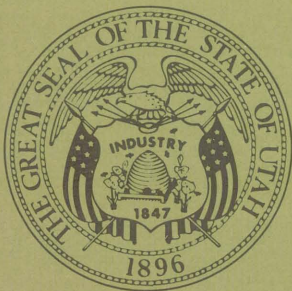


Petrographic Criteria for Recognition of
Lacustrine and Fluvial Sandstone,
P. R. Spring Oil-Impregnated Sandstone Area,
Southeast Uinta Basin, Utah

by M. Dane Picard



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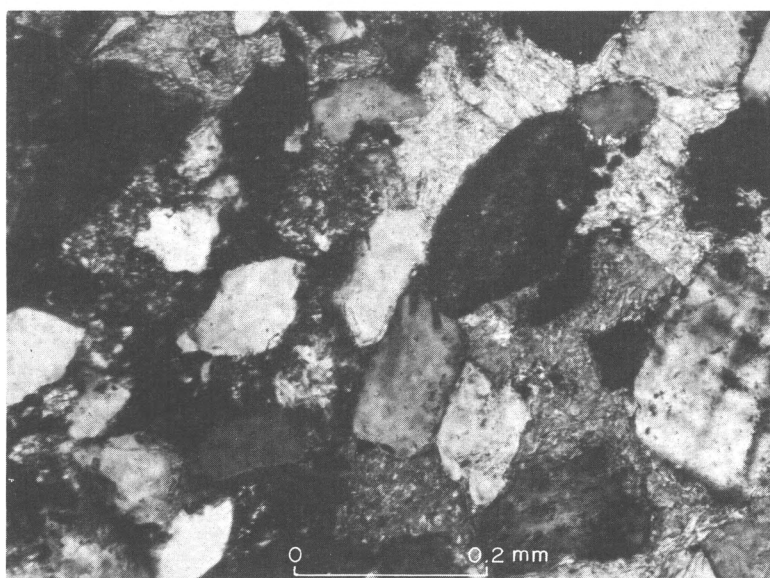
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Photomicrograph of lacustrine sandstone from Douglas Creek Member.

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PETROGRAPHIC CRITERIA FOR RECOGNITION OF
LACUSTRINE AND FLUVIAL SANDSTONE,
P. R. SPRING OIL-IMPREGNATED SANDSTONE AREA,
SOUTHEAST UINTA BASIN, UTAH

by *M. Dane Picard*¹

ABSTRACT

Reserve estimates indicate about 3.7 billion barrels of oil in place in the P. R. Spring area, most of which is in lacustrine sandstone of the Garden Gulch and Parachute Creek members of the Green River Formation (Eocene). Fluvial sandstone bodies in the Wasatch Formation (Paleocene?–Eocene) produce gas in the south and southeast Uinta Basin, Utah. Elsewhere in the Uinta Basin, however, free oil and oil-impregnated sandstone bodies are dominantly in lacustrine facies of the Green River Formation. For good economic exploration of oil and gas in the Tertiary of the Uinta Basin it is desirable to understand the petrography of lacustrine and fluvial sandstone and to be able to distinguish them. This paper presents information on the petrography of lacustrine and fluvial sandstone of the upper Wasatch Formation and the lower Green River Formation in the P. R. Spring area, southeast Uinta Basin, Utah.

Eighty-five percent of the lacustrine and fluvial sandstone is arkose. On the basis of modal analyses, the lacustrine sandstone contains significantly more quartz and authigenic carbonate cement and less plagioclase, matrix (terrigenous material less than 1/16 mm) and coarse mica than does fluvial sandstone. Some evidence indicates that lacustrine sandstone contains less potassium feldspar and rock fragments than fluvial sandstone.

Plots of quartz versus feldspar, authigenic carbonate versus matrix, quartz versus plagioclase, quartz versus matrix and feldspar versus matrix are especially useful in differentiating lacustrine and fluvial sandstone; allochems (intraclasts, oolites or fossils) and minor analcime also characterize lacustrine sandstone.

Detrital grains of the lacustrine and fluvial sandstone suggest heterogeneous sources. Plutonic rocks (granite, pegmatite and quartz vein) of the Uncompahgre uplift on the south and southeast probably were the main sources; weathered and eroded clastic and carbonate rocks possibly supplied almost as much sediment as the plutonic sources in some sandstone.

The lacustrine sandstone is mineralogically and texturally more mature than is the fluvial sandstone. This increased maturity reflects the energy applied to the detritus after transport from its source areas. The present differences are independent of tectonism; mineral changes that took place during weathering in the source areas and during transportation of the grains also do not contribute greatly to the variations between the two types of sandstone. Significant differences are essentially a function of the environments of deposition.

Minor red pigment (generally less than 1 percent) in both the lacustrine and fluvial sandstone is essentially post-depositional in origin. The fluvial sandstone contains more red pigment than the lacustrine sandstone.

INTRODUCTION

Oil-impregnated lacustrine and fluvial sandstone in the P. R. Spring area of the southeast Uinta Basin, Utah, occupies at least 214 square miles and extends northward beneath younger strata (Byrd, 1967 and 1970). Oil-saturated intervals to 75 feet thick within a stratigraphic interval of about 250 feet are exposed at or near the surface in northward-dipping beds. Reserve estimates indicate that there are about 3.7 billion barrels in place (Byrd, 1967 and 1970).

The presence of these large hydrocarbon reserves and of oil seeps in the area (figure 1) prompted study of the lacustrine and fluvial sandstone bodies within and adjacent to the oil-impregnated intervals. Paleocurrent directions in the upper part of the Wasatch Formation (Paleocene? – Eocene) and the lower part of the Green River Formation (Eocene) in the P. R. Spring area were determined (Picard and High, 1970). In addition, Picard and High (1970) developed field criteria for the recognition of lacustrine and fluvial sandstone (figures 2-3) and analyzed the depositional environments of the sandstone bodies. Orientation of average shorelines during deposition of lacustrine sandstone bodies was constructed on the basis of analysis of paleogeography and paleocurrents. Similarly, orientation of the paleoslope during deposition of fluvial sandstone

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Figure 1. Oil seep in Pine Spring Canyon section; fractured beds in upper part of Garden Gulch Member of Green River Formation near top of Douglas Creek Member of Cashion (1967).

bodies was determined. Application of these related aspects of the sedimentology of oil-impregnated and other associated rock units now allows differentiation of lacustrine and fluvial sandstone on the basis of field criteria. This is important in the P. R. Spring area and elsewhere in the Uinta Basin because free oil and oil-impregnated sandstone in the Green River Formation are dominantly in lacustrine sandstone bodies. Although in many areas of the Uinta Basin fluvial sandstone is closely associated with lacustrine sandstone and intertongues with it, the fluvial sandstone contains considerably less oil than does the lacustrine sandstone. It is desirable therefore to be able to distinguish lacustrine sandstone from fluvial sandstone by several methods.

Following detailed field examination, an appropriate follow up study is petrographic analysis. Picard (1957b) suggested that there are mineralogic differences between lacustrine and fluvial sandstone. Some of these petrographic criteria (Picard, 1957b) have been applied to other areas in the Uinta Basin and

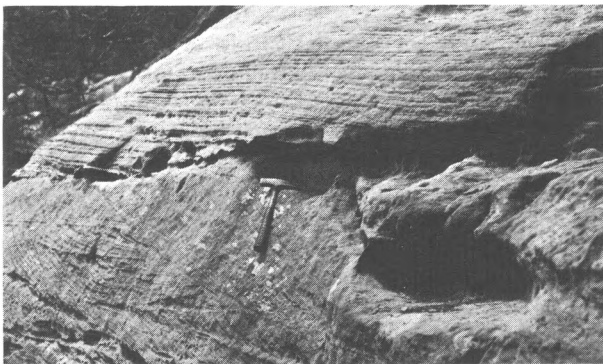


Figure 2. Horizontally stratified lacustrine sandstone on erosion surface above medium-scale cross-stratification, Horse Canyon section. Scale = hammer.

were used to a slight extent in an earlier study of the P. R. Spring area (Picard and High, 1970); a detailed petrographic study, however, has not been attempted previously. Comprehensive petrographic studies of lacustrine sandstone are few, but several good studies of the petrography of fluvial sandstones have been published recently (Allen, 1962, Doty and Hubert, 1962, Selley, 1966, Kohls, 1967, McBride, Lindemann and Freeman, 1968, McCormick and Picard, 1969 and Wellman, 1970).

Improved oil exploration in the southeast Uinta Basin and in other areas of the Uinta Basin where lacustrine and fluvial sandstone intertongue will result if lacustrine sandstone can be distinguished. Similarly, means of exploration for oil-impregnated sandstone bodies can be improved if more criteria for lacustrine deposition are available which can easily be applied to specific deposits.

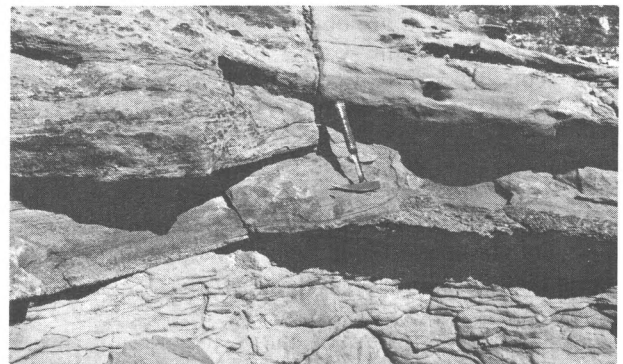


Figure 3. Fluvial sandstone in channels of Douglas Creek Member, Pine Spring Canyon section. Note conglomerate at base of channel-fill (just below hammer). This is a fining-upward sequence deposited by a meandering stream.

Although details will vary considerably, the approach and the results of this study are applicable not only to the Green River Formation and related rocks of the Uinta Basin, but also to other areas where similar conditions exist.

GENERAL STRATIGRAPHY

In accord with the nomenclature proposed by Bradley (1931, p. 9-14), the Green River Formation in the east Uinta Basin (Picard, 1955, p. 83), in the Red Wash field (Picard, 1957a, p. 83 and Chatfield, 1965, p. 166), and along Raven Ridge in the northeast Uinta Basin (Picard, 1967, p. 385) has been subdivided, in ascending order, into the Douglas Creek, Garden Gulch, Parachute Creek and Evacuation Creek members. Cashion (1967) made the most recent detailed study of the stratigraphy of the southeast

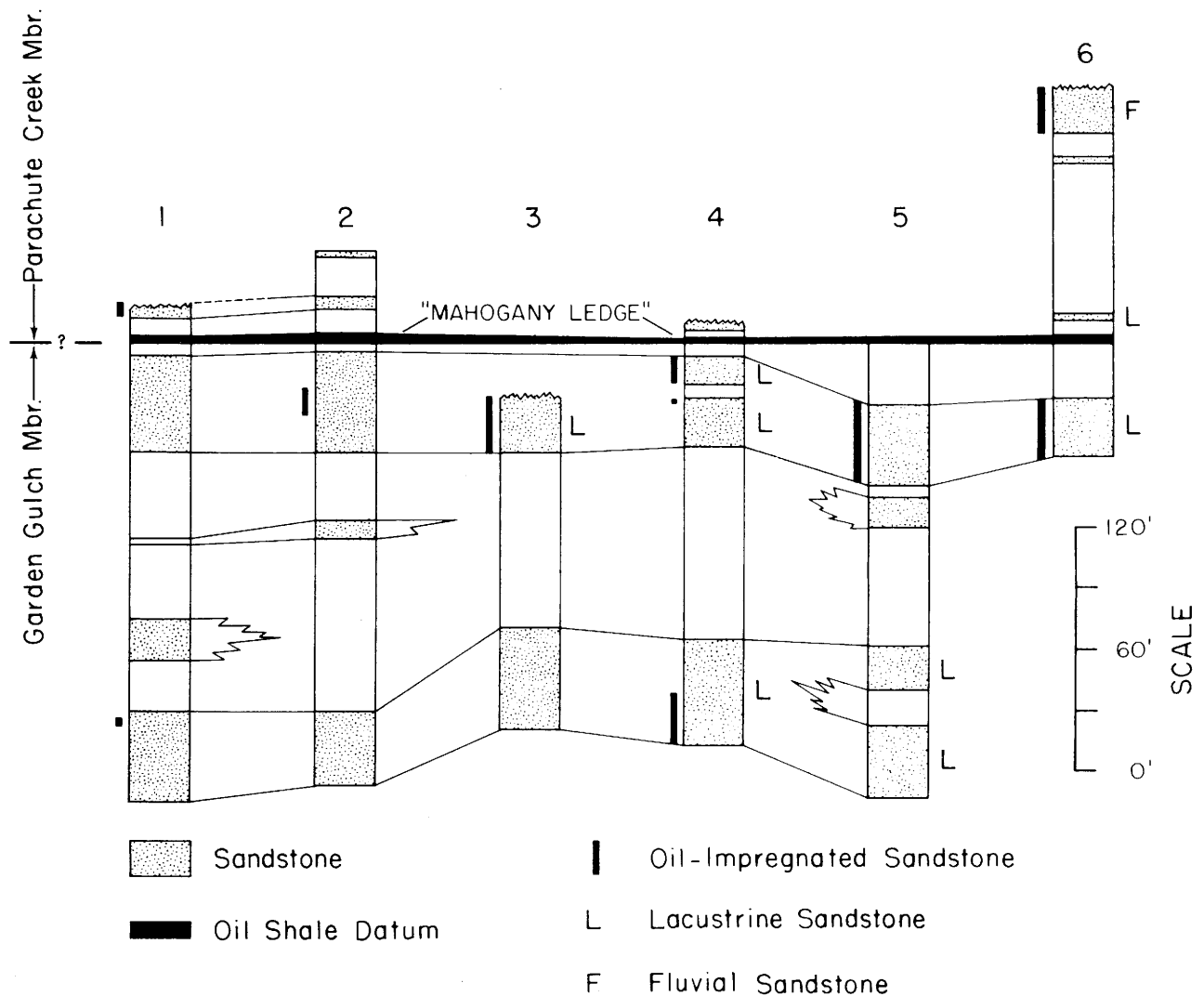


Figure 4. Cross section showing oil-impregnated sandstone in P. R. Spring area, southeast Uinta Basin, Utah. Oil-impregnation is dominantly in lacustrine sandstone (Byrd, 1970 and Picard and High, 1970). Location of cross section is shown on figure 5.

Uinta Basin. According to his nomenclature (Cashion, 1967, plate 3), the Tertiary units in the P. R. Spring area are (from base upward): main body of Wasatch Formation; an interval of 1,200 to 1,300 feet of Wasatch and Douglas Creek tongues; Mahogany oil-shale bed and Mahogany marker; Parachute Creek Member; Horse Bench Sandstone bed, and Evacuation Creek Member. The oil-impregnated sandstone beds are stratigraphically above and below the Mahogany oil-shale bed (figures 4-5). Thus, in Cashion's (1967) scheme, the oil-impregnated sequence lies in the upper part of the Douglas Creek Member (upper part of Tongue A) and in the lower part of the Parachute Creek Member. Cashion (1967, plate 3) recognizes the Garden Gulch Member at only one section of his cross section.

Until detailed studies of the stratigraphy are completed, the writer prefers the formal Green River nomenclature. The conventional four rock units of the Green River Formation can be traced from the Red Wash oil and gas field on the northeast edge of the Uinta Basin to the P. R. Spring area on subsurface logs with no difficult problems of correlation. This paper deals with the upper Wasatch Formation, the Douglas Creek and Garden Gulch members, and the lower Parachute Creek Member.

As Cashion (1967) indicated, fluvial and shallow water lacustrine beds intertongue considerably in the P. R. Spring area. He assigned the fluvial tongues to the Wasatch Formation and the lacustrine tongues to the Douglas Creek Member but did not indicate the

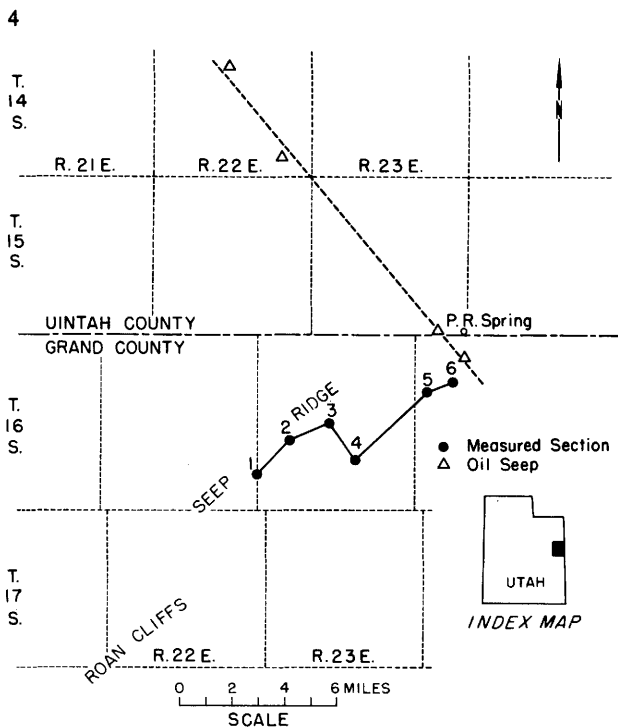


Figure 5. Index map showing location of cross section (1-6). Note northwest trend (dashed line) of oil seeps.

equivalence of some of these "transitional" beds to the Garden Gulch Member of other areas.

METHODS OF STUDY

The uppermost part of the Wasatch Formation, the Douglas Creek and Garden Gulch members of the Green River Formation and the lower part of the Parachute Creek Member of the Green River Formation were sampled in a relatively small geographic area of about 400 square miles in the P. R. Spring area of the southeast Uinta Basin, Utah. A stratigraphic thickness of about 1,500 feet was examined. The oil-impregnated sandstone bodies are in the upper part of the Garden Gulch Member and in the lower part of the Parachute Creek Member.

To reduce the variable of changing mineral composition with varying grain size, only very fine and fine-grained sandstone was studied - the modal grain sizes of the common sandstone in the area.

Because the samples were numbered consecutively as they were collected in the field, lacustrine and fluvial sandstone is mixed in the numbered thin sections. During modal analysis, locations of thin sections were disregarded and thin sections were selected at random for examination to minimize bias.

Each of the samples was designated lacustrine or fluvial in the field on the basis of paleocurrent

information, bedding characteristics, sedimentary structures, gross lithology or fossil content (Picard and High, 1970); several criteria indicative of a lacustrine or fluvial origin were required for a sample to be collected. None of the environmental assignments made in the field were changed after examination of the thin sections.

Twenty thin sections of lacustrine sandstone and twenty thin sections of fluvial sandstone were examined (tables 1-2). Most of the thin sections were cut perpendicular to bedding. Two hundred points in each thin section were counted to determine percentage compositions; for ease in comparing mineral changes, means and standard deviations for each major group were calculated. Results of the modal analyses were reproducible to ±10 percent of the major constituents (quartz, feldspar, authigenic carbonate and matrix). Potassium feldspar was stained on all of the thin sections. Gross mineralogy of each sample was determined by X-ray diffraction analysis before the thin sections were studied with the petrographic microscope at a magnification of 400X. Only two oil-impregnated sandstones were used for modal analysis because of the difficulty in determining mineral composition in some oil-impregnated sandstone.

Apparently, major constituents in the sandstone do not vary consistently from the base to the top of the examined sequence (table 3). The majority of the lacustrine samples (table 1) is from the Douglas Creek Member. No significant changes in mineralogy related to stratigraphic position were noted for either the lacustrine or the fluvial sandstone.

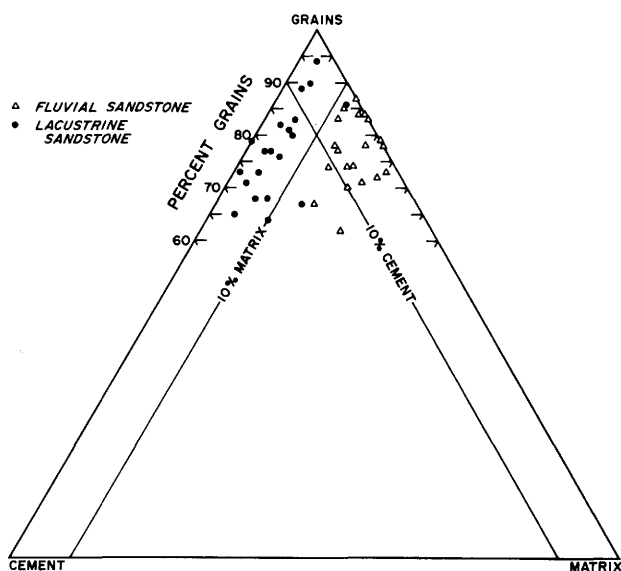


Figure 6. Ternary plot of grains, cement and matrix in lacustrine and fluvial sandstone.

Table 1. Composition of lacustrine sandstone in Douglas Creek and Garden Gulch members and lower part of Parachute Creek Member, P. R. Spring area. (Modal analyses of 20 lacustrine sandstones; 200 points counted per thin section.)

Framework Constituents in Percent										Cement and Matrix			
Quartz	K-feldspar	Plagioclase	Rock fragments	Quartzite, chert	Coarse Mica	Accessory Minerals	Intra-clasts	Oolites	Fossils	Other	Authigenic Carbonate	Matrix	Q/F Ratio
50	23	5		1	1	2					15	3	1.8
45	14	3				1	1				26	10	2.4
47	15	7		4	2	1	1				19	4	2.1
46	18	3				2	1			3 ¹	23	4	2.2
36	23	9		2	2		5				20	3	1.1
49	12	3			1	1	1				19	14	3.3
52	16	7		4				1		9 ²	6	5	2.3
31	18	8		1			4	11			26	1	1.2
37	26	2			1	2					26	6	1.3
40	16	4		2			1	1	1		31	4	2.0
34	13	3	2	1		1	5	6	3		24	8	2.1
49	18	3	2	1		2	1				18	6	2.3
51	25	7	4	3							6	4	1.6
51	23	5		5	2						2	12	1.8
55	10	3		2		1	6	2			21		4.2
58	15	3	2	3						4 ³	10	5	3.2
51	18	6	1		1	1	2				14	6	2.1
45	31	6		3	2	1	1				8	3	1.2
37	23	4	2	1	1		3				26	3	1.4
60	14	9	2	3	1		2	3			3	3	2.6
Mean:													
46.2	18.5	5.0	0.8	1.8	0.7	0.7	1.7	1.2	0.2	0.8	17.2	5.2	2.1
Standard Deviation:													
8.1	5.4	1.1	1.1	1.5	0.8						8.7	3.5	0.7

¹ Analcime.² Silica cement (6 percent), analcime (3 percent).³ Silica cement.

GENERAL PETROGRAPHIC RELATIONSHIPS

The lacustrine and fluvial sandstone is from a single population if the gross relationships of grains, cement and matrix are considered (figure 6). Ninety-five percent of the samples contain from 65 to 95 percent grains. But on the basis of the amounts contained of cement and matrix (defined as all terrigenous grains less than 1/16 mm in diameter), lacustrine and fluvial sandstone can be divided into two groups: only two lacustrine sandstones contain more than 10 percent matrix and only three fluvial sandstones contain more than 10 percent cement (figure 6). Nearly all the cement in both types of sandstone is authigenic carbonate.

SANDSTONE TYPES

An abundance of sandstone classifications has caused considerable nomenclatural confusion among geologists; seventeen field and laboratory classifications of sandstone were proposed in the North American geological literature between 1940 and 1960

(Klein, 1963, p. 556). Foreign literature is equally chaotic.

Classifications in this paper are those of Folk (1968) and McBride (1963). Both systems employ the same terminology on a quartz-feldspar-rock fragment triangle, but boundaries between sandstone classes are different. According to Folk's nomenclature the sandstones studied here are: arkose 34, lithic arkose 4 and subarkose 2 (figure 7). Classified by McBride's system, the sandstones are: arkose 33, subarkose 4 and lithic arkose 3 (figure 8). Thus, sandstone types are essentially the same using these classifications. Folk in contrast to McBride assigns all quartzite and chert fragments to the rock fragment pole (figure 8).

At this level of study, the lacustrine and fluvial sandstones form two distinct groups with little overlap considering the characteristics of this type of plot. The differences in mineral composition that lead to this separation are discussed in sections that follow.

Table 2. Composition of fluvial sandstone in P. R. Spring area. (Modal analyses of 20 fluvial sandstones; 200 points counted per thin section.)

Rock Unit	Framework Constituents in Percent							Cement and Matrix				
	Quartz	K-feldspar	Plagioclase	Rock Fragments	Quartzite, Chert	Coarse Mica	Accessory Minerals	Authigenic Carbonate	Other	Matrix	Q/F Ratio	
Garden Gulch Member	42	23	11	1	1	2	4			16	1.2	
	37	19	14		3	3	3			21	1.1	
	41	23	11	1	2	5	1	1		15	1.2	
	42	19	11		1	5				22	1.4	
	40	14	10	2	1	3	1	7		22	1.7	
Douglas Creek Member	32	24	8	1	3			11	6 ¹	15	1.0	
	46	9	5		1		1	15		23	3.3	
	40	25	10	2	3	3	2	3		12	1.1	
	40	25	12	1	3	5	1			13	1.1	
	36	26	9	2	3	7				17	1.0	
	35	21	6	3	1	4		10		20	1.3	
	40	18	11	1	2	5		8		15	1.4	
	38	21	12	2	2	2	1	3		19	1.1	
	39	18	4	2	1	1	2	17		16	1.8	
	40	26	7	1	1	2	1	8		14	1.2	
Wasatch Formation	39	26	5			2	1	2		25	1.3	
	36	22	10	1	2	3		8		18	1.1	
	35	27	5		1	4		4		24	1.1	
	40	19	9	8	5	2		5	1 ¹	12	1.4	
	39	21	4	3	4	3		6		19	1.6	
	Mean	38.8	21.3	8.7	2.1	2.0	3.0	0.8	5.4		17.9	1.4
	Standard Deviation	3.1	4.5	3.0	1.8	1.3	1.8		5.1		4.0	0.5

¹Silica cement.

MAJOR CONSTITUENTS OF SANDSTONE

On the basis of the modal analyses, lacustrine sandstone contains more quartz and authigenic carbonate and less potassium feldspar, plagioclase and matrix than does fluvial sandstone (figure 9). A comparison of the ranges ($\pm 1\sigma$) indicates that quartz, plagioclase and authigenic carbonate differ in the lacustrine and fluvial sandstone by nearly one standard deviation (table 4); the amount of matrix in the two types of sandstone differs by more than one standard deviation. These results suggest that the amounts of quartz, plagioclase, authigenic carbonate and matrix are significantly different in lacustrine and fluvial sandstone in the P. R. Spring area.

A scatter plot of authigenic carbonate versus matrix (figure 10) illustrates the distribution of the major constituents with little overlap between lacustrine and fluvial sandstone. The lacustrine sandstone contains much more authigenic carbonate, but apparently there is no pattern of distribution of type of carbonate. Either calcite or dolomite is the dominant or only authigenic carbonate in lacustrine or fluvial sandstone (figure 11).

Quartz:feldspar ratios also distinguish lacustrine and fluvial sandstone (figure 12). Seventy-five percent

of the lacustrine sandstone has quartz:feldspar ratios of more than 1:5. In contrast, eighty percent of the fluvial sandstone has a quartz:feldspar ratio of less than 1:5.

If quartz and plagioclase are plotted, two distinct groups result (figure 13). Eighty percent of the lacustrine sandstone has a quartz:plagioclase ratio of more than 7:1; eighty percent of the fluvial sandstone has a ratio less than 7:1. The 7:1 ratio boundary between the two groups is not applicable to other areas, even in the Uinta Basin. It does, however, separate the two types of sandstone in the P. R. Spring area.

A plot of quartz versus potassium feldspar showed a considerable overlap between lacustrine and fluvial sandstone (figure 14). This plot and the ranges of the modal analyses (table 4) indicate that quartz:potassium feldspar ratios are not a reliable means of distinguishing lacustrine sandstone. Likewise, potassium feldspar:plagioclase feldspar ratios (figure 15) do not differentiate between lacustrine and fluvial sandstone.

Scatter diagrams of quartz versus matrix (figure 16) and feldspar versus matrix (figure 17) show a good separation of lacustrine and fluvial sandstone in-

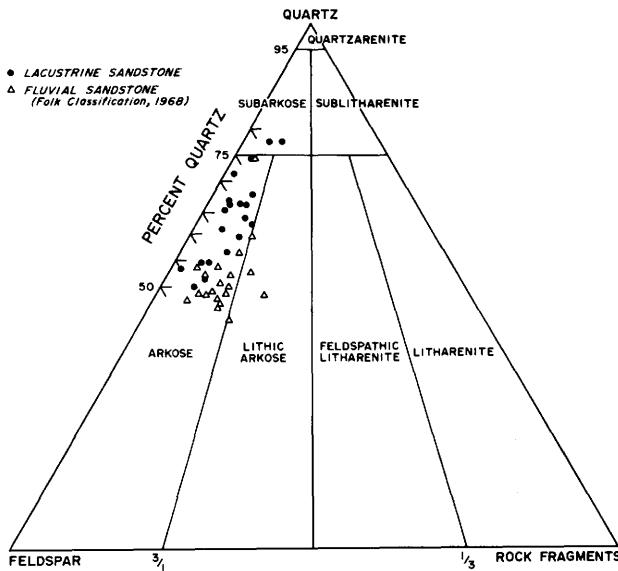


Figure 7. Ternary plot of quartz, feldspar and rock fragments in lacustrine and fluvial sandstone.

to two groups. The amount of matrix tends to increase as the amount of feldspar increases (figure 17). The fluvial sandstone contains more matrix and more feldspar, especially plagioclase, than the lacustrine sandstone. These two relationships may not reflect the same processes, however.

MINOR CONSTITUENTS OF SANDSTONE

Fluvial sandstone contains considerably more coarse mica (detrital mica larger than 1/16 mm in diameter) than does lacustrine sandstone (figure 18). Most of the mica is larger than the principal framework constituents (quartz and feldspar). In the modal analyses, mica smaller than 1/16 is included with the matrix.

The means and ranges of coarse mica in fluvial and lacustrine sandstone are significantly different (table 4). The dominant coarse mica is muscovite that was derived mainly from plutonic source areas. Biotite is also present, but is much less abundant than muscovite.

A plot of feldspar versus coarse mica is somewhat useful in distinguishing fluvial and lacustrine sandstone (figure 19). The fluvial sandstone contains more feldspar and coarse mica than does the lacustrine sandstone.

Rock fragments are also more abundant in fluvial sandstone than in lacustrine sandstone (figure 18); this differ-

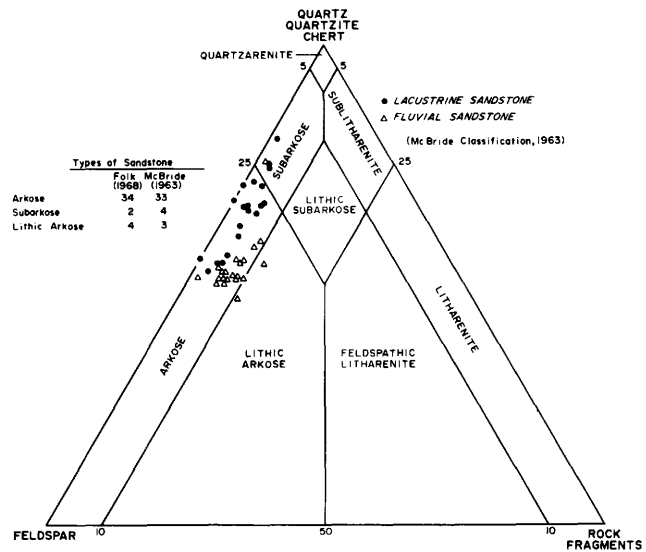


Figure 8. Ternary plot of quartz, feldspar and rock fragments (sandstone classification from McBride, 1963).

ence may not be significant. Table 5 compares rock fragments, quartzite, chert and accessory minerals; the ranges in fluvial and lacustrine sandstone show considerable overlap. Table 5 also demonstrates the significant differences in coarse mica content in the two types of sandstone.

Figures 20-27 are photomicrographs of fluvial and lacustrine sandstone from the P. R. Spring area.

ALLOCHEMS AND ANALCIME IN LACUSTRINE SANDSTONE

Seventy-five percent of the lacustrine sandstone contains allochems (intraclasts, oolites or fossils) in contrast to the fluvial sandstone with no allochems (tables 1-2). Although the allochems are a minor constituent in most of the lacustrine sandstone, they generally characterize lacustrine sandstone in the Uinta Basin. In the Raven Ridge area of the northeast Uinta Basin, lacustrine sandstone contains about 12 percent allochems; fluvial sandstone in the area is composed of about 5 percent allochems. The fluvial sandstone studied in the Raven Ridge area is believed to have been deposited much closer to lake shores

Table 3. Comparison of means of major constituents in fluvial rocks of Wasatch Formation and Douglas Creek and Garden Gulch members (from modal analyses).

Rock Unit	Number of Samples	Quartz	K-feldspar	Plagioclase	Coarse Mica	Authigenic Carbonate	Matrix
Garden Gulch Member	5	40.5	19.6	11.4	3.6	1.6	19.2
Douglas Creek Member	9	38.4	20.8	8.5	3.0	7.4	16.6
Wasatch Formation	6	38.2	23.5	6.7	2.7	5.5	18.6
All fluvial samples	20	38.8	21.3	8.7	3.0	5.4	17.9

than most of the fluvial sandstone in the P. R. Spring area.

Two of the lacustrine sandstones in the P. R. Spring area contain minor analcime (table 1); it was not noted in any of the fluvial sandstone.

PROVENANCE

The Uncompahgre uplift (east central Utah and west central Colorado) was the source area of the detritus for the lacustrine and fluvial sandstone in the P. R. Spring area. This interpretation has been made previously. Picard (1957c, p. 126) indicated that the major source areas during deposition of the lower half of the Green River Formation in the Uinta Basin were on the south and southeast (Uncompahgre uplift). Murany (1964, p. 151) found that sand:shale ratios in the Wasatch Formation of the Uinta Basin

increase markedly toward the southeast (toward the Uncompahgre uplift). He also noted (p. 150) that conglomerate is common in the Wasatch Formation of the Book Cliffs area east of Green River. On the basis of the general petrography of oil-impregnated sandstone in the Green River Formation of the southeast Uinta Basin, Wiley (1967, p. 57) proposed that the Uncompahgre uplift and mountains in western Colorado were the probable source areas for the detritus.

Table 5. Variation of rock fragments and coarse mica in fluvial and lacustrine sandstone, P. R. Spring area (from modal analyses).

Fluvial			Lacustrine		
Rock Fragments, Quartzite, Chert, Accessory Minerals	Coarse Mica	Total	Rock Fragments, Quartzite, Chert, Accessory Minerals	Coarse Mica	Total
6	2	8	3	1	4
6	3	9	1	0	1
4	5	9	5	2	7
1	5	6	2	0	2
4	3	7	2	2	4
4	0	4	1	1	2
2	0	2	4	0	4
7	3	10	1	0	1
5	5	10	2	1	3
5	7	12	2	0	2
4	4	8	2	0	2
3	5	8	3	0	3
5	2	7	3	0	3
5	1	6	5	2	7
3	2	5	3	0	3
1	2	3	5	0	5
3	3	6	2	1	3
1	4	5	4	2	6
13	2	15	3	1	4
7	3	10	5	1	6
Mean (percent):					
4.5	3.0	7.5	2.9	0.7	3.6
Standard Deviation:					
2.7	1.8	3.9	1.3	0.8	1.8
Range (± 1 S.D.):					
1.8-7.2	1.2-4.8	3.6-11.4	1.6-4.2	0.0-1.5	1.8-5.4

Table 4. Comparison of means, standard deviations and ranges of significant constituents in lacustrine and fluvial sandstone.

Constituent	Lacustrine Sandstone			Fluvial Sandstone		
	Mean (percent)	Standard Deviation	Range (± 1 S.D.)	Mean (percent)	Standard Deviation	Range (± 1 S.D.)
Quartz	46.2	8.1	38.1-54.3	38.8	3.1	35.7-41.9
K-feldspar	18.5	5.4	13.1-23.9	21.3	4.5	16.8-25.8
Plagioclase	5.0	1.1	3.9-6.1	8.7	3.0	5.7-11.7
Authigenic carbonate	17.2	8.7	8.5-25.9	5.4	5.1	0.3-10.5
Matrix	5.2	3.5	1.7-8.7	17.9	4.0	13.9-21.9
Coarse mica	0.7	0.8	0.0-1.5	3.0	1.8	1.2-4.8
Rock fragments	0.8	1.1	0.0-1.9	2.1	1.8	0.3-3.9

Table 5. Variation of rock fragments and coarse mica in fluvial and lacustrine sandstone, P. R. Spring area (from modal analyses).

Paleocurrent measurements also indicate that the Uncompahgre uplift was the source area of the detritus. Fluvial paleocurrent directions dominantly northwest or north in the P. R. Spring area suggest that the source areas were on the southeast or south (Picard and High, 1970, p. 28). Although the lacustrine paleocurrent directions indicate only the current system of Lake Uinta in the P. R. Spring area, the interpreted northeast-southwest orientation of shore-

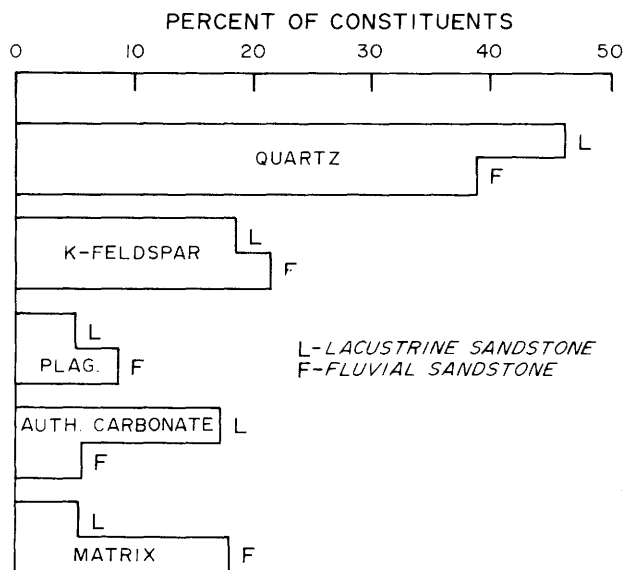


Figure 9. Histogram showing the distribution of major constituents in lacustrine and fluvial sandstone. Means of each constituent are plotted on the basis of modal analyses.

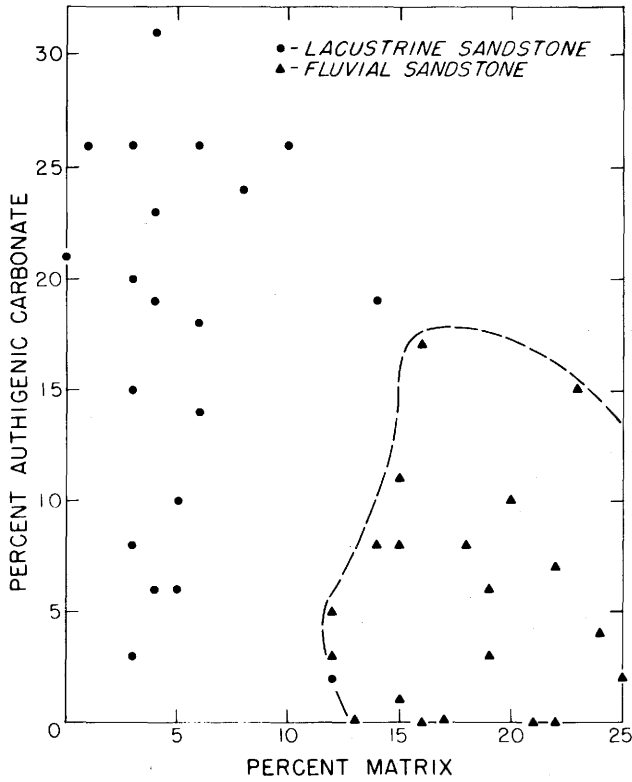


Figure 10. Scatter plot of authigenic carbonate versus matrix.

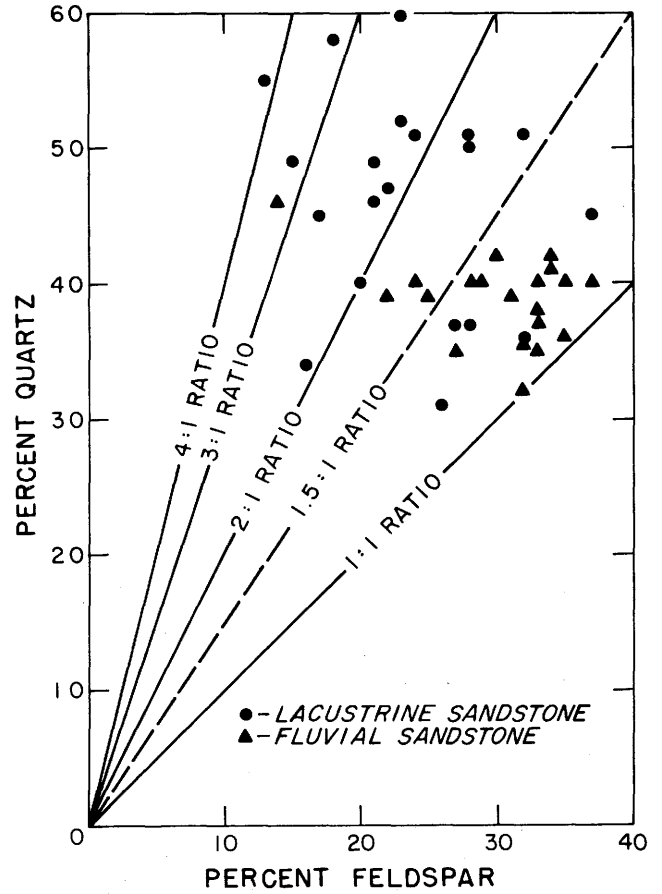


Figure 12. Scatter plot of quartz:feldspar ratios.

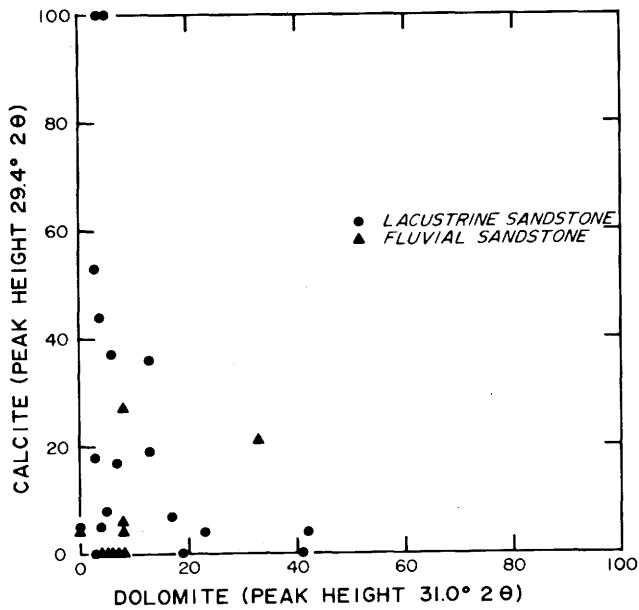


Figure 11. Scatter plot of calcite (peak height $29.4^\circ 2\theta$) versus dolomite (peak height $31.0^\circ 2\theta$) based on X-ray analysis.

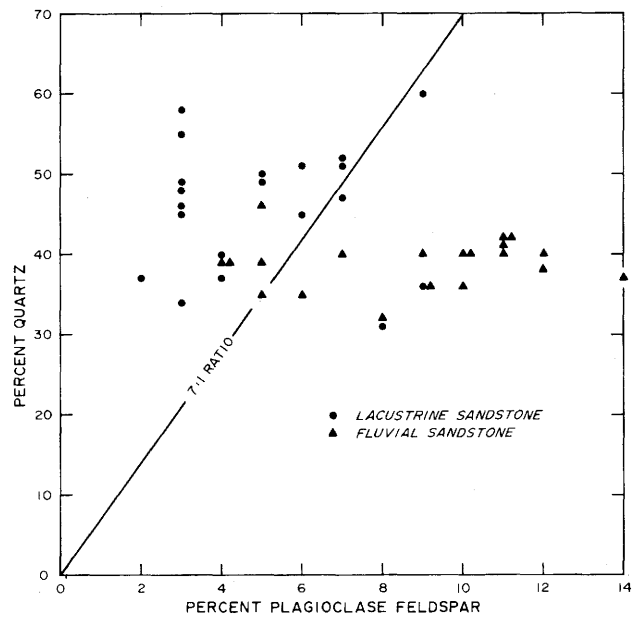


Figure 13. Scatter plot of quartz versus plagioclase feldspar.

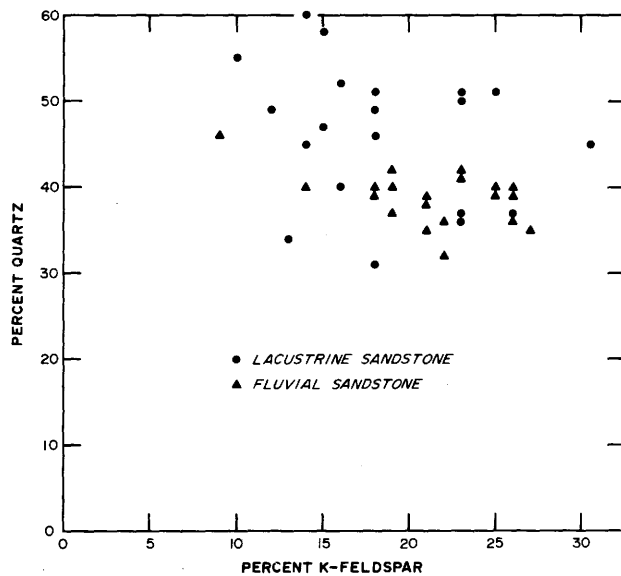


Figure 14. Scatter plot of quartz versus K-feldspar. Eighty-five percent of the fluvial sandstone plots within a relatively small area even with the overlap between constituents.

lines (Picard and High, 1970, p. 28) is consistent with a source area on the southeast.

Varied sources are inferred from the compositions of the lacustrine and fluvial sandstones. Most of the quartz is common quartz and much may be recycled from sedimentary sources. Evidence includes the well-rounded nature of some grains which are associated with much more angular grains, and reworked overgrowths noted in rare grains. The remainder of the common quartz may be indicative of granitic or granite-gneiss terrains. Muscovite, which is relatively abundant in the fluvial sandstone, is a common constituent of pegmatites, the more acidic granites, and some metamorphic rocks including phyllites, schists and fine-grained gneisses. Muscovite is also resistant to weathering and could be derived from pre-existing sedimentary rocks. However, the abundance of muscovite in the fluvial sandstone of the P. R. Spring area and the presence of lesser amounts of biotite is believed to be indicative of acid igneous terrains.

Chert and quartzite constitute about 2 percent of both lacustrine and fluvial sandstone. The chert is evidence of a pre-existing carbonate rock source.

In a paper on provenance determinations, Blatt (1967, p. 1032) stressed the subjectiveness of many interpretations. He particularly urged restraint in the use of feldspars and rock fragments as diagnostic criteria for provenance. He noted (1967, p. 1032), for

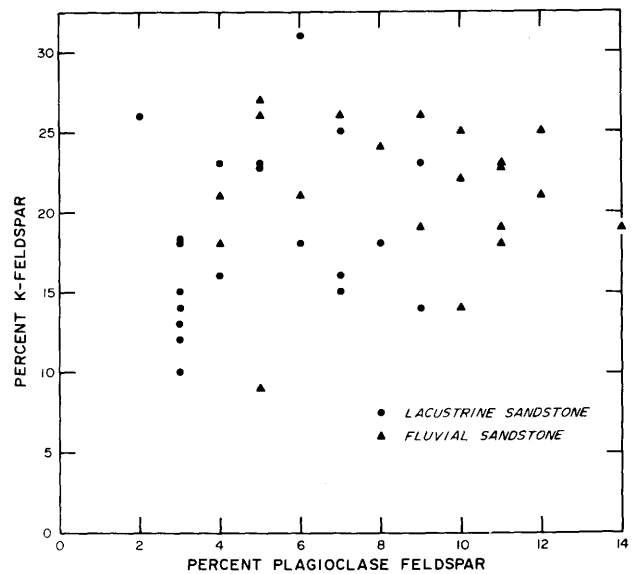


Figure 15. Scatter plot of K-feldspar versus plagioclase feldspar. Considerable overlap of constituents indicates that this is not a useful means of differentiating lacustrine and fluvial sandstone.

example, that some modern sands contain an average of 20 percent feldspars and unstable rock fragments. Feldspars and unstable rock fragments can travel great distances in low gradient streams without suffer-

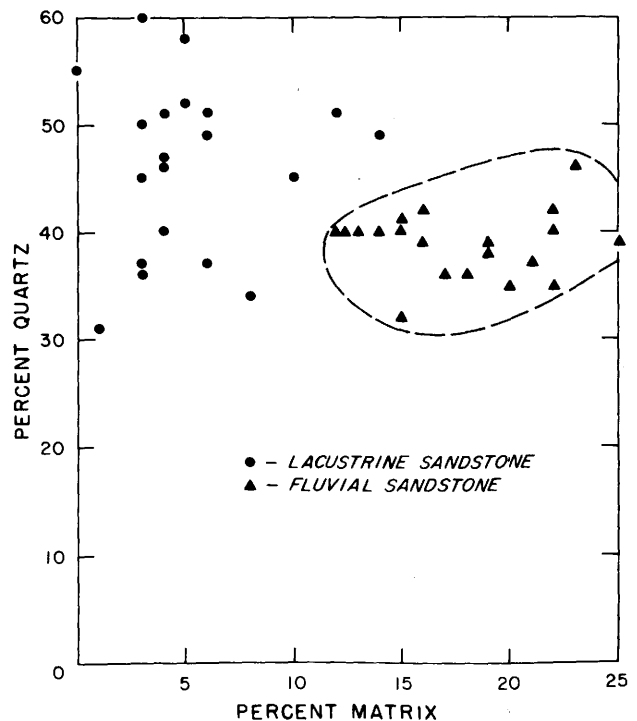


Figure 16. Scatter plot of quartz versus matrix. All of the fluvial sandstone plots within a relatively small area distinct from the lacustrine sandstone.

ing a significant reduction in percentage. Blatt concluded that 10 to 20 percent of feldspar can be derived easily from older sandstones.

Nevertheless, the large amounts of feldspar in the sandstone of the P. R. Spring area are believed to be indicative of detritus from plutonic rocks. Some of the feldspar probably is polycyclic and derived from arkosic sandstone whose detritus originally came from feldspar-rich rocks of the Uncompahgre uplift.

In summary, the detrital grains of the lacustrine and fluvial sandstone of the Green River Formation and the upper part of the Wasatch Formation suggest varied source terrains. Plutonic (granite, pegmatite and quartz vein) rocks probably were the main sources. Weathering and erosion of pre-existing clastic and carbonate rocks also supplied an appreciable amount of the sediment, possibly almost as much as the plutonic sources in some sandstone. The contribution of metamorphic rocks is unknown, but is believed to have been much less than that of plutonic and sedimentary rocks.

INTERPRETATION OF RESULTS

General

Amounts of the various minerals in lacustrine and fluvial sandstone of the P. R. Spring area differ significantly. Although fluvial and lacustrine rocks intertongue extensively in the P. R. Spring area and are closely associated in other parts, the two types of sandstone can be distinguished. Detrital grains were derived from the same source area (Uncompahgre uplift) and deposited in a fluvial complex bordering Lake Uinta and at the mouths of streams that entered the lake. Subsequently, the detritus deposited near the lake shores was subjected to the action of waves and currents in shallow lacustrine settings. It seems probable that essentially the same original detritus evolved into two distinct rocks, lacustrine and fluvial, because of differences in the two environments of deposition.

The lacustrine sandstone is mineralogically and texturally more mature than is the fluvial sandstone. This increased maturity reflects the energy applied to the detritus after its travel from the source areas. The present differences are independent of tectonism; mineral changes that took place during weathering in the source areas and during transportation of the grains also did not contribute greatly to the observed differences in the two types of sandstone. Significant differences are essentially a function of the environments of deposition.

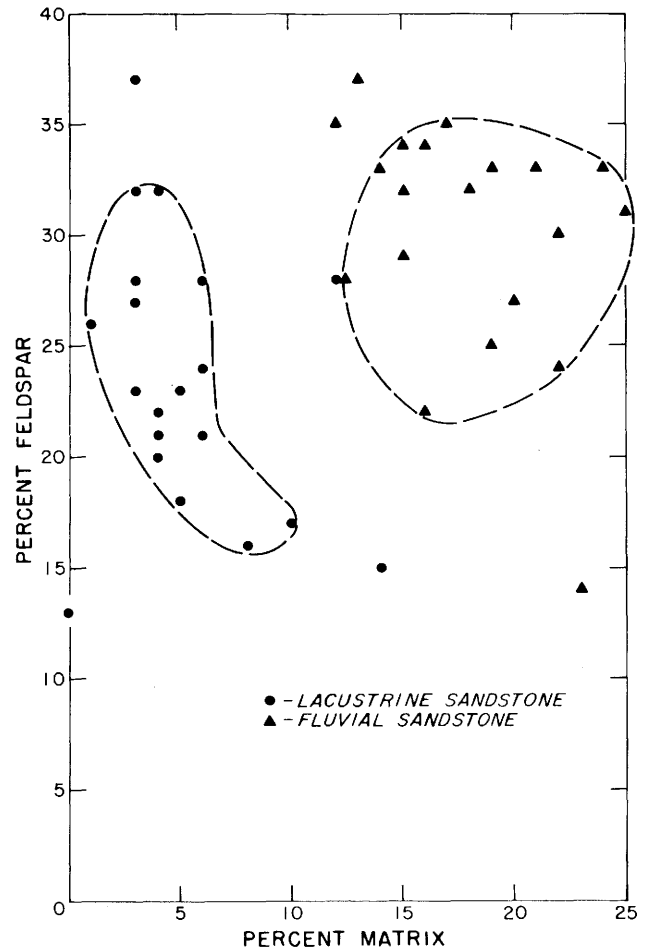


Figure 17. Scatter plot of total feldspar versus matrix. Two distinct groups corresponding to lacustrine and fluvial sandstone are present.

Authigenic Carbonate and Matrix

The average lacustrine sandstone contains about 17 percent authigenic carbonate and 5 percent matrix; the average fluvial sandstone contains about 5 percent authigenic carbonate and 18 percent matrix. Petrographic examination and X-ray diffraction studies reveal the presence of calcite and dolomite in both lacustrine and fluvial sandstone with no apparent difference in abundance (figure 11); the fluvial sandstone contains much less carbonate cement. The matrix in the two types of sandstone consists of material less than 1/16 mm in diameter and is mainly detrital grains of the same mineral composition as the framework grains of the sandstone.

In nearshore areas, considerable matrix material was winnowed from the dominantly sand-sized detritus by waves and currents and was deposited in deeper water lacustrine settings farther from shore. This fine-grained material is common in micritic car-

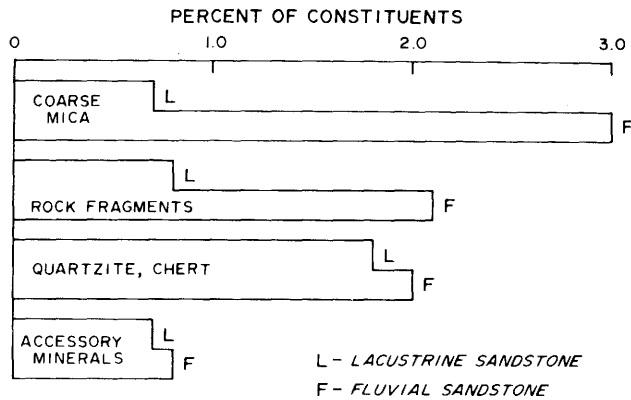


Figure 18. Histogram showing distribution of minor constituents in lacustrine and fluvial sandstone.

bonate beds, as well as in siltstone, claystone and mudstone beds. The removal of fine material (matrix) led to increased initial permeability and porosity in the lacustrine sand-sized material, and an average of about 12 percent more authigenic carbonate was precipitated as cement in the lacustrine sandstone. In contrast, the fluvial sand-sized material was not sorted to the same degree; much more fine-grained detritus was retained.

An inverse relationship between matrix content and the amount of mineral cement has been noted previously (Krynine, 1948, Pettijohn, 1957 and Siever, 1959). In his study of silica cementation in some Pennsylvanian sandstones, Siever (1959) stated that the most extensive quartz cementation is found in the nearly matrix-free (clay-free) sandstones, but many sandstones with 5 to 10 percent matrix and large amounts of quartz cement occur. Siever (1959, p. 69) also found that rocks with high carbonate contents tend to have low matrix. Small amounts of carbonate may be present in the matrix-rich Pennsylvanian rocks.

The inverse relationship between matrix and authigenic carbonate in the sandstone of the P. R. Spring area commonly is ascribed to two factors: lack of pore space and permeability (Siever, 1959, p. 69-70). If matrix completely filled the pore space between the sand-sized detrital grains, authigenic carbonate could not be precipitated. Such is not the case for the sandstone studied here. Seventy-five percent of the fluvial sandstone contains more than trace amounts of authigenic carbonate (table 2). Even in those fluvial sandstones that do not contain authigenic carbonate (on the basis of the modal analyses) there is some pore space in which authigenic carbonate could have been precipitated. Thus, the inverse relationship between authigenic carbonate and matrix noted here was not caused by the absence of pore space. The most important factor is a decrease in

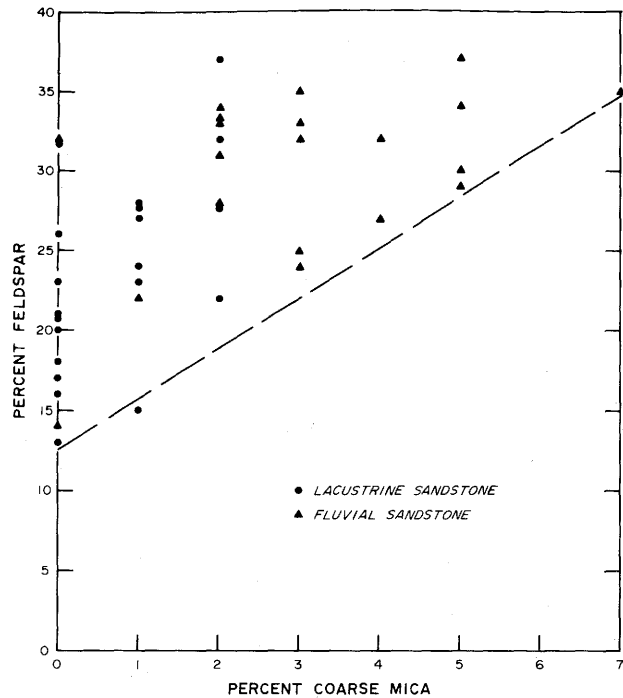


Figure 19. Scatter plot of total feldspar versus coarse mica.

permeability (Siever, 1959, p. 69-70). The permeability of the matrix-rich sandstone was probably so low that solutions that might have precipitated authigenic carbonate were preferentially excluded. The fluvial sandstones have low permeabilities compared with the lacustrine sandstones. In many parts of the Uinta Basin fluvial sandstone contains only gas, in comparison with lacustrine sandstone which contains both oil and gas. If this interpretation is correct, much of the cementation took place after compaction of the sand-sized sediment when permeability had been greatly decreased. Examination of the petrographic relationships between framework grains and authigenic carbonate cement indicates that the carbonate cement did not replace a matrix network, especially in the lacustrine sandstone.

Coarse Mica

The average lacustrine sandstone contains 0.7 percent coarse mica in contrast to fluvial sandstone which contains 3 percent coarse mica; well-sorted sediments contain less coarse mica than poorly sorted sediments. Coarse mica remains in suspension longer and is deposited in less turbulent environments than quartz and feldspar because of its large surface area and slower settling velocity. Fine-grained sedimentary rocks (siltstone, claystone and mudstone) contain more coarse mica than closely associated sandstone beds. In a study of the petrography of the Red Peak Formation (Triassic), Picard (1966, p. 924) found

Table 6. Comparison of average framework constituents in lacustrine and fluvial sandstone (based on modal analyses).

Constituent	Percent	
	Lacustrine Sandstone	Fluvial Sandstone
Quartz	46.2	38.8
K-feldspar	18.5	21.3
Plagioclase	5.0	8.7
Rock fragments	0.8	2.1
Quartzite, chert	1.8	2.0
Total	72.3	72.9

that the amount of coarse mica increases as the modal grain size of the rocks decreases (from very fine sandstone to well-sorted siltstone to poorly sorted siltstone to silty claystone). Many other workers have made similar observations.

The marked difference in coarse mica content in the lacustrine and fluvial sandstone of the P. R. Spring area is attributed to differences in sorting in the two major environments. Better sorting in the lacustrine environment led to a separation of much of the coarse mica and its deposition in associated fine-grained sedimentary rocks (siltstone, claystone and mudstone). Relatively poorer sorting in the fluvial environments entrapped considerably more coarse mica in the fluvial sandstone.

Quartz and Feldspar

The percentage of framework grains (mostly quartz and feldspar) is essentially the same in both lacustrine and fluvial sandstone (table 6); mean percentages of major minerals are different, however, and lacustrine sandstone contains more quartz and less feldspar. These differences in the major minerals are more difficult to account for than other differences noted in the two types of sandstone.

Data on the amount of feldspar in the lacustrine and fluvial sandstone are in terms of K-feldspar and plagioclase. Identification at this level is relatively easy when thin sections are stained for K-feldspar; varieties of plagioclase and K-feldspar are difficult to distinguish in sandstone thin sections (Dickinson, 1970, p. 700). Albite is characterized by refractive indices lower than the mounting media. As noted by Dickinson (1970, p. 700), other plagioclases are difficult to differentiate, particularly because the optical properties at a given composition vary with the degree of ordering, as between plagioclase of volcanic and plutonic origin. Polysynthetic twinning is characteristic of much microcline, but it is not present in

all crystals. Despite these difficulties an attempt has been made to determine the relative amounts of the feldspar species.

On the basis of the modal analyses, the lacustrine sandstone contains about 18 percent K-feldspar and 5 percent plagioclase; the fluvial sandstone contains 21 percent K-feldspar and 9 percent plagioclase. Detailed examination of thin sections and counts of feldspar species indicate that orthoclase is much more abundant than microcline. The relative abundance of the major feldspar species in both types of sandstone is: orthoclase > plagioclase > microcline. The plagioclase, an Na-plagioclase whose composition is predominantly albite and oligoclase, is almost twice as abundant as microcline. Untwinned Na-plagioclase is more abundant than twinned plagioclase. In some rocks, Na-plagioclase is almost as abundant as orthoclase. Microperthite is rare in both types of sandstone. Albite twinning is common; Carlsbad twinning is rare.

According to Folk (1968, p. 83), the relative abundance of feldspar species in most sandstones is: orthoclase > microcline > plagioclase. In contrast, Baturin (1947, cited by Parfenova and Yarilova, 1965, p. 39) suggested that plagioclase is commonly more abundant than K-feldspar. In 178 massive plutonic rocks from throughout the world, Feniak (1944, p. 419) determined the order of abundance of feldspar species: plagioclase > orthoclase > microcline > microperthite.

Untwinned plagioclase is probably frequently reported as orthoclase because many sedimentary petrographers do not use staining techniques or X-ray analyses (Picard, 1966). Even so, research into recent North American literature indicates that Na-plagioclase may be as abundant as orthoclase in sandstones (tables 7-8). Both Na-plagioclase and orthoclase are more abundant than microcline (tables 7-8); microcline is more abundant than microperthite which is more abundant than sanidine.

Much more detailed work on feldspar species in sandstone is required before relative abundances are fully established. The resistance of Na-plagioclase, orthoclase and microcline to weathering and diagenetic reactions is especially pertinent. As was indicated, it is difficult to differentiate species of plagioclase and K-feldspar in thin sections of sandstone. Post-depositional albitization must also be considered. On the basis of present information, however, Na-plagioclase appears as stable at surface conditions and in sedimentary environments as orthoclase.

Feldspar species in both the lacustrine and fluvial sandstones of the P. R. Spring area were derived from the same rock types in the same source areas

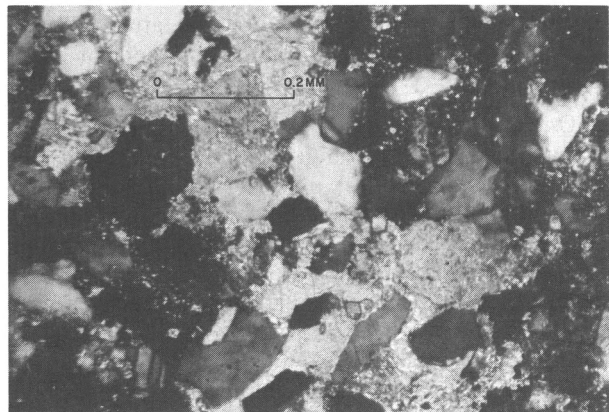


Figure 20. Lacustrine sandstone from near top of Douglas Creek Member, P. R. Spring area. Abundant authigenic carbonate (about 19 percent of rock) is mostly dolomite. Sandstone contains about 4 percent matrix.

Figure 21. Lacustrine sandstone from upper part of Douglas Creek Member. Abundant altered feldspar is mostly K-feldspar (about 23 percent of rock). Authigenic carbonate is dolomite. Sandstone contains about 3 percent matrix.

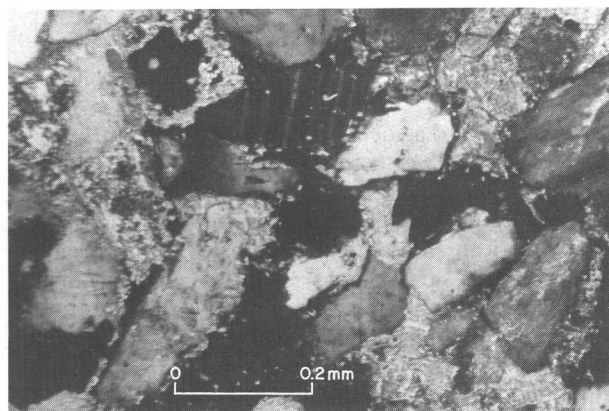
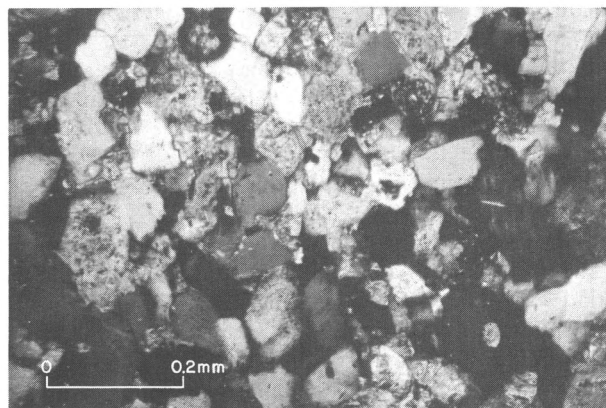
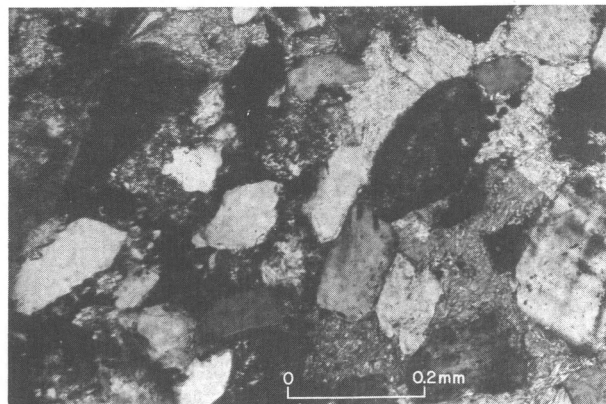


Figure 22. Lacustrine sandstone from Douglas Creek Member of Green River Formation. Authigenic carbonate (about 26 percent of rock) is dominantly calcite. On the basis of modal analysis, the sandstone contains about 1 percent matrix. Note albite-twinning feldspar grain near top of photomicrograph.

Figure 23. Lacustrine sandstone from Douglas Creek Member. Authigenic carbonate (about 31 percent of rock) is mostly calcite. Sandstone contains about 4 percent matrix.



PHOTOMICROGRAPHS

(All specimens are under cross nicols.)

Figure 24. Fluvial sandstone from upper part of Wasatch Formation, P. R. Spring area. Matrix is abundant (about 24 percent of rock). Authigenic carbonate is mostly dolomite (about 4 percent). Feldspar is almost as abundant as quartz. Note poor sorting compared to lacustrine sandstone.

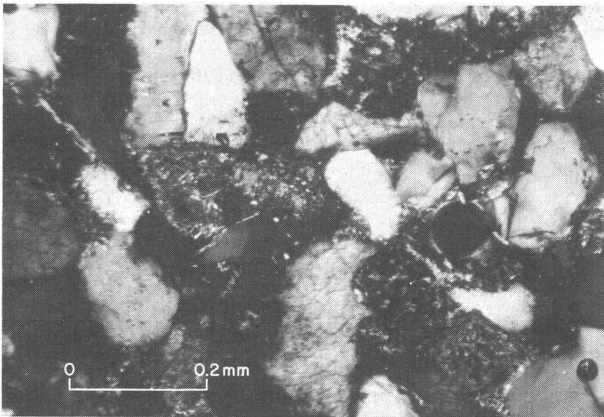
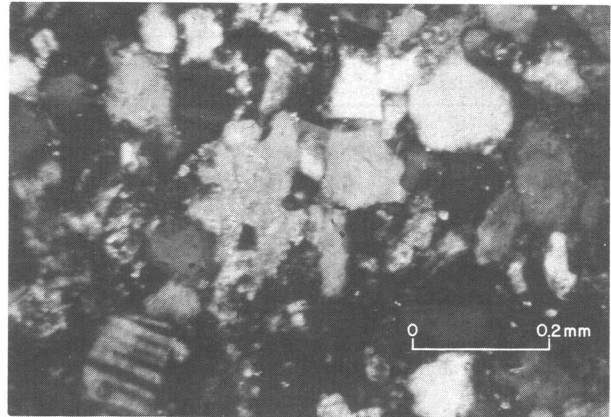


Figure 25. Fluvial sandstone from thick channel sequence (meandering stream deposits) in Douglas Creek Member. About 12 percent matrix and 3 percent authigenic carbonate in rock. Note common coarse mica.

Figure 26. Fluvial sandstone from fluvial tongue in Douglas Creek Member of Green River Formation. Authigenic carbonate is rare and none was encountered in point counting. Rock contains about 17 percent matrix and 7 percent coarse mica. Feldspar is as abundant as quartz.

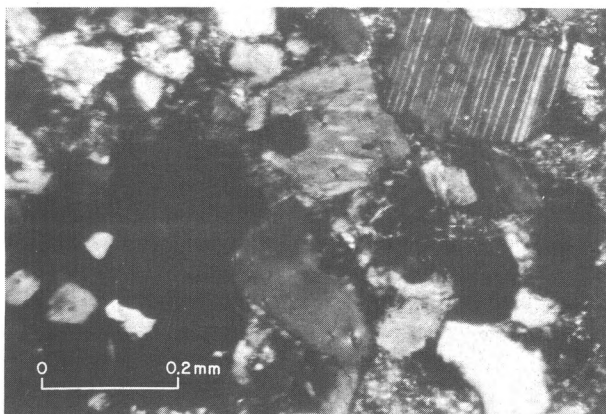
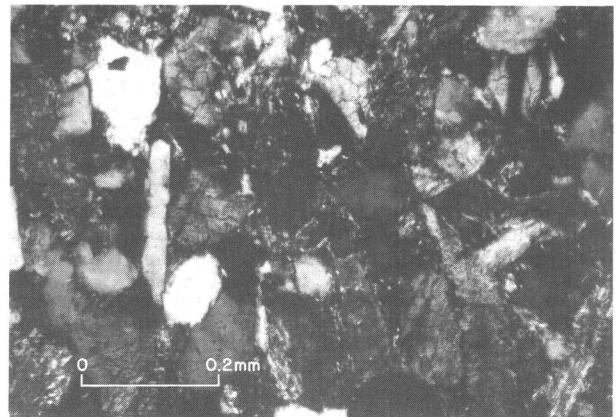


Figure 27. Fluvial sandstone from large channel sequence in Douglas Creek Member. Rock contains about 19 percent matrix and 3 percent authigenic carbonate. Feldspar is almost as abundant as quartz. Note relatively fresh and altered feldspar grains. Dark area in southwest quarter of photomicrograph is heavily stained with red pigment (hematite).

PHOTOMICROGRAPHS
(All specimens are under cross nicols.)

Table 7. Relative abundance of feldspar species in sandstone units.

Relative Abundance of Feldspar Species	Rock Unit	Environment of Deposition	Reference
1. Orthoclase } Na-plagioclase } microcline } micropertthite	Green River Formation (Eocene)	Lacustrine, fluvial	This paper
	Upper Wasatch Formation (Paleocene?-Eocene)	Fluvial	
2. Orthoclase } Na-plagioclase } microcline	Late Permian (south central Kansas)	Restricted marine	Swineford (1955)
3. Orthoclase } Na-plagioclase and microcline } micropertthite	Gartra Formation (Triassic)	Fluvial	McCormick and Picard (1969)
4. Orthoclase } Na-plagioclase and microcline } perthite	Smithwick Shale (Pennsylvanian)	Turbidity current origin	McBride and Kimberly (1963)
5. Orthoclase } microcline } plagioclase	Frontier Formation (Cretaceous)	Deltaic, marine	Beckmann (1967)
6. Orthoclase } microcline } plagioclase	Santa Rosa Sandstone (Triassic)		Miller (1966)
7. Orthoclase } microcline } plagioclase } micropertthite	Morrison Formation (Jurassic)	Fluvial	Brady (1969)
8. Orthoclase } microcline } sanidine } plagioclase	Pierce Canyon Formation (Permian)	Restricted marine	Miller (1966)
9. Orthoclase } Na-plagioclase, microcline and perthite	Warrensburg Sandstone (Pennsylvanian)	Fluvial	Doty and Hubert (1962)
10. Orthoclase } orthoclase micro- perthite } plagioclase } microcline	Domengine Formation (Eocene)	Fluvial	Todd (1968)
11. K-feldspar } plagioclase	Monitor Butte Member (Triassic)	Fluvial	Cadigan (1959)
12. K-feldspar } plagioclase	Moss Back Member (Triassic)	Fluvial	Cadigan (1959)
13. K-feldspar } plagioclase	Morrison Formation (Jurassic)	Fluvial, lacustrine	Cadigan (1967)
14. Microcline } orthoclase } plagioclase	Claiborne Group (Eocene)	Shallow marine	Todd and Folk (1957)
15. Microcline } orthoclase } Na-plagioclase	Fountain Formation (Permo-Penn.)	Fluvial	Hubert (1960)
16. Microcline } Na-plagioclase } micropertthite } orthoclase	Applecross Group (Precambrian)	Fluvial	Selley (1966)
17. Na-plagioclase } orthoclase } microcline	Haymond Formation (Pennsylvanian)	Turbidity current origin	McBride (1966)
18. Na-plagioclase } orthoclase } microcline	Black shale facies (Green River Formation)	Lacustrine	Thompson and Picard (unpubl.)
19. Na-plagioclase } orthoclase } microcline } micropertthite	Red Peak Formation (Triassic)	Shallow marine	Picard (1966)
20. Na-plagioclase } orthoclase and microcline	Crow Mountain Formation (Triassic)	Shallow marine	Tohill and Picard (1966)
21. Na-plagioclase } orthoclase } microcline, sanidine and perthite	Broughton Sandstone (Permian)	Shallow marine	Raam (1968)
22. Na-plagioclase } orthoclase } microcline } perthite	Martinsburg Formation (Ordovician)	Turbidity current origin	McBride (1962)
23. Na-plagioclase } orthoclase	Parry Group (Devonian-Carboniferous)	Deep water marine	Crook (1960b)
24. Na-plagioclase } orthoclase	Tamworth Group (Devonian)	Deep water marine	Crook (1960a)
25. Na-plagioclase } microcline } micropertthite } orthoclase	Diabaig Group (Precambrian)	Lacustrine, marine	Selley (1966)
26. Na-plagioclase } K-feldspar	Stockton Formation (Triassic)	Fluvial	Van Houten (1965)
27. Na-plagioclase } K-feldspar	Brunswick Formation (Triassic)	Fluvial	Van Houten (1965)
28. Na-plagioclase } K-feldspar	Lockatong Formation (Triassic)	Lacustrine	Van Houten (1965)
29. Na-plagioclase } K-feldspar	Popo Agie Formation (Triassic)	Lacustrine, fluvial	High and Picard (1965)
30. Plagioclase } K-feldspar	Great Valley sequence (Lower Mesozoic)		Gilbert and Dickinson (1970)
31. Plagioclase } orthoclase } microcline	Minturn Formation (Pennsylvanian)	Fluvial, marine	Boggs (1966)
32. Plagioclase } orthoclase and microcline	Perry Farm Shale (Pennsylvanian)	Marine	Keller and Ting (1950)
33. Plagioclase } sanidine } orthoclase and microcline	Gueydan Formation (Oligocene-Miocene)	Fluvial	McBride and others (1968)
34. Plagioclase } sanidine } orthoclase and microcline	Honda Group (Miocene)	Fluvial	Wellman (1970)

Table 8. Comparison of relative abundance of all K-feldspar and plagioclase (from table 7; feldspar species in the various comparisons are not duplicated).

Relative Abundance of Feldspar Species	Number of Instances of Relationship
Orthoclase > Na-plagioclase	6
Na-plagioclase > orthoclase	10
Orthoclase > plagioclase	6
Plagioclase > orthoclase	4
K-feldspar > plagioclase	3
Plagioclase > K-feldspar	1
Microcline > plagioclase	4
Plagioclase > microcline	5
Microcline > Na-plagioclase	2
Na-plagioclase > microcline	9
Orthoclase > microcline	16
Microcline > orthoclase	4

(Uncompahgre uplift). Average duration and intensity of weathering of the feldspar species in the source areas were probably the same. Fresh and badly weathered feldspar of the same species occur in the sandstone. Todd (1968, p. 839), in his study of the stability of feldspar minerals, saw no reason to believe that topography in the source areas was selectively related to species of feldspar.

The stabilities of feldspar species to different climatic and transportation regimes are poorly understood (Blatt, 1967, p. 1035 and Todd, 1968). Apparently the rate at which feldspar is reduced in size by transport depends primarily on its weathering state (Phillips, 1881, p. 22-23 and Martens, 1931), the duration and intensity of stream, surf or wind action, and the presence of structural weaknesses within grains, such as perthitic intergrowths or twin composition planes (Blatt, 1967, p. 1035). Phase boundaries between perthite lamellae act as surfaces along which decomposition readily takes place and as surfaces of relatively easy fracture. For example, a greater number of fine orthoclase micropertite fragments would be generated by breakage during transport than would be produced by similar transport of orthoclase (Todd, 1968, p. 840). Pittman (1969, p. 1432) found that in an area of high relief plagioclase breaks readily during stream transport along composition and twin planes. C-twins tend to be destroyed relative to A-twins during stream transport (Pittman, 1969, p. 1437). As a consequence, Carlsbad-twinned feldspar is rare in most feldspathic sandstone. Further, untwinned plagioclase increases relative to twinned plagioclase in a downstream direction (Pittman, 1969, p. 1437).

Distances from the source areas to the depositional sites in the P. R. Spring area were relatively short. Streams carrying detritus into Lake Uinta in the P. R. Spring area were probably the same as those streams in which fluvial sandstone was deposited. Within a set time, detritus deposited in the lake was slightly farther from the source areas than was detritus deposited by the streams. All of the sandstone studied in the P. R. Spring area was deposited near the lake shores. Thus, transport distance of quartz and feldspar was not greatly different in either lacustrine or fluvial sandstone. At the time of initial deposition, the feldspar species had been exposed to essentially the same weathering and transportation processes; it is suggested, therefore, that feldspar was differentially deleted in the two depositional environments.

It is not known if feldspar was subtracted in both the lacustrine and fluvial settings, but at a greater rate in the lacustrine setting; it is possible that little feldspar was deleted in the fluvial setting after initial deposition.

Some feldspar probably was completely removed in the lacustrine environment after initial deposition near the lake shores when grains were subjected to wave and current action. Feldspar species are more susceptible to abrasion and chemical change than quartz grains. Detritus deposited in the lacustrine environments may have been subjected to a slightly longer period of abrasion and chemical activity at the depositional sites than was the fluvial detritus. Little quantitative data concerning the relative effects of energy in depositional environments on quartz and feldspar are available.

Possibly some of the feldspar grains deposited in the lacustrine environments were reduced to silt- or clay-sized particles and redeposited with fine-grained material farther from shore in beds of siltstone, claystone and micritic carbonate. Siltstone in the P. R. Spring area contains K-feldspar and plagioclase, some of which may have been derived in this manner; most of the feldspar in the siltstone was probably originally deposited with quartz and other silt-sized detritus.

A third possibility for feldspar reduction is diagenetic removal. After compaction and lithification of the lacustrine sandstone, some feldspar may have been deleted by intrastratal solutions.

The relative importance of the suggested mechanisms of feldspar reduction in the lacustrine sandstone is difficult to evaluate. Even based on the results of modal analyses, which justify the interpreta-

tion, some geologists will not be convinced that lacustrine sandstone in the P. R. Spring area actually contains less feldspar than fluvial sandstone. Yet feldspar (especially plagioclase) is less abundant in the lacustrine sandstone. Further, the bulk of the feldspar was deleted in the depositional environment before the beds were lithified.

Allochems and Analcime

The intraclasts, oolites and fossils (ostracods and algae) found in the lacustrine sandstone are characteristic of lacustrine and not fluvial environments. Fluvial sandstone can contain allochems, but they are not characteristic of most fluvial sandstone. In the P. R. Spring area, beds dominantly composed of intraclasts, oolites, pisolites, ostracods and algae are closely associated with the lacustrine sandstone. Other types of bedded carbonate also are closely associated with the lacustrine sandstone but not with the fluvial sandstone.

Calcite readily crystallizes when the pH is higher than 7.8, but tends to dissolve at a pH lower than 7.8. It is inferred that the pH of the lake waters was greater than 7.8; the pH of the streams was probably about 7.0 or a little less. Rankama and Sahama (1950, p. 227) note a pH of 8.0 to 8.4 for calcareous, lake and river water, but a pH of 6.5 to 7.0 for noncalcareous, lake and river water. Streams do not commonly exceed 7.0 in pH.

Plant debris, trunks of trees and other carbonaceous material, and traces of vertebrate remains are present in some of the fluvial sandstone.

The rare analcime in the lacustrine sandstone is characteristic of lacustrine and not fluvial environments. The formation of analcime at surface temperatures requires high ratios of alkali ions to hydrogen ions. Hay and Moiola (1963, p. 76a) report that saline, alkaline, lake waters in Searles and China lakes, California, reacted with nontuffaceous clays to produce authigenic analcime. The salinity of interstitial brines in Searles Lake is 30 to 35 percent, the pH is 9 to 10. They suggest a salinity of 15 percent and a pH of 9 to 10 for China Lake. In Lake Uinta, the pH was possibly 8 to 9 during crystallization of the analcime. Material for the formation of the analcime probably came from volcanic debris. Beds of tuff partly or completely altered to analcime occur in the P. R. Spring area. During formation of the analcime noted in the lacustrine sandstone the interstitial waters were saline.

DIAGENETIC FEATURES

Physical Diagenesis

Diagenesis includes all changes that take place in a sediment or sedimentary rock immediately after the time of deposition to the time weathering begins (McBride, 1966, p. 44). Compaction and induration are the most significant physical sedimentologic changes that the lacustrine and fluvial sediments have undergone. The P. R. Spring area was subjected to tectonic deformation and joints, folds and faults were formed during the Laramide orogeny. The folds, however, generally have less than 50 feet of surface closure and displacement on faults is small. The area, then, did not undergo strong deformation and few mineralogic changes are related to it. Interpenetration between feldspar and unfractured quartz grains is slight. Coarse mica grains are draped around more resistant grains. Slumping prior to consolidation led to the formation of small folds and microfaults in both lacustrine and fluvial sandstone (Picard and High, 1970).

Red Pigment

Although none of the sandstones that were studied are redbeds, all of the fluvial sandstone and some of the lacustrine sandstone contain at least small areas of red pigment (hematite). Red pigmentation, as seen in thin sections, is characteristic of the fluvial sandstone and is, in general, more abundant in the fluvial sandstone than in the lacustrine sandstone. Red, fine-grained rocks (siltstone, claystone and mudstone) are interbedded with the fluvial sandstone in the P. R. Spring area. Red sandstone beds in the Wasatch Formation were not sampled.

It is difficult to determine the amount of red pigment in a particular thin section because of variations in the intensity of staining. In some thin sections the red pigment is only a thin, superficial coating on the matrix material. It occurs variously as grains coatings, and in pockets, lenses, stringers and veinlets. The red pigment occupies pore space in the sandstone and is distributed irregularly throughout it. Nearly all of the samples contain less than 1 percent red pigment.

In many of the thin sections a few grains of quartz and feldspar are enclosed by thin rims of red-pigmented, fine-grained material. Other rare grains show similar hematite-stained fine material that partly enclosed the grains. These grains, which are present in trace amounts, are believed to have been derived from pre-existing redbeds in the source areas. The red rims of the grains have withstood the rigors of stream transport and, in several instances, the near-

shore turbulence of the lake shore zone. The hematite has not been reduced in the depositional sites.

The red matrix or red pigment is present between grain contacts only in a few cases. Most of the red pigmentation took place after the grains were touching. No evidence suggests that red pigment between grains was removed by solution at grain contacts during diagenesis. The small amount that is present, other than the rare red-pigmented rims just discussed, formed during diagenesis.

Post-depositional red pigmentation is indicated as follows. Each of two or three zones of some non-detrital dolomite rhombohedrons is enclosed by a red rim, indicating that the red pigment was available in the environment at successively later times. Red pigment also moved into pore space that remained after the deposition of sparry carbonate cement and locally coated cement already in place.

Hematite radiates outward from some opaque grains (hematite, magnetite and ilmenite) and the intensity of the red pigmentation decreases outward from the altered grains. But not all opaque grains show red pigment radiating outward from grain boundaries. Hematite, the dominant opaque mineral in the sandstones, is present in localized patches, in small veinlets and lenses, as pore-space filler, as rare grain coatings and as detrital grains. Apparently, some detrital magnetite and ilmenite has altered to hematite.

The alteration of biotite also has yielded red pigment. Although muscovite is much more abundant in the sandstones than biotite, trace amounts of biotite occur in most thin sections, especially the fluvial thin sections. In some instances red, brown and tan pigment, presumably hematite, has moved outward from the biotite during diagenesis and stained adjacent grains.

Another example of diagenetic pigmentation is the patches of red-pigmented matrix that show red stain that has moved out from the matrix a fraction of a millimeter into nonpigmented matrix or onto grains. These patches are like the red material that moved out from some opaque grains.

Petrographic relations indicate that red pigment locally overlays matrix material regardless of previous mineral relations; it also coats authigenic carbonate irregularly. Red pigmentation apparently began early in the diagenetic history and continues to a lesser degree to the present. During diagenesis the mobile red pigment moved fractions of a millimeter in permeable directions. Principally, it moved out from some opaque grains and biotite and out from local

small areas of matrix. In the process grains and aggregates of grains were partly coated, as was authigenic carbonate. Thus, the red pigment is essentially post-depositional in origin (Picard, 1965, Walker, 1967 and Van Houten, 1968), although a few grains containing secondary material from pre-existing redbeds are preserved. It should be reemphasized, however, that these sandstones contain only small amounts of red pigment, generally less than 1 percent.

Cement

Pore-filling cement minerals in the sandstone in order of total abundance are: calcite-dolomite; clay minerals and feldspar alteration products (illite, sericite and kaolinite); hematite and quartz. In a few thin sections, minor amounts of analcime fill pore space. It is difficult to distinguish dolomite from calcite in some thin sections because the samples were not stained for them. Apparently, much of the micrite-microspar in the lacustrine sandstone is dolomite. The writer interprets this to be primary dolomite, or at least dolomite formed so soon after crystallization that it can not be distinguished from primary dolomite. Abundant dolomite is also present in former pore spaces as well-developed small and large rhombohedrons. The rhombohedral dolomite is distinctive and is easily distinguished from calcite. Sparry carbonate cement, both calcite and dolomite, is abundant in the lacustrine sandstone.

Rarely, each of two or three zones of non-detrital, zoned rhombohedrons of dolomite has a red-pigmented rim enclosing it, indicating that the red pigment (hematite) was available during diagenesis at successively later times. Dolomite growth ceased at times and red pigment and matrix material were concentrated along the outer borders; then dolomite growth was repeated. In some rhombohedrons, the successive dolomite zones are remarkably clean and did not incorporate matrix material during their growth. Locally, dolomite and calcite replace quartz and, to a much less extent, feldspar at grain contacts.

Small amounts of silica cement were noted in four sandstones (tables 1-2). Rarely, a few grains of quartz display secondary quartz overgrowths.

Diagenetic Sequence

Although minor exceptions in individual thin sections were noted, the diagenetic sequence for the lacustrine and the fluvial sandstone is similar. Major events are as follows:

1. Detrital grains of quartz, feldspar, rock fragments and so forth were deposited. A few grains with red-pigmented rims were preserved. Probably there were many more red-rimmed grains from pre-

existing redbeds whose red pigment could not stand the rigors of stream transport and current action in the depositional sites.

2. Processes that led to relative changes in the proportions of the detrital minerals in the depositional environments were discussed in previous sections.

3. Some physical aspects of the diagenesis were discussed previously. Compaction did not materially alter the mineralogy of the sandstone beds.

4. Secondary quartz overgrowths were formed on a few quartz grains during an early diagenetic event. It is probable that the minor silica cement was also emplaced early in the diagenetic history. Further, some red pigment began to form from the alteration of iron oxides and iron-rich silicate minerals early in the diagenetic history. The bulk of the red pigment originated later.

5. Authigenic carbonate was precipitated. Petrographic relations indicate that some primary dolomite (micrite-microspar) crystallized before most of the authigenic carbonate cement. Some of the sparry carbonate rhombohedrons of dolomite may also be primary and not dolomitized calcite cement. Relationships are not evident. The sparry carbonate filled pore spaces, formed after the secondary quartz overgrowths, and, in a minor way, replaced quartz, feldspar and chert at grain boundaries.

6. Although the formation of post-depositional red pigment began early and continues to some extent, the bulk of the red pigmentation took place after formation of the sparry carbonate. Redistribution of earlier formed red pigment was partly responsible. Most red pigment is localized near small areas where alteration of iron oxide minerals and iron-rich silicate minerals has been the mechanism for its formation.

MATURITY OF SANDSTONE

Various indices reflect the mineralogical maturity of a sedimentary rock (Pettijohn, 1957, p. 508-509). Of those, a good comparison can be made here with quartz:feldspar ratios in other rocks. The quartz:feldspar ratios for lacustrine and fluvial sandstone in the P. R. Spring area are 2:1 and 1:4 respectively. These ratios compare with 1:1 and 2:7 for the average arkosic sandstone and the average graywacke (table 9), which indicates that the sandstone in the P. R. Spring area is immature.

The petrography of both the lacustrine and fluvial sandstone and field relationships indicate that the

Table 9. Maturity indices of sandstone (after Pettijohn, 1957, p. 509).

Rock Type	Average	
	Q/F Ratio	Quartz + Chert/ Feldspar + Rock Fragments
Arkosic sandstone	1.1	1.1
Graywacke	2.7	1.2
Lithic sandstone	9.8	2.3
Orthoquartzite	>10.0	
Lacustrine sandstone, P. R. Spring area	2.1	1.9
Fluvial sandstone, P. R. Spring area	1.4	1.3

source areas were moderate to high compared with the depositional basin. The relief led to a moderate to high rate of erosion, but time was not sufficient for complete weathering. The arkose described here is interpreted to be mainly a tectonic arkose because its abundant feldspar is the result of tectonic uplift (Folk, 1968, p. 127). Some of the feldspar in the sandstone is fresh appearing (not altered), which also indicates that weathering was incomplete. Fresh and badly weathered feldspar of the same species are present. Plant debris in some of the fluvial sandstone also suggests that the source areas were of moderate to high relief and the topography was probably mature.

OIL AND GAS

All of the oil in the Green River Formation in the Uinta Basin probably originated in lacustrine facies of the formation. In a previous study, Picard (1962) proposed that the source rocks of oil in the Red Wash-Walker Hollow field were medium to dark gray or black shale beds and not oil shale beds. Further, it was suggested (Picard, 1962, p. 694) that oil shale units in the Green River Formation may not have readily given up their oil, whereas gray shale units have done so more easily.

The oil in the P. R. Spring area is mostly in lacustrine sandstone bodies (Picard and High, 1970, p. 7). It is suggested that the oil originated in lacustrine facies of the Green River Formation and migrated updip into the dominantly lacustrine reservoir beds of the P. R. Spring area. Migration distances were short; much of the oil may have originated in beds that are closely related to the lensing network of lacustrine sandstones that now contains the oil. The oil rarely migrated into fluvial sandstone bodies that are associated closely with the lacustrine sandstone in the P. R. Spring area.

As noted previously, nearly all of the oil in oil fields of the Uinta Basin is in lacustrine sandstone of the Green River Formation. The oil-impregnated sand-

stone along Raven Ridge in the northeast part of the Uinta Basin is predominantly lacustrine sandstone. The oil-impregnated sandstone at Sunnyside west of P. R. Spring is partly in older rock units than those in the P. R. Spring area, but the upper part of the saturation at Sunnyside is approximately equivalent to the oil-impregnated intervals at P. R. Spring. It is economically important, therefore, to be able to recognize lacustrine sandstone in the Tertiary of the Uinta Basin.

The more permeable, porous lacustrine sandstone of the P. R. Spring area furnished superior reservoir beds compared with those of the fluvial sandstone. The fluvial sandstone contains about 13 percent more matrix than does the lacustrine sandstone and more coarse mica and clay minerals, both of which inhibit porosity and permeability.

Gas has been located in fluvial sandstone reservoirs in the Wasatch Formation at several areas in the southeast Uinta Basin. Production tests, however, show low reservoir pressures (Picard, 1965). The poor sorting, large feldspar content, and large amounts of matrix and clay minerals in many of the sandstones have led to poor reservoir conditions. Porosity and permeability in these sandstones have been inhibited, just as in the P. R. Spring area. Many of the sandstone bodies are commonly less than 25 to 35 feet thick and are of limited areal extent.

For a good economic return from oil and gas exploration in the Tertiary of the Uinta Basin it is best to find oil and gas in lacustrine reservoirs. The results of this study will further this aim, especially in areas near the margins of the basin where fluvial and lacustrine beds intertongue extensively. Although petrographic differences in the P. R. Spring area limit generalization about other areas, the approach used here probably can be applied successfully throughout the Uinta Basin and elsewhere. Oil and gas can be explored for more successfully, and oil-impregnated sandstone in the Uinta Basin can be developed and new reserves found if the petrography of sandstone in other areas is studied carefully.

CONCLUSIONS

Through petrographic study of lacustrine and fluvial sandstone in the P. R. Spring area, it is possible to distinguish the two types of sandstone. Although the lacustrine and fluvial sandstone studied here was assigned in the field to one of the two general environments on the basis of other criteria, it apparently is possible to differentiate between lacustrine and fluvial sandstone on petrographic criteria alone. In retrospect petrographic criteria appear more

diagnostic than some of the other criteria that have been used. Bedding types and sedimentary structures do not, for example, distinguish the two facies as well (Picard and High, 1970, p. 14).

In the P. R. Spring area, the lacustrine sandstone contains more quartz and authigenic carbonate and less plagioclase, K-feldspar, matrix, rock fragments and coarse mica than does the fluvial sandstone. Not all of these differences are equally significant. The differences in quartz, plagioclase feldspar, authigenic carbonate, matrix and coarse mica are believed to be most important. The presence of allochems and analcime in the lacustrine sandstone and petrified wood in the fluvial sandstone is also significant.

The sand-sized detritus has been modified markedly in the environment of deposition. All of the sand-sized grains are from the same source areas and were transported to their depositional sites by essentially the same river system. The fluvial detritus was least affected after initial deposition. Weathering in the source areas and during transportation modified sand-sized grains to the same degree.

The mineralogic differences in the lacustrine and fluvial sandstone have arisen mainly because of better sorting, especially a longer period of sorting, in the lacustrine settings. During this longer sorting history, differences in mineral stability manifest themselves to contribute different characteristics to the lacustrine sandstone; increased permeability in the lacustrine detritus also developed because of its superior sorting history and led to the crystallization of more authigenic carbonate in the lacustrine sandstone. The lacustrine sandstone also has better porosity and permeability than the fluvial sandstone because it was better sorted before compaction and lithification took place.

The petrographic criteria discovered here are not applicable to all other areas, even within the Green River Formation in the Uinta Basin. The writer, however, has applied the same techniques in a study of the Parachute Creek Member in the Raven Ridge area of the northeast part of the Uinta Basin. Although the source areas were different and plutonic rocks did not contribute nearly as much detritus to the beds in the Raven Ridge area, results that can be analyzed and compared in the same way were obtained. Processes that are operative in lacustrine settings impress significant and diagnostic characteristics on sand-sized material.

The differences in lacustrine and fluvial sandstone presented here probably are reflected in differences in chemical composition of major and minor

elements. It is also likely that the light and heavy mineral suites of the two types of sandstone are different. Other dominantly mineralogical aspects should be studied in more detail in the future. This study does not even begin to exhaust the possibilities of the petrographic approach to the origin of sandstone. Others are urged to investigate the petrography of sandstone, using the approach used here and other methods they consider functional.

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UTAH GEOLOGICAL AND MINERALOGICAL SURVEY

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THE UTAH GEOLOGICAL AND MINERALOGICAL SURVEY since 1949 has been affiliated with the College of Mines and Mineral Industries at the University of Utah. It operates under a director with the advice and counsel of an Advisory Board appointed by the Board of Regents of the University of Utah from organizations and categories specified by law.

The survey is enjoined to cooperate with all existing agencies to the end that the geological and mineralogical resources of the state may be most advantageously investigated and publicized for the good of the state. The *Utah Code, Annotated, 1953 Replacement Volume 5, Chapter 36, 53-36-2*, describes the Survey's functions.

Official maps, bulletins, and circulars about Utah's resources are published. (Write to the Utah Geological and Mineralogical Survey for the latest list of publications available).

THE LIBRARY OF SAMPLES FOR GEOLOGIC RESEARCH. A modern library for stratigraphic sections, drill cores, well cuttings, and miscellaneous samples of geologic significance has been established by the Survey at the University of Utah. It was initiated by the Utah Geological and Mineralogical Survey in cooperation with the Departments of Geology of the universities in the state, the Utah Geological Society, and the Intermountain Association of Petroleum Geologists. This library was made possible in 1951 by a grant from the University of Utah Research Fund and by the donation of collections from various oil companies operating in Utah.

The objective is to collect, catalog, and systematically file geologically significant specimens for library reference, comparison, and research, particularly cuttings from all important wells driven in Utah, and from strategic wells in adjacent states, the formations, faunas, and structures of which have a direct bearing on the possibility of finding oil, gas, salines or other economically or geologically significant deposits in this state. For catalogs, facilities, hours, and service fees, contact the office of the Utah Geological and Mineralogical Survey.

THE SURVEY'S BASIC PHILOSOPHY is that of the U. S. Geological Survey, i.e., our employees shall have no interest in Utah lands. For permanent employees this restriction is lifted after a 2-year absence; for consultants employed on special problems, there is a similar time period which can be modified only after publication of the data or after the data have been acted upon. For consultants, there are no restrictions beyond the field of the problem, except where they are working on a broad area of the state and, here, as for all employees, we rely on their inherent integrity.

DIRECTORS:

William P. Hewitt, 1961-

Arthur L. Crawford, 1949-1961