A Petrologic Study of the Fox Hills Sandstone, Rock Springs Uplift, Wyoming

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A Petrologic Study of the Fox Hills Sandstone, Rock Springs Uplift, Wyoming

By NELSON L. HICKLING

A petrographic and stratigraphic study of the Fox Hills Sandstone interpreting provenance, depositional environment, and diagenesis

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CIP

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CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

To convert from	To	Multiply by
Inches (in)	Centimeters (cm)	2.54
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609

A Petrologic Study of the Fox Hills Sandstone, Rock Springs Uplift, Wyoming

By Nelson L. Hickling

Abstract

New petrographic data provide support for many earlier conclusions regarding the depositional history of the Fox Hills Sandstone, Rock Springs Uplift, Wyo., and also provide the basis for new interpretations. The presence of framework grains of primary dolomite, sedimentary structures, and coarsening-upward grain-size sequences supports a shallow-marine, regressive origin of the Fox Hills Sandstone. Detrital dolomite and limestone (rare) in conjunction with a large fraction of chert indicate that the source area provided a large volume of dolomite and limestone and was near enough to the depositional basin that small quantities of the carbonate rocks survived the transport. Moreover, numerous rock fragments consisting largely of shale, siltstone, and sandstone indicate that the Fox Hills Sandstone was derived from a sedimentary terrane that was probably in the vicinity of the Sevier orogenic belt to the west.

Secondary dolomite formed a partial to complete rim around all primary dolomite grains during diagenesis. This study suggests that secondary dolomite grew epitaxially with the separate subunits of oriented crystal exposed on the surface of the detrital grains and as a result formed an irregular rind around the grains that obscures the original rounded surface.

Investigation of the "white-cap" sandstone that lies beneath the Hall coal bed and overlies the brown sandstones of the Fox Hills reveals a number of differences in this occurrence from those "white-caps" that are thought to have resulted from a weathering regime that included organic-acid-charged ground waters. The present study concludes that the "white-cap" in the Fox Hills Sandstone resulted from its depositional setting, not from acid leaching.

INTRODUCTION

The Late Cretaceous (Maestrichtian) Fox Hills Sandstone crops out for 40 mi along the east flank of the Rock Springs Uplift in southwestern Wyoming (fig. 1). A 5-mi segment of this exposure in the Bitter Creek NW quadrangle was selected for this study, which focuses on the petrography of the Fox Hills Sandstone.

One hundred and twenty-six oriented sandstone samples were collected at 5-ft intervals along four traverses through the Fox Hills Sandstone (figs. 2 and 3). The sampling plan was formulated to provide representative samples throughout each unit. Only siltstone and sandstone beds in the Fox Hills Sandstone were sampled. A marine shale tongue of the Lewis Shale was measured but not sampled.

Occurrences of detrital, primary, and secondary dolomite support interpretations regarding provenance, depositional environments, and diagenesis. Of particular interest is a 25- to 40-ft-thick "white-cap" sandstone unit at the top of the Fox Hills Sandstone. The white sandstone underlies the 6- to 8-ft Hall coal bed, which is at the base of the Lance Formation. This study shows that these white-cap sands did not develop under coal beds because of organic-acid leaching and weathering. An alternative explanation based on depositional factors is proposed.

The numerous published and unpublished studies of the Fox Hills Sandstone and adjacent units by Roehler (1961, 1965, 1977, 1983) provided the stratigraphic and depositional framework for this petrologic study. Additional publications on the Late Cretaceous rocks of the Rock Springs Uplift that are relevant to this study are those by Douglas and Blazzard (1961), Pryor (1961), Smith (1961), Weimer (1961, 1965), Harms and others (1965), and Hoyt and Weimer (1965).

FIELD RELATIONS

The outcrops of the Fox Hills Sandstone in the study area strike about N. 45° W. and dip about 7° NE. The exposures typically form ledges and cliffs 140 to 270 ft high. At the base of the prominent sandstone outcrops is a 10- to 50-ft-thick zone of very thin parallel-bedded shale and siltstone that represents the lower shoreface environment of the Fox Hills Sandstone. In the covered valley below these beds, several hundred feet of Lewis Shale were deposited in an offshore marine environment.

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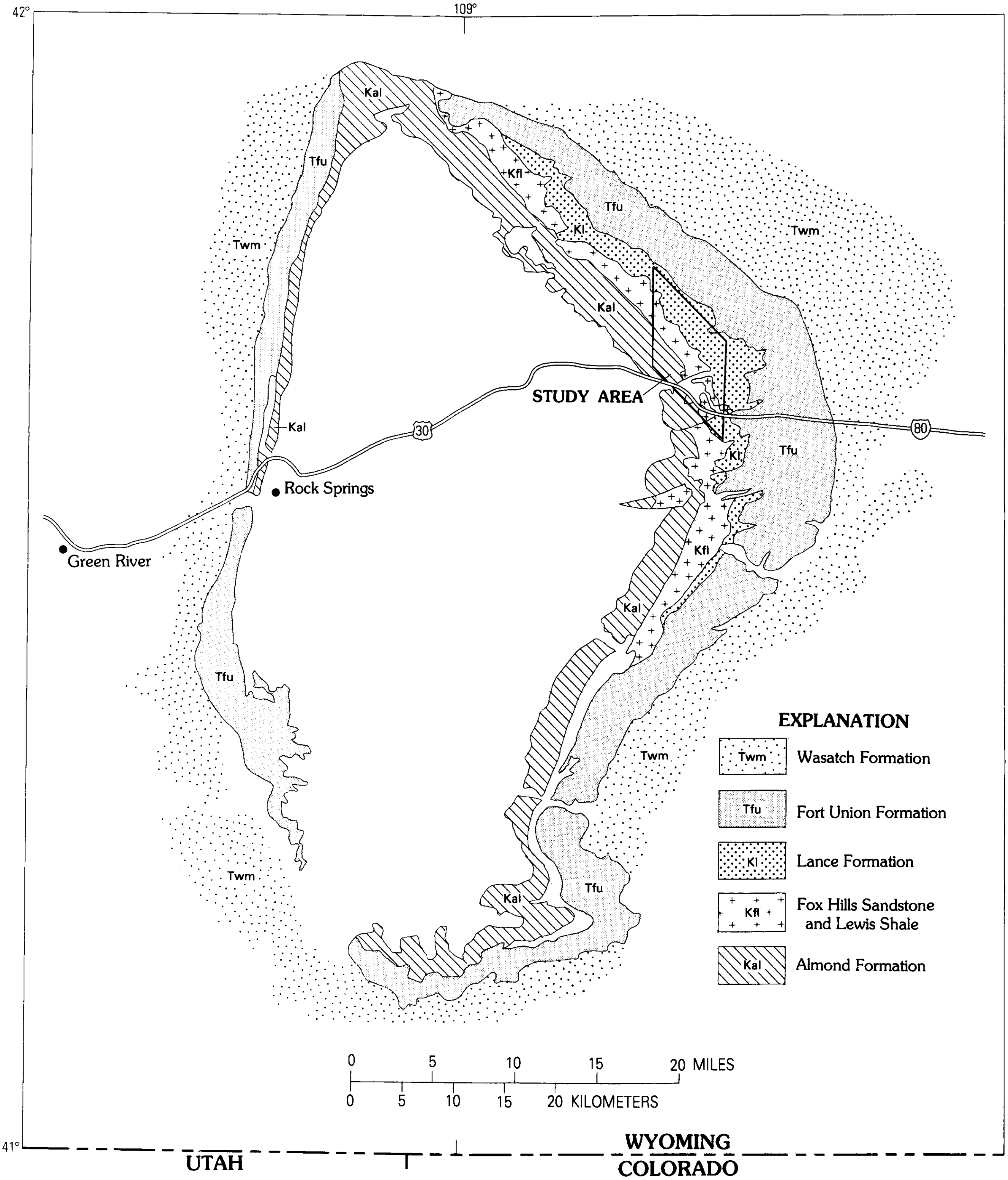

Figure 1. The study area in relation to the Rock Springs Uplift, Wyo. Map explanation is simplified to indicate only those formations in or adjoining the study area. Map is reproduced from the Geologic Map of Wyoming, compiled by Love and Christiansen (1985).

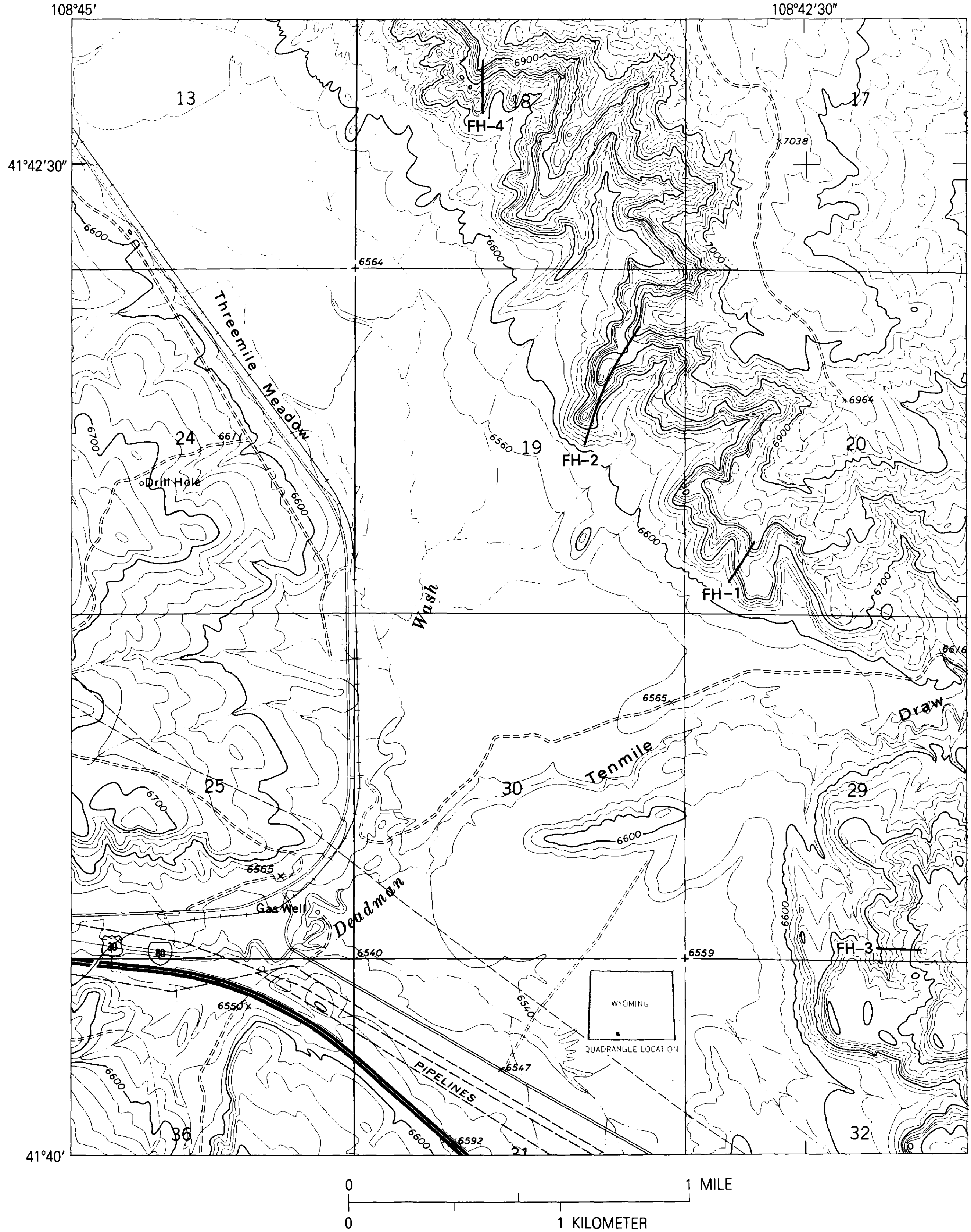

Figure 2. The four measured sections in the Fox Hills Sandstone, Rock Springs Uplift, Wyo., from which the samples studied in this report were collected. These sections are within the Bitter Creek NW quadrangle.

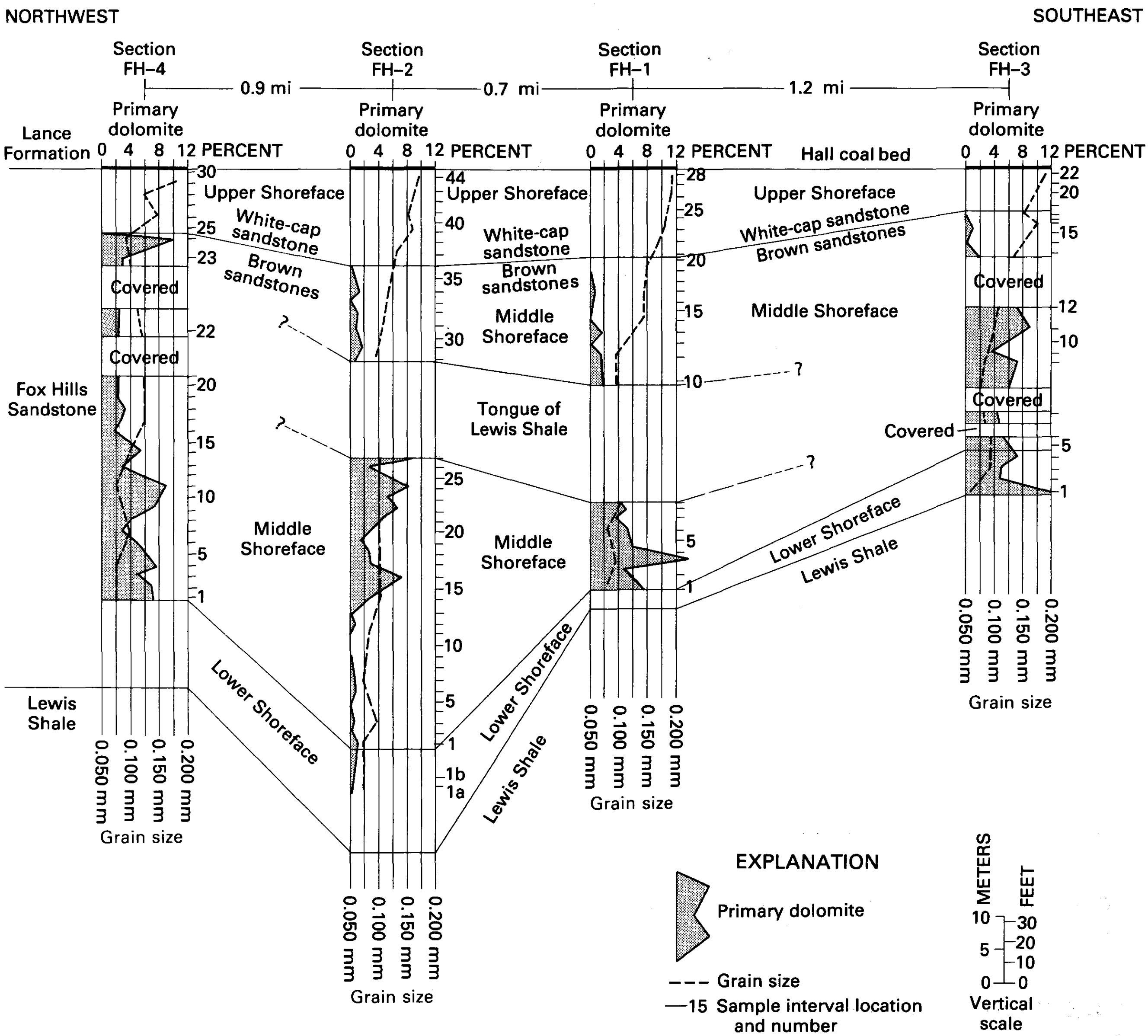

Figure 3. Framework grain size and primary dolomite abundance plotted by sample location to show relationship to depositional environment.

In the middle part of the Fox Hills Sandstone are deposits representing the middle shoreface environment (fig. 3). These sandstones are brown, generally massive, contain abundant *Ophiomorpha*, and have local low-angle trough crossbeds. A tongue of the marine Lewis Shale is exposed in sections FH–1 and FH–2 (fig. 3). It is difficult to correlate the marine tongue laterally across the study area because parts of sections FH–3 and FH–4 are covered.

Above the middle shoreface deposits in the Fox Hills Sandstone are 20 to 45 ft of upper shoreface sandstone deposits that form a white-cap along the outcrop. These sandstones are fine grained and have medium-scale herringbone crossbeds typical of the upper shoreface zone of deposition. In places, the top 4 ft of the upper shoreface deposits are rooted and may represent weathered backbeach sand dunes.

Overlying the Fox Hills Sandstone is the 6- to 8-ft-thick Hall coal bed of the Lance Formation. The coal bed formed in a lagoon behind a barrier island (Roehler, 1983) or in swamps or marshes related to a drowned coast. Although the Hall coal bed is time transgressive along the eastern flank of the Rock Springs Uplift, it was used as the datum for the four measured sections in the study area.

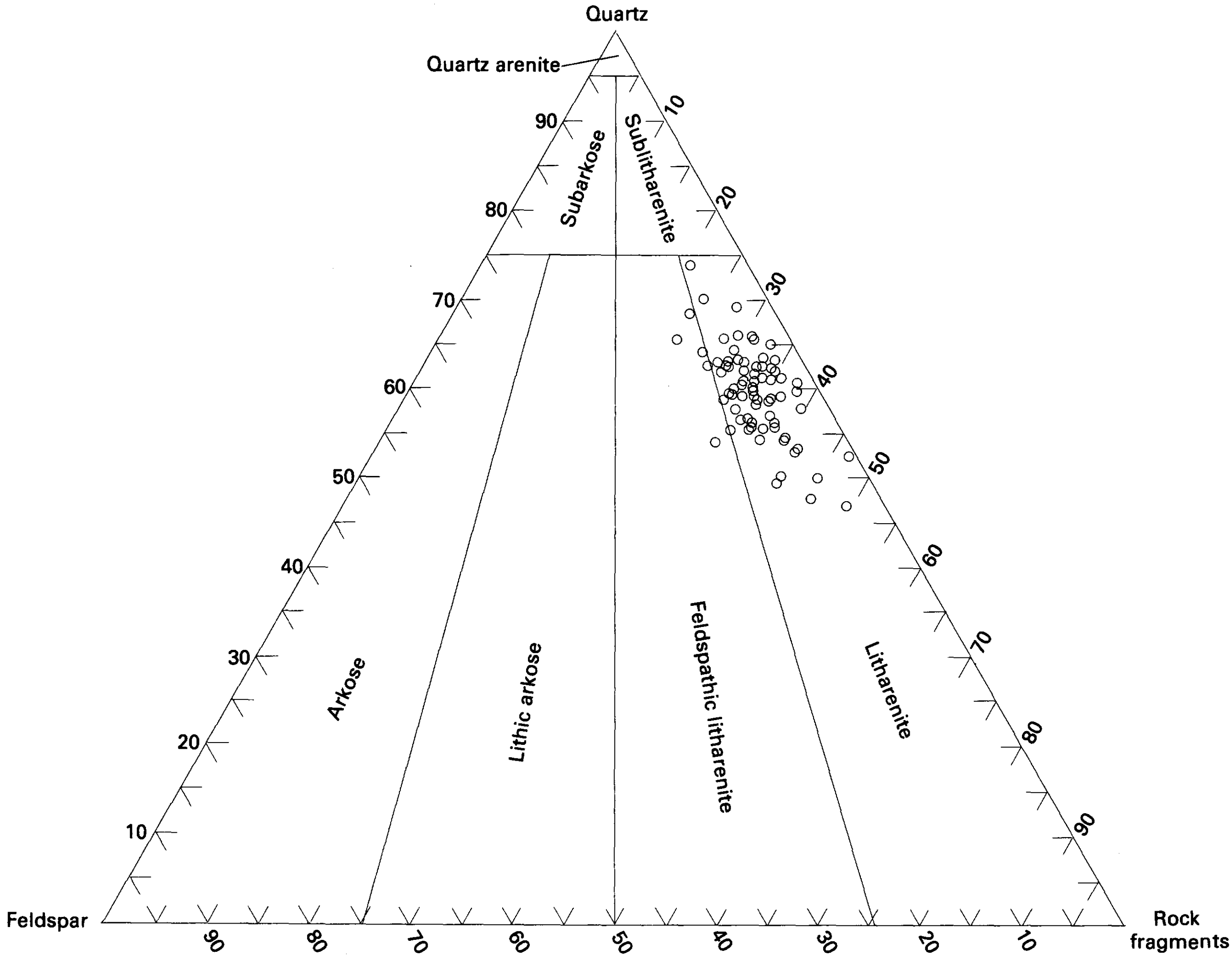

Figure 4. Compositional data from 81 thin sections of brown sandstone from the Fox Hills Sandstone, Rock Springs Uplift, Wyo. Rock classification after Folk (1974).

PETROGRAPHIC OBSERVATIONS AND INTERPRETATIONS

Sandstone Classification and General Characteristics

Modal compositions were calculated for 102 thin sections (table 1). The grains forming the framework were divided into three basic components: quartz, feldspar (all kinds), and rock fragments including chert and dolomite. Each of the three components was plotted on a ternary diagram. Because of the large number of modal analyses, a computer and plotter programmed with TRIANGL (Schacte and others, 1986) were used to plot the data according to Folk's (1974) classification. Data for the brown sandstones are plotted on figure 4, whereas data for the white-cap sandstones are plotted on figure 5. Both the brown and the white sandstones fall in the litharenite field. As much as 90 percent of the feldspar is potassium feldspar, of which less than 10 percent is microcline. The remaining feldspar is well-twinned plagioclase. Of the rock fragments, more than 80 percent is shale and fine-grained siltstone, and much of the remainder consists of phyllite.

The grains forming the sandstone framework are consistently subrounded throughout the sampled part of the outcrop belt. The average roundness value is between 3 and 4 on a chart presented in Pettijohn and others (1973), redrawn from Powers (1953, fig. 1).

The long dimension of 100 grains was measured for each sample by use of a calibrated ocular reticule. The grain-size measurements for 56 representative samples range from coarse silt to fine sand (fig. 3). Grain size coarsens upward. Evidence of only modest compaction is found in these sandstones. Examples of slender, elongate fragments of quartz and feldspar are found both broken and unbroken. Many samples contain mica or chlorite flakes that have been bent moderately as a result of compaction

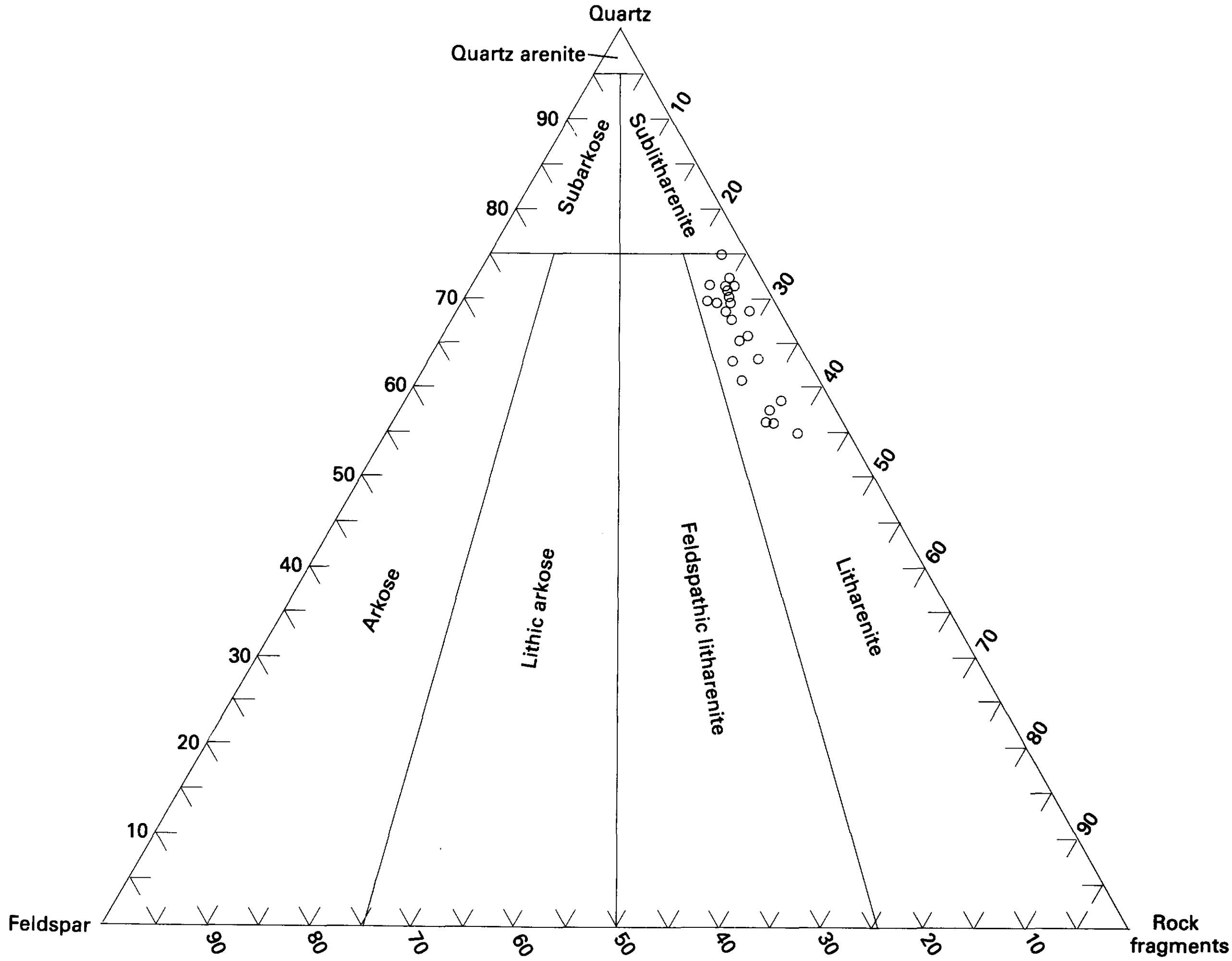

Figure 5. Compositional data from 21 thin sections of white-cap sandstone from the Fox Hills Sandstone, Rock Springs Uplift, Wyo. Rock classification after Folk (1974).

between other framework grains, but no examples of severely twisted mica grains were seen.

The small differences in composition of framework grains between the two groups of sandstones cannot account for the color difference (table 1; figs. 4 and 5). The matrix abundance in the brown sandstones averages 2½ times that in the white-cap sandstones and thus is the probable factor controlling the color difference. Microscopic study shows that the clay fraction of the matrix in the brown sandstones is reddish brown and iron stained, whereas the clay fraction in the white sandstones is light gray or white. Representative brown and white sandstones were carefully crushed and sieved to separate the matrix from the framework grains. The material that passed through a 400-mesh sieve from both sandstone types was analyzed quantitatively by use of computer-augmented X-ray-diffraction methods. The X-ray analysis shows that the white matrix contains no iron and the brown matrix contains as much as several percent argillaceous hematite. Microscopic examination shows that the hematite forms coatings on clumps of clay material (kaolinite and illite). Petrographic observation revealed the presence of dolomite framework grains in most of the brown sandstones and the complete absence of it in the white-cap sandstones.

Dolomite Grains and Cement

Three significantly different occurrences of dolomite are found in the Fox Hills Sandstone. These dolomite types have been recognized and written about since the early 1960's by Sabins (1960, 1962, 1964, 1965) and Sabins and Petersen (1961). Sabins' (1964) initial work on these occurrences resulted from a definitive study of the Cretaceous rocks of the San Juan Basin. Sabins (1965) subsequently documented the occurrence of these dolomite types in several other Cretaceous sandstones of the Rocky Mountain region, including the Fox Hills Sandstone in Wyoming.

Table 1. Modal compositions of the Fox Hills Sandstone, Rock Springs Uplift, Wyoming

[All values are in percent; following the sample number, a "w" stands for white-cap and a "b" for brown sandstone]

Sample no.	Quartz	Chert	Feldspar	Rock fragments	Detrital dolomite	Primary dolomite
FH–1–28w	69.6	13.3	6.6	10.5	0	0
FH–1–27w	56.1	20.3	7.6	15.9	0	0
FH–1–26w	60.8	22.3	7.6	9.3	0	0
FH–1–24w	70.8	16.9	4.0	8.2	0	0
FH–1–23w	71.3	11.0	4.0	13.6	0	0
FH–1–22w	58.5	18.5	4.9	18.2	0	0
FH–1–21w	57.4	15.3	6.6	20.7	0	0
FH–1–19b	49.8	14.4	5.3	30.5	0	0
FH–1–18b	61.9	15.9	3.4	18.8	0	.1
FH–1–17b	60.2	21.8	6.4	11.3	.2	.2
FH–1–16b	62.3	24.4	5.0	8.3	0	0
FH–1–14b	47.5	30.3	7.1	15.0	0	0
FH–1–13b	63.4	20.8	3.8	10.4	0	1.6
FH–1–12b	64.3	23.4	6.2	6.2	0	0
FH–1–11b	53.9	29.2	13.2	1.4	0	1.5
FH–1–9b	65.4	18.3	11.2	1.1	0	4.1
FH–1–8b	62.9	24.1	5.9	2.4	0	4.7
FH–1–7b	55.8	26.1	8.8	3.3	2.2	3.5
FH–1–6b	46.7	39.7	4.0	3.7	.6	5.2
FH–1–4b	54.1	18.1	6.4	12.4	2.7	6.2
FH–1–3b	49.3	17.4	9.6	2.2	7.4	14.0
FH–1–2b	61.8	18.5	8.7	1.4	4.7	4.7
FH–1–1b	58.6	23.1	6.8	1.0	2.0	7.5
FH–2–44w	74.9	18.0	2.6	4.6	0	0
FH–2–43w	63.2	15.0	4.8	17.0	0	0
FH–2–42w	68.5	14.7	3.0	13.7	0	0
FH–2–41w	54.9	21.4	5.1	18.7	0	0
FH–2–39w	70.0	12.8	4.3	12.9	0	0
FH–2–38w	71.4	14.2	5.5	8.8	0	0
FH–2–37b	69.4	14.7	5.8	10.1	0	0
FH–2–36b	68.4	9.8	5.4	16.2	.2	.2
FH–2–34b	61.9	11.8	6.4	18.3	.5	1.1
FH–2–33b	62.5	11.6	7.9	18.0	0	0
FH–2–32b	61.6	11.1	5.3	19.7	1.5	.9
FH–2–31b	63.2	12.1	6.3	16.3	1.0	1.0
FH–2–29b	58.1	13.0	7.1	18.6	1.2	1.9
FH–2–28b	62.2	11.8	3.6	20.8	.6	1.0
FH–2–27b	50.0	9.8	8.8	22.1	1.0	8.3
FH–2–26b	63.0	10.6	7.4	14.9	.7	2.8
FH–2–24b	54.2	7.8	8.7	19.3	1.9	8.1
FH–2–23b	61.1	7.9	5.1	18.2	2.3	5.5
FH–2–22b	56.1	10.8	6.3	19.6	.7	6.4
FH–2–21b	59.4	9.3	9.0	16.0	1.8	4.5
FH–2–19b	58.7	13.5	10.0	15.	.9	2.0
FH–2–18b	62.4	10.5	7.7	16.0	.9	2.5
FH–2–17b	60.7	12.2	6.0	16.6	1.4	3.2
FH–2–16b	61.5	12.6	5.6	11.4	1.7	7.2
FH–2–14b	59.4	10.1	9.1	17.3	.8	3.2
FH–2–13b	62.5	14.1	7.3	15.7	.2	.3
FH–2–12b	62.9	11.0	8.5	16.0	.8	.8
FH–2–11b	59.1	17.6	6.8	16.5	0	0
FH–2–9b	57.7	18.5	9.4	14.0	0.2	0.3
FH–2–8b	59.9	13.5	8.4	17.5	.3	.3
FH–2–7b	55.6	17.5	8.8	16.3	.5	1.3
FH–2–6b	65.9	13.9	5.0	13.8	.3	1.0
FH–2–4b	62.5	17.4	9.7	10.2	.1	.1
FH–2–3b	68.3	12.9	8.5	9.4	.2	.6
FH–2–2b	64.0	19.0	9.4	7.4	.1	.1
FH–2–1b	59.3	16.4	8.8	13.6	.6	1.3
FH–2–1b(b)	59.6	25.3	2.4	10.8	1.0	1.0
FH–2–1a(b)	56.5	24.0	9.4	8.3	.9	.9
FH–3–22w	71.3	11.9	3.1	13.7	0	0
FH–3–21w	65.1	14.5	5.7	14.8	0	0
FH–3–19w	56.0	19.2	6.9	17.8	0	0
FH–3–18w	62.9	16.1	7.5	13.5	0	0
FH–3–17b	69.1	17.1	3.5	10.4	0	0
FH–3–16b	73.7	12.2	5.7	7.5	.7	.2
FH–3–14b	69.9	9.4	6.4	14.3	0	0
FH–3–13b	62.4	16.1	4.4	13.7	2.1	1.4
FH–3–11b	52.3	19.0	1.0	10.3	8.7	8.7
FH–3–9b	60.6	15.4	1.8	14.4	3.9	3.9
FH–3–8b	64.9	15.6	2.3	6.3	3.2	7.6
FH–3–7b	65.8	15.9	3.7	7.7	2.8	4.1
FH–3–6b	57.7	25.0	2.9	5.8	3.4	5.3
FH–3–4b	61.0	14.1	3.2	9.8	4.7	7.2
FH–3–3b	63.1	14.8	2.8	11.1	3.1	5.0
FH–3–2b	65.4	13.8	3.7	8.9	3.3	4.9
FH–3–1b	59.0	14.8	4.2	5.1	5.1	11.9
FH–4–29w	72.1	7.5	3.2	17.2	0	0
FH–4–28w	69.3	12.9	4.5	13.3	0	0
FH–4–27w	67.4	12.0	5.3	15.3	0	0
FH–4–26w	65.7	11.8	4.6	17.9	0	0
FH–4–24b	55.4	10.2	9.1	9.7	6.2	9.4
FH–4–23b	58.5	11.6	5.7	19.9	1.3	2.9
FH–4–22b	60.3	14.7	7.3	14.5	1.0	2.2
FH–4–21b	65.5	14.0	6.6	10.5	1.1	2.3
FH–4–19b	60.9	13.9	4.3	16.9	1.6	2.4
FH–4–18b	59.1	15.9	8.0	12.3	1.9	2.8
FH–4–17b	60.5	14.2	7.1	15.3	.3	2.6
FH–4–16b	56.1	16.0	8.5	16.1	1.3	2.0
FH–4–14b	55.5	11.1	7.7	13.3	7.5	5.0
FH–4–13b	59.6	16.1	6.6	11.5	3.1	3.1
FH–4–12b	60.7	13.3	7.1	8.2	5.4	5.4
FH–4–11b	60.2	11.1	7.5	10.1	2.2	8.9
FH–4–9b	55.3	9.6	11.0	15.6	1.7	6.7
FH–4–8b	55.6	9.6	6.5	20.4	4.0	4.0
FH–4–7b	54.4	10.5	6.1	21.5	4.5	3.0
FH–4–6b	56.9	13.6	6.3	11.4	7.1	4.8
FH–4–4b	52.7	17.4	6.1	9.2	7.3	7.3
FH–4–3b	53.1	13.7	5.6	14.8	7.7	5.1
FH–4–2b	56.5	9.1	8.7	12.0	6.8	6.8
FH–4–1b	58.8	14.5	5.4	9.6	4.7	6.9

According to Sabins (1962), the dolomite types noted in this study and their petrologic significance are as follows.

1. Detrital—Clastic fragments eroded from dolomite source rocks. Usually well-rounded polycrystalline aggregate that is the relict fabric inherited from the source rock.
2. Secondary—Formed after deposition of the enclosing sediment. Usually small, euhedral rhombs that replaced calcite cement in lenticular marine sandstones.
3. Primary—Formed within the depositional basin prior to final settling down and burial of the sediment. These are single rhombic crystals abraded to various degrees of roundness and sorted to the size of associated clastic sand grains. They are always charged with uniformly distributed small, unidentifiable, nonzoned inclusions that impart a "dusty" appearance. A detrital origin is eliminated because inherited textures are absent and because the pattern of distribution is restricted to marine sandstones.

Some petrologists may initially question Sabins' (1962) definition of primary dolomite. This type of dolomite is described as having been moved and abraded by current action before it settled and was buried by other sediment. Although primary and detrital dolomite have a similar definition, they differ in that primary dolomite has not been derived from an extrabasinal source.

The brown sandstones average 2.2 percent detrital dolomite and 3.7 percent primary dolomite (table 1). Dolomite is absent in the white sandstone (table 1; fig. 3). Figure 6*D* shows a detrital dolomite grain under crossed nicols so that its polycrystalline texture can be seen. The grain is rounded from transport, and its relict texture is inherited from the dolomite in the source terrane. Continuous rims of secondary dolomite have not been noted on the detrital dolomite grains. This example is typical of the other detrital grains in the Fox Hills Sandstone and looks identical to those detrital dolomites shown and discussed by Sabins (1962).

Sabins (1962) described rhombic-shaped primary dolomite grains with various degrees of rounding that were poikilitically enclosed with other framework grains in optically continuous patches of calcite cement. The optical orientation of each primary dolomite grain is independent from that of the calcite cement. Sabins (1962) mentioned further that primary dolomite rhombs are found in rocks that have no calcite cement but did not discuss that type of occurrence in depth. Little calcite cement was found in this study of the Fox Hills Sandstone. In contrast to Sabins' (1962) observations, the primary dolomite in these rocks is always rimmed with a later generation of dolomite. The rim is thick and continuous around the primary dolomite core except where the core is in contact with other framework grains.

Figure 6*A–C* shows numerous primary dolomite grains from the Fox Hills Sandstone photographed under crossed nicols. Figure 6*A* illustrates a rhombic-shaped core that has irregularities along its straight edges that have resulted from local abrasion before burial. The core displays the dusty appearance that results from being charged with uniformly distributed inclusions. In contrast, the secondary dolomite rim is much more optically clear. The rim and core are in optical continuity. The continuity of the rim except where other grains make contact with the primary core suggests that the rims were formed after deposition, not before. Figure 6*C*, photographed with crossed nicols, shows two primary dolomite grains rimmed by secondary dolomite. The stage has been turned until one rhombic-shaped core/rim pair is nearly at extinction and the other core/rim pair is not. The optical continuity of each rim with its own core is shown. Because of this optical continuity of each pair, a boundary is observed midway between the cores that marks the juxtaposition of the secondary dolomite rims. Where many primary dolomite grains of random optical orientation are scattered and the quantity of secondary dolomite is sufficient to enclose them all, the patch of dolomite cement is not optically continuous. In contrast to optically continuous patches of calcite poikilitically enclosing dolomite and other framework grains (Sabins, 1962), the orientation of the individual primary dolomite cores (fig. 6) controls the optical orientation of the adjacent secondary dolomite growths. "Domains" of secondary dolomite having similar crystallographic orientations surround each core, and these domains extend outward from the cores to where they share perhaps several common boundaries with domains related to several nearby cores. Therefore, the dolomite cement in the Fox Hills Sandstones is a composite of domains of optically oriented cement controlled by the nearest primary dolomite core.

The cores in figure 6*C* show more rounding than the core in figure 6*A*, though some straight edges are left. Figure 6*B* shows four primary dolomite cores that have optically clear dolomite rims. This picture, taken with crossed nicols, shows the variable degree of rounding of the cores before they were rimmed by secondary dolomite even within the same thin section. The grain on the far left has several rhombic-shaped sides, whereas the grain below it is well rounded. The pair on the right side of the photograph shows one nearly rhombic-shaped grain and one rounded grain. The degree of roundness of the primary dolomite illustrates that the time span between primary dolomite rhomb crystallization and actual burial may be quite variable. Some primary grains obviously were abraded more vigorously and (or) for a longer time than others buried contemporaneously.

Figure 6*E* shows a primary dolomite core that has a secondary dolomite rim. In addition, a thin rim of calcite (see arrow) surrounds the thicker dolomite rim. The calcite rim was revealed when the section was stained with alizarin red, which stains calcite red and leaves dolomite un-

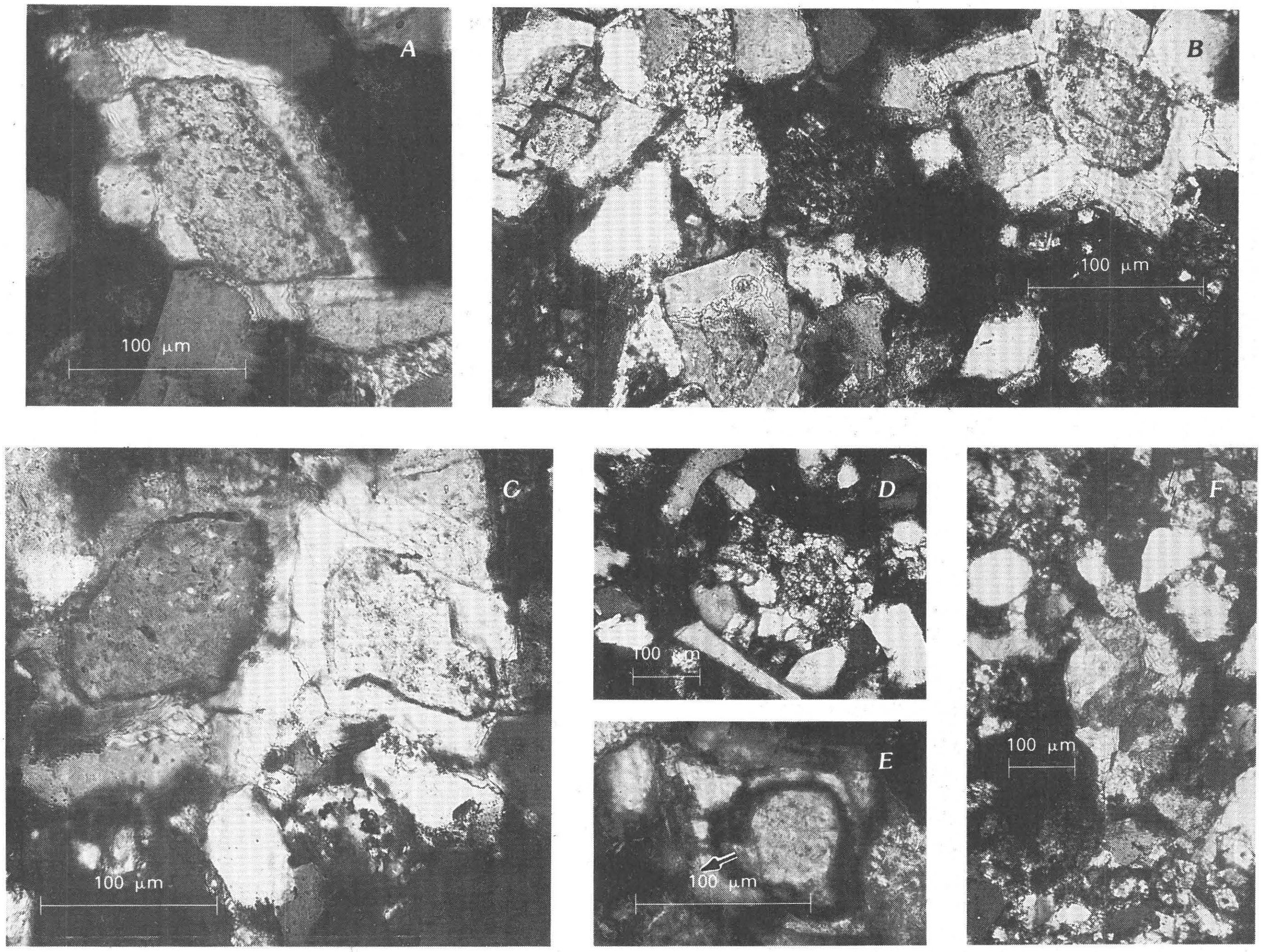

Figure 6. Photomicrographs of detrital dolomite, detrital limestone, secondary dolomite, and primary dolomite. All taken with crossed polarizers. *A*, A large, rhombic-shaped, "dusty" primary dolomite core that has a rim of more optically clear secondary dolomite. The rhombic core has been lightly abraded, as evidenced by "roughness" along the straight edges. The rim is absent where the core was impinged upon by other framework grains. *B*, Four examples of primary dolomite cores rimmed by secondary dolomite. Of the pair on the right, one core has several straight edges and the other is rounded. On the left is a rhombic core, and below it is a rounded one. This range in abrasion illustrates that the time between primary dolomite crystallization and its burial by other sediments is quite variable even within the span of a single thin section. *C*, Two core/rim pairs. The stage is turned so the set on the left is nearly at extinction. Each rim is in optical continuity with its own core. The two rims share a common boundary midway between the two cores that is marked by the change in birefringence. *D*, A detrital dolomite grain recognized by its polycrystallinity inherited from source rock. *E*, A rounded primary dolomite core rimmed by rhombic-shaped secondary dolomite, which is in turn rimmed by a very thin layer of calcite (arrow). Other examples of calcite rims exist but are uncommon. *F*, A large grain of detrital limestone as revealed by alizarin red stain. Note the inherited polycrystalline rock fabric. Detrital limestone grains are very uncommon in the Fox Hills Sandstone.

affected. Additional examples of secondary calcite are rare. Local dissolution of detrital limestone grains followed by recrystallization of the calcite about a nearby dolomite grain may explain these local occurrences.

The secondary dolomite in this study is of a different occurrence from that presented by Sabins (1962). Sabins (1962) described secondary dolomite grains as being very small (≤0.08 mm) and having perfect rhombic shapes; he found them only in calcite-cemented sandstones. Sabins (1962, p. 1186) stated "within the calcite cement are scattered the dolomite rhombs...which originated through replacement of calcite cement, rather than by precipitation from solution in unfilled pore spaces." As previously discussed, the secondary dolomite in this study forms rims about primary cores and fills or partially fills the pore spaces in the vicinity of the primary grain. Where enough space exists, the rim usually takes on a rhombic external form even though the core may be rounded (fig. 6*B*, *C*).

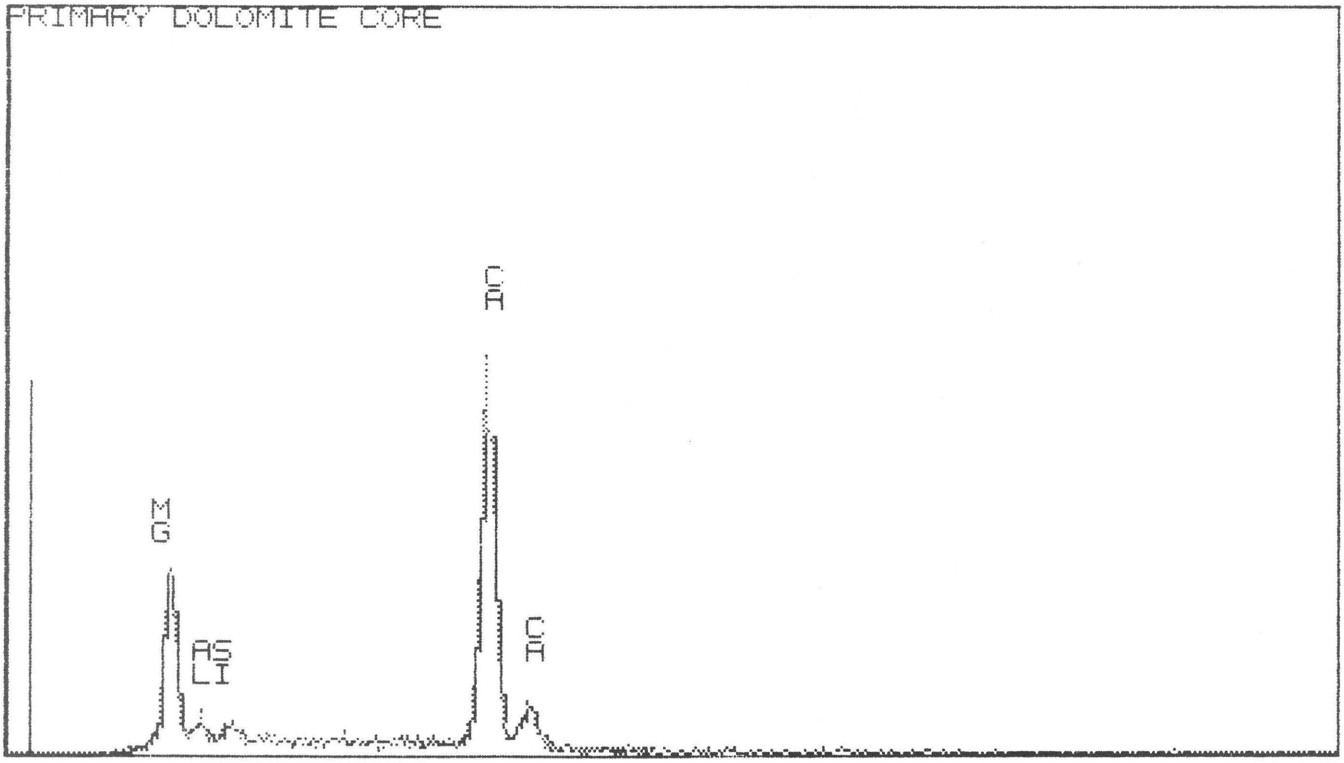

Figure 7. Energy dispersive X-ray spectrum of a representative primary dolomite core. Peak identification by Tracor Northern program. Scanning electron microscope is a Jeol JSM–840 operated at 15 kV.

Three individual primary dolomite cores and associated secondary rims were analyzed by energy dispersive X-ray analysis. A representative analysis for core material is shown in figure 7, and the analysis for rim material is shown in figure 8. The analysis of both types of dolomite confirms the petrographic identification. In addition, the rims characteristically contain a small amount of iron. That the cores are found to contain small amounts of silicon and aluminum suggests that their dusty appearance may be caused by cryptocrystalline silicate inclusions.

Figure 6*F* shows a large grain of detrital polycrystalline calcite or limestone. The photograph is taken with a ×25 objective under crossed nicols so that the relict texture of the limestone can be seen clearly. Several slides contain detrital limestone grains revealed by alizarin red, but they are very rare compared with detrital dolomite grains.

The reason detrital dolomite grains do not seem to be preferred as "seeds" for the crystallization of secondary dolomite rims may be related to their relict polycrystalline texture. It was shown earlier that secondary rims around primary dolomite (single crystal) cores always share the same crystallographic orientation. Within a polycrystalline core, which by definition is a composite of subunits having random crystallographic orientation, there is no dominant crystallographic orientation that would allow one optically continuous rim to form around it.

Some petrographic evidence indicates, though it is not entirely clear because of the difficulty of seeing such small grain sizes, that small secondary dolomite grains have grown epitaxially with some of the minute crystallographic units at the surface of these polycrystalline grains. Figure 9 is a sketch of what this writer proposes as the manner in which the detrital grains have been affected by growth of secondary dolomite. The rim adds a crudely "saw-toothed" rind around what was originally a rather well-rounded detrital grain. Each saw tooth segment with its own crystallographic direction has oriented with that of the surface subunit of the detrital dolomite grain to which it has grown epitaxially.

DEPOSITIONAL ENVIRONMENTS

Grain-size measurements on 52 thin sections document the coarsening-upward grain-size sequence expected during the deposition of a shoreline sandstone in a regressive sea (Roehler, 1983; fig. 3). The abundance of primary dolomite found in the thin sections of the brown sandstones that represent the lower and middle shoreface environment is in agreement with Sabins (1962), who stated "primary dolomite grains originated within the marine depositional basin." That the sediments containing primary dolomite were deposited into a marine basin is borne out by the presence of their marine fauna, the lithology, and the sedimentary structures.

The process of dolomite formation is not as clear as is its environment of formation. Alderman and Skinner

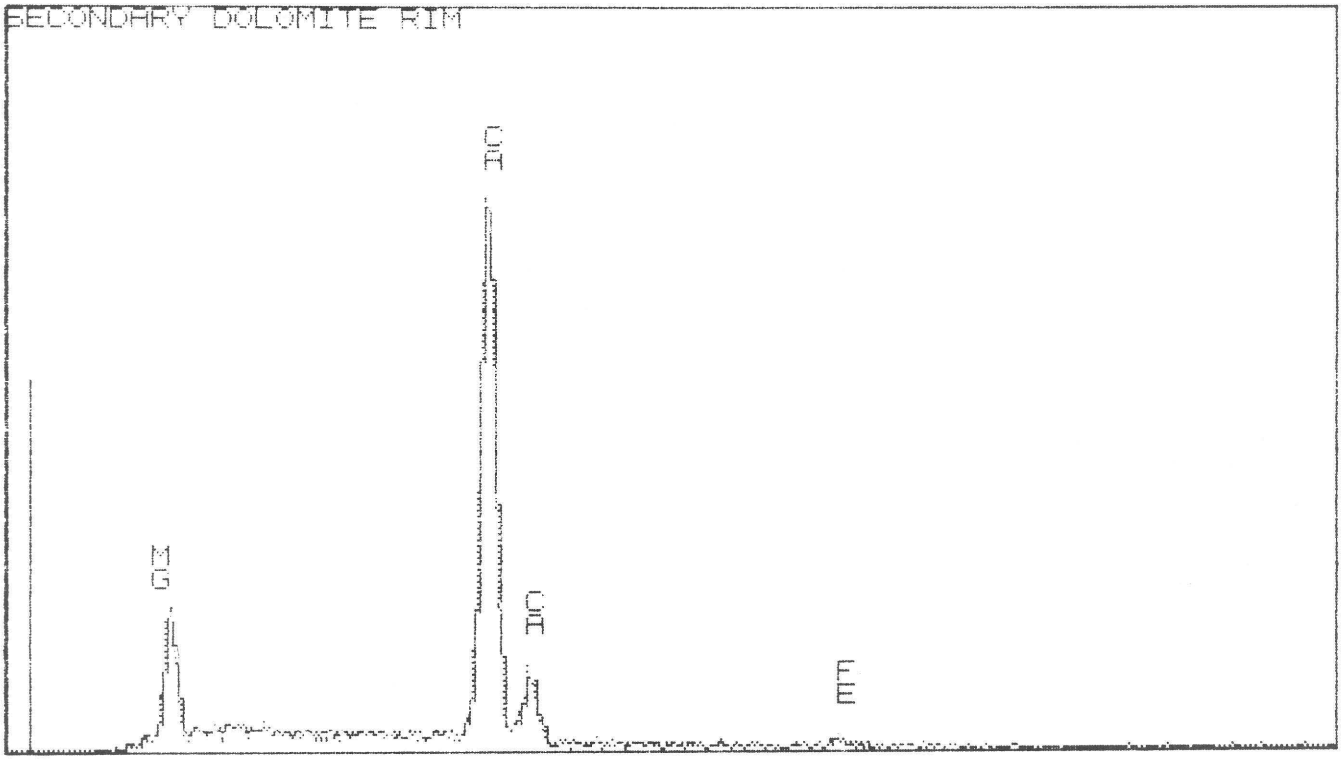

Figure 8. Energy dispersive X-ray spectrum of a representative secondary dolomite rim. Peak identification by Tracor Northern program. Scanning electron microscope is a Jeol JSM-840 operated at 15 kV.

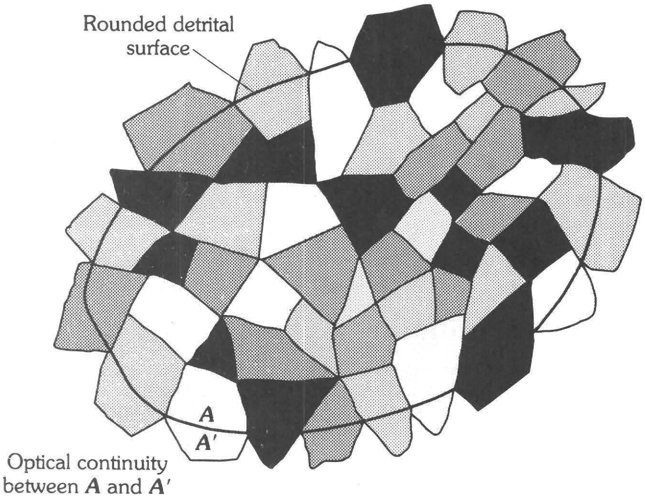

Figure 9. A rounded polycrystalline grain of detrital dolomite showing secondary dolomite growing epitaxially from the random crystallographic orientations represented on the rounded surface. Shading mimics birefringence under crossed nichols. About ×400 normal grain size.

(1957), who reported on modern dolomite precipitates from intermittent lakes and shallow lagoons in South Australia, suggest that the association of shallow sea water and the vigorous plant growth in the lakes and lagoons were important factors in the genesis of the primary dolomite. Others have suggested broad tidal flats as an environment suitable for dolomite formation because of the high salinities that result from the high ratio of evaporation to volume of water as compared with deeper ocean environments. The following is a discussion from Gadd (1986).

> Ordinary sea water is full of dissolved magnesium—saturated, in chemical terms—but dolomite won't form directly from sea water because the magnesium ion does not readily give up the water molecules attached to it and enter a crystal structure. For this reason no one has observed dolomite crystals forming in sea water at normal temperatures. However, when calcite is available, or its organically produced equivalent, aragonite, and water is evaporating from sea water that can't easily circulate with the rest of the ocean (as in a restricted lagoon), then the magnesium ion loses its water molecules and slips into the calcite crystal lattice, bumping calcium ions out....

All of the conditions discussed here that are thought to lead to dolomite formation—hypersalinity, vigorous plant growth, restricted circulation of seawater, availability of calcite or aragonite—could have been met in this setting, but the particular combination is not known. Detrital or primary dolomite is absent from the white-cap sandstone because the sands were deposited into a high-energy upper shoreface environment, and in such an environment brittle, chemically unstable materials like dolomite are quickly ground away.

PROVENANCE

The modal compositions (table 1, figs. 4 and 5) of the Fox Hills Sandstone permit the following interpretations regarding provenance.

Quartz.—61 percent average. These grains exhibit only slight undulose extinction, meaning they have not been affected by medium- to high-grade metamorphism. The source terrane probably consists of sedimentary rocks rather than plutonic or high-grade metamorphic rocks.

Feldspar.—6 percent average. About 10 percent of the total feldspar is well-twinned plagioclase; the rest is potassium feldspar. Several grains of "gridiron" twinned microcline are present, but they are uncommon in these rocks. Microcline is thought to be an indicator of a plutonic source, and its sparsity in these rocks probably means that it has been reworked from older sediments. The average feldspar content of the Fox Hills Sandstone is about 3 percent higher than that of the Late Cretaceous Mesaverde sandstones of Wyoming (Pryor, 1961). The Granite Mountains along the Sweetwater Arch east of the Wind River range may have been breached at the time so that a large amount of feldspar was supplied, some of which may have been carried into the Rock Springs area by longshore currents.

Lithic fragments (other than chert).—12 percent average. The fragments consist mostly of shale, siltstone, and phyllite. Most of these framework grains were derived from clastic sedimentary rocks.

Detrital dolomite and limestone.—2.2 percent average. Dolomite grains are much more abundant than limestone grains. These grains indicate that the source terrane for the Fox Hills Sandstone contained dolomite and limestone.

Chert.—15 percent average. The chert in the Fox Hills Sandstone probably was associated with carbonate rocks in the source terrane. Chert can form from silicious ooze during various stages of carbonate rock formation and thus is a common, though usually minor, constituent in carbonate rocks. Because chert is commonly a minor constituent in carbonate rocks, a large volume of carbonate rock must have been eroded to have supplied the large amounts of chert found in the Fox Hills Sandstone. Most of the carbonate minerals were lost by abrasion and solution during transport to the site of deposition. Because chert is much harder and more chemically resistant than the carbonate minerals, a much higher percentage of it survived transport. Thus, chert grains are much more common in the Fox Hills Sandstone than are dolomite and limestone. Dissolved carbonate and detrital carbonate minerals entering the marine basin may supply some of the necessary ions that affect the formation of the primary dolomite.

The modal composition of the Fox Hills Sandstone indicates that most of its detrital material was derived from a sedimentary terrane composed of shale, siltstone, sandstone, limestone, and dolomite. The sediments were transported generally eastward to the present-day area of the Rock Springs Uplift along the western margin of the western interior Cretaceous seaway, where they were incorporated into the eastward-prograding shoreline of the Fox Hills Sandstone (Weimer, 1961; Gill and Cobban, 1973; Roehler, 1983). Sediment could also have been contributed to the Fox Hills Sandstone by southerly directed longshore drift.

Additional criteria that must be met in regard to the provenance of the Fox Hills Sandstone are that the source rock must have been (1) older than the Fox Hills, (2) elevated high enough during the Late Cretaceous for an erosional gradient to exist to the east, (3) able to supply a large volume of chert, particularly from the Phosphria Formation, and (4) near enough to the depositional basin so that at least some dolomite and limestone could have survived the transport. The Sevier orogenic belt to the west meets all these criteria and is the most logical choice as a source of the Fox Hills Sandstone in the Rock Springs Uplift, but some feldspar may have come in from the Granite Mountains to the north, as a result of longshore currents.

ORIGIN OF WHITE-CAP SANDSTONES

The white-cap sandstones found in many Upper Cretaceous sandstones of the Rocky Mountain region could be the product of leaching by organic acids derived from overlying organic-rich material. A peat bog, a coal bed, or even a dense, mature forest floor could serve as the source for organic acids. In a complex series of reactions in a reducing environment, organic-acid-charged waters could percolate through and react with the sediments below the organic zone. Under these conditions, iron minerals would combine with the organic acids and lead to color changes and removal of iron. The rate of this procedure would be affected by the porosity and permeability of the sandstone. This "leaching" and removal of iron thus becomes a "bleaching" process whereby iron loses its role in pigmentation. The bleaching process may continue as long as the pH level remains below 7.0 and the redox potential is in a reducing range. The process will cease when those conditions change at the water table or when oxygenated ground water is introduced from a different source.

This study finds that the process of organic-acid bleaching is insufficient to account for the white-cap sandstones of the Rock Springs Uplift. Roehler (1983) concluded that the white-cap sandstones were deposited in the upper shoreface environment. In that high-energy environment, clay and other matrix-sized materials could be kept in suspension longer, transported farther from shore, and deposited in the quieter waters in the middle and lower shoreface zones. The process need not be 100 percent efficient, and though the largest part of the fine material was deposited farther out to sea, significant amounts of matrix were deposited in the upper shoreface as well. As noted previously, the brown sandstones contain more than twice as much matrix as the white-cap sandstones.

The brown sandstones average 6 percent dolomite (total detrital plus primary), an amount that makes dolomite the most probable source for iron pigmentation in these rocks. The absence of dolomite framework grains in the white-cap sandstones can be explained by the same mechanism as the one that explains the distribution of the matrix. Primary dolomite grains may form in quieter water beyond the surf zone and consequently be absent in the upper shoreface, as any detrital or primary dolomite that might be carried there would be ground away.

If organic-acid bleaching were the cause of the white-cap sandstone in the Fox Hills, then why does the zone of leaching stop abruptly at the juncture between middle and upper shoreface deposits? Perhaps the color break marks a change in the redox and pH regimes such as would be caused by a paleowater table, but the color break's consistent coincidence with the depositional break is troublesome. Even more troublesome is the fact that in the Rock Springs Uplift are at least two other examples of white-cap sandstones in formations of different ages, both of which underlie a rich organic zone and reside solely in upper shoreface deposits (Almond Formation and McCourt Tongue of the Rock Springs Formation; Roehler, 1988, 1989). An additional difficulty with this proposed cause is that the white-caps in the Rock Springs Uplift are 20 to 40 ft thick, and if their base represents a paleowater table, a swamp or peat bog could not have been perched so high above. One would expect the water table to be about coincident with the water level in the bog.

In white-caps in which acid bleaching has definitely taken place, the zone of bleached sand is commonly 3 ft or less thick, and the intense weathering under these acid conditions results in the destruction of primary sedimentary structures. The white sandstones of the Rock Springs Uplift are replete with packages of thin herringbone crossbeds in sharp definition.

An additional result of intensive weathering under acidic conditions is a breakdown or alteration of clay minerals. The crystallinity of the clays in the white, highly weathered matrix should be diminished compared with the clays undergoing milder weathering in the brown matrix. Loss of crystallinity would appear on an X-ray-diffraction trace as broader but shorter peak heights and would show more background "hash" and perhaps the complete loss of some of the larger 2Θ peaks. In addressing this, Frank Dulong (personal commun., 1989) stated "I am unable to determine that there is a quantitative difference in the crystallinity of the kaolinite and (or) illite between the two samples [white and brown matrix]."

The even distribution of the brown color of the Fox Hills is in contrast to a typical example from an acidic bleaching regime. As iron is removed by the organic acids and carried downward through the sandstone, it eventually reaches that layer or zone of oxidation where it is redeposited, often as an iron-rich hardpan. Below the initial concentration of the iron, the brown color is streaky and variable in intensity. In the Rock Springs Uplift, the color break is sharp and even, takes place within a vertical distance of 3 in or less, and continues for miles without deviation from the interface between middle shoreface and upper shoreface deposits. No hardpans or other concentrations of iron occur at the interface, and the brown color is uniform throughout the brown sandstone. Undoubtedly, many sandstones have been bleached under organic-acid-rich weathering conditions, but this does not seem to be the case for the white-cap sandstones from the Rock Springs Uplift. The evidence consistently indicates that the white-cap sandstones in the Rock Springs Uplift have been controlled by their depositional setting rather than by leaching.

SUMMARY AND CONCLUSIONS

A detailed petrographic study of the Fox Hills Sandstone has revealed significant data regarding the depositional and diagenetic history. Much of the new information confirms or supplements published interpretations based on stratigraphic, sedimentologic, and paleontologic studies.

Information on the occurrence and abundance of chert and detrital dolomite, obtained from a large number of samples, indicates that the source area must have had a major carbonate-rock component. The abundant sedimentary rock fragments found as framework grains have now been shown by more than 100 modal analyses to be characteristic of the Fox Hills; thus, the existence of a source rock that provided this material throughout its deposition is necessitated. The presence and the abundance of primary dolomite and the coarsening upward of framework grain size support the previous conclusion that the Fox Hills Sandstone represents deposition during a regressive sea.

The dolomite types described here fall into the three categories defined by Sabins (1962), which have some unique variations in the Fox Hills Sandstone. Variations include the rimming of primary dolomite cores during diagenesis by optically clear secondary dolomite and in some uncommon cases an additional thin rimming of calcite over the dolomite rim.

Energy dispersive X-ray analysis, showing compositional differences between the primary dolomite cores and the secondary dolomite rims, thus confirms the existence of two different generations of dolomite. The rim material contains a small amount of iron that commonly replaces magnesium in the dolomite structure. The core material contains a small amount of aluminum and silicon and may indicate that the inclusions that impart its characterisic dusty look are cryptocrystalline silicates.

This study also suggests that the detrital dolomite grains, within the same rocks, do not have continuous rims of secondary dolomite about them, because they are polycrystalline. On closer inspection, it appears that secondary dolomite has grown epitaxially with the very small subunits that have individual crystallographic orientations. These somewhat saw-toothed projections of secondary dolomite obscure the original rounding of the detrital grain.

Another suggestion resulting from this study is that the large amount of dissolved carbonate rock ingredients entering the basin from the source rocks may have stimulated the formation of the primary dolomite.

X-ray-diffraction data and microscopic examination show that the pigmentation factor in the matrix of the brown sandstones is illite and kaolinite coated by argillaceous hematite and that the hematite is absent in the white-cap sandstones. In other examples, redistribution of the hematite might be explained by a diagenetic organic-acid bleaching process that resulted in the white-cap sands. However, the present study concludes that depositional environment was the dominant factor in the formation of white-cap sands in the Fox Hills Sandstone, the Almond Formation, and the McCourt Tongue of the Rock Springs Formation within the Rock Springs Uplift.

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Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

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Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

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