Deformation associated with the movement of the Muddy Mountain overthrust in the Buffington window, southeastern Nevada

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ABSTRACT

The Muddy Mountain overthrust, exposed in the Buffington window, southeastern Nevada, consists of a Paleozoic carbonate sheet thrust over Mesozoic Aztec Sandstone, with a molasse filling topographic lows. Evidence suggests that the thrust sheet moved across an erosional surface and that the molasse may have been a forethrust debris. A sharp contact with gouge marks the fault surface. The base of the overthrust sheet is a tectonic breccia containing injections of gouge that are rooted at the contact. Thrust-related changes in the underlying rocks related to proximity of the thrust plane include (1) increase in abundance of microfractures and decrease in grain size due to cataclastic deformation; (2) increase in intensity of macrofracturing parallel and at a low angle to the contact; (3) increase in degree of induration; (4) loss of well-defined bedding planes and color contrast within the Aztec Sandstone; and (5) slabs of dolomite sheared from the upper plate. Laboratory mechanical tests in conjunction with field observations suggest that the shear strength of the undeformed Aztec Sandstone was lower than the frictional strength of the sandstone sliding on quartz gouge. Therefore, cataclastic deformation within a 10- to 100-m-thick zone accompanied the initial advance of the thrust sheet. Following induration, which strengthened the cataclastic sandstone, slip was localized at the thrust contact. During this later stage the high permeability of the fractured upper plate and the Aztec Sandstone suggests that fluid communication with the surface at the leading edge of the thrust was rapid and, therefore, the advance of the thrust could not have been aided by high pore pressure.

INTRODUCTION

A long-standing paradox of overthrust faulting is that the shear stress required to initiate lateral movement far exceeds the laboratory shear strength of the rock, if measured coefficients of friction for rock and lithostatic loads are considered. One solution to the paradox is that abnormally high pore pressure reduces the effective normal stress and thus the critical shear stress for slip at the base of the thrust sheet (Hubbert and Rubey, 1959). This hypothesis requires an impermeable seal to maintain the necessary pore pressure within the fault zone. However, Wilson (1970) has pointed out that the highly fractured wall rock associated with some overthrusts is permeable enough to permit rapid leakage and hence to prevent the build-up of abnormal pore pressure. To account for movement without rupture of the thrust sheet, Wilson has suggested that for the Lewis overthrust in Glacier National Park, Montana, a sheared shale behaved as a material of low shear strength to reduce the sliding friction. Both the Hubbert-Rubey and Wilson hypotheses conform with the Coulomb-Mohr equation that states that slip occurs on a fault when the shear stress on this plane exceeds the sum of the cohesive strength and the product of the coefficient of friction and the effective normal stress. The Hubbert-Rubey hypothesis suggests a mechanism for reducing the effective normal stress, whereas the Wilson hypothesis suggests a way to reduce the coefficient of friction.

We wished to study deformation associated with overthrust faulting where neither shale nor salt was intimately involved as either a pressure seal or lubricant. The Muddy Mountain overthrust in the Muddy Mountains of southeastern Nevada is a fault on which lateral movement occurred without the benefit of either abnormal pore pressure or low internal friction (Figs. 1, 2).

Geologic Setting

A trace of the Muddy Mountain overthrust is found in the midst of the southern Muddy Mountains along the edge of the 13- by 3-km Buffington window (Fig. 3). The mountains consist of an irregular mass of allochthonous Paleozoic carbonate rocks, whereas the window includes autochthonous Mesozoic eolian sandstone and molasse.

The Muddy Mountain overthrust is at the southern end of a belt of imbricated thrust sheets that extend into the Canadian Rockies. In Utah and Nevada, these imbricated thrusts comprise the Late Jurassic through Late Cretaceous Sevier orogenic belt in which thick sections of Paleozoic geosynclinal rocks have been thrust eastward over thinner sections of younger shelf sedimentary rocks (Armstrong, 1968). The Muddy Mountain thrust sheet is imbricated with Dry Lake and Gass Peak thrust sheets (Longwell and others, 1965).

Figure 1. Muddy Mountain overthrust. Dark Paleozoic carbonate thrust sheet moved from west to east (right to left); 50 m of molasse (smooth talus slope) separates thrust sheet from Aztec Sandstone; later faulting tilted this section toward west.

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The Muddy Mountain overthrust may also be exposed in the Spring Mountains, where it is called the Keystone thrust (Longwell, 1960). This Muddy Mountain–Keystone overthrust extends at least 210 km along strike from the Clark Mountains, California, to the Muddy Mountains and is offset by the Las Vegas shear zone. Minimum width of the thrust sheet (distance parallel to movement) is that of the Muddy Mountains, or approximately 24 to 40 km, depending on the assumed direction of movement (Longwell, 1949), but it can be as much as 88 km (Burchfiel and Davis, 1968). Its minimum area is about 3,800 km^2. The youngest formation preserved in the thrust sheet is a Triassic sandstone in the northern area of the Muddy Mountains (Longwell, 1949). Thus, the minimum thickness of the thrust sheet is about 4 to 5 km (2 to 2.5 km of Paleozoic dolomite and limestone overlain by 2 to 2.5 km of Mesozoic sandstone and shale).

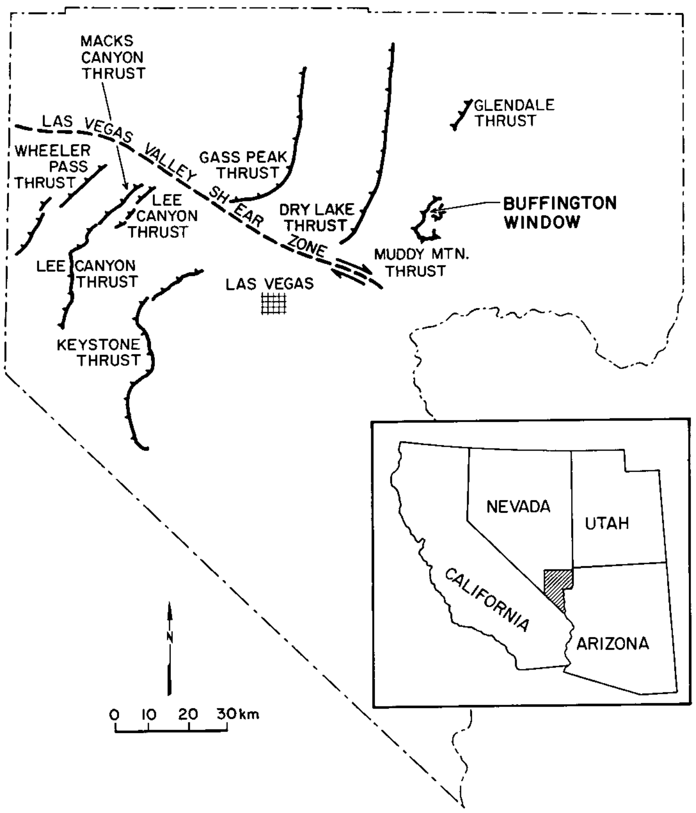

Figure 2. Major overthrust faults in Clark County, Nevada.

Stratigraphy

Three distinct lithologic units are found in the Buffington window: an undifferentiated Paleozoic carbonate, the Aztec Sandstone, and an unnamed fluvial sandstone. The base of the thrust sheet consists almost exclusively of limestone and dolomite, the latter in large part of secondary origin (Longwell, 1949). Longwell suggested that dolomitized limestone near the fault plane has a mottled pattern similar to Middle Cambrian limestones 40 km to the south and, therefore, is likely to be of the same age. Late Cambrian trilobites are found higher in the section.

Below the fault plane is the Jurassic Aztec Sandstone, a medium- to fine-grained quartz arenite with well-rounded and, in large part, frosted grains indicative of an eolian sandstone (Fig. 4, a). Longwell and others (1965) observed that this sandstone commonly has a uniform brick-red color; but in many places, particularly near large faults, bleaching has changed the color to lavender, orange, buff, and whitish gray. Large-scale cross-bedding is common, with sets as much as 7 m thick.

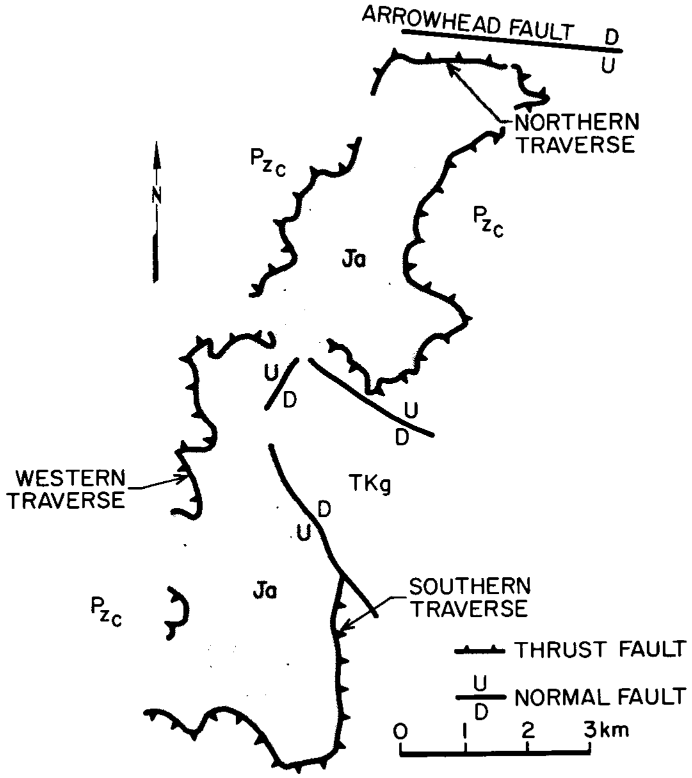

Figure 3. Geology of Buffington window, Muddy Mountains, Nevada. P_{zc} = lower Paleozoic carbonate rocks; J_a = Aztec Sandstone covered with minor amounts of molasse; TK_g = Gale Hills Formation.

In places, the Muddy Mountain thrust has moved over a sandstone that had filled the topographic depressions in an erosional surface that had developed on the Aztec Sandstone. This light-yellowish to tan sandstone is predominantly composed of reworked quartz grains and carbonate fragments (Fig. 4, b). With some exceptions, the grain size of this sandstone is similar to that of the underlying Aztec Sandstone. However, the former is much more poorly sorted and contains more angular grains. In contrast to the eolian Aztec Sandstone, the overlying sandstone contains trough cross-bedding, channel cuts, and graded bedding (Fig. 5). Near the western traverse (Fig. 3), the sandstone contains a massive 10- to 15-m-thick ledge of conglomerate with carbonate clasts as much as 10 cm in diameter. Above the ledge, another conglomerate contains subangular to subrounded carbonate and sandstone clasts, 1 cm in diameter, which are enclosed by a finer-grained sand and carbonate matrix (Fig. 6). In general, this unit overlying the Aztec Sandstone resembles the Baseline Sandstone identified by Longwell (1949) in the northern Muddy Mountains.

The sandstone described here between the Aztec Sandstone and the thrust sheet is similar to Cayeux's (1929) molasse, a poorly rounded, poorly sorted, coarse sand rich in rock fragments. Cayeux suggested that this rock was formed by the rapid erosion of a newly elevated orogenic belt. Because we cannot make a positive correlation with any of Longwell and others' (1965) units, we use the term molasse when referring to the sand deposited on the erosional surface developed in the Aztec Sandstone.

The trough cross-bedding, channel cuts, and graded bedding indicate a fluvial depositional environment for the molasse. Angularity of the clasts in the molasse reflect the proximity of the source rock. One possible interpretation of the molasse is that it is an outwash crossed by intermittently active channels.

The presence of a molasse filling erosional pockets and channels cut in the Aztec Sandstone begs a question concerning the proximity of the overthrust fault plane to the Earth's surface. Elsewhere, geologists have suggested that the Keystone–Muddy Mountain and other overthrust sheets have moved across the Earth's surface. In the Spring Mountains, where the Keystone overthrust in located (Fig. 2), Longwell (1926) observed conglomerate lenses at the base of the Red Spring overthrust sheet and proposed that it had overridden a forethrust debris. Secor (1963) described a similar conglomerate beneath the Keystone overthrust sheet and suggested

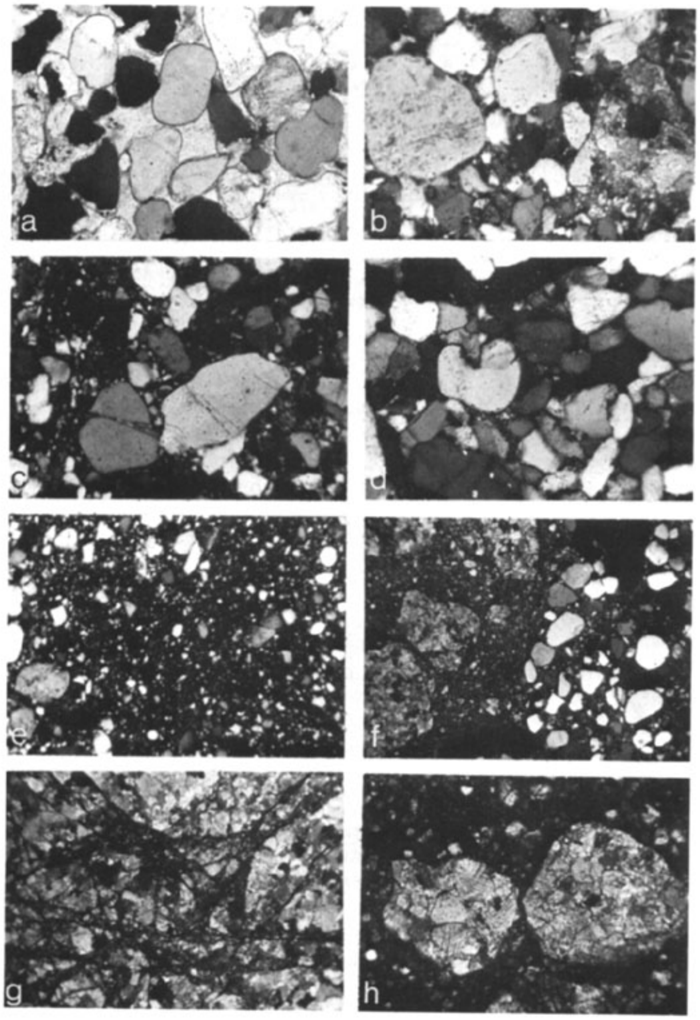

Figure 4. Microphotographs of textures associated with Muddy Mountain overthrust. Width of areas shown in a, b, c, d, e, and h is 1.0 mm. Width of area in f and g is 2.0 mm. a, Aztec Sandstone with single crystal of calcite forming cement between quartz grains. Note small amount of pressure solution in this relatively undeformed sample taken 100 m below overthrust contact. b, Molasse below overthrust contact. Carbonate rock fragment about 0.4 mm in diameter is visible at right. Others are mainly quartz grains with few carbonate fragments. c, Cataclastic Aztec Sandstone sampled 2 m below overthrust contact. Note extensive microfracturing and quartz grain size reduction. d, Indurated Aztec Sandstone with serrated grain boundaries, which are manifestation of pressure solution. e, Quartz fault gouge injected 3 m into overthrust sheet. Sample locality shown in Figure 15. f, Tectonic breccia sampled 3 m above Muddy Mountain overthrust contact. Left side of field of view consists of dolomite fragments; Aztec sand grains are incorporated in breccia in right side of field of view. g, Cataclastically shattered dolomite sampled 5 m above overthrust contact. h, dolomite fault gouge with deformed fragments of dolomite. Deformation manifested by twinning.

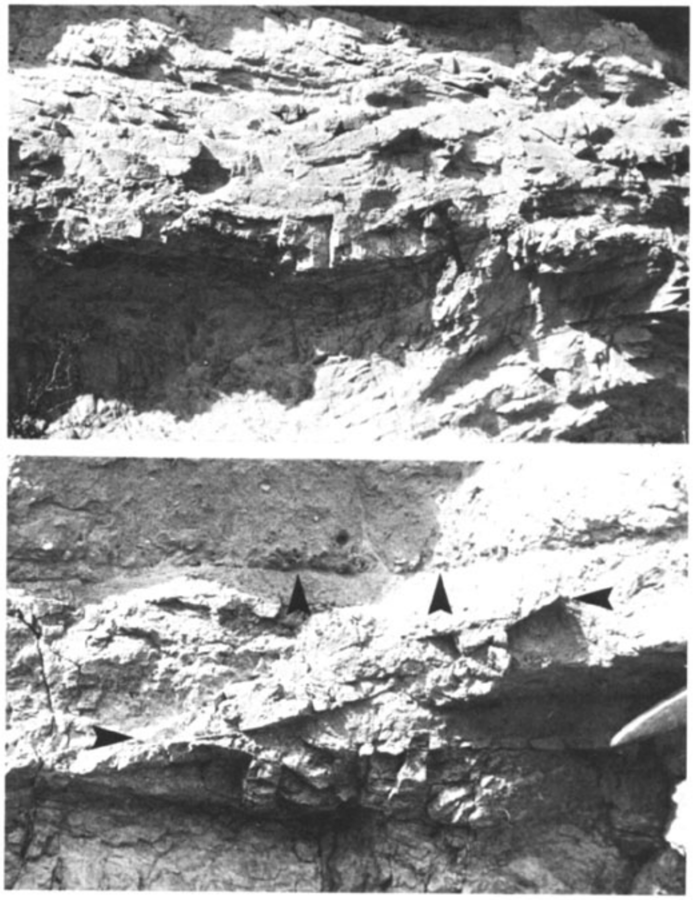

Figure 5. Molasse less than 2 m under Muddy Mountain thrust contact, showing graded cross-bedding (vertical arrows). Wedging is indicated by small amounts of slip along base of cross-beds. Horizontal arrows point to both ends of dolomite slab that has been cut and offset by wedging.

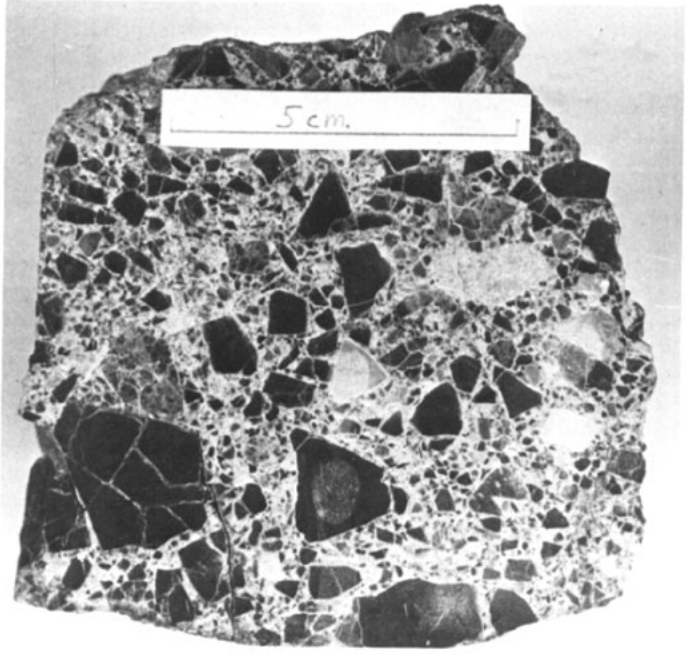

Figure 6. Dolomitic conglomerate. Dark clasts are dolomite; light clasts are sandstone.

that this sheet had also moved across the Earth's surface in the eastern Spring Mountains. Davis (1973) restudied these two conglomerates and corroborated Longwell's interpretation. The strongest evidence for this interpretation is that the conglomerates are stratified. Low in the section the clasts and matrix material appear to be derived from the underlying, autochthonous Mesozoic stratigraphic section. Yet the upper part contains 50% subrounded clasts of carbonate rocks derived from a Cambrian to late Paleozoic sequence present only in the thrust sheets. Davis (1973, p. 3711) said, "The abrupt appearance and striking upward increase in carbonate clasts in the conglomerate beneath the Red Spring thrust [sheet] appear to herald the approach of the thrust plate as it moved across the land surface and over stream channels choked with detritus; detritus derived initially from the surrounding autochthonous Mesozoic terrain and then from the Paleozoic allochthon as well."

As implied by Secor (1963) and Davis (1973), the Keystone–Muddy Mountain overthrust is an erosional thrust distinguished by the presence of an erosional surface — the top of the Aztec Sandstone — and coarse detritus derived from rocks in the overthrust sheet. The main body of the overthrust sheet is envisioned as constant in thickness, with a leading edge composed of a sloping erosional wedge onlapped by forethrust debris.

The fault plane of the Muddy Mountain overthrust sheet contacts the molasse only in places where it has filled erosional depressions. Otherwise, the fault plane contacts the Aztec Sandstone. The same can be said of the Keystone overthrust in the Spring Mountains (Longwell, 1926). The difference between the molasse under the Muddy Mountain sheet and the conglomerate under the Red Spring and Keystone sheets is that the molasse does not grade into a coarse conglomerate with carbonate clasts near the fault plane. The molasse is primarily a quartz sandstone, containing only small amounts of carbonate fragments, with the exception of the few conglomeratic lenses. If the molasse exposed in the Buffington window was indeed deposited at the leading edge of the advancing overthrust sheet, it should be far more dolomitic and also coarser than it is. Apparently the molasse was deposited some distance from the leading edge of the thrust. The lack of coarse carbonate material at the top of the molasse probably indicates that all depositional sinks were filled before the sheet had advanced over the Buffington window area. Any additional coarse material was either deposited elsewhere or pushed along in front of the thrust. Despite the lack of coarse carbonate clasts near the top of the molasse, we are probably correct in calling the molasse a forethrust debris.

DEFORMATION OF OVERTHRUST SHEET

Deformation associated with the advance of the overthrust extends as much as 75 m below and 200 m above the fault plane. By our definition, the fault zone includes all rocks either fractured or otherwise deformed during the faulting. Because of preoccupation with the spectacularly sharp fault plane at the base of overthrust sheets, the deformation of the adjacent rocks during faulting has often been overlooked. Here we first describe the deformation distant from the fault plane to emphasize its importance.

During his original reconnaissance, Longwell (1922) noted brittle deformation of the overthrust sheet manifested by intensely shattered carbonate rock through a thickness of as much as 165 m. In some regions of shattered rock the bedding planes are still visible. There is no visible trend of macrofractures and no apparent increase in fractures conjugate or parallel to the thrust contact as the fault plane is approached from the overthrust sheet. In addition to the shattered carbonate rocks, Longwell (1922) observed a breccia above the base of the thrust, extending into the upper plate. The brecciation is neither confined to nor rooted with the thrust contact, and there is no consistency in the occurrence of brecciation. We found that in places brecciation continues to as much as 200 m from the fault contact; whereas in other places intact carbonate rock with no visible brecciation is found at the fault contact.

Some isolated zones well above the fault contact are collapse breccias; other brecciation is tectonic. The tectonic breccia of the shattered carbonate rock is characterized by red veinlike zones of granulated material, which is cataclastically pulverized dolomite with an appreciable amount of ferruginous material (Fig. 4, g). Often zones of cataclastic dolomite separate large fractured clasts of dolomite. Near the base of the thrust, some pieces of Aztec Sandstone are incorporated into this tectonic breccia (Fig. 4, f).

DEFORMATION OF LOWER PLATE

Several features indicate that a differential stress was transmitted well below the fault contact during the advance of the thrust. Pervasive cataclasis, pressure solution of quartz grains, and extensive macrofracturing all are manifestations of the drag of the massive overthrust sheet (Brock, 1973). In order to study the effect of thrusting, rocks below the fault plane were sampled in detail along three traverses (Fig. 3). Along the northern traverse the Aztec Sandstone is in direct contact with the thrust sheet. In the western and southern traverses the Aztec Sandstone is separated from the fault plane by 34 and 2 m, respectively, of molasse.

Cataclastic Deformation

In a preliminary study, we found that cataclastic deformation of the Aztec Sandstone occurs as much as 75 m below the fault contact (Fig. 4, c). Grain-size reduction by cataclasis is shown by using cumulative frequency curves (Fig. 7) drawn from measurements of maximum apparent diameter of grains in thin sections cut parallel with and normal to the fault plane. Details of this method for generating cumulative frequency curves are given in Engelder (1974a). Undeformed Aztec Sandstone (curve I in Fig. 7) contains well-rounded quartz grains, few of which are less than 100 μm in diameter. Cataclastic fragments are found in the sandstone as much as 75 m from the fault contact (curve II). In this case, the poorer sorting of the finer portion indicates a cataclastic sandstone. Within 1 m of the fault contact, cataclasis pervades the sandstone, as indicated by a well-developed fine-grained matrix (curve III). To document further the nature of cataclasis under the sheet, specimens of Aztec Sandstone were collected at regular intervals on three traverses away from the fault plane (Fig. 3). The specimens were examined in thin sections cut parallel to the fault contact. Cumulative frequency curves, like those presented in Figure 7, were constructed for these three traverses. Figure 8 is a plot of the median grain size from cumulative frequency curves versus distance from the fault plane. Clearly, the grain size of samples taken nearer the fault plane is finer than that of samples from farther away. The

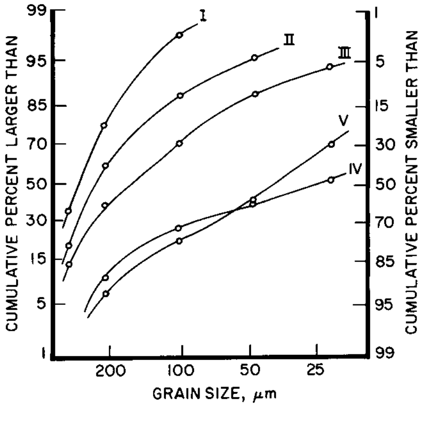

Figure 7. Cumulative frequency curves for Aztec Sandstone in vicinity of Muddy Mountain overthrust. Each curve is based on 300 apparent long axes. Curve I, undeformed Aztec Sandstone; curve II, cataclastic sandstone 75 m below fault contact; curve III, cataclastic sandstone 1 m below fault contact; curve IV, fault gouge injected into upper plate of thrust fault; curve V, fault gouge at fault contact.

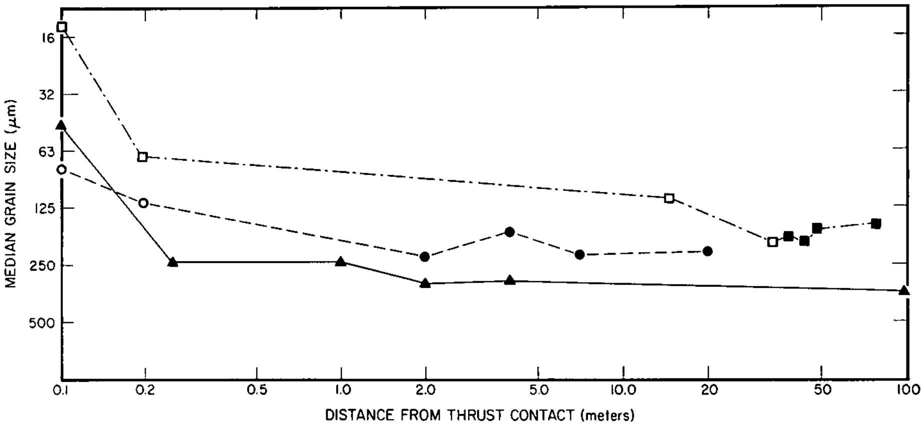

Figure 8. Graphic median grain size versus distances from Muddy Mountain thrust contact. Open symbols = forethrust debris; solid symbols = Aztec Sandstone. Triangles = northern traverse; squares = western traverse; circles = southern traverse.

marked increase in the amount of fine particles indicates an increase in the intensity of cataclasis as the thrust plane is approached. In the northern traverse, where Aztec Sandstone is not separated from the fault plane by molasse, most cataclastic deformation occurs within 4 to 5 m of the plane, and the largest gradient in intensity of cataclasis occurs within the first 20 to 30 cm.

It can be argued, using Figure 8, that there was no significant cataclasis more than 1 m below the thrust plane, primarily because the generation of a small volume of fine particles by cataclasis does not appreciably change the median grain size. A more sensitive plot is the standard deviation of grain sizes. The graphic standard deviation of each grain-size distribution, as computed by the procedure of Folk (1968), is plotted against distance from the thrust contact (Fig. 9). This deviation is a measure of sorting; larger values indicate poorer sorting. Specimens of the forethrust debris from the western and southern traverses are more poorly sorted than are Aztec Sandstone samples at an equivalent distance from the thrust contact. However, regardless of the initial degree of sorting of either formation, deformation by cataclasis during advance of the thrust sheet generated more poorly sorted sandstone. In all three traverses, grain-size deviation increases as the thrust plane is approached. The intensity of cataclasis is roughly proportional to the deviation, although here again the standard deviation is not sensitive to incipient cataclasis occurring as much as 75 m below the fault plane.

The grain-size trend in the western traverse (Fig. 8) indicates that material from the molasse is finer grained as well as more poorly sorted. The Aztec Sandstone has a large standard deviation in grain size because of local fracturing rather than pervasive cataclasis (Fig. 9). In general, the effects of cataclasis rapidly decrease within 10 m of the thrust contact to a level comparable with that of the Aztec Sandstone well away (100 m) from the fault plane.

Further evidence of cataclasis is an increase in the microfracture index as computed by the procedure of Borg and others (1960) and Friedman (1963). The microfracture index is indicative of the relative intensity of cataclasis, as is the cumulative frequency curve. However, very intense cataclasis results in the rupturing of grains along microfractures; therefore, finely comminuted quartz gouge is likely to have a lower fracture index than a cataclastic sandstone.

A plot of the microfracture index versus distance from the thrust contact for the north and south traverses shows a general increase with approach to the contact, the largest increase being 4 to 5 m away (Fig. 10). If the value of 190 to 200 is the level of background microfracturing before thrusting, then the effects of thrusting are not seen at more than 5 to 10 m from the contact. In the western traverse the indices for molasse are relatively low. This may be expected for an aggregate with a smaller median grain size. The higher index in the Aztec Sandstone below the forethrust debris indicates cataclastic deformation related to local fracturing of the sandstone.

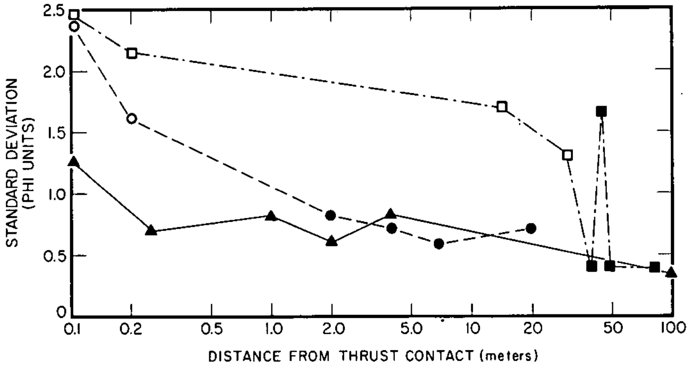

Figure 9. Standard deviation of grain-size distribution versus distance from Muddy Mountain thrust contact. Open symbols = molasse; solid symbols = Aztec Sandstone. Triangles = northern traverse; squares = western traverse; circles = southern traverse.

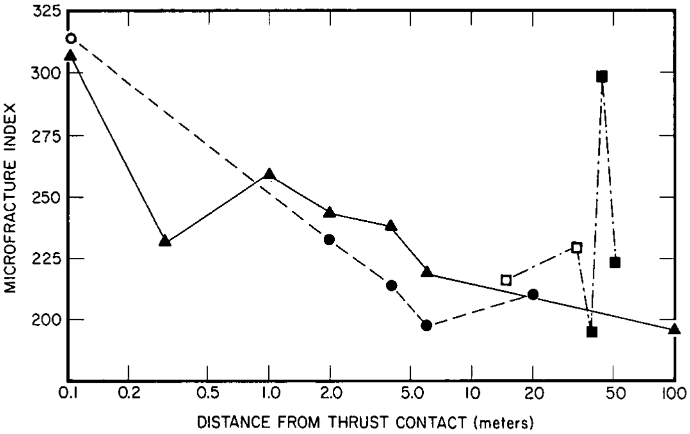

Figure 10. Microfracture index versus distance from Muddy Mountain thrust contact. Open symbols = molasse; solid symbols = Aztec Sandstone. Triangles = northern traverse; squares = western traverse; circles = southern traverse.

Microfracture orientations were measured in three mutually perpendicular thin sections from four sample locations at various disances from the fault contact along the northern traverse. Rotating all data into a common plane reveals that all sample localities contain randomly oriented microfractures, a property expectable in an aggregate undergoing cataclasis that involves rigid-body rotations (Fig. 11).

Another manifestation of cataclasis is the destruction of easily observable bedding planes as the thrust contact is approached. The Aztec Sandstone is composed of cross-bedded units 6 to 8 m thick, plainly visible at least 100 m below the thrust contact. As the fault is approached, bedding planes become obscured first by the elimination of smaller laminae while the major cross-beds are retained and finally by the elimination of any visible traces of bedding. This also results from large cataclastic deformation involving microfracturing and grain rotations. This deformation goes farther into the lower plate than does thrust-related macrofracturing.

Induration and Fracturing

Another striking feature of the Aztec Sandstone near the thrust plane in the northern sector is the increase in induration. Just 100 m below the thrust plane this rock is friable and loosely cemented. Just below, it is more strongly cemented and harder. The thickness of the highly indurated zone varies from 1 to 5 m. In some areas, normally cemented sandstone occurs 10 to 15 m from the fault, but in others induration extends as much as 50 m below the plane. A zone of low-angle, thrust-related fractures is always associated with the highly indurated zone. The degree of fracturing decreases faster than does the degree of induration away from the thrust.

Inspection of the indurated Aztec Sandstone in thin section reveals a larger number of serrated grain boundaries than is found in the more friable facies (Fig. 4, d). This induration is attributed to compaction, with welding together of intact grains and interstitial quartz by pressure solution. No quartz overgrowths or secondary cements are found, so cementation by deposition from circulating pore fluids seems to be ruled out. Likewise, no recrystallization is observed adjacent to the fault contact where frictional heating is expected to be greatest. Induration by pressure solution would be expectable under the great lithostatic load placed on the Aztec Sandstone by the 4- to 5-km-thick thrust sheet.

A plot of the number of fractures per metre versus the distance from the top of the Aztec Sandstone along four traverses shows significant increases as the thrust plane or top of the formation is approached (Fig. 12). Because the plane in which the fracture index is taken is essentially normal to the plane of the thrust, the index is predominantly a measure of fractures oriented parallel to the thrust and at a low angle to the thrust contact. A rapid decrease in the number of fractures occurs within 1 to 2 m from the top of the formation. The zone of highly fractured sandstone is readily observable in the field, especially where Liesegang weathering is associated with it (Fig. 13).

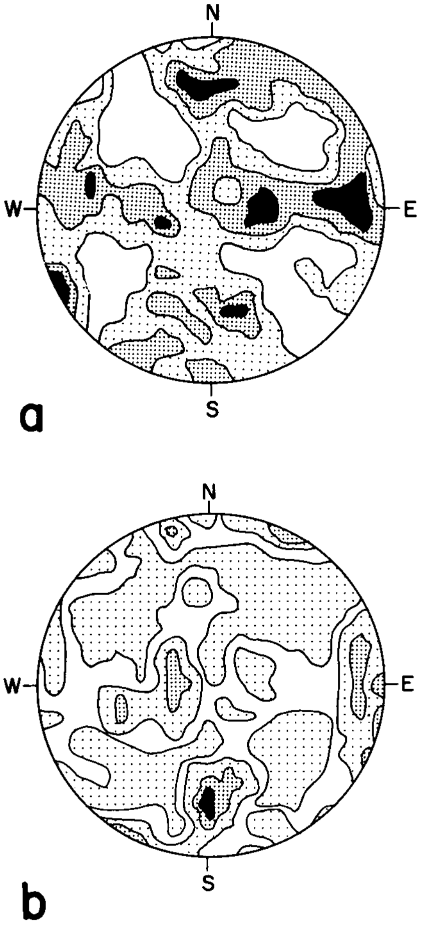

Figure 11. a, Orientation of normals to 202 microfractures from Aztec Sandstone 100 m below Muddy Mountain thrust contact in northern sector. Plane of diagram is a horizontal; data are measured from three mutually perpendicular thin sections and plotted in equal-area lower-hemisphere projection. Contours are at 4% (black area), 3%, and 2% per 1% area; unpatterned area represents zero concentration. Maximum concentration is 4% per 1% area. b, Orientation of normals to 163 microfractures from Aztec Sandstone 1 m below Muddy Mountain thrust contact in northern sector. Plane of diagram is a horizontal; data are measured from three mutually perpendicular thin sections and plotted in equal-area lower-hemisphere projection. Contours are at 5% (black area), 4%, and 2% per 1% area; unpatterned area represents zero concentration. Maximum concentration (8% per 1% area) corresponds to maximum concentration for poles to macrofractures (Fig. 14).

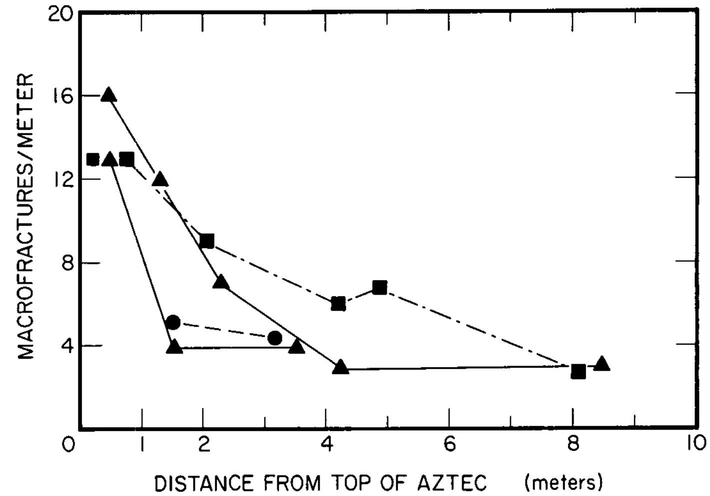

Figure 12. Macrofractures per metre versus distance from top of Aztec Sandstone. Top is thrust contact in northern traverse. In southern and western traverses, top is in contact with forethrust debris. Triangle = northern traverse; square = western traverse; circle = southern traverse.

Figure 13. Thrust-related macrofractures in Aztec Sandstone of northern sector. Area shown is within 2 m of Muddy Mountain thrust contact. Pencil parallels extension fractures; fractures at 30° to pencil are parallel to Muddy Mountain thrust plane. Liesegang weathering patterns are also visible within fractured blocks.

The macrofracture index for the western sector starts at 34 m from the thrust sheet, because molasse separates the Aztec Sandstone from the thrust contact. The high fracture index at approximately 34 m occurs in the Aztec Sandstone just below the contact with the molasse (Fig. 12). This rock has all the characteristics of the formation within 4 to 5 m of the thrust plane as seen in the northern sector. It is a highly indurated and fractured cataclastic sandstone. There are many low-angle fractures and indications of Liesegang weathering. In thin section it also appears identical to the thrust-related cataclastic sandstone in the northern sector. The comparatively higher macrofracture indices for the northern and western sectors, relative to the southern, correlate with the degree of induration. The Aztec Sandstone under the contact in the southern section is quite friable.

Two reasons why these low-angle fractures less than 5 m below the top of the Aztec Sandstone seem related to thrusting are (1) they are statistically parallel and conjugate to the thrust surface (Fig. 14), and (2) later high-angle fractures cut them. For fractures from the northern sector, the concentration is parallel to the major thrust, which here has an average dip of 55°north. The idealized orientations of the associated extension and conjugate shear fracture are shown in Figure 14 with an angle of 30° between the shear and extension fractures. The assumption of the 30° angle is confirmed by a triaxial compression test at 0.5-kb confining pressure on Aztec Sandstone, collected 1 m below the thrust, for which a measured value of 28° was obtained. The sampling procedure for the data in Figure 13 accords the same weight to poorly developed fractures as to well-developed ones. In the field, the dominant low-angle fractures near the thrust fault occur in the position of the shear fracture parallel to the thrust and the extension fracture (Fig. 14). In the western sector the orientation of macrofractures in the molasse and adjacent Aztec Sandstone statistically coincides with the main fault. Macrofractures are concentrated parallel to the thrust.

THRUST CONTACT

Longwell (1922) described the base of the overthrust plate as a smoothly polished breccia. The most striking characteristic of the thrust contact is the planar surface between the upper plate and the fault gouge on which it slid (Stanley and Morse, 1974). A lot of slip seems to have occurred along this nearly planar contact (Fig. 15, a). Local irregularities do occur at the base of the upper plate. Slabs of carbonate as much as 5 m long are partially detached from the overthrust sheet and have fault gouge injected around them. Elsewhere, slabs have been isolated from the upper plate and are now incorporated within the gouge below the very sharp planar contact (Fig. 15, a).

Gouge

Quartz fault gouge consists of less than 30% by volume of fragments larger than 100 μm (Fig. 7). This gouge is generally a yellow-stained aggregate 3 to 30 cm thick, with a granular to foliated texture (Fig. 4, e). When present, dolomite fragments are restricted to the uppermost part of the gouge and are probably late additions that have been plucked from the upper plate (Fig. 4, h). As many as three thin (0.5 to 1 cm), highly foliated gouge layers are dispersed within the more granular material. These foliated layers are shear zones, consisting of extremely comminuted gouge, which reflects internal differential movement as well as relative slip along the upper-plate contact. Occasionally a dolomite gouge is found adjacent to the upper plate.

The mobility of the quartz gouge is demonstrated by its injection upward into cracks of the upper plate (Fig. 15, B). In some places the gouge, which is generated by cataclasis, flows around asperities that are being torn from the upper plate. At other places it appears

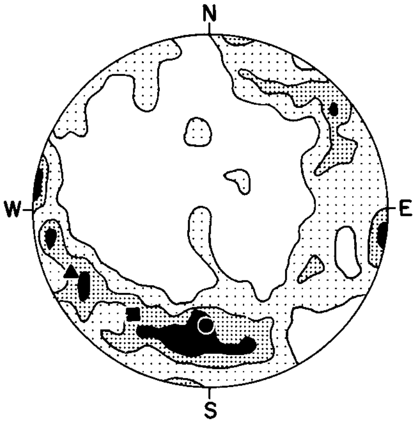

Figure 14. Orientation of normals to 122 macrofractures measured less than 2 m below thrust-fault contact in Aztec Sandstone along northern traverse. Plane of lower-hemisphere projection stereonet diagram is horizontal. Contours are 5% (black area), 3%, and 1% per 1% area. Circle is normal to shear fracture parallel to Muddy Mountain thrust plane (average strike is east, dipping 55° north); square is normal for corresponding extension fracture; and triangle is normal for conjugate shear fracture (assuming angle between conjugate shears is 60°). Maximum concentration (6% for 1% area) is around circle.

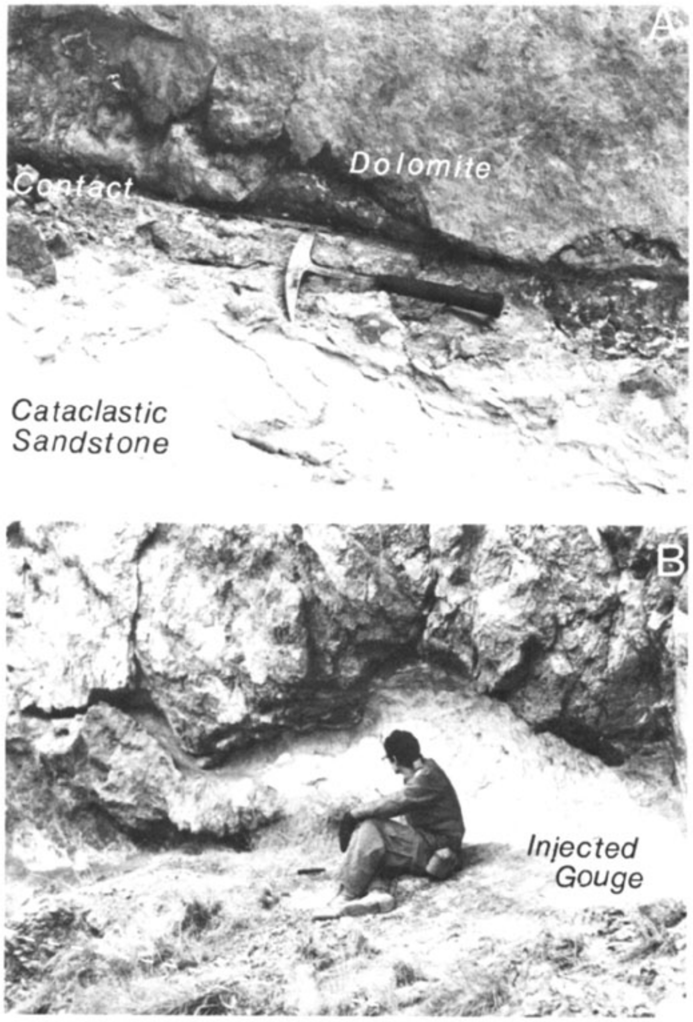

Figure 15. Muddy Mountain overthrust. A, Planar fault contact. Hammer rests on slab of dolomite incorporated below fault contact. B, Quartz fault injected into upper plate; fault contact indicated by dashed line.

to have forced open fractures in the upper plate much as a fluid generates a hydraulic fracture. In all cases the quartz gouge is rooted to the thrust contact.

Gouge from injections is finer grained than gouge along the thrust surface; the injected gouge (Fig. 7, curve IV) contains the largest percentage of fragments of less than 25 μm. Evidently, the movement of gouge from its source favors the concentration of finer fragments because either the injected material is subjected to more cataclastic deformation during movement or the flow process acts as a filter that somehow partially excludes the coarser fractions.

Forethrust Debris near Contact

The intensity of deformation within the molasse less than 2 m from the fault contact is highly variable. At an outcrop in the southern sector, the formation exhibits macroscopic ductility as manifested by boudinage. The boudins are surrounded by clay that may have originated from minor ponding during deposition of the forethrust debris. They are extended in an east-west direction, compatible with the direction of thrusting, and they are bounded top and bottom by shear planes.

Large slabs of dolomite are found in the debris (Fig. 15, A). Those torn from the upper plate have been encased by uncemented molasse that must have flowed during thrusting. Where the debris was macroscopically ductile, large strain completely obliterates all sedimentary features characteristic of the less intensely deformed formation.

In the western sector, molasse with its original sedimentary structure extends to within 20 cm of the thrust contact (Fig. 5). Small dolomite slabs rest on the bottom of individual fluvial cross-beds. During the advance of the thrust, slip has occurred along the base of the cross-beds, as indicated by the offset of shears through the small dolomite slabs. Often the shear offset of the small slabs is in the opposite direction to the overall movement of the thrust plate. This type of bedding-plane slip, called thrust wedging by Geiser (1970), is a mechanism for adjusting the thickness of a section during faulting or folding. Despite the large drag exerted by the thrust plate on parts of the Aztec Sandstone and molasse, there are locations under the base of the thrust where the drag was relatively small.

LABORATORY TESTS

Standard triaxial-compression and sliding-friction tests were conducted to characterize the strength and frictional properties of the quartzose rocks associated with the Muddy Mountain thrust. Three 2.5- by 5-cm specimens each tested for strength include (1) a friable sample of Navajo Sandstone stratigraphically equivalent to the Aztec Sandstone, found 100 m from the thrust contact (no sample of friable Aztec Sandstone large enough to core an appropriately sized specimen was available); (2) a sample of cataclastic Aztec Sandstone with a high degree of induration caused by the effects of pressure solution, collected 1 m from the thrust contact in the northern sector; and (3) an indurated sample of forethrust debris, collected 30 m below the thrust contact in the western sector. All were tested at a confining pressure of 0.5 kb, room temperature, a constant strain rate of 10^{-4}/s, and full water saturation by loading parallel to bedding. The confining pressure is equivalent to the effective pressure under the 4- to 5-km-thick thrust plate. Strain rate is arbitrary. A temperature of 150 °C (30 °C/km of depth) at the base of the thrust sheet is assumed. Because Handin and Hager (1958) showed that the ultimate strength and ductility of a quartz sandstone are not greatly affected by temperatures as high as 300 °C, a room-temperature experiment should adequately simulate the natural environment.

The stress-strain curves indicate that under the same conditions, there are large variations in the mechanical behavior of the three major constituents of the lower thrust plate (Fig. 16). There is an eightfold to tenfold increase in the ultimate strength with induration, and at least a fivefold to sixfold decrease in ductility. The indurated Aztec Sandstone and the forethrust debris both fail on throughgoing shear fractures. The Navajo Sandstone test was stopped at 6.6% shortening with no fracture or well-defined fault zone.

To understand the mechanical significance of rock sliding on quartz fault gouge, cylinders with a quartz sand distributed along a sawcut at 35° to the compression axes were shortened in triaxial compression (Engelder, 1974b; Engelder and others, 1975). At least three types of experiments are significant to any discussion of overthrust mechanics: (1) sandstone sliding on itself, (2) sandstone with an irregular surface sliding on a discrete layer of quartz gouge, and (3) sandstone with a uniform polished surface sliding on quartz gouge. Tennessee Sandstone or Coconino sandstone were used; all were tested dry at room temperatures, with a sliding-displacement rate of 1×10^{-3} cm/s. The kinetic coefficients of friction μ_k for each series of tests are plotted as a function of normal stress (Fig. 17). The presence of quartz gouge along the sliding surface profoundly

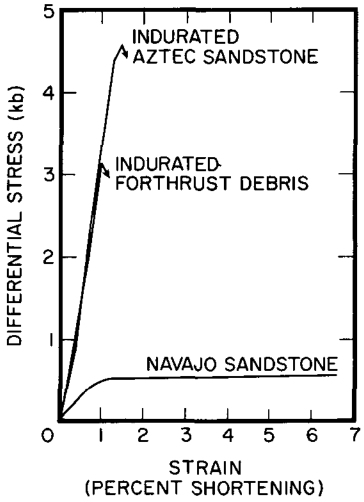

Figure 16. Differential stress (in kilobars) versus strain (percentage shortening) for specimen of indurated Aztec Sandstone, indurated forethrust debris, and Navajo Sandstone. All specimens were deformed at 0.5-kb confining pressure, 25 °C, constant strain rate of 10^{-4}/s, water saturated, and loaded parallel to bedding.

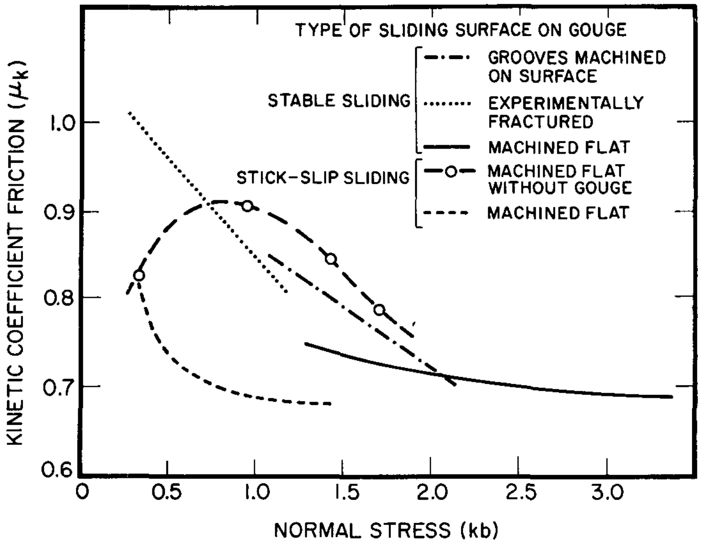

Figure 17. Effect of surface morphology on kinetic coefficient of friction versus normal stress for sandstone slid at 10^{-3} cm/s. Experimentally fractured surfaces are Coconino Sandstone. All other surfaces are Tennessee Sandstone.

lowers the frictional resistance to slip. In addition, we observe a greater resistance to slip on a sandstone surface with irregularities in gouge than on a smooth surface on gouge. At less than 1.5-kb normal stress, stick-slip occurs on a smooth surface on quartz gouge, whereas the irregular surface always slides stably. When stick-slip occurs for sandstone on gouge, the slip occurs along the contact rather than along slip planes within the gouge. The irregular surface prevents a discrete sliding surface from forming, and therefore, impedes stick-slip.

DISCUSSION

Overthrust Sheet Moving on Earth's Surface

As the Muddy Mountain overthrust moved across the Buffington window area, it appears to have slid from peak to peak of an erosional surface on Aztec Sandstone. This erosional surface was choked with a molasse consisting in large part of detritus from the autochthonous Mesozoic terrain but occasionally including a conglomerate with carbonate clasts derived from the advancing overthrust sheet. In the Buffington window the thrust sheet seems not to have passed over conglomerates spilling directly from its leading edge, because none were found at the contact between the molasse and the thrust sheet.

That the thrust sheet was moving horizontally over an "erosional" surface rather than cutting up through the molasse debris as a high-angle imbricate is indicated by both the position of the valley bottoms on the erosional surface and the bedding planes of the molasse relative to the overthrust plane. Figure 1 shows about 50 m of molasse between the Aztec Sandstone and the overthrust sheet. The contact between the molasse and erosional surface on the Aztec Sandstone is parallel to the overthrust fault plane. Post-thrusting tectonics has tilted this section toward the west. The bottom of the trough cross-bedding in the molasse shown in Figure 5 is also parallel to the fault plane. If the overthrust sheet cut through the molasse at some unknown depth, it cut in a horizontal plane parallel to bedding. This latter interpretation requires that the overthrust sheet push a great deal of molasse much like a snow plow. We prefer the conclusion reached by Longwell (1926), Secor (1963), and Davis (1973), that the Keystone–Muddy Mountain overthurst sheet moved across the Earth's surface.

Permeability and Gouge Injections

The idea that high pore pressure aids overthrust faulting, as proposed by Hubbert and Rubey (1959), does not apply to the Muddy Mountain overthrust. All evidence indicates high permeability of the fault zone during the advance of the upper plate, and there is no compelling evidence for the long-term development of an abnormally high pore pressure. The severely fractured and brecciated upper plate, the very porous Aztec Sandstone, and molasse are all highly permeable rocks. High ground-water circulation is also indicated by the strong leaching of ferruginous cement from the Aztec Sandstone below the fault contact and the redeposition of this ferruginous material in breccia dikes of the upper plate.

A fault moving across an erosional surface emerges at an air-rock interface where an abnormal pore pressure could not exist. The high permeability of the fault zone suggests that there was probably good communication of water between points along the fault well back from the air-rock interface and the leading edge of the fault. The normal hydrostatic pore pressure was about 500 b under 4 to 5 km of overburden. The pore pressure along that part of the fault that has not climbed across the stratigraphic section cannot be estimated.

Evidence for transient abnormal pore pressures depends on the interpretation of sand-gouge injections into the upper plate and on the inferred mode of slip of the fault. If the upper plate advanced by stick-slip, the instantaneous rate of slip would be high, perhaps as much as 20 cm/s (Johnson and others, 1973). Conceivably, the rupture of the sliding surface preceding slip could load the 3- to 30-cm-thick layer of gouge rapidly enough to cause a collapse of pore space that would result in sudden increase in pore pressure along the gouge zone. If this gouge-zone pore pressure were high enough, hydraulic fracturing of the upper plate might occur. The hydraulic fracture would immediately be filled with a gouge slurry and propped open in much the same manner as the gouge-filled fractures seen along the base of the upper plate of the Muddy Mountain thrust.

If, on the other hand, the thrust moved by stable sliding, sand-gouge injections would be a passive response to the opening of fractures at the base of the upper plate. Presumably, high local stresses might hold open fractures long enough for a gouge slurry to migrate into the void along the open fracture.

Data from the cumulative frequency curves indicate the passive injection of fault gouge. Gouge injected into the upper plate is finer grained than gouge along the fault plane (Fig. 7). Essentially, a slow injection upward may permit time for larger particles to settle or be left behind at the fault plane. Such sorting of fine gouge would not occur during a rapid injection by hydraulic fracturing.

Cataclasis and Friction

Deformation of the autochthonous Mesozoic clastic rocks appears to have changed during the advance of the thrust sheet. Initially, cataclasis pervaded a zone as much as 75 m from the fault plane, thus distributing shear strain due to the drag of the thrust sheet. Induration and fracture of the cataclastic sandstone appears to follow cataclasis. Upon induration, most shear strain is restricted to gouge within a few centimetres of the major slip surface. Neither the absolute duration of each deformational stage nor the amount of slip is known.

As the thrust sheet moved, high stresses must have existed beneath it in the undeformed Aztec sandstone and molasse. The magnitude of the stresses resulting from the drag of the thrust sheet may be estimated from experimental data. Although the loading history must have been complicated, we assume for simplicity that the autochthon was instantaneously subjected to an overburden of about 5 km, resulting in a 0.5-kb effective normal stress across the potential sliding surface. Experiments indicate that a shear stress of more than 300 b is necessary for the slip of carbonate on sandstone at 0.5-kb normal stress (Logan and others, 1973), and a shear stress of at least 300 b is necessary for slip on quartz fault gouge (Fig. 17). This stress is not high enough to cause brittle faulting of an indurated sandstone (Handin and Hager, 1958), but it will cause macroscopically ductile flow in a poorly cemented sandstone (Fig. 16) or a sand aggregate (Borg and others, 1960). Macroscopic ductility is the manifestation of cataclastic deformation in a sandstone (Stearns, 1968). Because the Aztec Sandstone below the thrust has been deformed by pervasive cataclasis, we conclude that its shear strength at the onset of faulting was less than the strength of the initial slip surface below the thrust sheet. Initially, shear strain accompanying the slip was distributed over a 75-m-thick zone rather than concentrated along a discrete fault plane. Upon induration, the shear strength of the gouge at the fault plane is lower than the indurated sandstone. Subsequent slip is restricted to the fault plane, with deformation below the fault plane being restricted to shear fracturing.

Although the drag on the Aztec Sandstone was high enough to cause incipient cataclasis as much as 75 m below the fault contact, there are outcrops of molasse just below the fault contact in which there can have been little internal deformation, as indicated by undeformed primary sedimentary structures. We suggest that the weight of the thrust sheet caused enough compaction of the fore-thrust debris that a major part of the overburden weight was carried by the topographic highs of cemented Aztec Sandstone, which are less compactible. The effect of compaction may have reduced normal stress concentrations and, therefore, the high shear stress on the molasse. However, the presence of wedging indicates that the molasse absorbed a certain amount of shear strain (Fig. 5).

Haphazard brecciation of the upper plate may have resulted from local bending. The upper plate may have been contorted locally either at points where it climbed stratigraphically or over areas where forethrust debris had compacted and left the upper plate supported by topographic highs.

The base of overthrusts in general and the Muddy Mountain overthrust in particular have planar surfaces along which most slip has occurred. It seems intuitively obvious that faults develop as sharp planar contacts, because such sliding surfaces offer the path of least frictional resistance. Laboratory sliding-friction tests confirm this notion; friction for sliding of a surface with teeth or large asperities on gouge is as much as 30% greater than for sliding of a smooth surface on gouge (Fig. 15). One mechanism of achieving a smooth fault contact is the shearing off of asperities on the sliding surface. Numerous such sheared asperities exist along the contact of the Muddy Mountain thrust (Fig. 15).

Laboratory tests for slip of a smooth sandstone on fault gouge show that either stick-slip or stable sliding occurs. Stable sliding is accompanied by a pervasive shear within the gouge. In contrast, stick-slip occurs when slip follows a plane between the gouge and wall rock (Engelder and others, 1975). There are many places where the Muddy Mountain thrust surface is a single plane, suggesting that stick-slip may have been the mode of sliding during at least part of the thrust fault's history. Gretener (1972) and Price (1973) have suggested that movement on a large thrust fault may be irregular; different parts of the fault slip over small increments at different points in time. To date, however, there is no evidence that large overthrusts move by stick-slip to release seismic energy (Elliott, 1976).

Induration

Induration of the Aztec Sandstone must have been contemporaneous with thrusting, because there is evidence for deformation in it both preceding and following induration. The Aztec Sandstone was cataclastically deformed prior to induration, as indicated by the reduction in grain size. The indurated sandstone is cut by thrust-related macrofractures, which can be related to drag of the advancing thrust sheet after induration.

A significant characteristic of the indurated sandstone is its serrated grain boudaries (Fig. 4, d). More occur in several samples close to the thrust than in those in undisturbed Aztec Sandstone at greater distances from the thrust. The serrated grain boundaries are the result of compaction and welding by tectonically induced pressure solution, as has been shown experimentally (Sprunt, 1975).

The higher microfracture index from the northern traverse (Fig. 10) and the finer grain size distributions from the southern traverse (Fig. 8) are compatible with the relative degree of induration in the rocks of both sections. The Aztec Sandstone under the northern section of the Muddy Mountain thrust is more highly indurated than under the southern section. The greater degree of induration of rocks in the northern section inhibited cataclasis beneath the thrust there; thus, large microfractured grains were protected and did not break apart because of further rigid-body rotation. On the other hand, lack of induration allowed cataclasis to progress further during later stages of the thrusting in the southern section. The result was a finer-grained cataclastic sandstone produced by the rupturing of microfractured grains. In addition, the more ductile and less indurated rocks in the southern section sustained fewer macrofractures per metre during thrusting (Fig. 12).

CONCLUSIONS

The Muddy Mountain fault is an example of overthrusting aided by neither a steady-state, abnormal pore pressure nor a low coefficient of friction due to salt or shale at its base. The high coefficient of friction ($\mu_k = 0.7$) and low ultimate strength (500 b) of Aztec sandstone resulted in an initial advance on a zone sheared by pervasive cataclasis. Eventually, induration by pressure solution strengthened the sandstone below the fault contact enough so that slip was restricted to a discrete surface. High friction along the fault contact and lack of abnormal pore pressure suggest that this fault of great width (40 km) must have been pushed down a pre-existing slope.

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REFERENCES CITED

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: Geol. Soc. America Bull., v. 79, p. 429–458.

Borg, I., Friedman, M., Handin, J., and Higgs, D. V., 1960, Experimental deformation of St. Peter sand: A study of cataclastic flow, *in* Griggs, D., and Handin, J., eds., Rock deformation: Geol. Soc. America Mem. 79, p. 133–191.

Brock, W. G., 1973, Characterization of the Muddy Mountain–Keystone thrust contact and related deformation [M.S. thesis]: College Station, Texas A & M Univ., 179 p.

Burchfiel, B. C., and Davis, G. A., 1968, Source terrain of the Keystone thrust plate, southern Nevada and southeastern California: Geol. Soc. America Program with Abstracts, Ann. Mtg. p. 41–42.

Cayeux, L., 1929, Les roches sédimentaires de France — Roches siliceuses: Paris, Imprimerie Nationale, 774 p.

Davis, G. A., 1973, Relations between the Keystone and Red Spring thrust faults, eastern Spring Mountains, Nevada: Geol. Soc. America Bull., v. 84, p. 3709–3716.

Elliott, D., 1976, The motion of thrust sheets: Jour. Geophys. Research, v. 81, p. 949–963.

Engelder, T., 1974a, Cataclasis and the generation of fault gouge: Geol. Soc. America Bull., v. 85, p. 1515–1522.

——1974b, Coefficients of friction and their values for sandstone sliding on quartz gouge: Internat. Soc. Rock Mechanics Cong., 3rd, Denver 1974, v. II, p. 499–504.

Engelder, T., Logan, J. M., and Handin, J., 1975, The sliding characteristics of sandstone on quartz fault-gouge: Pure and Appl. Geophysics, v. 113, p. 68–86.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's, 170 p.

Friedman, M., 1963, Petrofabric analysis of experimentally deformed calcite-cemented sandstones: Jour. Geology, v. 71, p. 1–37.

Geiser, P. A., 1970, Deformation of the Bloomsburg Formation, Cacapon Mountain anticline, Hancock, Maryland [Ph.D. dissert.]: Baltimore, Johns Hopkins Univ., 128 p.

Gretener, P. E., 1972, Thoughts on overthrust faulting in a layered sequence: Bull. Canadian Petroleum Geology, v. 20, p. 583–607.

Handin, J., and Hager, R. V., Jr., 1958, Experimental deformation of sedimentary rocks under confining pressure: Tests at high temperature: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 2892–2934.

Hubbert, M. K., and Rubey, W. W., 1959, Role of fluid pressure in mechanics of overthrust faulting: I, Mechanics of fluid-filled porous solids and its application to overthrust faulting: Geol. Soc. America Bull., v. 70, p. 115–166.

Johnson, T., Wu, F., and Scholz, C., 1973, Source parameters for stick-slip and for earthquakes: Science, v. 179, p. 278–280.

Logan, J. M., Iwasaki, T., Friedman, M., and Kling, S. A., 1973, Experimental investigation of sliding friction in multilithologic specimens, *in* Pincus, H., ed., Geological factors in rapid excavation: Geol. Soc. America Engineering Geology Case History 9, p. 55–67.

Longwell, C. R., 1922, Muddy Mountain overthrust in southeastern Nevada: Jour. Geology, v. 30, p. 63–72.

——1926, Structural studies in southern Nevada and western Arizona: Geol. Soc. America Bull., v. 37, p. 551–584.

——1949, Structure of the northern Muddy Mountain area, Nevada: Geol. Soc. America Bull., v. 60, p. 923–967.

——1960, Possible explanation of diverse structural patterns in southern Nevada: Am. Jour. Sci., v. 258-A, p. 192–203.

Longwell, C. R., Pampeyan, E. H., Bowyer, B., and Roberts, R. J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bur. Mines Bull. 62, 218 p.

Price, R. A., 1973, The mechanical paradox of large overthrusts: Geol. Soc. America Abs. with Programs, v. 5, p. 772.

Secor, D. R., 1963, Geology of the central Spring Mountains, Nevada [Ph.D. dissert.]: Stanford, Calif., Stanford Univ., 152 p.

Sprunt, E. S., 1975, Pressure solution and stress solution of quartz: EOS (Am. Geophys. Union Trans.), v. 56, p. 1062.

Stanley, R. S., and Morse, J. D., 1974, Fault zone characteristics of two well-exposed overthrusts: The Muddy Mountain thrust, Nevada, and the Champlain thrust at Burlington, Vermont: Geol. Soc. America Abs. with Programs, v. 5, p. 78.

Stearns, D. W., 1968, Fracture as a mechanism of flow in naturally deformed rocks: Canada Geol. Survey Paper 68-52, p. 79–96.

Wilson, R. C., Jr., 1970, The mechanical properties of the shear zone of the Lewis overthrust, Glacier National Park, Montana [Ph.D. dissert.]: College Station, Texas A & M Univ., 89 p.

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