depth is accompanied by a loss of calcite. Is the transition from random to ordered I/S in the Tertiary pelitic sediments of the Gulf Coast in response to increased temperature, a change in pore-fluid chemistry, or both? The above arguments underscore the importance of determining to what extent, in addition to thermal history, observed mineral assemblages are influenced by (1) initial (detrital) mineral assemblages, (2) minerals formed as a result of premetamorphic alteration, (3) bulk chemical composition, e.g., isochemical reactions in closed systems as proposed by Hower *et al.* (1976), and (4) metasomatic processes, e.g., open chemical systems as proposed by Weaver and Beck (1971).

Bulk composition, particularly with respect to the presence of calcium carbonate, has been shown here to inhibit the formation of ordered I/S, primarily during the incipient stages of the reaction. Despite these effects, however, the distribution of random vs. ordered I/S in Cretaceous marine shales and bentonites from the southern Rocky Mountains delineates areas of burial metamorphism from unmetamorphosed areas on both a regional and local scale. This distribution correlates well with other geologic data, and suggests that metamorphosed clay suites represent areas of deeper burial and/or higher geothermal gradients on a regional scale and areas more proximal to the thermal effects of igneous intrusions on a local scale.

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Резюме—Образцы глин из сланцев и бентониты из Манкос Сланца (мелового) и их стратиграфические эквиваленты в южных Сколистых Горах и на Плато Колорадо анализировались методом порощковой рентгеновской дифракции. Гдавной глиной в сланцах являлся смешанно-слойный иллит/смектит с 20–60% иллитовых слоев. Местное распределение упорядоченной-случайной внутренней стратификации в иллите/смектите соответствует гипотезе метаторфизма захоронений, при котором слои смектита преобразовавались в иллит, результатом чего была упорядоченная внутренняя стратификация. Данные по этой стратификации соответствовали другим геологическим информациям, включая степень науглероживания угля и ларамидо-тектоническую активность. Дополнительно, контактный метаморфизм сланца приводил к образованию подобных систем глин путем третичных изверженных интрузии. Химические изменения внутри этих сланцев (особенно присутствие или отсутствие карбонатов) влияли на реакции преобразования глин во внутринапластованных бентонитах и самых сланцах в течение ранних стадий трансформации. В исключительных случаях сланцы и бентониты из одного обнажения пород могут содержать глины от чистого смектита (известковые сланцы) до упорядоченных иллитов/смектитов, содержащих ≥50% иллитовых слоев (неизвестковые сланцы). Использование составов смещанно-слойных иллитов/смектитов для определения термальных режимов, таким образом, может быть ощибочным, если не принять во внимание местный химический контроль. [E.C.]

Resümee—Es wurden Tonproben aus Schiefertonen und Bentoniten im Mancos Schieferton (Kreidezeit) und aus den stratigraphisch äquivalenten Schichten der südlichen Rocky Mountain und des Colorado Plateau mittels Röntgenpulverdiffraktometer-Methoden untersucht. Das überwiegende Tonmineral in den Schiefertonen ist eine Illit/Smektit-Wechsellagerung mit 20–60% Illitlagen. Die regionale Verteilung von regelmäßigen vs. unregelmäßigen Wechsellagerungen im Illit/Smektit stimmt mit der Vorstellung einer Versenkungsmetamorphose überein, durch die die Smektit-Zwischenlagen in Illit umgewandelt werden, wodurch letztlich eine regelmäßige Wechsellagerung entsteht. Die Ergebnisse über die Wechsellagerung stimmen mit anderen geologischen Informationen einschließlich Kohlearten und laramische Tektonik überein. Darüberhinaus lieferte die Kontaktmetamorphose der Schierfertone durch tertiäre Intrusionen eine ähnliche Tonabfolge. Chemische Schwankungen innerhalb dieser Schiefertone (vor allem das Vorhandensein oder Nichtvorhandensein von Karbonat) beeinflussen während der ersten Umwandlungsstadien die Umwandlungsreaktionen des Tons in den zwischengelagerten Bentoniten und im Schieferton selbst. In extremen Fällen können Schiefertone und Bentonite aus einem einzigen Aufschluß Tonminerale enthalten, die vom reinen Smektit (kalkhaltiger Schieferton) bis zur regelmäßigen Illit/Smektit-Wechsellagerung mit ≥50% Illitlagen (kalkfreier Schieferton) reichen. Eine Schlußfolgerung von den Zusammensetzungen der Illit/Smektit-Wechsellagerungen auf thermische Einflüsse kann daher irreführend sein, wenn nicht lokale chemische Untersuchungen in Betracht gezogen werden. [U.W.]

Résumé—On a analysé par des méthodes de diffraction poudrée aux rayons-X des échantillons d'argile de shales et de bentonites dans le shale Mancos (crétacé) et dans ses équivalents stratigraphiques dans les Montagnes Rocheuses du sud et sur le plateau du Colorado. L'argile majeure dans les shales est l'illite/smectite à couches mélangées, avec 20–60% de couches d'illite. La distribution régionale d'interstratification ordonnée par rapport à l'interstratification sans ordre dans l'illite/smectite est compatible avec le concept de métamorphisme à l'enterrement, dans lequel les intercouches de smectite sont converties à l'illite, résultant finalement en une interstratification ordonnée. Les données d'interstratification s'accordent avec d'autres renseignements géologiques, y compris le rang de charbon, et l'activité tectonique Laramide. De plus, le métamorphisme par contact du shale par des intrusions ignées a produit la même suite argileuse. La variation chimique au sein de ces shales (particulièrement la présence ou l'absence de carbonate) affecte les réactions de conversion d'argile dans les bentonites interfeuillets et dans le shale lui-même pendant les premiers stages de la transformation. Dans les cas extrèmes, les shales et les bentonites d'un seul affleurement peuvent contenir des argiles qui s'étagent de smectite pure (shales calcareux) à une illite/smectite ordonnée contenant ≥50% de couches d'illite (shales non calcareux). C'est pourquoi l'emploi de compositions d'illite/smectite à couches mélangées pour impliquer des régimes thermaux peut être trompeur, à moins qu'on ne tienne compte de contrôles chimiques locaux. [D.J.]