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NON-OPAQUE AND OPAQUE GRAIN FABRICS OF SILTSTONES IN RED PEAK MEMBER (TRIASSIC), CENTRAL WYOMING[1]

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ABSTRACT

The fabrics of non-opaque grains of oriented siltstones from the Red Peak Member of the Chugwater Formation (Triassic) are anisotropic in planes parallel to bedding. Six of seven samples show a preferred orientation averaging 360° (all orientations are for nothern hemisphere). A sample with disturbed bedding is nearly isotropic in the bedding plane. A mean paleocurrent direction of 21° was obtained from asymmetric, parallel ripple marks in the interval that contained the oriented samples of the fabric study.

Siltstone fabrics in thin sections perpendicular to bedding show little imbrication but less dispersion than in thin sections parallel to bedding. Two samples, sectioned parallel to the preferred grain orientation, deviate from the bedding plane by about +8° and −1°. Similar values occur, however, in four samples that were sectioned perpendicular to the preferred orientation.

Measurement of 1174 opaque grains in thin sections parallel to bedding yielded a mean elongation (length/width) ratio of 1.62, a standard deviation of 0.43 and a median interval of 1.50–1.59. Similar measurement of 639 grains in thin sections perpendicular to bedding yielded a mean elongation ratio of 1.79, a standard deviation of 0.50 and a median interval of 1.70–1.79.

Opaque grains are anisotropic in planes parallel to bedding with a mean direction of 324°, differing by 36° from the mean of the non-opaque grain fabrics. In planes perpendicular to bedding, the "preferred inclination" of elongate opaque grains corresponds closely with the bedding plane. There is little difference in imbrication between the opaque and non-opaque grains in planes perpendicular to bedding.

The mean (324°) for the preferred orientations of the opaque grains nearly coincides with the declination of the predominant (normal and reverse) magnetic directions, suggesting that the two are related.

INTRODUCTION

This is a study of the fabrics of some red, well-sorted and poorly sorted siltstones from the Red Peak Member of the Chugwater Formation (Triassic) from a section north of Rawlins, Wyoming. The principal objectives were: the development and application of techniques pertinent to the study of siltstone fabrics; the fabric analysis of selected siltstones; the comparison of fabric data with paleocurrent directions from asymmetrical ripple marks; the comparison of opaque grain fabrics and non-opaque grain fabrics; and the application of results of the fabric study to the remanent magnetism of the rocks.

ASPECTS OF SEDIMENTARY FABRICS

General.—Fabric, a textural property of sedimentary rocks, refers to the orientation and spatial arrangements of fabric elements (Potter and Pettijohn, 1963, p. 23). Any component that behaves as a single unit in relation to an applied force is a fabric element, specifically, a detrital fragment. Anisotropic fabrics are developed through the alignment of fabric elements in a force field, such as the Earth's gravitational field, the Earth's magnetic field, and the current force fields produced by ice, wind and water movement.

The orientation of individual components in space is defined in terms of two angles. The azimuth angle between some defined axis of the fabric element and north gives the orientation within a horizontal plane. The inclination of this axis (from the horizontal) defines the orientation within a vertical plane.

Factors influencing grain orientation.—The shape of fabric elements may approximate spheres, disks or rods, but an inherent feature of a useful element to fabric studies is dimensional inequality. Dimensionally unequal or elongate grains, in response to the stresses acting upon them, tend to align themselves in a position of maximum stability. A particle is stable when all the stresses acting upon it are in equilibrium. Disturbance of this equilibrium produces a stress couple, which attempts to re-establish equilibrium. Rusnak (1957, p. 391) concluded that, "... the most stable positions which particles will acquire on the bottom will be with lengths parallel to the direction of fluid motion and with a slight negative angle of attack."

Principal forces acting upon a grain during and immediately following deposition are gravity and currents. Suspended particles, settling to

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the bottom, achieve a position of stability in which the longest and intermediate dimensions parallel the depositional surface. When the current effect is added to the gravitational force, particle orientation is induced within, or nearly within, the plane of the bedding surface. Rusnak (1957, p. 389) has shown that this anisotropy may be directly controlled by "bottom-roughness elements." A smooth bottom favors a rolling motion with the long grain dimension perpendicular to the current direction. As the bottom-roughness elements increase, elongate grains pivot erratically about their points of contact with the bottom surface and fall into pockets, some nearly parallel to the current directions. For a threshold velocity, broadside movement can not be initiated again, and a position parallel to the current is most stable.

If a grain is inclined upward (positive angle of attack) into the direction of current movement, a lift stress, resulting from a high pressure under the grain and a lower pressure above it, tends to flip the grain. Conversely, when there is a negative angle of attack, gravitational and current forces combine to insure stability.

Several factors may modify the idealized situation, with consequent modification of the orientation and imbrication of fabric elements. Some of these factors are: velocity and type of flow (laminar or turbulent); particle size and shape; bottom roughness and packing of particles; rate of sediment supply; and composition and physical properties of individual particles (Rusnak, 1957, p. 392; Spotts, 1964, p. 231). With present techniques, and the state of knowledge about sedimentary fabrics, the modifications that would be induced by some of these factors are difficult to evaluate.

Additional factors affecting orientation of magnetic particles.—Magnetic particles, and to a lesser extent paramagnetic particles, tend to be aligned in the ambient geomagnetic field upon deposition. Declination and inclination variations from the prevailing magnetic field are introduced by opposing current action and gravity. Based on experimental results from artificial sediment deposition, Rees (1961, p. 235–236) defines an *inclination error* and a *bedding error* as follows. When sediment is deposited on a horizontal bed, I_O, the inclination of the remanent magnetic direction to the horizontal, is less than I_F, the inclination of the ambient field. The difference, I_F-I_O, has been defined as the inclination error, which depends on the field inclination. The inclination error can reach a maximum of about 25° at a field inclination of about 60°, but falls to negligible values at low field inclinations. Deposition on a sloping bed produces a further deviation of the remanence vector, the bedding error, which is nearly independent of field inclination. The bedding error ($I\alpha$-I_O) is the difference between the inclination of the remanence when deposition occurs on a northern slope ($I\alpha$) and the inclination when deposition occurs on a horizontal surface. A model to explain these deviations has been developed (Griffiths, King, and Rees, 1962, p. 138). Upon deposition, quasi-spherical, magnetic and non-magnetic particles of uniform size fall into hollows in the surface of accumulation. Rolling about a horizontal axis into these hollows will statistically reduce the inclination angle, producing the inclination error. The bedding error is of about the same magnitude as the slope of the bed, and in a direction that results from down-slope rolling of magnetic particles. A third deviation of the remanence direction has been noted. This deviation, the rotation angle, ". . . appears to be a rotation of the remanence about a horizontal axis at right angles to the direction of flow . . ." (Rees, 1961, p. 236) and affects the declination as well as the inclination. The remanence direction may be deflected by angles up to 10° in current velocities of 5 to 30 cm/sec, the magnitude of the affect being independent of the velocity within this range (Irving, 1964, p. 31). The rotation angle is related to the shear produced by the water flowing over the bed during deposition (Griffiths, King, and Rees, 1962, p. 136).

SAMPLES STUDIED: GENERAL

The samples for the fabric study were collected from the north Rawlins section (fig. 1) of the Chugwater Formation on U. S. Highway 287, about 14 miles north of Rawlins, Wyoming (NW. quarter of Sec. 16, T. 23 N., R. 88 W.). These samples are from 7 to 160 feet below the base of the Alcova Limestone Member of the Chugwater Formation in the upper platy facies and in the upper part of the alternating facies of the Red Peak Member (Picard and High, 1963, p. 91–93; Picard, 1965b). Each oriented sample was collected within a few inches of known magnetic directions in magnetic interval 5c (Picard, 1964, p. 272). Similarly, paleocurrent azimuths from parallel ripple marks were determined from 1 to 12 inches above or below an anomalous magnetic direction in interval 5c.

The siltstones are red, calcareous and flaggy to massive (McKee and Weir, 1953, p. 383). The silt grains are dominantly 1/16 to 1/64 mm in diameter, well-sorted to poorly sorted and predominantly quartz and feldspar. Some small-scale cross-stratification (McKee and Weir, 1953, p. 388) was noted. Disturbed bedding and

FIG. 1.—Index map showing localities.

sublenticular laminations (Picard and High, 1963, p. 92–93) occur in one of the oriented samples (sample 7).

The exposures of the upper part of the alternating facies and the upper platy facies at north Rawlins dip about 8–9 degrees; therefore the orientation data were not restored to horizontal. Rotation through such small angles would involve azimuth changes in orientation that are less than the certainty of the measured orientation direction, as noted by Spotts (1964, p. 235).

General data on the opaque grains in the siltstones are as follows. Modal analyses of 22 thin sections from rocks of the Red Peak and Crow Mountain Sandstone Members of the Chugwater Formation indicate a range in opaque minerals from about 0.3 to 3.7 percent (Picard, 1965a, p. 466). Based on 75 measurements, the opaque minerals in the siltstones have an average diameter of about 0.05 mm, ranging from 0.005 to 0.153 mm.

Hematite, ilmenite and magnetite were identified by X-ray diffractometer in several opaque mineral separations from red, well-sorted siltstone and from very fine sandstone. X-ray patterns of standard mixtures of hematite, ilmenite and magnetite were prepared for comparison. In these separations, hematite predominates, and ilmenite is apparently more abundant than magnetite. X-ray data, examination of opaque mineral separations with the binocular microscope, and examination of thin sections in reflected light indicate that hematite is the domin-and opaque mineral in the siltstones. Leucoxene is common. Unidentified opaque grains are present. Goethite and pyrite have been noted in drab rocks from the Red Peak but were not seen in the red samples studied here.

PALEOCURRENT DIRECTIONS

Parallel ripple marks (McKee, 1954, p. 57–58), which are dominant in the Red Peak, were used to determine paleocurrent directions in the interval where the oriented samples for fabric study were collected. Parallel ripple marks are believed (McKee, 1954, p. 58) to be the result of water-currents; they are characterized by even, parallel ridges and troughs, which range from about 0.5 to 2.0 inches from crest to crest in the Red Peak.

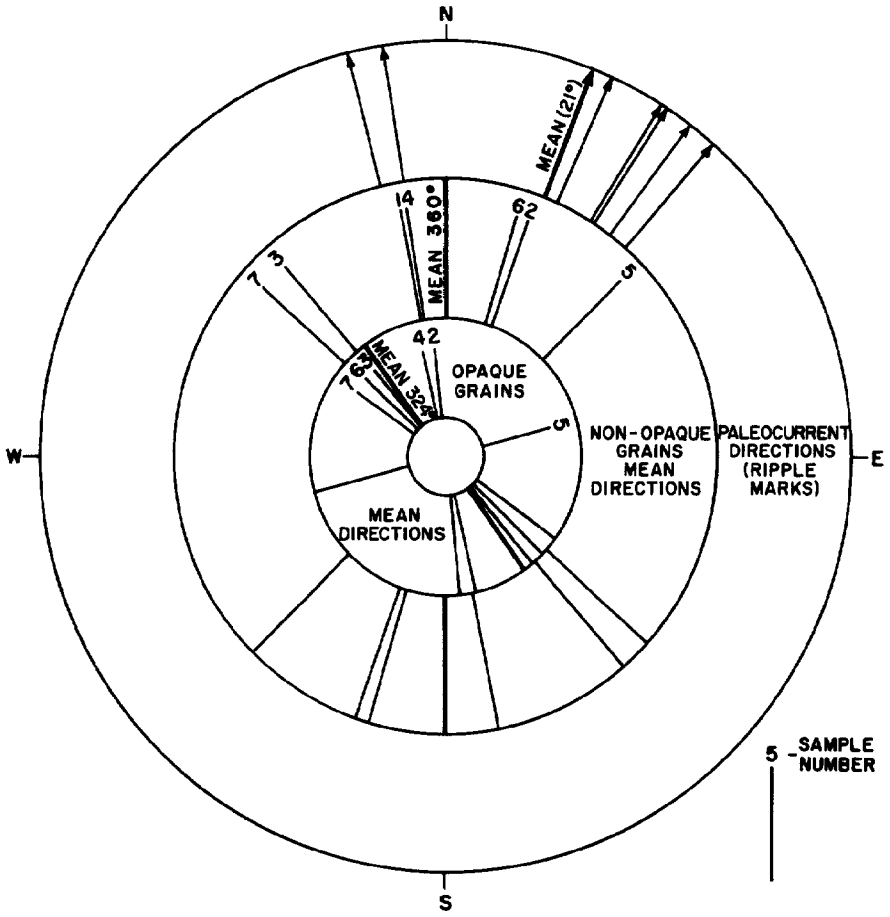

FIG. 2.—Paleocurrent directions from ripple marks and mean orientations of non-opaque and opaque grain fabrics.

Paleocurrent directions were assumed to be perpendicular to the strike of ripple mark crests, and in the direction of asymmetry. Each ripple mark was examined to see if the direction of inclination of foreset laminae coincides with the direction of asymmetry.

The reliability of ripple marks as indicators of paleocurrent directions is difficult to evaluate. Pettijohn (1962, p. 1475) notes that, "Asymmetrical ripples would be expected to be transverse to the current flow and the few data available bear this out." Picard's experience in this study, and in a more extensive study of the sedimentary petrology of the Chugwater Formation has led to the conclusion that asymmetrical ripple marks of the parallel type provide reliable paleocurrent directions. Paleocurrent direction indicators do not occur throughout much of the Red Peak. Paleocurrent directions indicated by cross-stratification and asymmetric, parallel ripple marks in the Crow Mountain are similar; there is less variation (arc of azimuths) in the ripple marks than there is in the cross-stratification.

Asymmetric, parallel ripple marks mainly from the upper platy facies and the upper part of the alternating facies in the north Rawlins section yielded paleocurrent azimuths of 346, 351, 24, 32, 33, 37 and 41, a mean direction of 21° (figs. 2, 3). In the Red Peak in west-central Wyoming, Picard (unpublished data) has found that 52.1 percent of 473 paleocurrent directions, determined mainly from ripple marks, are between 300° and 61°. In the north Rawlins section, and elsewhere, other paleocurrent directions than northward are also common. For example, 22.0 percent of 473 paleocurrent directions in the Red Peak range from 211° to 300°.

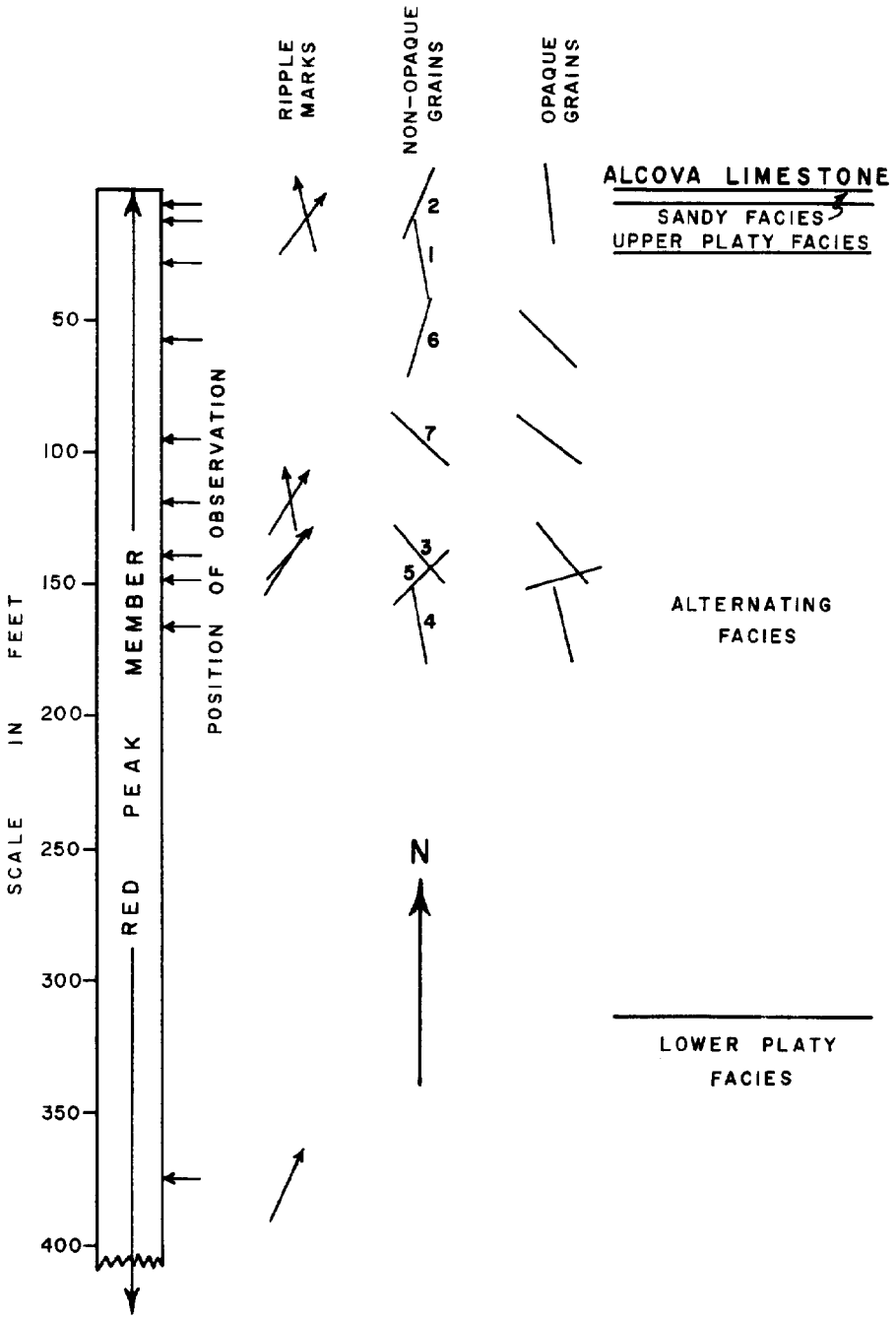

FIG. 3.—Stratigraphic position of samples in north Rawlins section. Paleocurrent directions of ripple marks and orientations of fabric means.

Paleocurrent directions are variable, and within a vertical distance of 2 to 3 inches some of them yield azimuths at 180° to each other. The close correlation of the ripple mark data (fig. 3) is uncommon in the Red Peak throughout west-central Wyoming.

PROCEDURES OF FABRIC ANALYSIS

The grain fabric data consist of dimensional, or grain-shape orientation determinations. Apparent grain shape, although only two-dimensional, represents satisfactorily the orientation of fabric elements. Procedures and techniques developed by other workers in studies of sand-sized material were generally used, and they were satisfactory in this study of siltstone fabrics. Fabric data from this study are compared with fabric data from studies of sand-sized material.

Thin sections prepared from orientated samples correspond with the three principal defined directions of a directional structure reference system: a section parallel to bedding; a section perpendicular to bedding and parallel to the current direction (preferred orientation); and a section perpendicular to both bedding and the current direction. Though individual sections are two dimensional, a combination of the three mutually perpendicular sections yields an approximate three-dimensional representation.

To insure unbiased selection of grains, several linear traverses of the whole thin section were made with a mechanical point counter attached to the stage of a microscope. Each traverse proceeded in a series of systematic jumps. Grain size determined the distance between adjacent fields. All elongate grains within a single field were used for orientation determination. The method used is essentially the one outlined by Curray (1956a, p. 2442) in preference to continuous linear traverses.

The number of grains counted per sample by other workers has varied from 60 to 500 (Potter and Pettijohn, 1963, p. 42). Spotts recently (1964, p. 237) used approximately 500 grains in each sample. Griffiths (1952, p. 49) reduced his count from 800 to 200 grains per thin section in his study of the Bradford Sand (Upper Devonian) " . . . without loss of efficiency." Commonly counts of from 100 to 200 grains have been used and found to give satisfactory results (Potter and Pettijohn, 1963, p. 42). For this study, 54 to 170 (average of 105) grains were counted in thin sections parallel to bedding and 90 to 154 (average of 122) grains in thin sections perpendicular to bedding.

Grain images were projected onto paper and traced, which afforded a permanent record of the grain shapes for measurement of elongation ratios and orientations. An elongation ratio (length/width) of 1.5:1 was used for non-opaque grains. Potter and Mast (1963, p. 499) obtained reliable results using a ratio of 1.3:1. Curray (1956a, p. 2442) used a somewhat lower ratio. Rusnak (1957, p. 409) emphasized use of " . . . the more elongate (rod-shaped) sand grains." A ratio of 1.5:1 facilitates determination of the apparent long dimension and minimizes the effects of sectioning. The opaque grains, because of their crystal structure, have mean elongation ratios smaller than those of the non-opaque grains. Consequently, the minimum elongation ratio for opaque grains was lowered to 1.4:1, which permitted use of more than 65 percent of the opaque grains for orientation determinations. All of the opaque grains in each thin section were traced.

The apparent long dimension was positioned by use of the least-projection elongation of Dapples and Rominger (1945, p. 251), which is the direction of two parallel lines tangent to the grain and with the least amount of separation. Theoretically, this smallest dimension, " . . . offers least resistance to a circumfluent medium." The azimuth positions of the long dimensions in thin sections parallel to bedding were grouped in 20° intervals. Because of less dispersion in sections perpendicular to bedding, data on inclination from the bedding surface were grouped in 10° intervals. Circular histograms (current-roses) facilitate direct visual comparison of the data. In summary, the technique of fabric analysis outlined here proved satisfactory in the study of these siltstones.

STATISTICAL METHODS

Although ready correlation of data through visual examination makes a rigid statistical analysis unnecessary, and the limited samples and number of grains measured per thin section preclude such an analysis, a convenient method of describing and correlating results is desirable. A useful method (Curray, 1956b), treating the distribution in its circular form, is applied. The chosen axis of each particle is treated as a vector with direction and magnitude. Each vector is resolved into east-west and north-south components, the respective components summed to yield the components of a resultant vector, which also has direction and magnitude. The direction of this resultant is a measure of central tendency; the vector magnitude is a measure of dispersion comparable to standard deviation. The vector magnitude may range from 0 to 100 percent. If all the observations fall within the same azimuth group, the vector magnitude is 100 percent. A random distribution gives a vector magnitude of 0. No tests of significance are applied because of the limited sample, and because there are no significance tests that are entirely satisfactory.

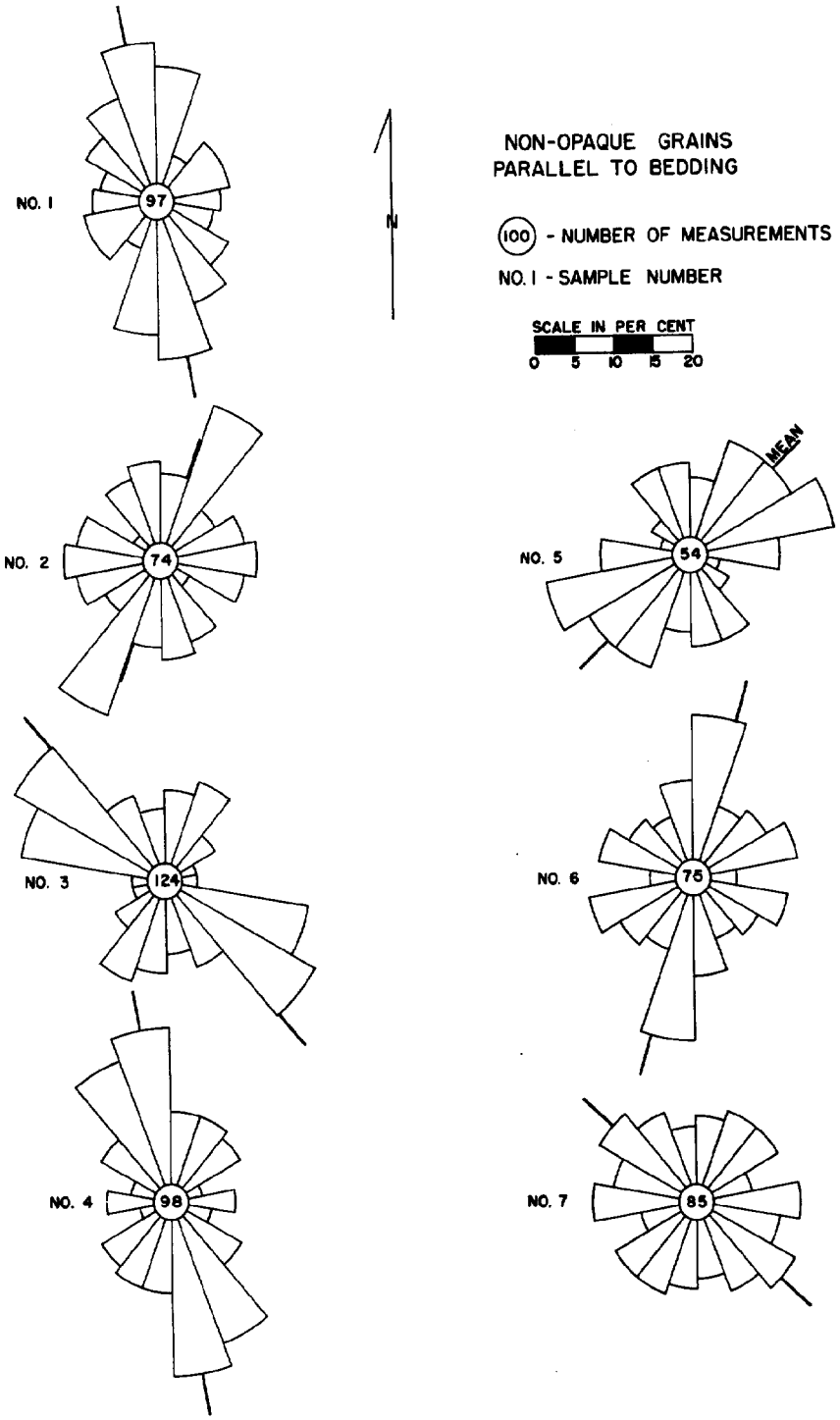

FIG. 4.—Non-opaque grain fabrics in thin sections parallel to bedding.

TABLE 1.—*Orientation data on thin sections parallel to bedding*

Sample No.	Non-Opaque Grains			Opaque Grains		
	Vector Mean	Vector Magnitude (%)	Total Meas.	Vector Mean	Vector Magnitude (%)	Total Meas.
1	349°	18	97			
2	19°	9	74	354°	48	170
3	319°	26	124	320°	29	123
4	350°	27	98	347°	14	102
5	45°	21	54	75°	19	134
6	16°	8	75	314°	23	117
7	312°	4	85	306°	25	116
Mean	353°	31%		324°	48%	

RESULTS OF FABRIC STUDY

Fabric of Non-Opaque Grains

Anisotropy in plane parallel to bedding.—Preferred grain orientation was investigated in thin sections of seven samples, sectioned parallel to bedding. Dimensional (grain-shape) orientations were determined on from 54 to 124 grains per thin section. The data are illustrated as circular histograms (fig. 4), and statistically summarized (table 1). Table 1, based on the vector-mean-method of Curray (1956b),gives a close approximation of the preferred grain orientation and the dispersion about that direction.

Four of the seven samples show distinct preferred orientations within 20° of north (table 1; fig. 4). (Grain fabrics indicate a line of movement rather than a direction of movement. The ripple mark data suggest that paleocurrents were generally northward. The fabric data are, therefore, treated in this hemisphere; for example, an azimuth of 10° instead of 190°.) The relatively low vector magnitudes of samples 2 and 6 (table 1) would ordinarily suggest that their distribution is not significant. The close correlation, however, of the mean directions of samples 2 and 6 with the ripple mark data (fig. 2) and with the mean directions of the other samples (fig. 4) suggests that the data on samples 2 and 6 are significant. A summary of the vector means gives a vector direction of 353° with a vector magnitude of 31 percent.

Sample 7, which has disturbed bedding, is included because it represents a common class of rocks in the alternating facies of the Red Peak. The nearly isotropic distribution (fig. 4; table 1) of the non-opaque grains is the result of destruction of most of the primary sedimentary fabric, partly by burrowing organisms, and probably partly by inorganic means. The vector mean of sample 7 is not greatly different from the vector means of the other samples and is close to the vector mean for sample 3 (table 1). This correspondence of vector means, although sample 7 is nearly isotropic, occurs because not all of the primary sedimentary fabric in sample 7 was destroyed. Disturbed bedding and sublenticular lamination in a siltstone from the alternating facies of the same kind that is present in sample 7 was illustrated by Picard (1964, p. 288).

A special study of samples 2 and 3 was undertaken to establish the relationships between the degree of preferred orientation and maximum grain elongation, and preferred orientation and mean grain elongation. These appear to be similar relationships, and indeed they compliment each other, but each has unique properties that warrants its study. Figure 5 compares a "normal" circular histogram (circular distribution of azimuth measurements from grains exceeding an elongation ratio of 1.5) with a "select" circular histogram based on grains whose elongation ratio exceeds 2.0. Although the sample size is approximately halved, the select group yields a decreased spread, or variance, of grain-shape orientations. In sample 2, the vector magnitude increases from 9 to 26 percent, and in sample 3 there is an increase from 26 to 44 percent. McBride (1962, p. 69) achieved similar results by comparing histograms of 85 grains greater than 0.25 mm in length with 145 grains greater than 0.12 mm in length.

Figure 5, in addition, shows the relationship between the preferred orientation direction and the mean grain elongation. The mean grain elongation ratio of each 20° class is plotted against the midpoint of that class. The resulting figure approaches an ellipse, with the long axis parallel to the preferred grain orientation. The appearance of a semi-major axis normal to the major axis suggests that there may be secondary preferred orientation at right angles to the primary orientation. A secondary orientation is not clearly shown (fig. 5) by the normal or select circular histograms.

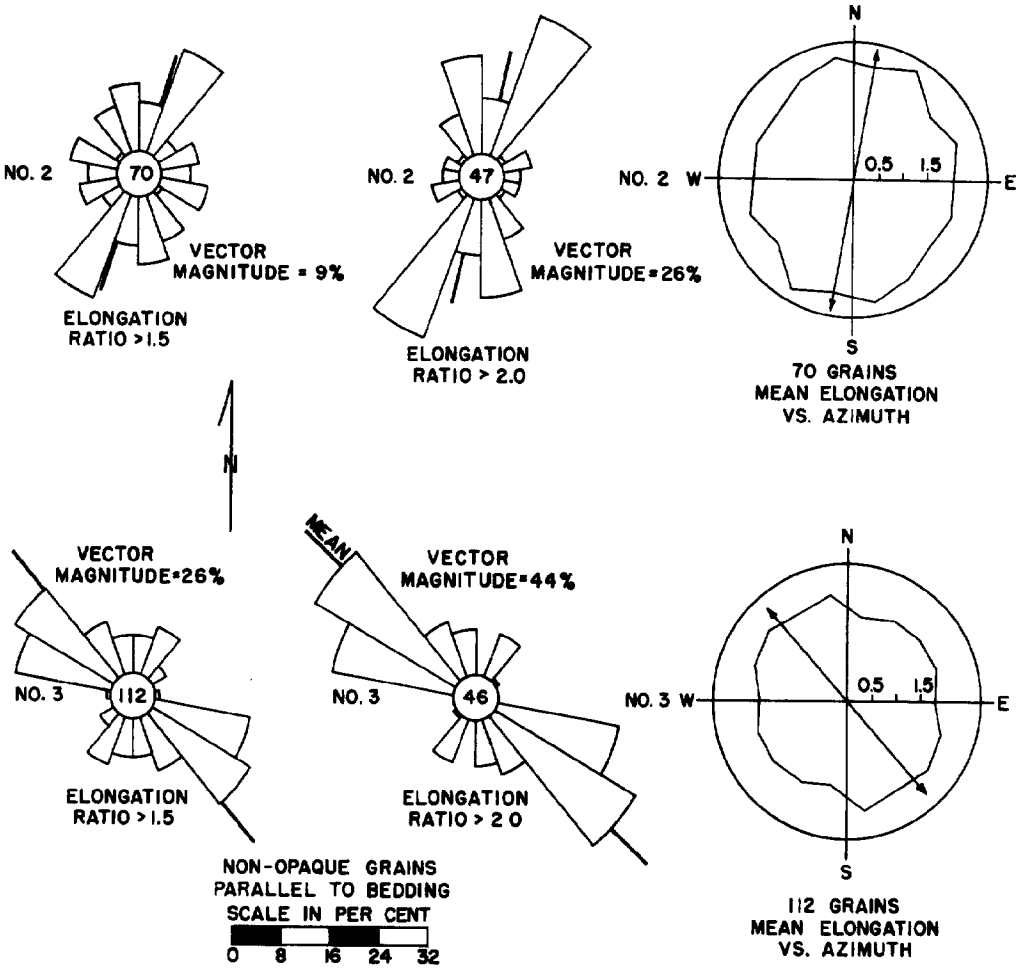

FIG. 5.—Non-opaque grain fabrics in two samples parallel to bedding. Fabrics of grains with elongation ratios >1.5 and >2.0. Plots of mean elongation versus azimuth included.

Anisotropy in planes perpendicular to bedding.—Five samples were sectioned perpendicular to the bedding plane. Thin sections of samples 2 and 5 are parallel to the preferred grain orientation, while samples 1, 2, 3 and 7 are prependicular, or nearly perpendicular, to the preferred orientation (table 2). In general, siltstone fabrics are characterized in sections perpendicular to

TABLE 2.—*Orientation data of thin sections perpendicular to bedding*

Sample No.	Non-Opaque Grains				Opaque Grains		
	Orientation of Thin Section	Vector Mean	Vector Magnitude (%)	Total Meas.	Vector Mean	Vector Magnitude (%)	Total Meas.
2	N 30° E	+8° 24′	51	144	− 20′	58	129
5	N 60° E	− 38′	57	120	−3° 42′	45	135
1	N 75° W	+8° 51′	59	98			
2	N 60° W	− 30′	49	108			
3	N 25° E	+7° 14′	50	108	+4° 4′	45	154
7	N 35° E	+2° 10′	37	133	+2° 44′	51	90

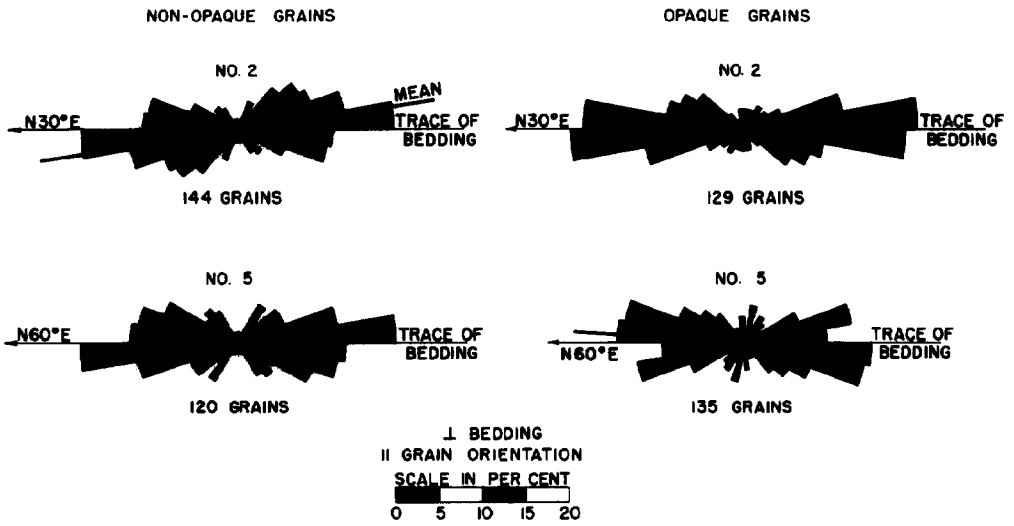

FIG. 6.—Non-opaque and opaque grain imbrication in two samples. Thin sections parallel to preferred grain orientation and perpendicular to bedding. Means shown by heavy lines.

bedding by less dispersion than in sections parallel to bedding, and, perhaps, by imbrication. Figures 6 and 7 illustrate these relationships.

Vector mean values (table 2) indicate that these siltstones have very little imbrication. Samples 2 and 5, sectioned parallel to the preferred grain orientation, show deviations from the bedding plane of about $+8°$ and $-1°$. Similar values occur, however, in samples 1, 2, 3 and 7, which were sectioned perpendicular, or nearly perpendicular, to the preferred orientation. Three of the normal sections (table 2) have essentially no imbrication. In those samples with imbrication, the deviation from bedding is posi-

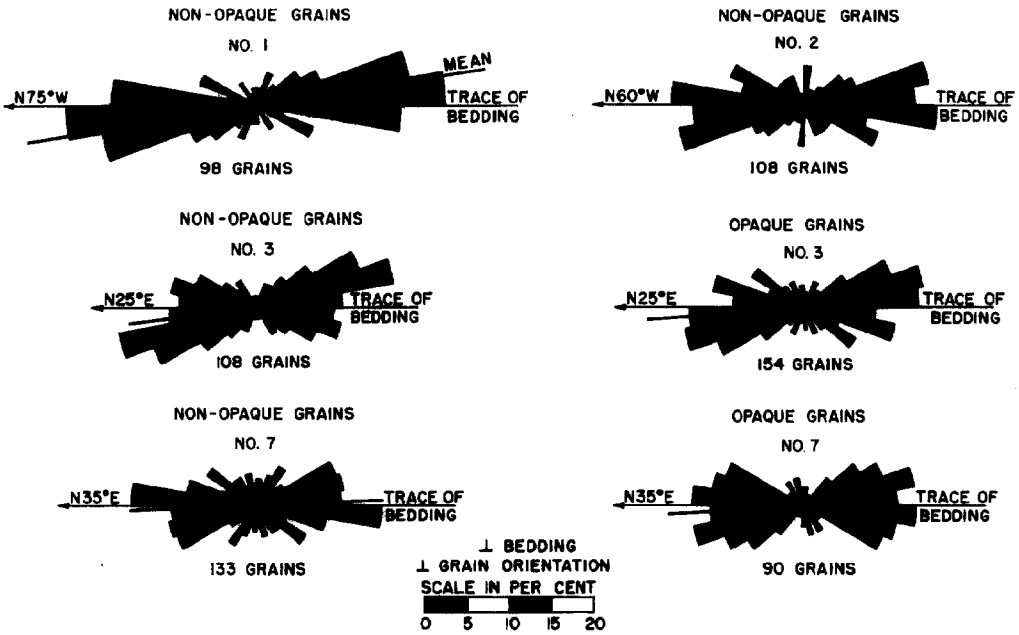

FIG. 7.—Grain fabric of non-opaque and opaque grains in thin sections approximately perpendicular to preferred grain orientation and perpendicular to bedding. Means shown by heavy lines.

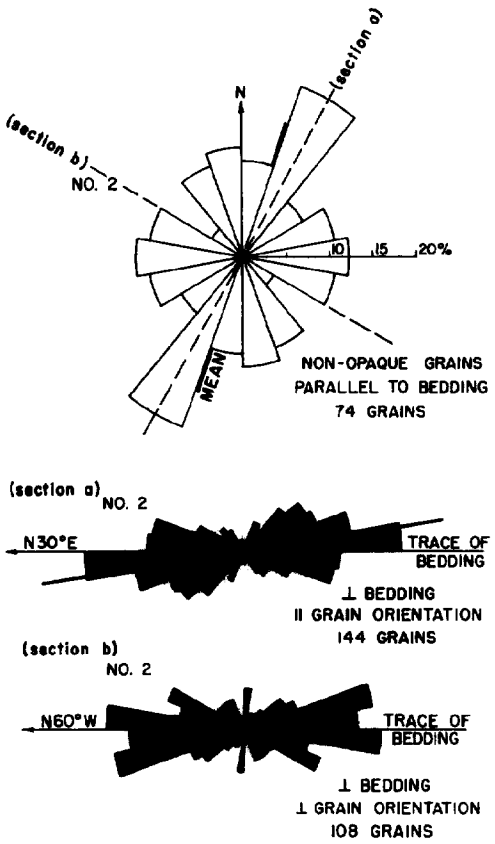

FIG. 8.—Three dimensional non-opaque grain orientation in sample of siltstone from upper platy facies of Red Peak Member. Means shown by heavy lines.

tive to the north (table 2), suggesting the possibility of imbrication by currents flowing generally south instead of north.

Three-dimensional diagram.—A summary of the non-opaque grain fabric is presented in three dimensions (fig. 8), using sample 2. This model is generally representative of the samples that were not modified by bedding disturbance. Preferred grain orientation exists parallel to the bedding plane but shows a large amount of scatter. Section a, which is perpendicular to the bedding and parallel to the grain orientation, shows an apparent imbrication of +8° to the northeast. Section b, which is perpendicular to the bedding and the grain orientation, shows no imbrication. There is much less scatter in the sections perpendicular to bedding than there is in the section parallel to bedding.

Correlation of anisotropic fabric data with paleocurrent directions.—Non-opaque grain fabrics agree closely with the paleocurrent directions as defined by asymmetric ripple marks (fig. 2). Ripple mark directions range from 346° to 41°, a mean direction of 21°. Excepting sample 7 (examplative of disturbed bedding), the preferred grain orientation directions range from 319° to 45°, a mean of 360°. Although the vector means differ by 21°, only sample 3 deviates significantly from the range of ripple mark directions.

In some samples there is an imbrication to the north (figs. 6, 8). According to theory, this inclination would have been unstable relative to a predominant northward current movement (Rusnak, 1957). A down-current imbrication is also not consistent with the results of some other investigators (McBride, 1962, p. 67; Schwarzacher, 1951, p. 172; Spotts, 1964, p. 252). Curray (1956a, p. 2447–2448) in a study of imbrication on the foreshore in Recent coastal sands noted that the preferred orientation direction is landward, apparently because the ebb flow affects the dimensional fabric more than the oncoming surf. Sestini and Pranzini (1965, p. 105–106) found an up-current inclination in one-half of their samples from two flysch-type sections of the northern Apennines, Italy. Some of the samples show a down-current inclination; others are not inclined (Sestini and Pranzini, 1965, p. 106). In some of the Red Peak samples a southern current may have effected imbrication, since longshore currents sometimes flow in directions at about 180° to each other.

Fabric of Opaque Grains

Elongation data and interpretation.—The predominant opaque grains (hematite, magnetite and ilmenite) have crystal shapes that more closely approximate spheres than they do rod-shaped particles. Hematite occurs in rhombohedral crystals whose a-axis—c-axis ratio is 1:1.36. Ilmenite develops thick, tabular, tri-rhombohedral crystals in which the a-axis—c-axis ratio is 1:1.38. Magnetite occurs in isometric crystals, usually octahedral, where all axes are equal. The elongation (length/width) ratios of a large sample (1813 opaque grains) indicate, however, that the opaque grains are sufficiently elongate to allow delineation of a long axis in a representative sample. Histograms, summarizing the elongation ratio measurements in thin sections parallel and perpendicular to bedding, are given in figure 9. Delineation and measurement of 1174 opaque grains in thin sections parallel to the bedding surfaces yielded a mean elongation ratio of 1.62, a standard deviation of 0.43 and a median interval of 1.50–1.59. Similar measurement of 639 grains in thin sections perpendicular to bedding yielded a mean elongation ratio of 1.79, a standard deviation of 0.50 and a median interval of 1.70–1.79.

Several conclusions and positive features that are illustrated by the elongation ratio measurements are summarized.

1. Opaque grains are not spherical, but are sufficiently elongate to be used in fabric orientation studies.
2. Preferred orientation of the opaque grains may occur, as suggested by the difference in elongation ratios.
3. Opaque grains exhibit a smaller apparent elongation in thin sections parallel to bedding than they do in thin sections perpendicular to bedding (fig. 9). Generally, in thin sections parallel to bedding, the longest and the intermediate apparent axes are measured. In thin sections perpendicular to bedding, the longest and the shortest apparent axes are measured.
4. The standard deviation of the measurements in thin sections perpendicular to bedding exceeds that in thin sections parallel to bedding because of the relative degree of apparent preferred orientation in each. The orientation of grains is not as good in thin sections parallel to bedding as it is in thin sections perpendicular to bedding. Hence, more apparent grain shapes are viewed in cross sections than in thin sections parallel to bedding, resulting in a larger deviation from the mean.

Anisotropy in plane parallel to bedding.—The dimensional opaque grain orientations of six samples sectioned parallel to bedding are illustrated in figures 2 and 10, and table 1. Fabric anisotropy exists in each sample, with the degree of preferred orientation exceeding that present in the non-opaque grain fabrics (table 1), as indicated by the large vector magnitudes. Except for sample 5, there is a close grouping from 306° to 354° (table 1). The mean for all samples is 324° with a vector magnitude of 48 percent.

For samples 2 and 3, grain elongation was related to the degree of preferred orientation (fig. 11). In sample 2, the use of a minimum elongation ratio of 2.0 rather than one of 1.5 produces a noticeable increase in degree of preferred orientation. The mean elongation ratio of each interval is plotted versus the midpoint of that interval (fig. 11). Sample 2 forms an ellipse whose major axis parallels the anisotropic fabric. Two dominant orientation directions are suggested by the plot of sample 3, corresponding to data (fig. 5) on the non-opaque grain fabric of the same sample. This kind of grain fabric representation is particularly useful in recognizing secondary, preferred grain orientations.

Comparison of the mean directions shows a 36° difference (fig. 2) between the mean opaque grain fabric and the mean non-opaque grain fabric. Although the non-opaque grain fabric of sample 7 is nearly isotropic, the opaque grain fabric is anisotropic (vector mean, 306°) with a vector magnitude of 25 percent (fig. 10; table 1). Similarly, the opaque fabric of sample 6 shows good orientation at 314°, deviating 62° from its non-opaque fabric (table 1).

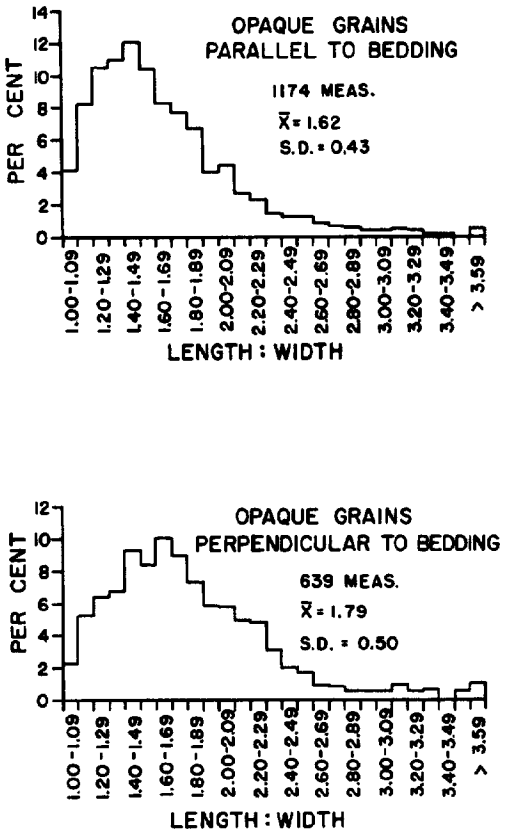

FIG. 9.—Histograms of elongation ratios of opaque grains in thin sections parallel to bedding and perpendicular to bedding.

Orientation in planes perpendicular to bedding.—The inclination of elongate opaque grains corresponds closely with the bedding planes (figs. 6, 7; table 2). There is little imbrication. Samples 3 and 7 have about the same imbrication in both non-opaque and opaque grains in thin sections perpendicular to both bedding and the preferred orientations (table 2). Only sample 2 of the opaque grain measurements is much different from the non-opaque grain measurements (table 2). The vector magnitudes are about the same for all the thin sections (table 2) perpendicular to bedding. Vector magnitudes in all

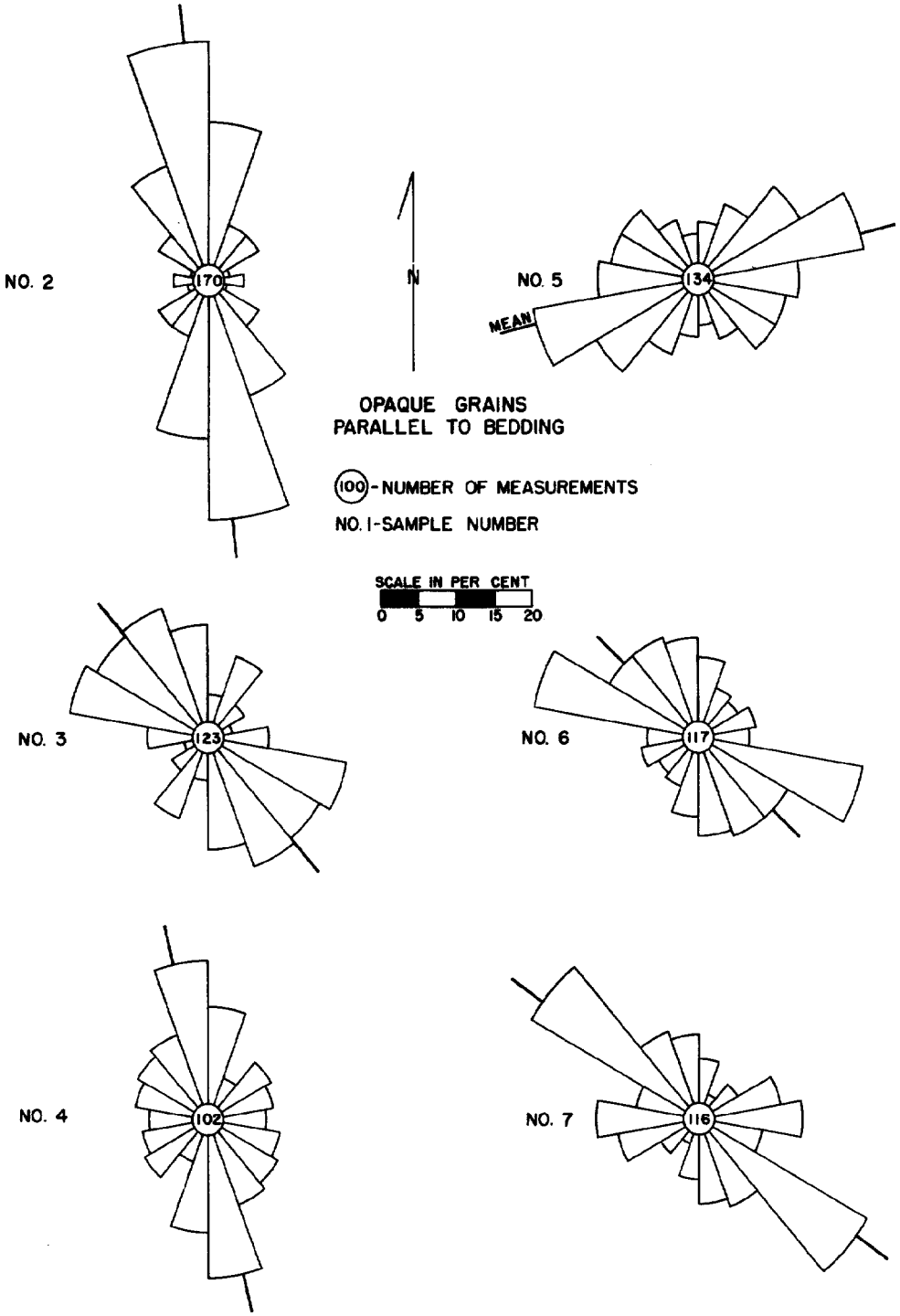

FIG. 10.—Opaque grain fabrics in thin sections parallel to bedding.

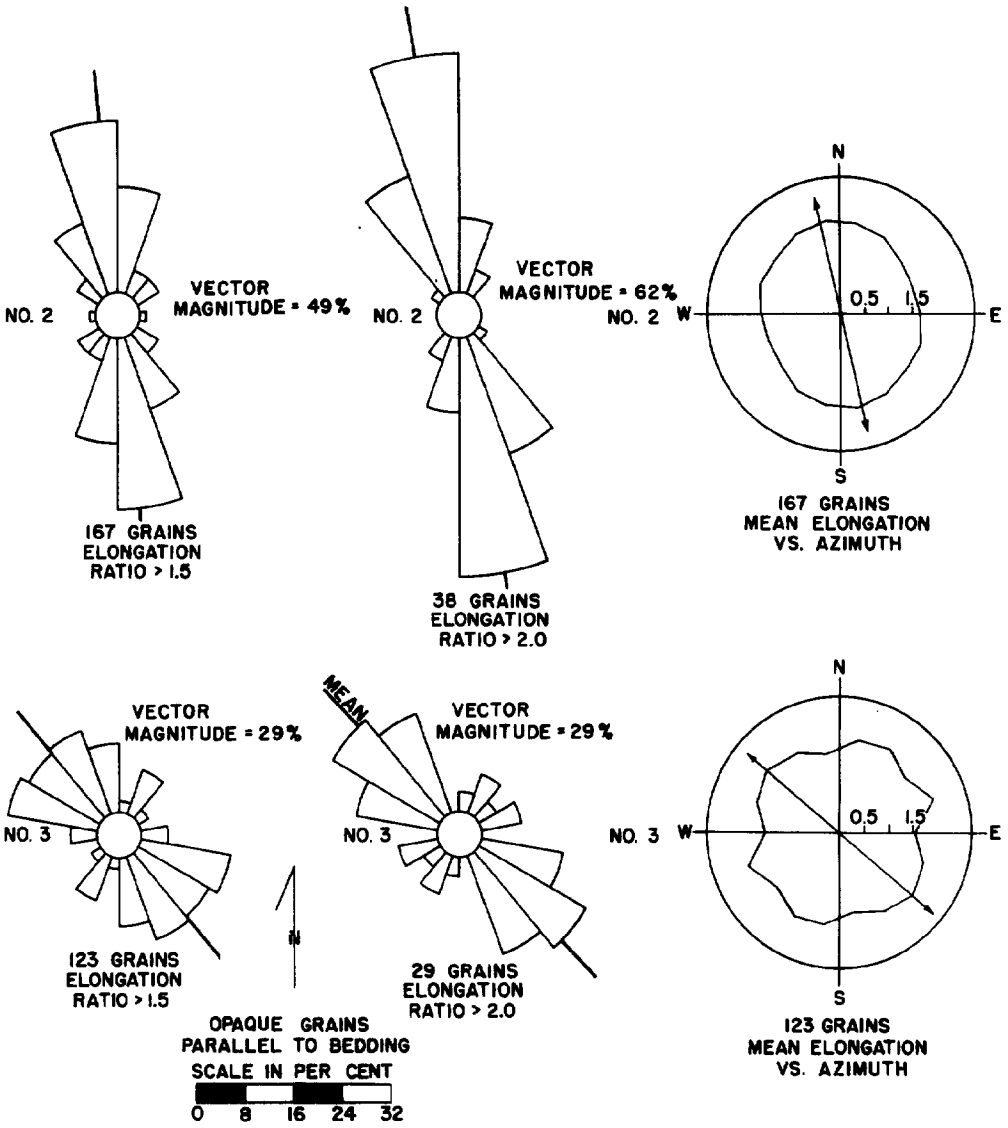

FIG. 11.—Opaque grain fabrics in two samples parallel to bedding. Fabrics of grains with elongation ratios >1.5 and >2.0. Plots of mean elongation versus azimuth included.

samples indicate excellent preferred orientation of opaque grains.

IMPLICATIONS OF FABRIC STUDY TO REMANENT MAGNETISM

The average direction (Fisher mean) of magnetization for the two predominant magnetic directions in the Chugwater Formation is 343° declination (clockwise from 0°), +46° inclination (+below horizontal; lower hemisphere of stereonet) for one group termed *normal*, and 141.5° declination, −31° inclination for a second group termed *reversed* (Picard, 1964, p. 270). The mean (324°; or 144°) for the preferred orientations of the opaque grains (fig. 2) nearly coincides with the declination of the predominant magnetic directions, suggesting that the two are related. The mean for the opaque grains and the mean for the non-opaque grains are 36° apart; the mean for the opaque grains and the mean for ripple mark directions are 57° apart. The correspondence of the vector mean of the disturbed

sample (number 7) with the other samples (table 1), together with its large vector magnitude (25 percent), further supports the interpretation that the declination of the opaque grains was controlled by the magnetic field during deposition. Picard (1964, p. 288–289) believes that the predominant magnetization in the Chugwater Formation is chemical remanent magnetization (CRM) that was induced diagenetically, commencing soon after deposition.

This paper was submitted before an important paper by Rees (1965) on the feasibility of using anisotropy of magnetic susceptibility to estimate sedimentary fabrics in some California localities appeared. Rees (1965, p. 270–271) found: 1. close agreement between preferred orientation determined optically and by maximum susceptibility for Scripps Beach sands; 2. good agreement between current directions from macroscopic features and directions of susceptibility maxima (except for a silt horizon) for Pliocene samples of Santa Paula Creek; and 3. the direction of maximum susceptibility perpendicular to the principal preferred grain orientation and to the current direction in Eocene rocks of Wheeler Canyon. He concluded (p. 271) that, " . . . over a comparatively wide range of conditions the axis of maximum susceptibility lies in very nearly the direction of preferred orientation of grain long axes . . . ," a conclusion not supported by the work reported here.

Apparently further study is needed before magnetic susceptibility can confidently be used to determine preferred grain orientations in siltstones or sandstones. Magnetic, silt-size grains are at least partly controlled by the magnetic field at the time of deposition, as noted here and by Rees (1965, p. 267). Although magnetic susceptibility will be higher in the bedding plane than perpendicular to it, the mean of the maximum susceptibility may be controlled by the magnetic field at the time of deposition rather than by the current system. No simple generalization is possible. A sedimentary rock may have two fabrics: a non-opaque grain fabric imparted by the current system and an opaque (magnetic particle) grain fabric imparted through depositional alignment of magnetic particles in the magnetic field. Further, the final magnetic mean of the rock may represent a resultant imposed during a post-depositional event through chemical or physical changes. Thus it is unlikely that the final magnetic mean and the mean of the non-opaque grain fabric will coincide. The post-depositional history of both magnetic particles and magnetic field must be considered in analyzing the fabric of a sedimentary rock and its remanent magnetic history.

CONCLUSIONS

1. Non-opaque grains of siltstones from the Red Peak Member at north Rawlins are anisotropic in planes parallel to bedding. A summary of the vector means gives a vector "direction" (orientation for northern hemisphere) of 360° (vector magnitude of 31 percent), which correlates with a mean paleocurrent direction of 21° from asymmetric, parallel ripple marks in the interval that contained the fabric samples. Opaque grains are also anisotropic in planes parallel to bedding, yielding a mean direction of 324°. The mean (324°; or 144°) for the preferred orientations of the opaque grains nearly coincides with the mean declination of normal (343°) or reversed (141.5°) magnetic directions in the Chugwater Formation, suggesting that the two are related.

2. A sample with disturbed bedding has a nearly isotropic non-opaque grain fabric parallel to bedding, but an anisotropic (vector mean, 306°) opaque grain fabric. This suggests that there was a post-disturbance re-alignment (or growth?) of the opaque grains, which aligned the magnetic particles parallel to the magnetic field, but did not affect the alignment of the non-opaque grains.

3. The preferred orientation both of non-opaque and opaque grains in planes parallel to bedding is greater if grains with an elongation ratio (length/width) greater than 2.0 are used rather than grains with an elongation ratio greater than 1.5.

4. A plot of the preferred orientation direction versus the mean grain elongation in both non-opaque and opaque grains suggests that in some samples there may be a secondary preferred orientation at right angles to the primary orientation.

5. Imbrication studies of siltstone fabrics of both non-opaque and opaque grains in sections perpendicular to bedding are characterized by only minor inclinations and by less dispersion than in sections aprallel to bedding. No clear pattern of up-current or down-current inclination is apparent from the limited data. Imbrication is apparently less in these Red Peak siltstones than it is in sand-grain and sandstone fabrics studied by others.

6. Elongation ratio data indicate that the opaque grains are not spherical, but elongate, and that they assume a position of stability where the longest and the intermediate axes are parallel to the surface of accumulation.

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