DETRITAL QUARTZ AS AN INDICATOR OF DISTANCE FROM SHORE IN MARINE MUDROCKS

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ABSTRACT: Eighty-nine surface samples and 17 subsurface samples of shale from the Blaine Formation (Permian) in western Oklahoma were examined to determine the variation in percentage of quartz and mean size of quartz with distance from a known shoreline. Samples were fused using sodium bisulfate to release the quartz from the mass of clay minerals.

The surface samples gave areally and statistically meaningful trends; subsurface samples did not do so because of sampling difficulties. The mean percentage of quartz in surface samples decreases from 47 percent at a distance of 60 km from shore (more precisely, the sand-mud line) to 11 percent at 270 km from shore ($r = .70$), a loss of 10 percent quartz with each 60 km increase in distance. Mean grain size decreases from 5.2 at 60 km from shore to 6.9 at 270 km from shore ($r = .71$). Extrapolation of the data indicates that at the sand-mud boundary the percentage of quartz is 57 percent and the mean size of the quartz is between 4.75 and 5.16.

The percentage of quartz in mudrocks can be a useful indicator of the position of the shoreline in ancient fine-grained epicontinental sea deposits.

INTRODUCTION AND PURPOSE

Approximately two-thirds of the stratigraphic column consists of mudrocks, many of which were deposited in the shallow epicontinental seas that covered large parts of the cratons during Phanerozoic time. Typically, these laterally extensive fine-grained rocks appear to be homogeneous throughout the length and width of the depositional basin. No method currently exists to determine either the distance from the shoreline or the contour of the shoreline in such deposits although several methods have been tried.

Most attempts have concentrated on the clay mineral fraction of modern muds, for example, studies of decrease in clay mineral "size" in the offshore direction (Gibbs, 1977); studies of increased boron content in more saline waters (Couch, 1971); and studies of changes in clay mineralogy with increased salinity (Meade, 1972). None of these methods has produced satisfactory results. The best that can be said is that a particular method may work in one area but fail in another area. This result is to be expected for several reasons. Clay minerals are not carried offshore as individual flakes but rather as porous flocs whose diameter and specific gravity are set by their mineral composition, crystal size, and the salinity of the sea water (Krank, 1975). In addition, these flocs are rapidly compacted by a few meters of overburden and lose their identity soon after deposition. With burial to depths of a few thousand meters the clays are recrystallized (Hower et al., 1976) so that the size distribution at the time of deposition is destroyed (Weaver, 1980).

It is clear, therefore, that an attempt to determine distance from shore in an ancient marine mudrock will have to concentrate on the nonclay mineral fraction, the quartz and feldspar. These minerals remain essentially unchanged from the time of deposition, although small amounts of very fine-grained quartz are produced in mudrocks during the diagenetic change from smectite to illite (Yeh and Savin, 1977). It is also possible that some detrital orthoclase and microcline are destroyed during
clay mineral diagenesis to supply potassium for illitization of smectite, although this is still uncertain. In either event, however, feldspars form less than 15 percent of the quartz-plus-feldspar fraction of the average mudrock (Shaw and Weaver, 1965) so that the possible loss of some feldspar during diagenesis is not lethal to the hypothesis we wish to test. The purpose of this study is to determine the gradient of decrease in percentage and grain size of quartz with increasing distance offshore in an ancient marine mudrock.

PREVIOUS STUDIES

Most studies of ancient mudrocks and modern muds emphasize clay mineral composition and areal distribution. Few studies do more than note that quartz (or feldspar) is present. Exceptions to this generalization are the investigations by Devine et al. (1973), Müller and Stoffers (1974), and Kolla and Biscaye (1977). Devine et al. (1973) determined mineral distribution patterns in the surficial muddy sediments of the Gulf of Mexico in water depths greater than 200 m. In the area offshore of the Mississippi River delta they found that the percentage of detrital quartz, on a carbonate-free basis, decreased from a maximum of 43 percent about 80 km offshore in a water depth of 1,000 m to a minimum of 23 percent 300 km offshore at a water depth of 3,500 m. Kolla and Biscaye (1977) determined the distribution of quartz in surficial sediments of the Indian Ocean. They found a decrease in percentage of quartz offshore of the major river systems, the Ganges-Brahmaputra and the Indus, but the gradient of decrease is indeterminate from the large-scale map in their publication. The data of Müller and Stoffers from the Black Sea (1974) also are on too large a scale to be useful to our purposes. There is no published study of the distribution of quartz (± feldspar) with distance from the shoreline in an ancient mudrock.

BLAINE FORMATION (PERMIAN), WESTERN OKLAHOMA

In choosing a suitable mudrock unit for our investigation, we required several criteria to be satisfied. 1) The mudrock must be marine. 2) The stratigraphy of the unit must be well understood. 3) The geologic age of the unit should be precisely known so that all samples can be of penecontemporaneous age. 4) The position of the shoreline must be well established from existing stratigraphic and paleontologic data. 5) The unit must crop out over a wide geographic area to permit adequate sampling. These requirements are satisfied by the Blaine Formation in western Oklahoma.

The Blaine Formation is a redbed sequence of fine-grained clastics and gypsum that crops out in a north-south band for more than 400 km (Fig. 1). Its maximum thickness is 60 m but typically it ranges between 35 m and 40 m. Two persistent beds of gypsum, one in the middle of the formation, the other at the top, divide the Blaine into two parts. The Blaine represents only part of Guadalupian time, certainly less than 15 million years and possibly very much less, but more accurate dating is not now possible. The position of the southern half of the eastern shoreline during the period of Blaine deposition is reliable to within ±20 km and was established using palynomorphs (Clapham, 1970) and information on sedimentary facies from Clifton (1944) and Hills (1942). The shoreline position is speculative in the northern half of the study area because of erosion. The position shown in Figure 2 is simply extrapolated linearly from south to north.

METHOD OF INVESTIGATION

One hundred six samples of shale were collected, 89 from outcrops and 17 from bags of chips recovered from wells in the Anadarko
Basin (Fig. 1) drilled in search of petroleum and natural gas. The stratigraphic position of each outcrop sample was noted in relation to the gypsum bed that divides the Blaine into an upper and lower part. Subsequent laboratory analyses revealed no significant difference in quartz content or grain size between the two parts.

Subsurface samples were taken from well cuttings, the stratigraphic position determined by inspection of electric logs. Because contamination of the sample is possible from other formations higher in the hole, red mud chips that appeared to be from the Blaine were hand-picked from each subsurface sample. Nevertheless, it is likely that contamination was not eliminated completely because the difference in color between the shales in the Blaine and those in the overlying units is small.

A small piece of each sample (approximately 2 gm) was fragmented using a rubber pestle until it passed through a 2.5\(\phi\) sieve. The fragments were divided into equal parts using a riffle splitter, weighed to 0.5 mg, and one part fused using the sodium bisulfate technique described by Blatt and Schultz (1976). The fusion destroys all constituents of the shale except quartz and feldspar and does not affect either the amount or the grain size distribution of these minerals. X-ray diffraction analyses of the fused material were performed from several sites throughout the study area to verify that only quartz and feldspar were present. Comparison of areas under the major X-ray peaks in Blaine Formation samples with areas in artificial standards indicated that the feldspar content of the samples approximates 5 percent in all samples.

The size frequency distribution of the fused, weighed samples was determined using standard sieves at 0.5\(\phi\) intervals down to 4.5\(\phi\) (43 \(\mu\)m) and micromesh sieves for smaller sizes. Micromesh sieves used were 5\(\phi\) (30 \(\mu\)m), 5.6\(\phi\) (20 \(\mu\)m), and 6.6\(\phi\) (10 \(\mu\)m). The sediment finer grained than 10 \(\mu\)m was assumed to have a minimum size of 1 \(\mu\)m so that cumulative frequency curves could be extrapolated to 100 percent. The graphic mean was calculated for each sample using the formulas of Folk and Ward (1957).

**RESULTS AND DISCUSSION**

**Percentage of Quartz**

The areal distribution of quartz percentage (Fig. 2) shows a general parallelism with the published shoreline determined using palynology and sedimentary facies, but the pattern is not as regular as might be wished elsewhere on the map. It seems likely that the bulk of the non-parallelism between the ancient shoreline and contours of quartz percentage results from two factors: 1) imprecision in sampling in the west-central part of the study area (subsurface samples); and 2) the speculative position of the shoreline in the northern part of the area, where erosion has removed the nearshore sediments. In the southern half of the area, the 50 percent through 20 percent contours, which are well established by outcrop samples, seem satisfactory. They bulge systematically in a westerly direction, reflecting the low-lying landmass of the Wichita Mountains during Permian time (Johnson and Denison, 1973). In the center of the map, west of the 30 percent contour, there is a great deal of "noise" in the data, probably because the subsurface samples were all chips carried up from depth by the...
circulating drilling fluid. Apparently our attempt at hand-picking Blaine shale chips from the sample bag of red shale chips collected by the well-site geologist was only partially successful. As noted earlier, the shales stratigraphically above the Blaine differ in color only slightly from Blaine shales. In the northern part of the map area, the data seem to reflect the presence of a marine (deltaic) accumulation of mud or a cratonic shoreline position and orientation different from the one we assumed.

Figure 3 shows the relationship between the percentage of quartz and distance from the shoreline for the surface and for the subsurface samples of Blaine shale. A strong correlation is present between quartz percentage and distance for the surface samples ($r = .70$, $P = .999$), with the percentage of quartz decreasing linearly by 10 percent for each 60 km increase in distance from the shoreline. The regression equation is $Y = -0.17X + 57.13$. The $r$-value of .7 indicates that about 50 percent of the estimated percentage of quartz depends on factors other than distance from shore.

Our surface samples were collected at distances from the shoreline ranging from 60 km to 270 km. Extrapolation of the data indicates that at the shoreline or, more precisely, the sand/mud line the sediment will contain 57 percent quartz and 43 percent clay (including minor amounts of organic matter, hematite, carbonate, and heavy minerals).

Extrapolation of the data in a direction away from the shoreline indicates zero percent of quartz at 336 km (95% confidence limits = ±15 km) offshore. However, there always will be at least a few percent of quartz in marine muds and mudrocks because small amounts of very fine-grained quartz are carried to the sea floor far from shore in lightweight porous clay flocules. In addition, winds blowing seaward will carry small amounts of silt-size quartz into the basin of deposition.

The regression line based on the 17 subsurface samples is poorly defined ($r = .26$) and the percentage of quartz at the shoreline is projected to be only 31 percent. As suspected, based on the map of areal distribution of quartz, the subsurface samples were highly contaminated by fragments of red shale from Permian rocks higher in the stratigraphic section in western Oklahoma.
Mean Grain Size of Quartz

The areal variation in mean grain size of quartz (Fig. 4) shows a pattern very similar to that shown by the percentage of quartz. The effect of the Wichita landmass is quite prominent at the southern end of the map, as is the high level of "noise" in the central area where the position of the contour lines is determined by subsurface samples.

The mean grain size of quartz in the surface samples of Blaine shales decreases linearly with increasing distance from shore (Fig. 5) according to the equation $Y = 0.0081X + 4.75$ and the correlation coefficient of .71 is significant at the .999 level. Extrapolation of the regression line to the shoreline results in a mean grain size of $4.75\mu m$ (37 $\mu m$). This value is a reasonable estimate of the boundary between the traction transport characteristic of sands and the suspensions from which muds are deposited. Davies and Etheridge (1975, p. 249) reported a similar size for a composite sample of the quartz grains in Mississippi delta muds immediately adjacent to the modern shoreline. At a distance of 336 km from the shoreline, the point at which the mean percent of quartz goes to zero (Fig. 3), the mean size of the quartz predicted by Figure 5 is $7.47\mu m$ (5.6 $\mu m$).

The data from the 17 subsurface samples once again form a poorly defined regression line ($r = .25$).

Correlation Between Quartz Percentage and Mean Size

Blatt and Schultz (1976) established that a strong correlation exists between the percentage of quartz in mudrocks and the mean grain size of the quartz. Spears (1980) found that the ratio $TiO_2/Al_2O_3$ in mudrocks increases linearly with increasing percentages of quartz, reflecting the same correlation. The Blaine shales follow the same pattern (Fig. 6) with a correlation coefficient of .72 and a regression line $Y = -15.85X + 124.47$.

At the shoreline the percentage of quartz is 57 percent and, therefore, the mean size of the quartz is 5.1$\mu m$ (from a regression equation with size as the dependent variable). Our data indicate that the best estimate of the mean grain size of quartz at which the mineral should disappear from mudrocks is $7.9\mu m$ (4 $\mu m$) in contrast to the value of $9.1\mu m$ (2 $\mu m$) projected by Blatt and Schultz (1976).

Dispersal Mechanism

The results of this study demonstrate that there exists a strong and geologically useful relationship among the percentage of quartz, the mean size of quartz, and the distance from shore in shales of the Blaine Formation. During Blaine deposition, selective sorting occurred in sizes at least as small as $7.2\mu m$ (7 $\mu m$). Gibbs (1977) has shown that sorting can be effective with grains as small as 1 $\mu m$.

Two types of processes might explain the trends in percentage and size of the quartz grains in the Blaine shales. The first of these is hypopycnal (hypo = less than; pycno = dense) plane jet flow of sediment-laden river water into a salt-water basin, a phenomenon that occurs at the mouths of most large rivers (Bates, 1953; Wright and Coleman, 1974). The muddy fresh water has a lower density than the sea water and is visible as a brownish layer covering the underlying clear sea water.
The horizontal surface between the fresh water and sea water is very stable and little vertical mixing occurs for tens or perhaps hundreds of kilometers outward from the shoreline. Hypopycnal flow would be most effective in a depositional basin lacking strong onshore or longshore surface currents.

The second process that might result in the areal patterns of quartz grains that are present in the Blaine shales is relatively dilute, fine-grained turbidity currents on a submarine sediment cone, possibly generated by debris flows (Hampton, 1972, 1975; McCave, 1972). Debris flows are known to occur on the Mississippi delta and elsewhere (Stuart and Caughey, 1976).

Eolian transport of terrigenous sediment into ocean basins occurs in all parts of the world. However, its effect on the textural relations of shallow marine sediments such as those in the Blaine sea probably is slight. Analyses of eolian dust in the lower atmosphere over the modern oceans by Aston et al. (1973) revealed that quartz comprises only 3–7 percent of the dust. This is much less than the percentage of quartz in the Blaine shales. In addition, Windom (1969) studied atmospheric dust deposited in several permanent snowfields and determined that the mean size of the quartz particles was consistently less than 5 μm. Only a very small percentage of the quartz in the Blaine shales is this small.

CONCLUSIONS

The percentage of quartz and the mean grain size of quartz in surface samples of shales of the Blaine Formation can be used to determine the distance from the shoreline in this study. The results of this study appear to have acceptable precision for geologic purposes as indicated by the following facts.

1) Extrapolation of our data indicates that at the sand-mud line the composition of the sediment is 57 percent quartz and 43 percent clay (Fig. 3) and the mean size of the quartz is 5.1 μm (Fig. 6). These values seem reasonable for sediment at the boundary between traction
DETRITAL QUARTZ DISTANCE INDICATOR

FIG. 6.—Percent quartz versus mean size of quartz in Blaine shales. The regression line of Blatt and Schultz (1976) is shown for comparison.

transport and suspension transport. Extrapolation of the regression line relating mean grain size of quartz to distance (Fig. 5) results in a prediction of 4.75 φ (37 µm) at the sand-mud line, a value substantially the same as the 5.1 φ (29 µm) obtained using the other plots.

2) The areal distribution of both the percentage of quartz and the mean size of quartz accurately reflects the location and extent of the land area of the Wichita Mountains, which was low-lying during deposition of the Blaine shales.

The mechanism that produced the observed relationships between distance from shore and both grain size and percentage of quartz probably is dilute, fine-grained turbidity currents initiated by subaqueous debris flows. The rate of decrease of size and percentage should be related to the slope of the marine depositional surface, and therefore future refinements of the technique we used may permit estimates of the slope of submarine fans in ancient basins.

What are the limitations of this method of estimating shoreline position in ancient basins?

1) The need for either extensive outcrops or precision in subsurface sampling is clear. Because the Blaine Formation is overlain by other red shales we were unable to identify successfully pieces of Blaine Formation among the red shale chips brought up by the drill. In other areas and with other formations, however, this limitation may not be present, for example, in studying a gray shale in a section of red shales.

2) The bisulfate fusion technique becomes inaccurate in proportion to the percentage of very calcic plagioclase in the samples. Although there is no significant loss of potassic and sodic feldspars caused by the fusion, 10–30 percent of plagioclase in the andesine through bytownite compositional range normally is destroyed by the fusion process (unpublished studies in our laboratory). This loss could seriously affect the results of studies in depositional basins along convergent plate margins where calcic feldspars may form a large part of the sediment.

3) In deeply buried mudrocks, such as those of Tertiary age in the Gulf Coast, a considerable percentage of the potassic feldspar in the sediment may be lost during the diagenetic conversion from interlayered smectite/illite to illite. The importance of this effect certainly will vary among basins and its overall importance is still uncertain.

4) During the conversion of smectite/illite to illite, some quartz is produced as a byproduct. Probably this quartz is small in both amount and grain size but precise quantitative data are lacking. A large amount of diagenetic quartz could introduce a great deal of noise into the original depositional trends.

5) It is possible that noise could also be added to the data by storms within the depositional basin, particularly in shallow epeirogenic basins. The high correlation coefficients we obtained in the Blaine Formation, however, suggest that storm effects are not a serious problem. The extensive interbedded gypsum units within the formation indicate that the shales we studied were very shallow-water deposits.

6) Finally, it is possible that local sources
of silt-size quartz might be very restricted in size variation, precluding the use of the technique we used. For example, loess deposits have a restricted size range. In general, however, sources of silt-size quartz are so diverse that all sizes should be present in most drainage basins.

REFERENCES


