SEDIMENTOLOGY OF OIL-IMPREGNATED, LACUSTRINE AND FLUVIAL SANDSTONE, P. R. SPRING AREA, SOUTHEAST UINTA BASIN, UTAH

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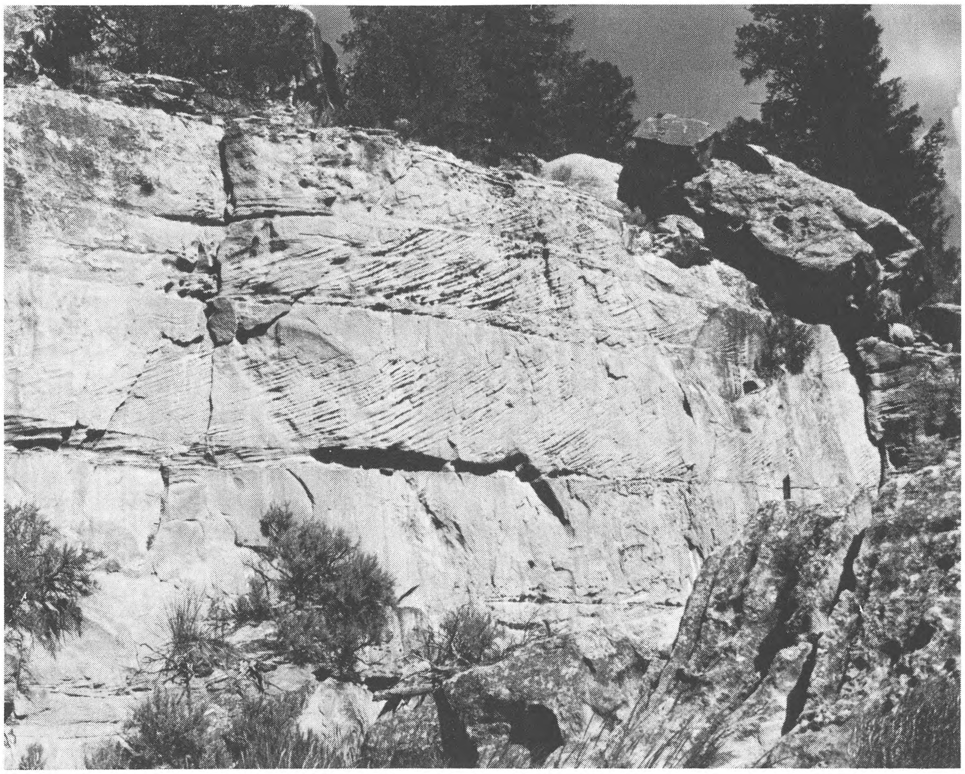

Cross-stratified fluvial sandstone complex in uppermost Wasatch Formation, Main Canyon section (see figure 5).

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SEDIMENTOLOGY OF OIL-IMPREGNATED, LACUSTRINE AND FLUVIAL SANDSTONE, P. R. SPRING AREA, SOUTHEAST UINTA BASIN, UTAH

by M. Dane Picard[1] and Lee R. High, Jr.[2]

ABSTRACT

Oil-impregnated intervals, up to 75 feet thick within a stratigraphic interval of about 250 feet in the Garden Gulch and Parachute Creek Members of the Green River Formation (Eocene), are exposed in beds that dip gently northward in the P. R. Spring area. Reserve estimates indicate that there may be about 3.7 billion barrels of oil in place. Sedimentologic study of oil-impregnated and related beds in the area was started in 1969.

Paleocurrent measurements from cross-stratification and ripple marks are related to paleoslope, orientations of shorelines and sandstone-body trends in the lacustrine and fluvial setting of the upper Wasatch Formation (Paleocene?-Eocene) and the lower Green River Formation. A total of 308 paleocurrent measurements was made at 13 localities in the P. R. Spring area: 123 from sandstone beds of fluvial origin and 185 from lacustrine sandstone bodies.

Seven of nine fluvial paleocurrent patterns indicate that streams flowed northward into Lake Uinta in the P. R. Spring area. The considerable scatter in the paleocurrent measurements suggests that the streams had low gradients and were meandering. Many of the fluvial sandstone bodies are oriented approximately north-south and contain northward-inclined foreset laminae.

Nine of ten lacustrine paleocurrent patterns have significant intervals in the south half of the compass. These directions are interpreted to be dominantly the result of onshore lake currents. The shorelines of Lake Uinta probably trended northeast through much of the P. R. Spring area, but on the northeast, in the Cooper Canyon and Threemile Canyon areas, shorelines were oriented northwest-southeast.

The paleocurrent patterns of fluvial and lacustrine sandstone are both unimodal. The two environments can be differentiated, however, on the basis of paleocurrent orientations. The fluvial currents flowed northward; the lacustrine currents were southerly.

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). Oil-saturated intervals, up 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 is about 3.7 billion barrels of oil in place (Byrd, 1967).

The presence of these large hydrocarbon reserves and of oil seeps (figure 1) in the area prompted sedimentologic study of lacustrine and fluvial sandstone bodies within and adjacent to the oil-impregnated intervals (figure 2). A major aim was to determine the 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, with particular attention to analysis of depositional environments of the sandstone bodies. Criteria for recognition of lacustrine and fluvial sandstone evolved during the course of the study. Orientation of average shorelines during deposition of lacustrine sandstone bodies was reconstructed on the basis of analysis of the paleogeography and paleocurrents. Similarly, orientation of the paleoslope during deposition of fluvial sandstone bodies was determined. These related aspects of the sedimentology of oil-impregnated and other associated rock units in the P. R. Spring area lead to the possibility of improved oil and gas exploration in the southeast Uinta Basin and to the best means of exploring oil-impregnated sandstone bodies. Our suggestions and interpretations are given in a concluding section. About one month was spent by the writers in the field on this study during the summer of 1969.

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. 928; Chatfield, 1965, p. 166), and along Raven Ridge in the northeast Uinta Basin (Picard, 1967b, p. 385) has been subdivided, in ascending order, into the Douglas

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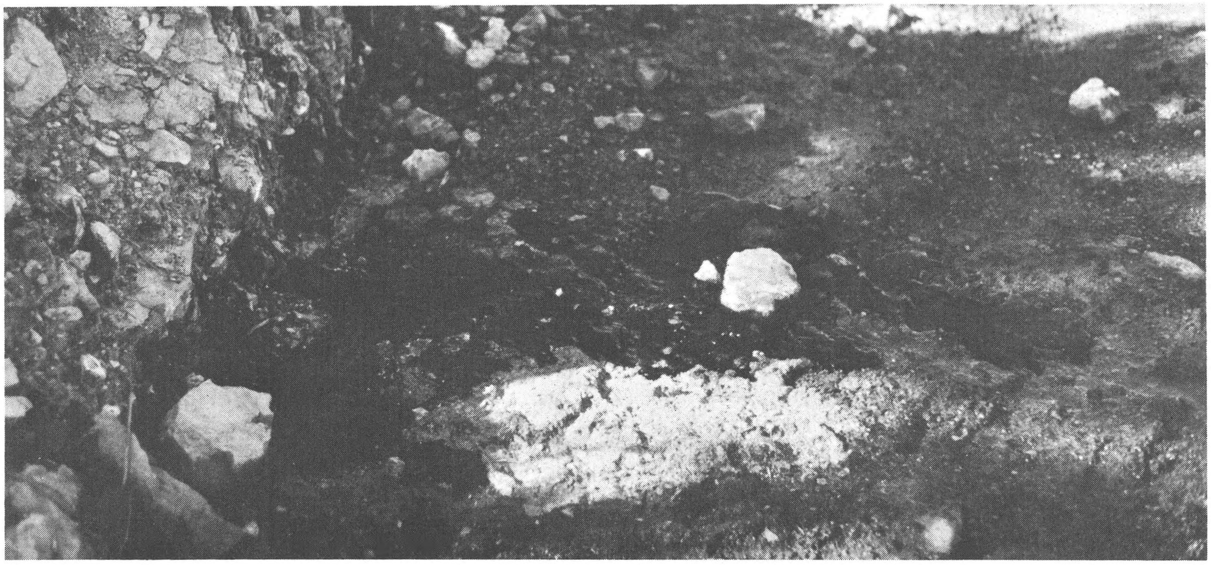


Figure 1. Oil seep in Pine Spring Canyon section. Fractured beds in upper part of Garden Gulch Member of Green River Formation. Near top of Douglas Creek Member of Cashion (1967).

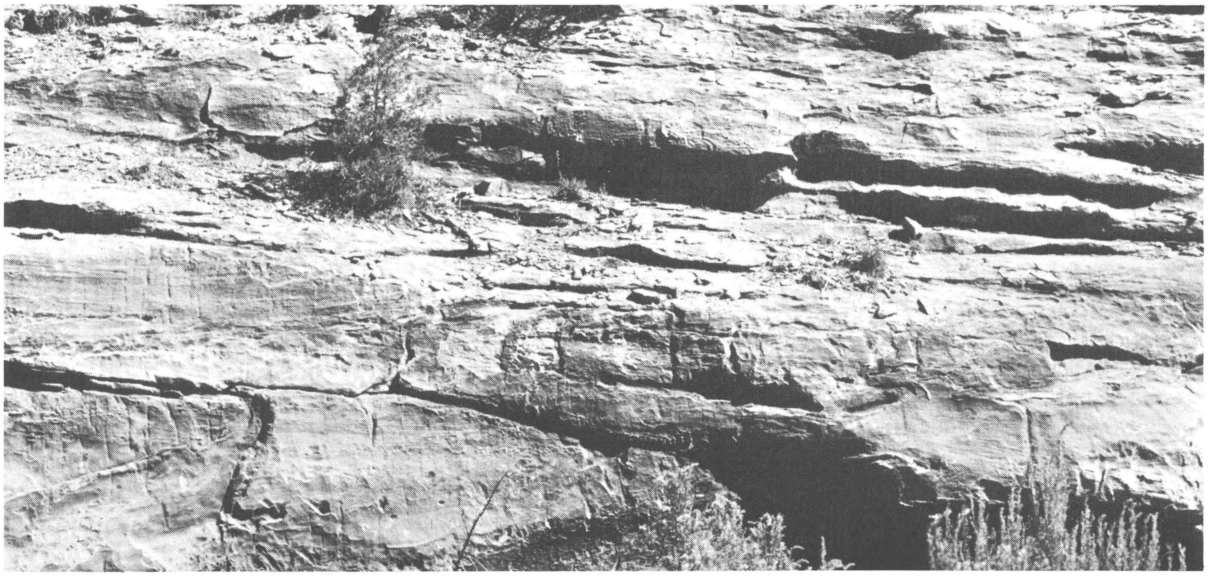


Figure 2. Oil-impregnated lacustrine sandstone in Pine Spring Canyon section. Bedding is dominantly medium-scale trough cross-stratification. Sandstone is a subarkose whose grains are fine, subrounded and well sorted.

Creek. Garden Gulch, Parachute Creek and Evacuation Creek Members. At Raven Ridge, Cashion and Brown (1965) differentiated two units, the Douglas Creek Member and the upper marly member. Their nomenclature, however, has not been followed by later workers, probably because their Douglas Creek included the Garden Gulch and the lower part of the Parachute Creek of other workers.

The most recent detailed study of the stratigraphy of the southeast Uinta Basin is that of Cashion (1967). According to his nomenclature (Cashion, 1967, plate 3), the Tertiary units (from base upward) in the P. R. Spring area are: main body of Wasatch Formation; an interval of 1,200-1,300 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 below and above the Mahogany oil-shale bed (figure 3). Thus, in Cashion's (1967) scheme, the oil-impregnated sequence is 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 where it is an island of rock about 250 feet thick, which is almost enclosed by his expanded Douglas Creek Member but partly by the Parachute Creek Member.

Until detailed studies of the stratigraphy are completed, we prefer the formal Green River nomenclature. Picard recently traced the conventional four rock units of the Green River Formation 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. There were no difficult problems of correlation. It is not advisable, then, to abandon the formal nomenclature, which Cashion (1967) has done. Thus, this paper presents information from the upper part of the Wasatch Formation, from the Douglas Creek and Garden Gulch Members, and from the lower part of the Parachute Creek Member. The oil-impregnated sandstone bodies occur in the upper part of the Garden Gulch Member and in the lower part of the Parachute Creek Member.

We agree with Cashion (1967) that there is considerable intertonguing of fluvial and shallow water lacustrine beds in the P. R. Spring area. He assigned the fluvial tongues to the Wasatch and the lacustrine tongues to the Douglas Creek. However, the equivalence of some of these "transitional" beds to the Garden Gulch of other areas is not indicated by Cashion (1967).

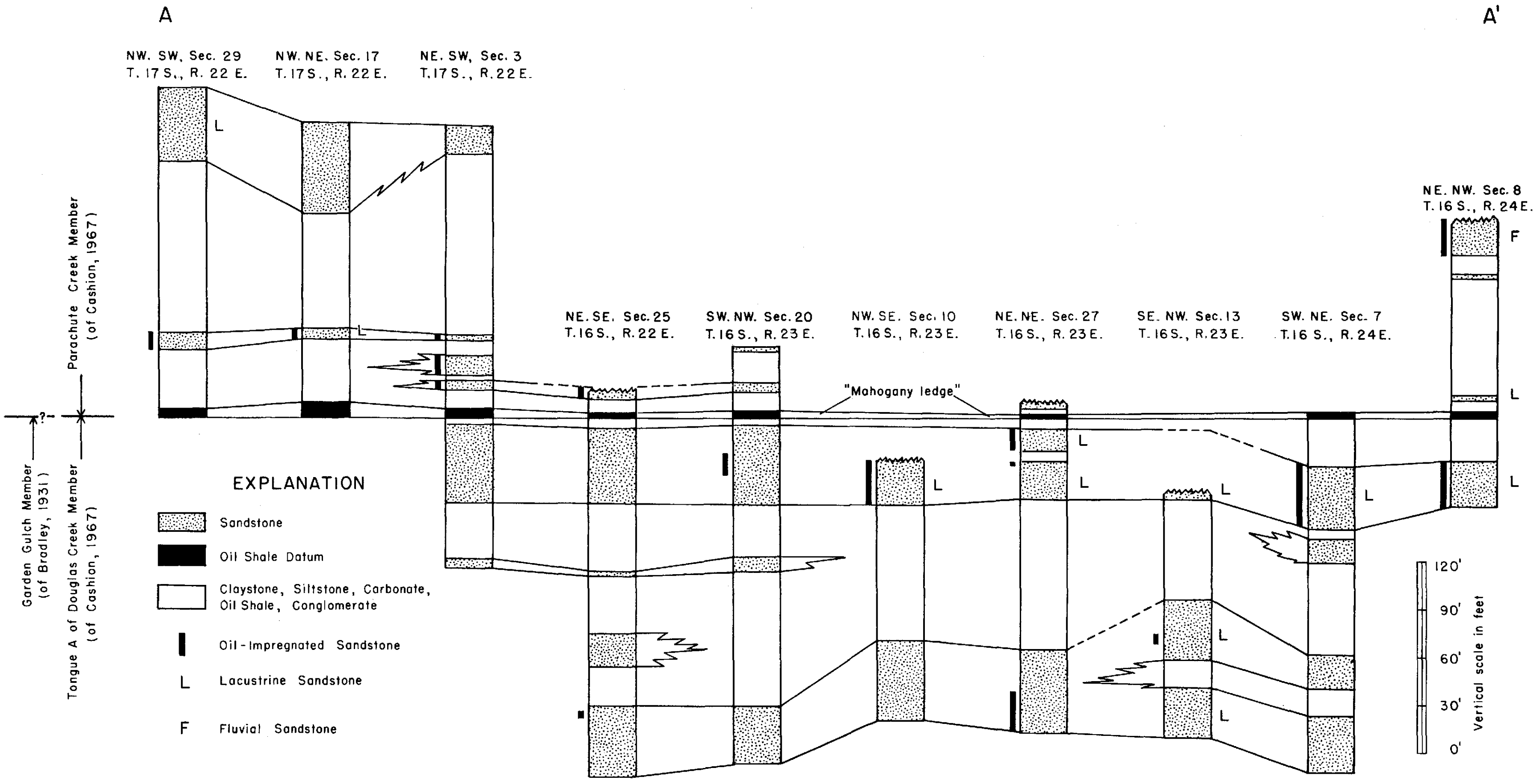
The oil-impregnated sandstone bodies in the P. R. Spring area are at about the same stratigraphic position as some of the oil-impregnated sandstone along Raven Ridge in the northeast part of the Uinta Basin. Preliminary studies suggest that the oil-impregnated sandstone at Sunnyside west of P. R. Spring is partly in older rock units than the oil-impregnation in the P. R. Spring area, but the upper part of the saturation at Sunnyside is approximately equivalent to the oil-stained intervals at P. R. Spring.

Figure 3 shows the position and facies relationships of the significant sandstone bodies in the oil-impregnated interval of the study area. Along this line of section (figure 4), exposures are good and lateral relationships can be delineated. The letter "L" by a sandstone unit means that we examined the sandstone at that locality in detail and consider it of lacustrine origin. Similarly the letter "F" means that the sandstone is fluvial. On the basis of this cross section and our reconnaissance of the whole area, we believe that most of the oil-impregnation is in lacustrine sandstone bodies.

Oil seeps in the P. R. Spring area trend northwest and are remarkably aligned (figure 4). The alignment is parallel with the axes of folds in the area and with fault and fracture patterns in the southeast Uinta Basin. Movement on the Uncompahgre uplift was responsible for the structural features of the area. Fracturing was noted near some of the oil seeps, but no fault displacement was observed. During post-Green River growth of the Uncompahgre uplift, folds in the southeast Uinta Basin were rejuvenated and minor faulting and fracturing occurred.

FLUVIAL SANDSTONE BODIES

More is known about fluvial sandstone bodies than any other type (Pettijohn, Potter and Siever, 1965, p. 177). Many good descriptions of the petrography, textures, types of bedding and sedimentary structures have been published recently (Allen, 1962 and 1964; Doty and Hubert, 1962; Stokes, 1961; Schlee and Moench, 1961; Stanley, 1968; Belt, 1968; Pelletier, 1958; Yeakel, 1962; McCormick and Picard, 1969). Experimental flume studies and detailed examination of modern stream deposits have contributed greatly to an understanding of fluvial processes and their products (Allen, 1965; Brush, 1965a and b; Harms and Fahnestock, 1965; Harms and others, 1963; Jopling, 1964, 1965 and 1966; McKee, 1957 and 1964; Nordin, 1963; Ore, 1963; Rubey, 1938; Simons and Richardson, 1961; Simons and others, 1965; Williams and Rust, 1969). For further significant studies the interested reader can consult the references in Pettijohn, Potter and Siever (1965) and in Special Publication No. 12 of the Society of Economic Paleontologists and Mineralogists.



Note: Cross section modified after Byrd (1967; 1970)

Figure 3. Cross section showing oil-impregnated sandstone in P. R. Spring area, southeast Uinta Basin, Utah. Note large lateral extent of oil-impregnated lacustrine sandstone below "Mahogany ledge". Location of cross section is shown on figure 4.

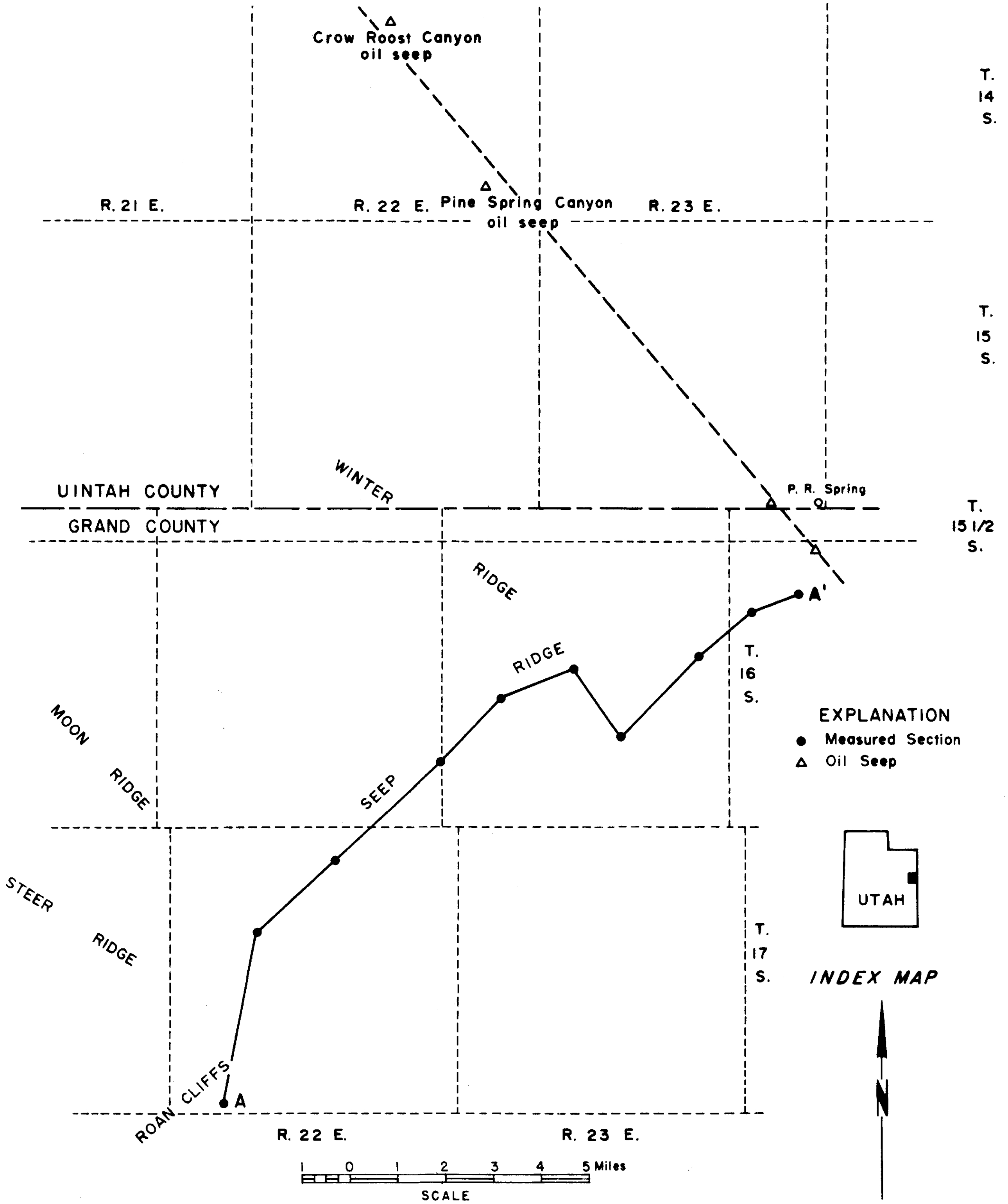


Figure 4. Index map showing location of cross section (AA'). Note northwest trend (dotted line) of oil seeps.

A guide to the relative abundance of bedding types and sedimentary structures in modern and ancient fluvial deposits is given in table 1. The sources used to construct this table give a broad view of particular streams or fluvial deposits; several include the relative abundance of a sedimentary structure or bedding type or the information to deduce it. Other papers contain similar information, but often they are concerned with detailed study of only several sedimentary structures of a fluvial deposit. Frequently the relative abundance of bedding types and sedimentary structures is not given at all in papers published recently.

Table 1 was compiled by Picard, who also constructed a general guide for fluvial and other depositional environments a few years ago (1967). Except for Ore's paper (1963), Picard used other sources in table 1 than were used in his previous study. Despite this difference, the summary of relative abundances of the various features given in table 1 is almost the same as that presented in the earlier paper (Picard, 1967). Whether this is partial confirmation of the usefulness of the present guide or an indication of Picard's subjectivity must await similar studies by other workers. In either case, charts, such as table 1, are not keys that allow unequivocal recognition of a particular environment. Although they can be used to eliminate some possible environments, study of all field relationships is still required for environmental reconstruction. Similar processes produce similar products in diverse environments of deposition.

A summary of fluvial sandstone characteristics in the P. R. Spring area is given in table 2. The relative abundances of bedding types and sedimentary structures and other features that were useful in distinguishing between fluvial and lacustrine sandstone are stressed. Generally, these criteria were applied before paleocurrent measurements were made. The origin of some sandstone bodies is difficult to determine, however.

Cross-stratification is common in fluvial sandstone in the P. R. Spring area, but ripple marks are not. Fining-upward sequences of fluvial sandstone are developed, a reflection of generally decreasing current velocities during deposition. Cross-stratified beds are generally thicker in the lower half of a sequence than in the upper half, but exceptions are found. Many channel-filling sandstone units are lenticular, linear, and grade upward into other sandstone units (figures 5-7). Disturbed bedding (figure 8), the result of compactional and other soft-sediment deformation, is common at some localities. Our impression based on reconnaissance studies is that many of the fluvial sandstone bodies in the P. R. Spring area reflect a more complex origin than is thought to be characteristic of fluvial deposits in general.

LACUSTRINE SANDSTONE BODIES

In contrast to fluvial sandstone, lacustrine sandstone has been little studied and its characteristics are not well known. Recently we reviewed the criteria for recognizing lacustrine rocks (Picard and High, 1970), but it will be several months before the paper is published. General petrologic criteria for distinguishing lacustrine and fluvial rocks in Tertiary beds of the Uinta Basin were proposed by Picard in 1957. Our interpretation of the characteristics of lacustrine sandstone and associated beds in the P. R. Spring area is given in table 2. Preferred associations of bedding types and sedimentary structures for rocks deposited in lacustrine environments by several other workers are suggested in table 3.

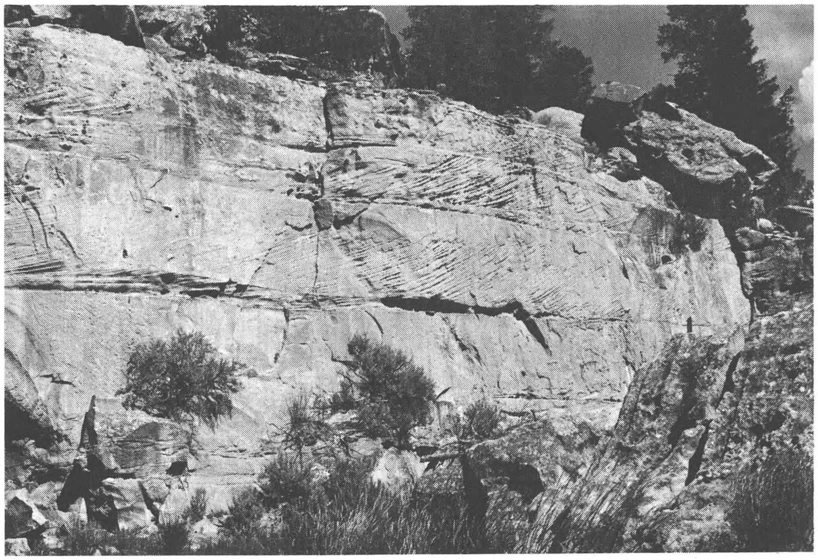


Figure 5. Cross-stratified fluvial sandstone complex in uppermost Wasatch Formation, Main Canyon section (between Pine Spring Canyon and Berry Canyon). Bedding is dominantly medium- and large-scale trough cross-stratification. Note wedge-shaped channels, especially on left side.

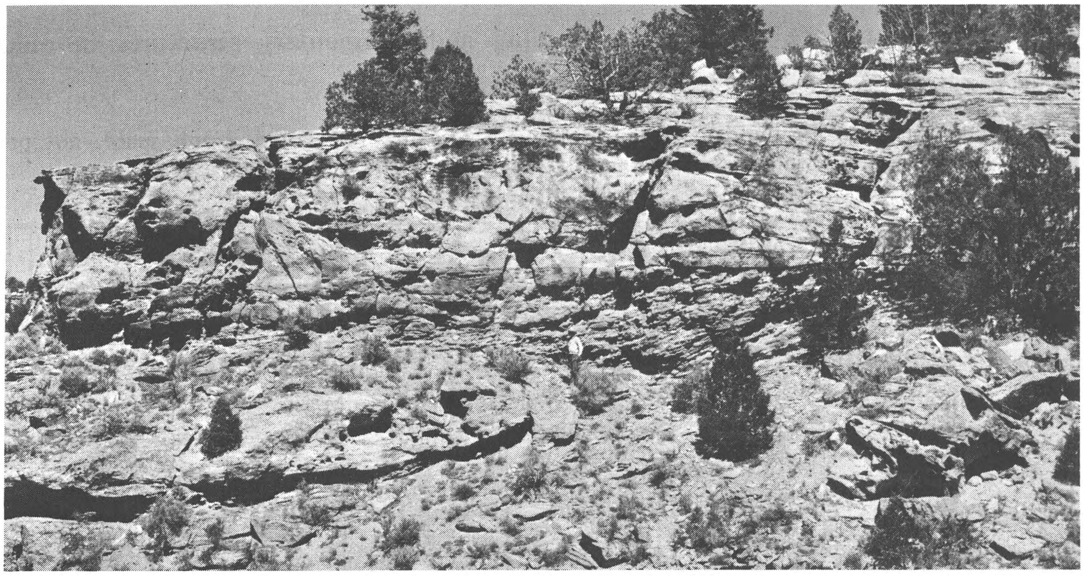


Figure 6. Fluvial sandstone complex in uppermost Wasatch Formation, Meadow Creek section. Channels are abundant.

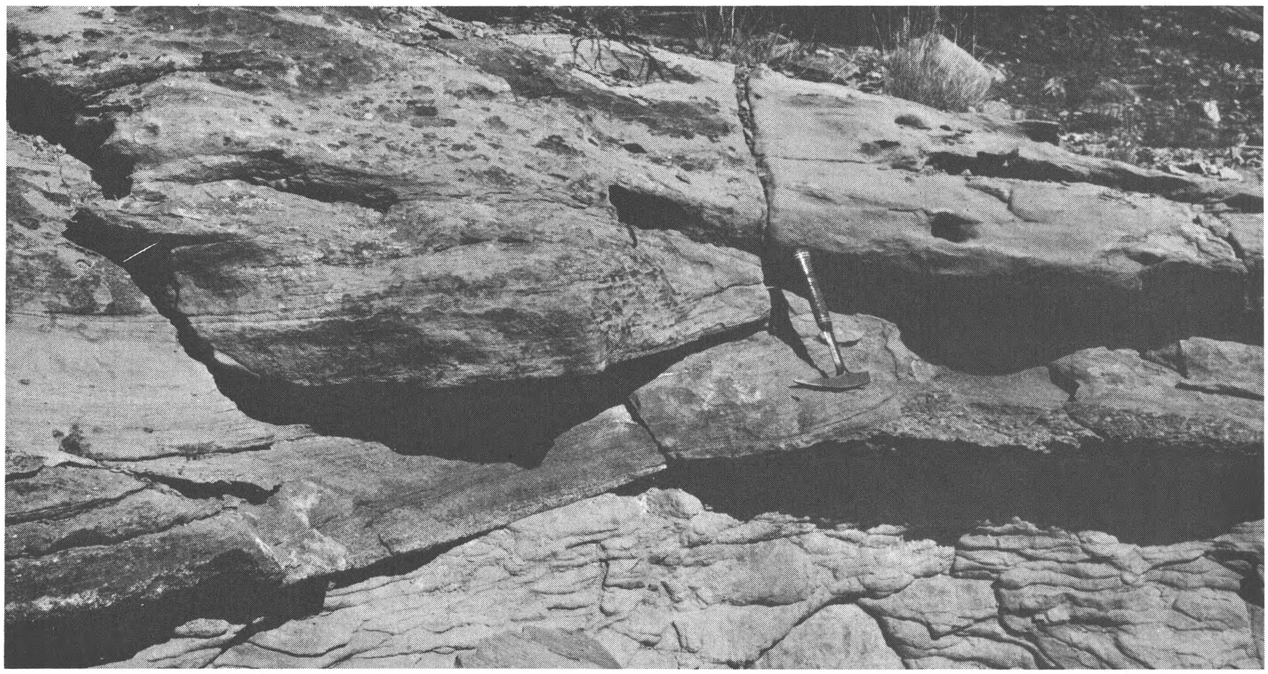


Figure 7. Fluvial sandstone in channels of Douglas Creek Member, Pine Spring Canyon section. Note conglomerate at base of channel-fill (just below hammer).

Table 1. Relative abundance of types of bedding and sedimentary structures in modern and ancient fluvial deposits.

(r, trace to rare; c, common; a, abundant; x, present but abundance not noted; blank space, not present, not observed, or not mentioned; --, probably not formed)

Bedding Types, Sedimentary Structures, Other Features	General Abundance [Picard, 1967a]	Pocono Formation (Mississippian) [Pelletier, 1958]	Old Red Sandstone (Devonian) [Allen, 1962]	Wamsutta Formation (Pennsylvanian) [Stanley, 1968]	Carboniferous, Eastern Canada [Belt, 1968]	Gartra Formation (Triassic) [McCormick and Picard, 1969]
Cross-stratification (trough)	c-a	r	r		c	a
Cross-stratification (planar)	c	a	c	r-c	c	c
Horizontal stratification	c	c	c	c	c	c
Disturbed bedding	r	r		r	r	r
Graded bedding	r-c			a		r-c
Ripple-stratification	c-a			c	c	r
Massive bedding		c				c
Parting lineation	r-c	c	c	c	c	r
Channel	c	c	c	a	c-a	a
Cuspate (linguoid) ripple mark		r	r		c	r
Asymmetric, parallel (linear) ripple mark	r-c	r	r	r-c		r
Symmetric, parallel ripple mark	r	r		r	c	--
Interference ripple mark	r	r				r
Giant ripple mark	r					r
Current crescent						
Load cast						r
Flute cast	r		r	a	r-c	
Groove cast				a	r-c	
Polygonal shrinkage crack	c			a	c	r
Raindrop impression	r			r	r	
Worm trail, burrowed structure	r			r	r	r
Mud-pebble conglomerate	r-c	r-c	r	c	r-c	r-c
Pebble imbrication			r			
Point bar						
Longitudinal bar						
Terrace						
Transverse bar						

Modern Braided Streams [Ore, 1963]	Modern Braided River [Williams and Rust, 1969]	Slightly Meandering Ephemeral Streams, Utah and Colorado [Picard, unpubl.]	Wood Bay Series (Devonian) [Friend, 1965]	Tuscarora Quartzite (Silurian) [Yeakel, 1962]	Solund District, Norway (Devonian) [Nilsen, 1968]	Summary of Relative Abundance
a	r-c	c-a	x	x	x	c-a
c		r	x	x	x	c
c	r-c	c	x	x	x	c
r	r-a	r	x			r
c	r	r	x			r-c
	c	r-c	x		x	c
	r	r		x	x	r-c
		r-c	x	x	x	r-c
a	a	c-a	x	x	x	c-a
x	a	a	x			c
x	c	c	x	x	x	r-c
	c	--				--
x	r	r	x			r
	r	r			x	r
	a	c	x	x		
			x			r
		r-c	x	x		r-c
		r	x			r
	r-c	c-a		x		c
	r-c	c				r
	r-c	c		x		r
		r	x	x	x	r-c
c	r	r		x	x	r
	r	c				
a	a	c				
c	c	r-c				
r-c	r	r				

Table 2. Guide to characteristics of fluvial and lacustrine sandstone and associated beds in Green River Formation and upper part of Wasatch Formation, P. R. Spring area.

(r, trace to rare; c, common; a, abundant; blank space, not present, or not observed; --, probably does not occur)

Bedding Types, Sedimentary Structures, Lithology	Fluvial Sandstone	Lacustrine Sandstone
Cross-stratification (trough)	c-a	c
Thickness of cross-sets	Fluvial cross-sets thicker than lacustrine	
Cross-stratification (planar)	r	r
Horizontal stratification	c	c-a
Disturbed bedding	r-c	r-c
Graded bedding	r	r
Ripple-stratification	Less abundant in fluvial sandstone	
Massive bedding	r	r
Channel	c	r
Bed lenticularity	Greater bed lenticularity in fluvial sandstone	
Cuspate (linguoid) ripple mark	r	
Asymmetric, parallel (linear) ripple mark	r	r-c
Symmetric, parallel ripple mark	--	--
Rib-and-furrow, pseudo rib-and-furrow	Less abundant in fluvial sandstone	
Parting lineation	r-c	r-c
Flute cast	r	r
Polygonal shrinkage crack	r	r
Linear-shrinkage crack		r-c
Worm trail, burrowed structure	r	r-c
Mud-pebble conglomerate	Less abundant in fluvial sandstone	
Carbonate-pebble conglomerate	r-c	r-c
Chert-pebble conglomerate	r-c	r
Oolite	--	c
Algal debris, stromatolite	--	c
Carbonate beds	--	r-c
Oil shale	--	r-c
Conglomerate	c (at base of fluvial x-strat. sets)	
Green, silty mudstone	c (beneath fluvial channels)	
Carbonate cement	r	c-a
Matrix	Much more abundant in fluvial sandstone	
Sorting	Sorting better in lacustrine sandstone	
Petrified wood	r-c	
Vertebrate remains	r	
Ostracods		c
Pelecypods		r

Table 3. Bedding types and sedimentary structures believed to be characteristic of lacustrine environments.

(x, characteristic; r, rare)

Bedding Types, Sedimentary Structures	Keuper (below wave base) [Klein, 1962]	Marl (above wave base) [Klein, 1962]	General Lacustrine [Klein, 1962]	Lockatong Formation [Van Houten, 1964]	General Lacustrine [Visher, 1965]	Albert Formation [Greiner, 1962]	Green River Formation [Bradley, 1931]
Thin bedding, rhythmic bedding, varves	x	x	x	x	x	x	x
Even, horizontal bedding	x	x	x	x	x	x	x
Cross-stratification		x	x	x	x	r	r
Trough		x	x	x			
Planar		x					
Ripple-stratification	x	x	x	x			r
Disturbed stratification	x		x	x	x	x	x
Graded bedding	x		x	x	x		
Asymmetrical ripple mark		x		r	r	r	
Symmetrical ripple mark	x	x	x		r	x	r
Shrinkage cracks		x		x		x	x
Parting lineation		x					
Rib-and-furrow		x					
Groove cast		x					
Load cast	x				x		
Pull-apart structure	x			x			x
Raindrop impression		x					
Burrowed structure, worm trail	x	x	x	x			

There has been a tendency in recent years to search for unique and indicative features of a particular environment. The existence of such "keys" for most environments is doubtful, however. Nevertheless, associations of features, such as those in table 2, are useful in interpretation and tend to summarize much of the information that is gathered and used in field studies.

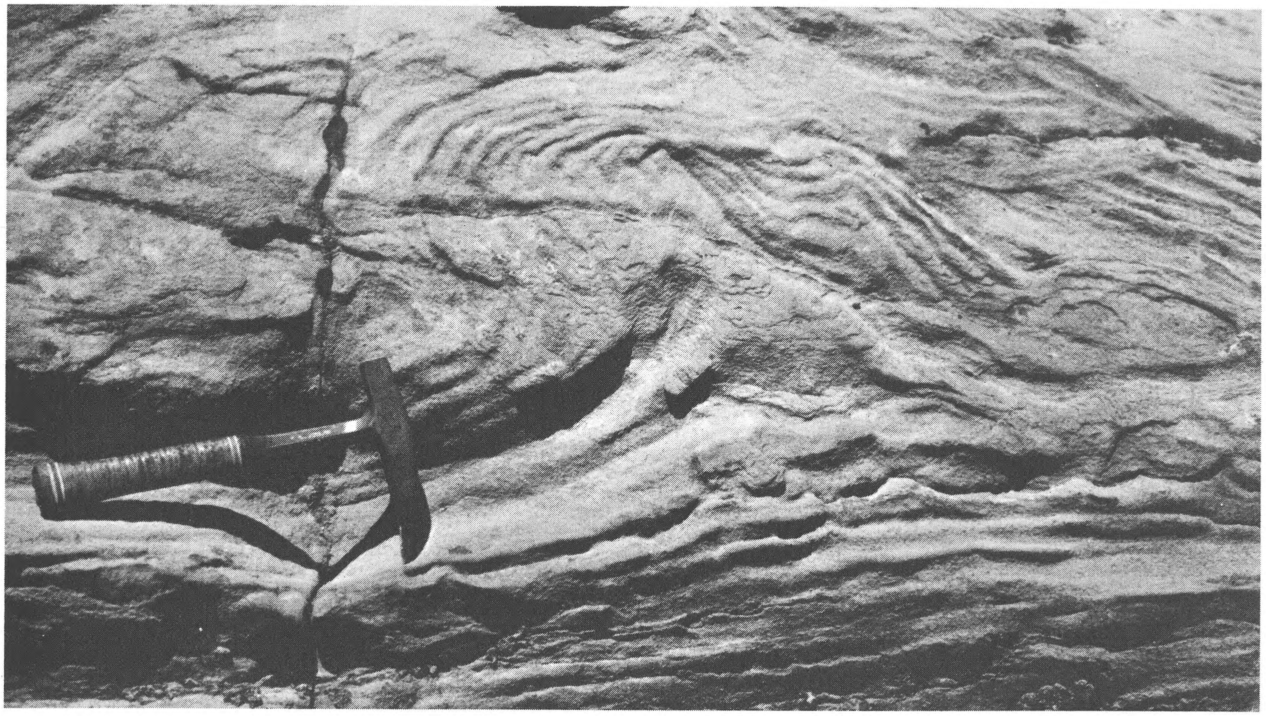


Figure 8. Disturbed bedding in fluvial sandstone, Douglas Creek Member, Pine Spring Canyon section. Scale=hammer.

Lacustrine sandstone (figures 9-11) in the P. R. Spring area is less lenticular than is fluvial sandstone (figures 6-7); some units can be traced continually for miles along the outcrop. The bases of lacustrine sandstone bodies tend to be flat or gently undulatory (figure 11) in contrast to the scour-and-fill channel configurations of many fluvial sandstone bodies (figures 6-7). The close associations of algal, oolite and pisolite beds (figures 12-13) and lacustrine sandstone at many localities is also striking.

Horizontal (plane) stratification (figures 14-15) is common to abundant in various lacustrine sandstone bodies of the Douglas Creek and Garden Gulch Members. Thin laminae, the result of fine-grained particles settling from suspension, are characteristic of lacustrine mudstone in the P. R. Spring area and of many lacustrine sequences elsewhere. Trough cross-stratification is more abundant than planar cross-stratification (figures 16-18). Trough sets are lenticular and wedge-shaped, plunging, concave and dominantly asymmetrical (terminology of McKee and Weir, 1953, p. 386). Planar sets are tabular- and wedge-shaped, straight and concave, nonplunging to slightly plunging, and either symmetrical or asymmetrical. Both types are dominantly medium scale. Although ripple marks are less abundant in the lacustrine sequences of the P. R. Spring area than in other parts of the Uinta Basin, many different types of ripple marks (figures 19-22) are found locally. Ripple marks are scarce in the fluvial sandstone of the P. R. Spring area (table 2). Disturbed stratification (figure 23) in lacustrine sandstone is frequently similar to that found in fluvial sandstone (figure 8).

To summarize, lacustrine sandstone can be distinguished from fluvial sandstone on the basis of several characteristics that differ appreciably between the two types of sandstone (table 2). Because of its economic importance in oil and gas areas of the Rocky Mountain region, further study of lacustrine sandstone is urgently needed; however, sufficient criteria are available to recognize lacustrine sandstone.

PALEOCURRENTS

General

Paleocurrents are useful to interpret environments of deposition, to reconstruct average shorelines in shallow marine (Picard and High, 1968) and lacustrine settings (Picard, 1967b), and to delineate the paleoslope of fluvial settings. Paleocurrent information

Above:
Figure 9. Dominantly lacustrine sandstone units, Douglas Creek Member, Pine Spring Canyon.

Right:
Figure 10. View of Douglas Creek and Garden Gulch Members at Cooper Canyon section. Sandstone in sequence is dominantly lacustrine. Oil-impregnated sandstone at top of section.

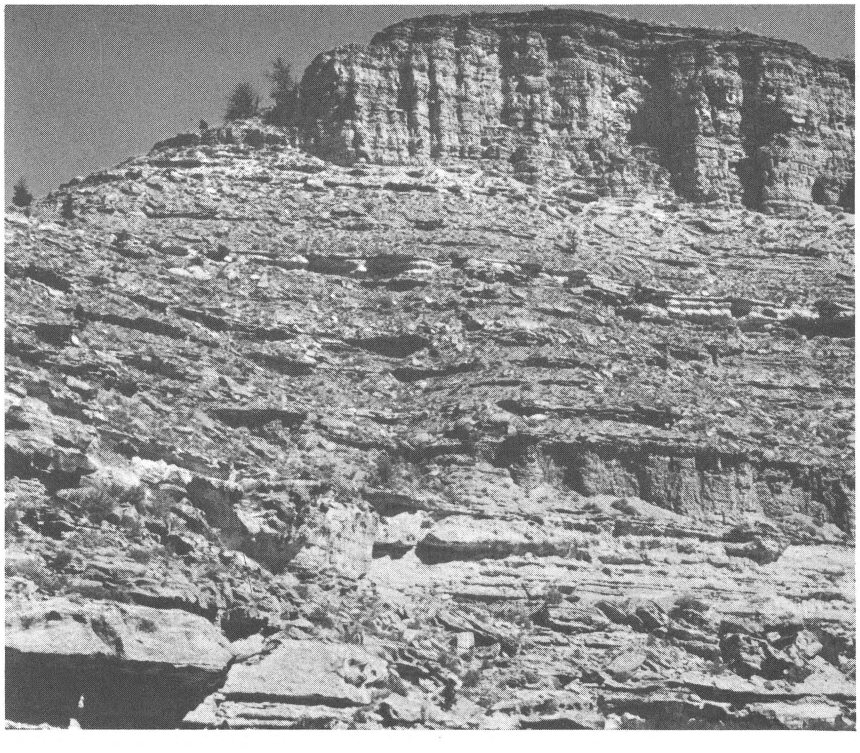


Figure 11. Oolite, pisolite and algal units interbedded with lacustrine sandstone in Douglas Creek Member, Cooper Canyon section.

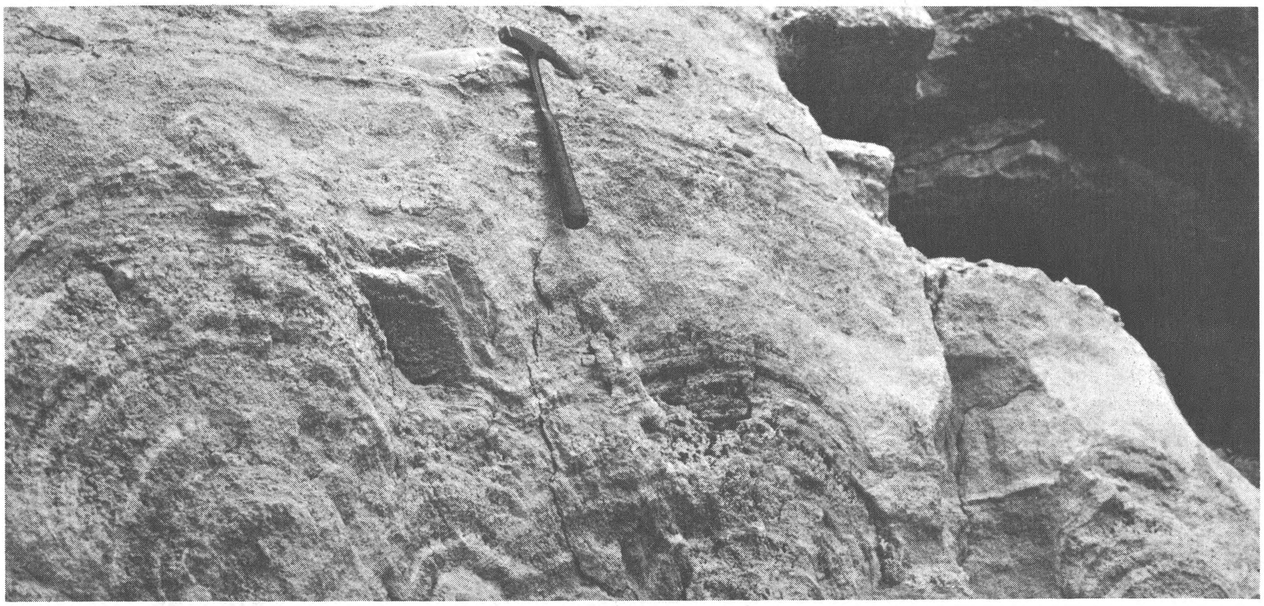


Figure 12. Algal and pisolite unit in Garden Gulch Member, Horse Canyon section. Scale=hammer.

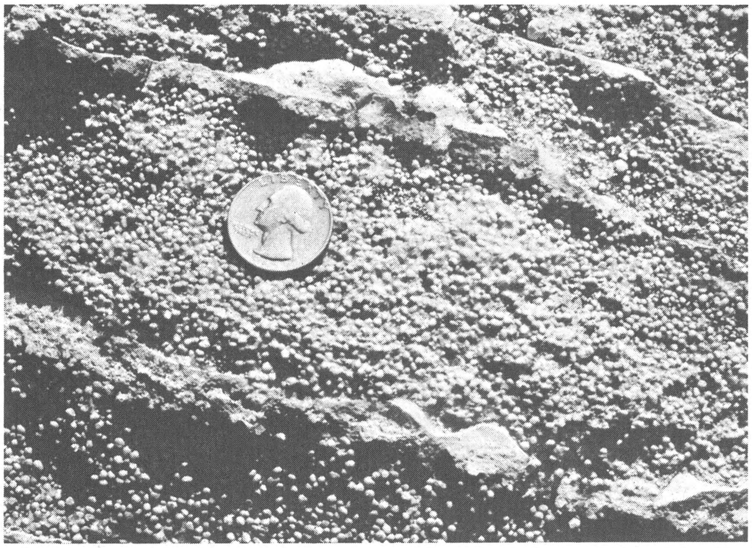


Figure 13. Pisolite and thin algal interbeds in Garden Gulch Member, Horse Canyon section. Scale= hammer.

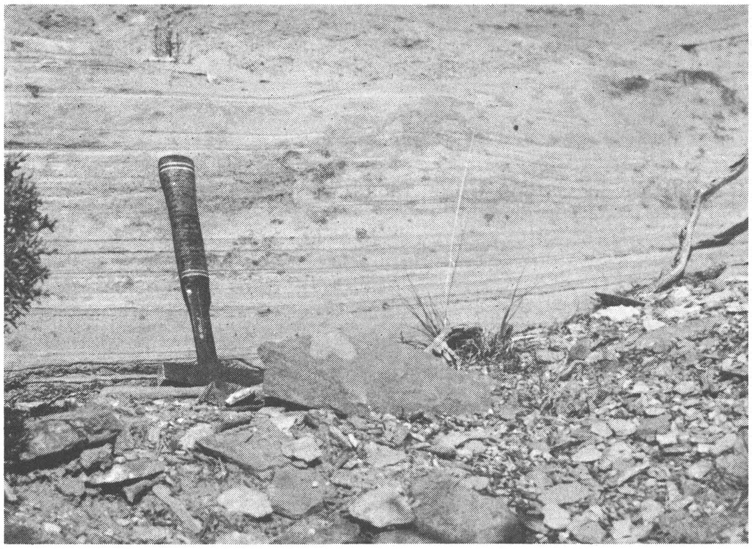


Figure 14. Horizontally stratified beach deposit in Douglas Creek Member, Pine Spring Canyon section.

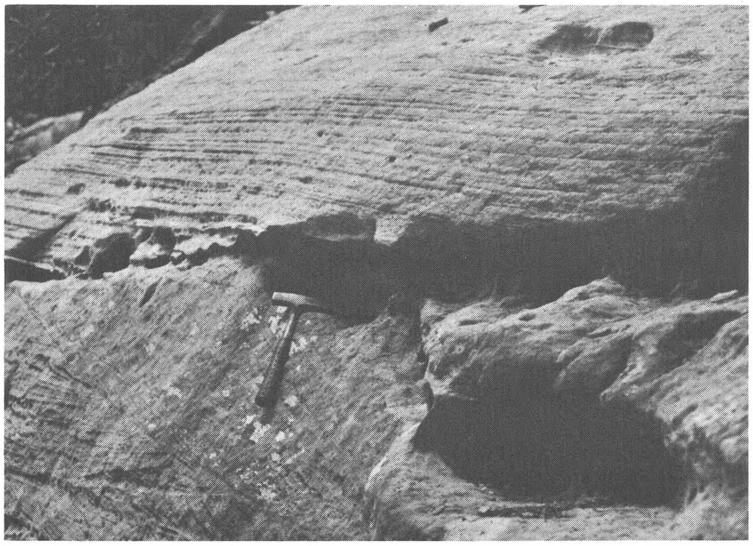


Figure 15. Horizontally stratified lacustrine sandstone on erosion surface above medium-scale trough cross-stratification, Horse Canyon section. Scale=hammer.

Figure 16. Medium- and large-scale cross-stratification in Garden Gulch Member, Horse Canyon section.

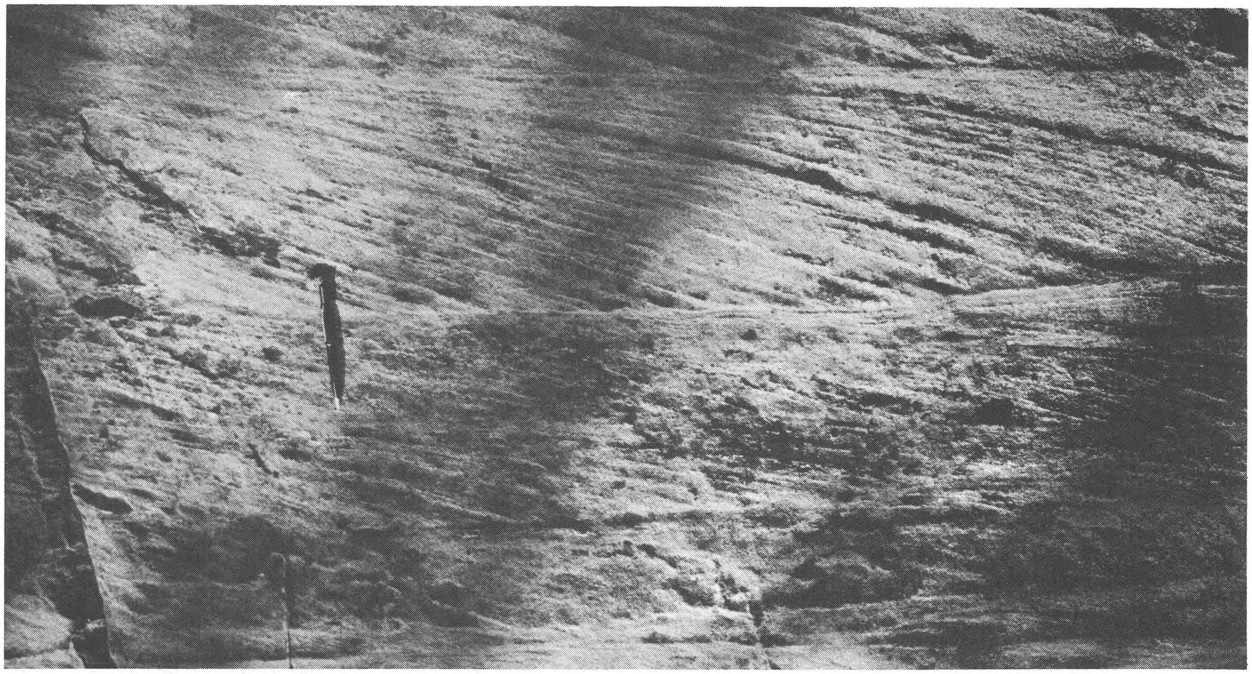


Figure 17. Medium-scale, trough and planar cross-stratification in Garden Gulch Member, Horse Canyon section.

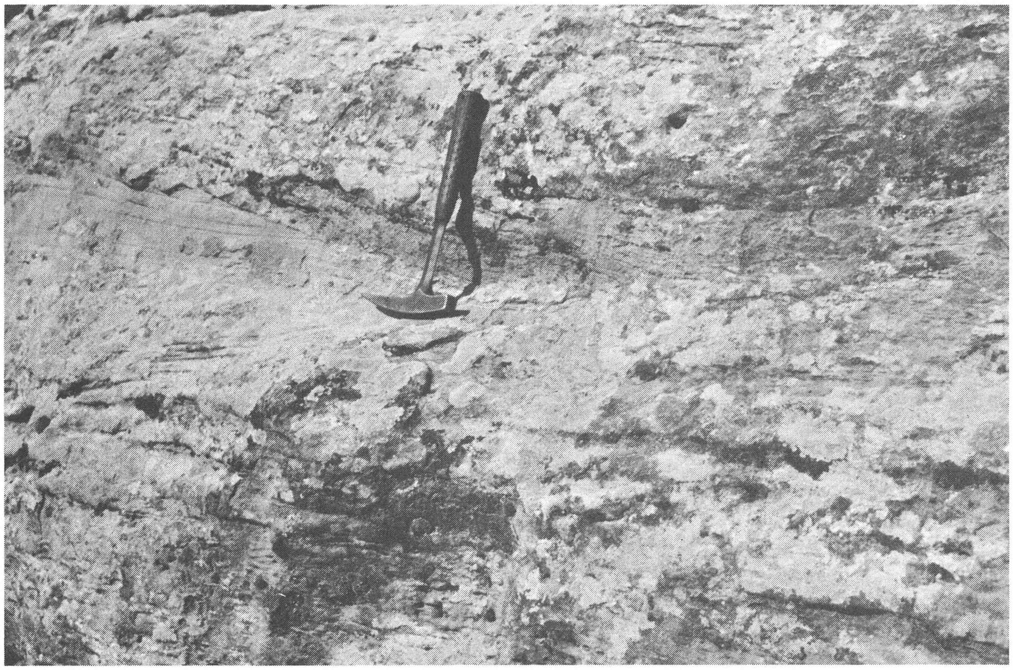


Figure 18. Cross-stratified shoal deposit in Douglas Creek Member, Pine Spring Canyon section.

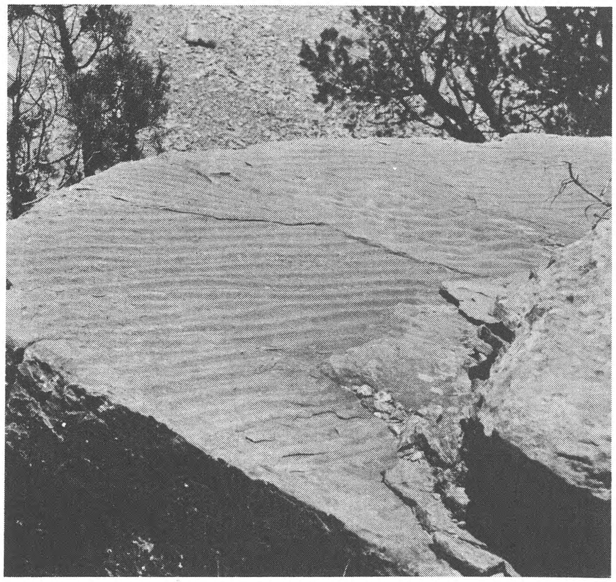


Figure 19. Parallel (linear), asymmetric ripple marks in lacustrine sandstone, Douglas Creek Member, Meadow Creek section.

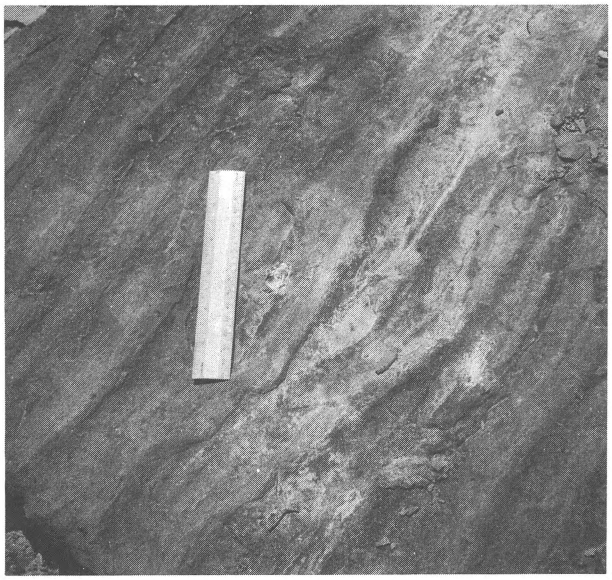


Figure 20. Parallel, asymmetric ripple marks in lacustrine sandstone, Garden Gulch Member, Meadow Creek section. Current from left to right. Scale= six-inch ruler.

Figure 21. Parallel, asymmetric ripple marks in lacustrine sandstone, Garden Gulch Member, Meadow Creek section. Note sharp crests. Scale=six-inch ruler.

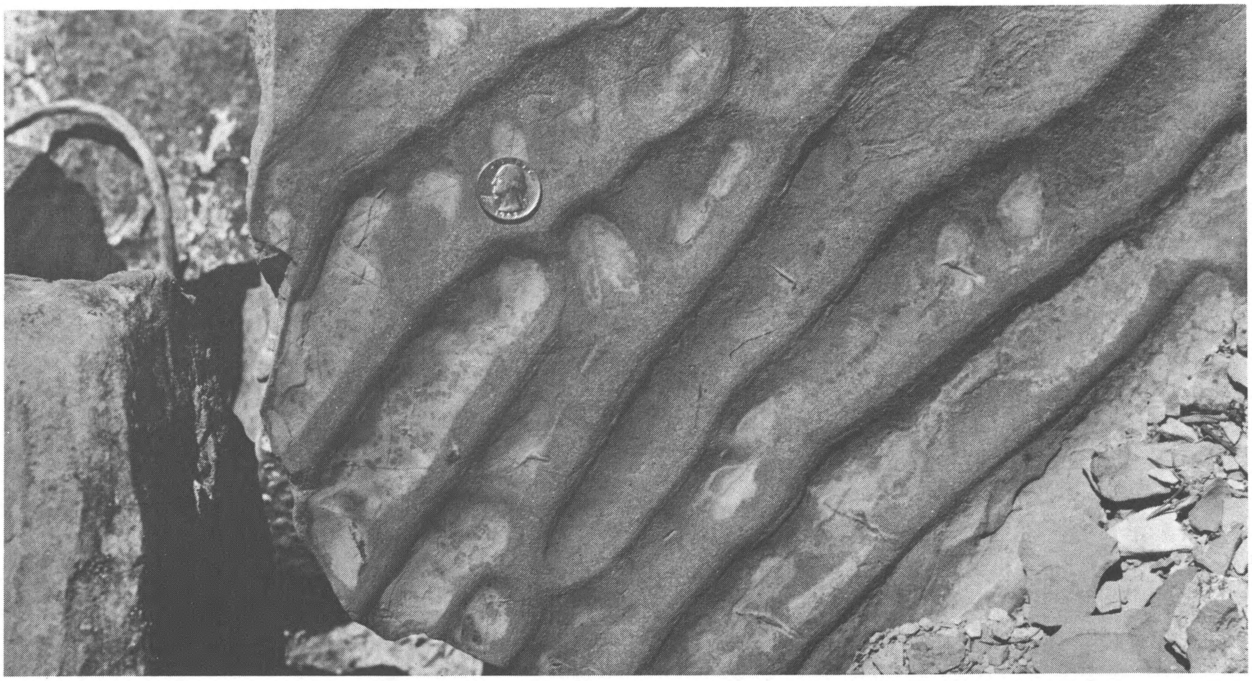


Figure 22. Interference ripple marks in lacustrine sandstone, Douglas Creek Member, Meadow Creek section. Primary current from left to right. Scale=quarter.

can be applied also to reconstruct the orientation of linear sandstone bodies. Although paleocurrent patterns are not diagnostic of depositional environments, they rank with bedding types and sedimentary structures in usefulness and reliability as environmental indicators.

Paleocurrent directions were measured, therefore, in a number of sandstone bodies in the upper part of the Wasatch Formation, in the Wasatch-Green River Formation transition zone, and in the Douglas Creek and Garden Gulch Members of the Green River Formation. A total of 308 paleocurrent measurements was made at 13 localities in the P. R. Spring area. Of these, 123 were from sandstone beds of fluvial origin and 185 were from lacustrine sandstone bodies. Both oil-impregnated and barren sandstone units were studied. From this information, ten lacustrine and nine fluvial paleocurrent trends were obtained (figures 24-25 and tables 4-5).

Field Procedure

Paleocurrent directions were measured from 271 sets of cross-stratification and from 37 beds containing asymmetric, parallel (linear) ripple marks. Cross strata were measured in the direction of maximum foreset inclination; ripple marks were measured normal to the ripple crests in the direction of inclination of foreset laminae. The internal structure of the ripple marks was examined.

In the P. R. Spring area, the only common paleocurrent indicator in the upper part of the Wasatch Formation and the lower part of the Green River Formation is cross-stratification. Asymmetric ripple marks are locally abundant, particularly in the north localities. Throughout most of the study area, however, measurement of cross-stratification is the only means for determining the regional paleocurrent pattern.

Only medium- and large-scale cross-stratification were measured. Small-scale cross-stratification sets were not used because they probably do not reflect regional current patterns.

At each locality, sandstone units were examined for paleocurrent indicators. If medium- or large-scale cross-stratification or ripple marks were present, these were measured. Generally, all visible directional structures at each outcrop were examined. Beds that exhibited post-depositional soft-sediment deformation were not used in the study.

Analysis of Measurements

Paleocurrent directions measured in the field are interpreted here without correction for tectonic tilt, because the changes in paleocurrent orientation that would result are less than the errors of field measurement. In the P. R. Spring area, the maximum regional dip is about 2°.

For each locality, paleocurrent directions from individual sandstone units are plotted on circular graphs (figures 24-25). Where the current directions from separate sandstone bodies are similar, the measurements are grouped into either fluvial or lacustrine according to their origin. Only at Meadow Creek did separate sandstone units of the same origin have different current directions. Thus, two fluvial paleocurrent patterns are shown for Meadow Creek (figure 24 and table 4). At all other localities, a single fluvial and/or lacustrine pattern is shown.

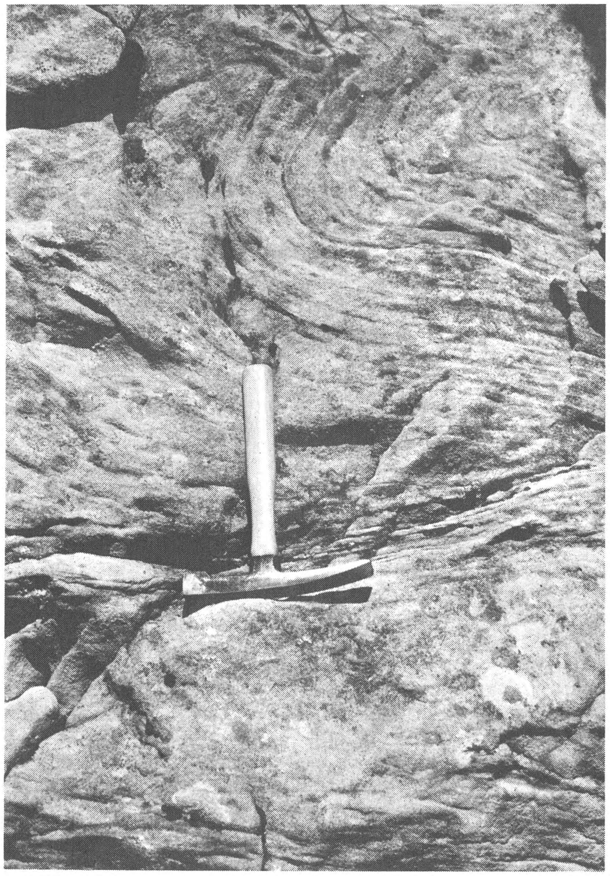


Figure 23. Disturbed bedding in lacustrine sandstone, lower Green River Formation, Horse Canyon section.

Individual groups of measurements are analyzed by a method suggested by Tanner (1959). The compass is divided into twelve 30° segments and the number of paleocurrent observations present within each segment is noted. The mean number of measurements for each segment and the standard deviation are calculated. Those segments that contain observed measurements in excess of one standard deviation

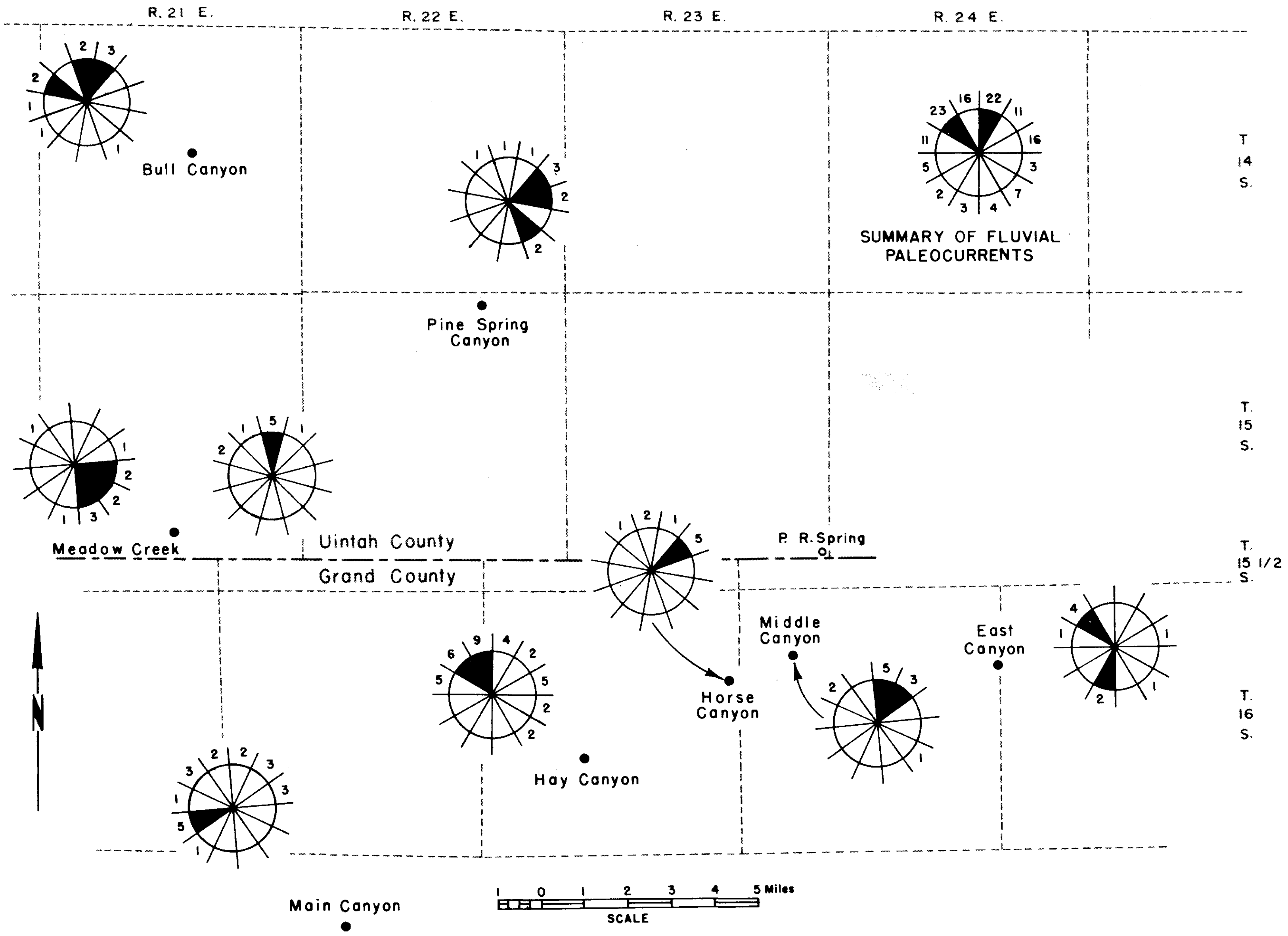


Figure 24. Fluvial paleocurrent map, P. R. Spring area.

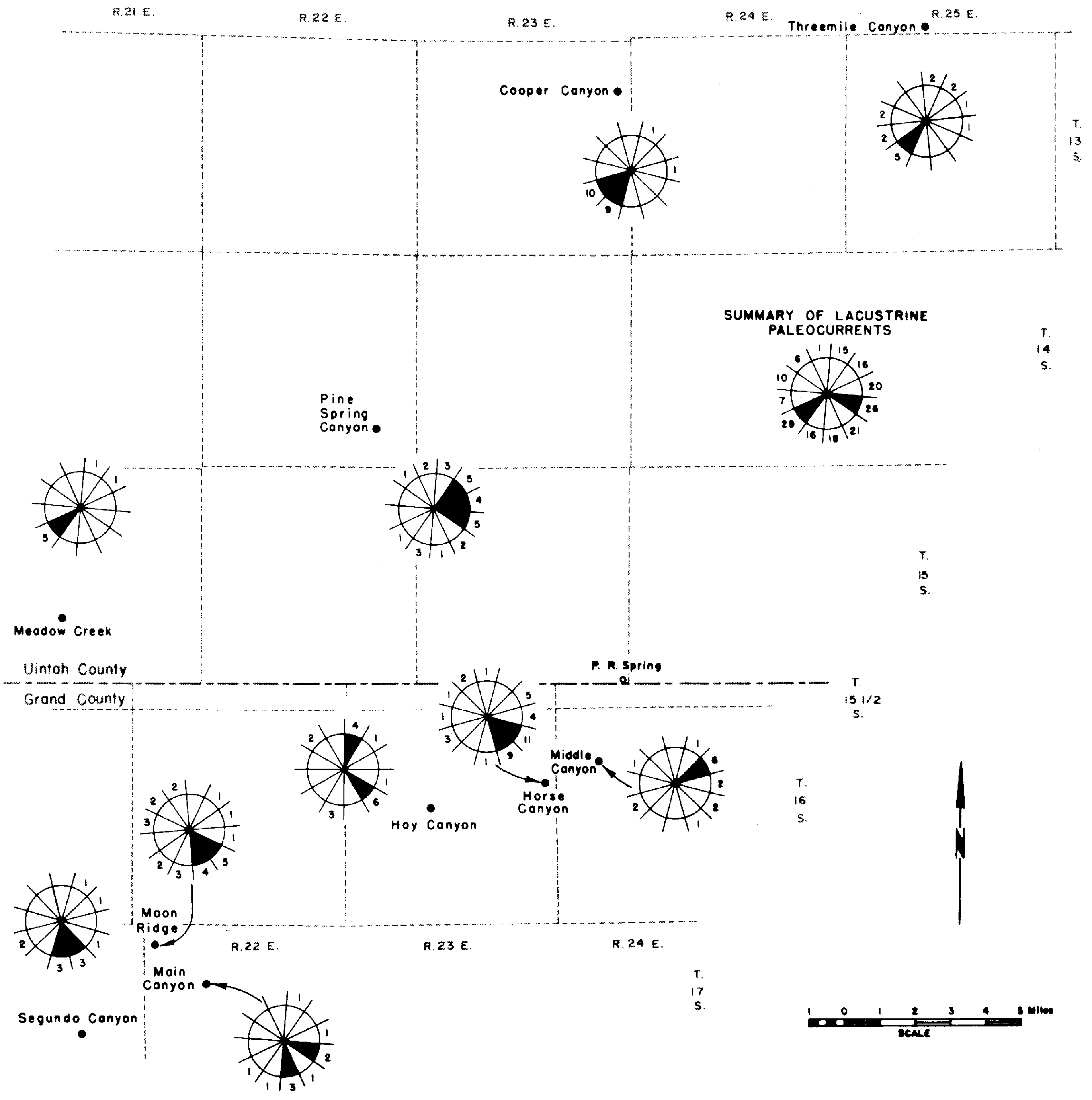


Figure 25. Lacustrine paleocurrent map, P. R. Spring area.

Table 4. Summary of significant fluvial paleocurrent directions.

Locality	Midpoint of Significant Interval (30°)	Modality	Significant Direction (single vector for each mode)	Remarks
Main Canyon	250°	Unimodal	250°	Considerable scatter for fluvial paleocurrent directions
Hay Canyon	313°, 343°	Unimodal	328°	Considerable scatter
Horse Canyon	55°	Unimodal	55°	
Middle Canyon	10°, 40°	Unimodal	25°	
East Canyon	195°, 315°	Bimodal (90°)	195°, 315°	
Meadow Creek	100°, 130°, 160°	Unimodal	130°	
Meadow Creek	0°	Unimodal	0°	
Bull Canyon	25°, 295°, 355°	Unimodal	355° (weighted vector)	
Pine Spring Canyon	55°, 85°, 145°	Unimodal	85° (weighted vector)	
Composite Fluvial	17°, 317°	Unimodal	347°	

Table 5. Summary of significant lacustrine paleocurrent directions.

Locality	Midpoint of Significant Interval (30°)	Modality	Significant Direction (single vector for each mode)	Remarks
Segundo Canyon	152°, 182°	Unimodal	167°	Onshore
Main Canyon	110°, 170°	Unimodal	145°	Onshore
Moon Ridge	130°, 160°	Unimodal	145°	Onshore; some probable offshore directions at about 180° to the significant intervals
Hay Canyon	13°, 133°	Bimodal (90°)	13°, 133°	Onshore and longshore
Horse Canyon	120°, 150°	Unimodal	135°	Probable strong onshore paleocurrent directions; other directions are scattered
Middle Canyon	57°	Unimodal	57°	Longshore (?)
Meadow Creek	230°	Unimodal	230°	Onshore
Pine Spring Canyon	80°, 110°	Unimodal	95°	Onshore (?); considerable scatter
Cooper Canyon	210°, 240°	Unimodal	225°	Onshore
Threemile Canyon	220°	Unimodal	220°	Onshore; some probable offshore directions at about 180° to the significant interval
Composite Lacustrine	108°, 228°	Bimodal (90°)	108°, 228°	Two different onshore directions; not onshore and longshore

above the mean are considered significant paleocurrent intervals. The significant intervals are shown in black on figures 24 and 25; the midpoints of significant intervals are given in tables 4 and 5.

Paleocurrent Maps

The two paleocurrent maps (figures 24-25) show the fluvial and lacustrine current directions during deposition of the sandstone bodies. Seven of the nine fluvial patterns indicate that the currents flowed northward, a direction that is well expressed in the summary diagram for the fluvial sandstone units. Inasmuch as the P. R. Spring area is located along what was the southern edge of Eocene Lake Uinta, the northerly fluvial pattern is consistent with regional paleogeographic and stratigraphic information. The considerable scatter, both within measurements from a single locality and between localities, suggests that the streams had low gradients and were meandering. Extensive floodplains were formed and deposition in the P. R. Spring area fluctuated between fluvial, deltaic and lacustrine conditions.

On the lacustrine paleocurrent map, southerly directions are pronounced. Nine of the ten lacustrine patterns have significant intervals in the south half of the compass. Because onshore currents are more abundant in shallow, nearshore water than offshore and longshore currents, these paleocurrent patterns can be used to reconstruct the paleogeography (Picard, 1967b; Picard and High, 1968, p. 417). Thus, the shorelines of Lake Uinta probably trended northeast through much of the P. R. Spring area. However, on the northeast in the Cooper Canyon and Threemile Canyon areas, shorelines were oriented northwest-southeast, possibly reflecting a peninsula, or the Douglas Creek arch that separated the Uinta and Piceance Creek Basins during part of their history. In the west part of the study area, a similar orientation was obtained at the Meadow Creek section. In summary, the shorelines of Lake Uinta in the P. R. Spring area were generally oriented northeast-southwest, but they were irregular and broken by local embayments.

Provenance

Several petrographic and sedimentologic characteristics aid in determining the distribution of source areas for the fluvial and lacustrine sandstone. The fluvial paleocurrent directions are dominantly to the northwest or north (figure 24), suggesting that the source areas were on the southeast or south. 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 shorelines is consistent with a source area on the southeast. The presence of appreciable amounts of feldspar in sandstone of the upper part of the Wasatch Formation and in sandstone of the lower part of the Green River Formation suggests that the source areas contained plutonic rocks. The Uncompahgre uplift (east central Utah and west central Colorado) is interpreted to be the source area of the detritus for the sandstone in the P. R. Spring area.

A similar interpretation has been made by other workers. 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 of the Book Cliffs area east of Green River. On the basis of the 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. Previously, Picard (1957, p. 126) indicated that the major source areas during deposition of the lower half of the Green River Formation were on the south and southeast.

PALEOCURRENTS AS ENVIRONMENTAL CRITERIA

Recently, several attempts have been made to define characteristic current patterns of a particular sedimentary environment (Klein, 1967; Selley, 1967). From these studies and from our previous work on shallow-marine units (Tohill and Picard, 1966; Picard and High, 1968), ideal fluvial and lacustrine paleocurrent patterns can be generalized. Currents in fluvial environments are more complex than has been supposed, but are, in general, unimodal downstream. Because of meandering and other complexities of current flow, the observed paleocurrent direction at a given point can lie anywhere within a 180° arc about the regional slope direction. The degree of scatter of individual measurements is dependent on stream gradient, channel type, local flow conditions and other factors. Exceptions to the general unimodal fluvial pattern can arise if small-scale cross-stratification and ripple marks are used as paleocurrent indicators. Ripple marks in modern ephemeral stream deposits are formed by currents that flow downstream, upstream and both obliquely and perpendicular to the banks. The oblique, perpendicular and upstream currents are refracted currents from the main downstream channel flow. Reflected currents (back from the banks) are also present but rarely form ripple marks. Although the foresets of cuspate (linguoid) and asymmetrical, parallel ripple marks are dominantly inclined downstream, these structures must be used with caution in studies of fluvial deposits. Present information indicates that only medium- and large-scale cross-stratification reliably record the downstream direction in most fluvial deposits. Flute casts are rarely abundant enough for paleocurrent reconstructions of fluvial settings.

Although lacustrine current systems are not well known, consideration of the physical processes indicates that lakes should resemble shallow seas in current pattern (Picard and High, 1970). A study of lacustrine paleocurrents in the Green River Formation (Picard, 1967) along Raven Ridge in the northeast Uinta Basin yielded a pattern similar to that of the marine Triassic Crow Mountain Formation of northwest Wyoming (Tohill and Picard, 1966). In both rock units the pattern is bimodal opposed (modes separated by 180°). In the Red Peak Formation (Triassic), the bimodal pattern is modified by the addition of one or two modes at right angles to the other two modes. This tri- or quadramodal pattern of the Red Peak is interpreted to record onshore, offshore and longshore currents. In modern settings, onshore directions are more abundant than other directions by a factor of several times. Thus, the most pronounced mode of lacustrine and shallow marine paleocurrent patterns should record onshore directions. On the basis of a few studies of Recent settings, other directions (oblique, offshore, longshore) are approximately equal insofar as the development of inclined foreset laminae is concerned.

A quadramodal pattern is found only where large numbers of directional structures are available for measurement. In the Red Peak, more than 50 measurements at a locality were required to define a quadramodal pattern. The onshore mode and possibly one of the other three modes should be identifiable at localities where there are few directional structures exposed.

PALEOCURRENT PATTERNS IN WASATCH AND GREEN RIVER

Figures 26 and 27 show the fluvial and lacustrine paleocurrent *patterns* in the P. R. Spring area. These patterns were derived by setting the significant directions, onshore for lacustrine and downstream for fluvial (tables 4 and 5), equal to 180° and 0° respectively before replotting all measurements. This procedure helped compensate for locality-to-locality scatter produced by indented shorelines and by meandering streams (see the fluvial and lacustrine summary diagrams for comparison). The plots were analyzed for significant concentrations of measurements. Both diagrams contain two significant 30° intervals about either the onshore or downstream direction. Other measurements are scattered about the remainder of the compass. This relationship is also shown in table 6 where the percentages of all measurements present within an arc centered on the onshore or downstream direction are tabulated. The similarity of the two patterns is striking although the significant paleocurrent directions are quite different. The lacustrine pattern is incomplete, and the offshore and longshore modes are not developed at most localities because too few directional structures are available. The flu-

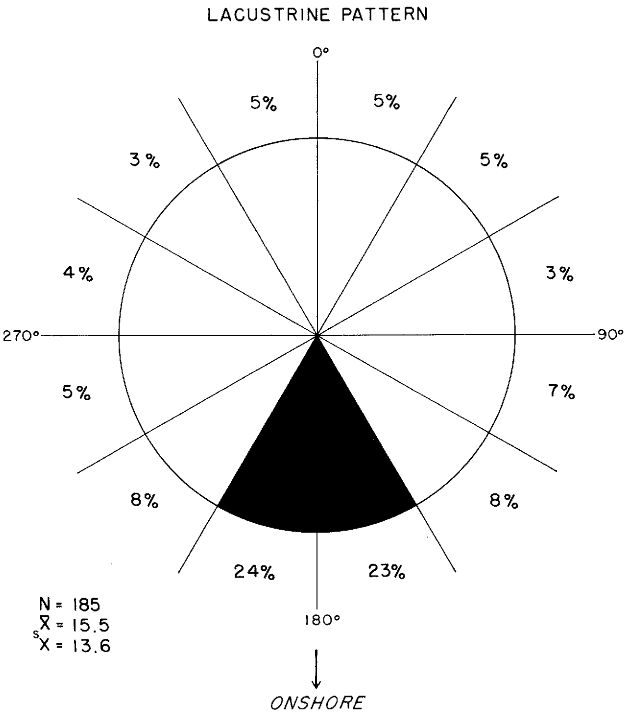


Figure 26. Fluvial paleocurrent pattern, P. R. Spring area.

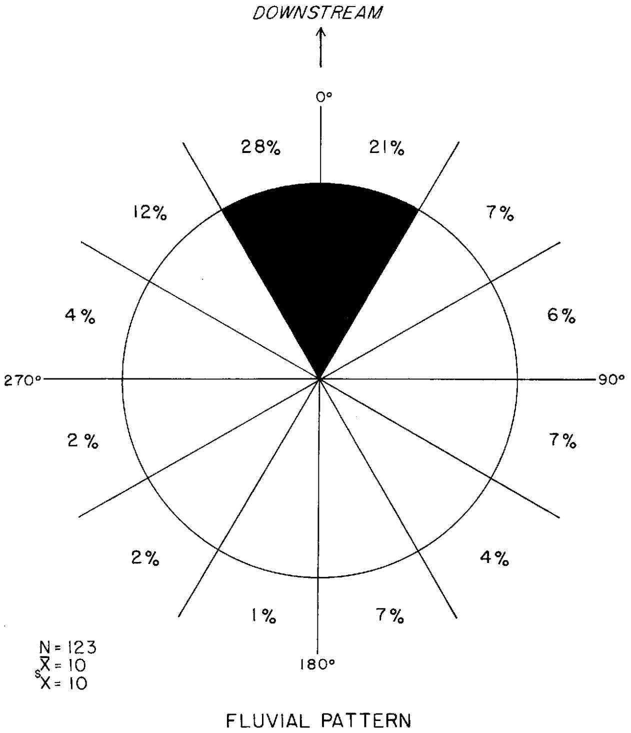


Figure 27. Lacustrine paleocurrent pattern, P. R. Spring area.

Table 6. Degree of scatter of paleocurrent directions.

Direction (in degrees)	Percentage of All Measurements Within Arc About Significant Directions	
	Lacustrine	Fluvial
±30	47	49
45	53	58
60	63	68
90	75	78
120	82	87
150	90	93
180	100	100

vial paleocurrent pattern reflects more lateral and upstream scatter of paleocurrent directions than do most other studies of fluvial deposits, probably because the streams were meandering.

CONCLUSIONS

During deposition of the upper part of the Wasatch Formation and the Douglas Creek and Garden Gulch Members of the Green River Formation, streams flowed northward into Lake Uinta in the P. R. Spring area. These streams had low gradients and meandered across extensive floodplains. In this part of the Uinta Basin, fluctuations between fluvial, deltaic and shallow water lacustrine environments were frequent during deposition of the lower half of the Green River Formation.

Fluvial sandstone bodies are dominantly linear and are generally parallel with the significant paleocurrent directions. Many of them, therefore, are oriented approximately north-south and exhibit northward-inclined foreset laminae. These relationships will be advantageous in exploring for oil and gas and undiscovered oil-impregnated sandstone bodies.

Shorelines of Lake Uinta in the P. R. Spring area generally trended northeast, and were irregular and broken by local embayments. On the northeast, however, shorelines were oriented northwest-southeast. Linear sandstone bodies of lacustrine origin in the majority of occurrences probably trend with their long axes northeast-southwest or northwest-southeast. If the average lacustrine sandstone is oriented northeast-southwest, it may be almost at 90° to the orientation of the average fluvial sandstone in the area.

The paleocurrent patterns of fluvial and lacustrine sandstone do not differ in this study. They are both unimodal. Fluvial and lacustrine sandstone can be differentiated, however, on the basis of paleocurrent orientations. The fluvial currents flowed northward, the lacustrine currents, southerly.

ACKNOWLEDGEMENTS

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UTAH GEOLOGICAL AND MINERALOGICAL SURVEY

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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