Structural setting of Teton Pass with emphasis on fault breccia associated with the Jackson thrust fault, Wyoming
by Ann Marlene Vasko

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:

The Jackson thrust fault, exposed on Teton Pass, Wyoming, consists of Cambrian Gallatin Limestone thrust over the Cretaceous Bear River Formation. The Jackson fault is a Late Paleocene, thin-skinned, listric thrust fault that forms the main frontal fault of the foreland fold and thrust belt. The Cache Creek thrust sheet overrode the Jackson thrust sheet from the northeast overturning the Jackson thrust fault to the southwest.

The fault zone of the Jackson thrust fault is defined by a severely deformed cataclastic zone approximately nine meters wide. Thrust- ' related changes in the hanging wall rock (Gallatin Limestone) are: (1) a severely brecciated zone 0-4 m from the fault plane, (2) a relatively less brecciated zone 4-9 m from the fault plane, (3) a decrease in grain size of breccia fragments as the fault plane is approached, (4) an increase in the degree of sorting of breccia fragments nearer the fault plane, and (5) a loss of well defined bedding planes. Movement along the Jackson thrust fault is interpreted to have been aided by (1) loss of cohesion between hanging wall rock and footwall rock units, (2) decrease in normal stress due to pore fluid pressure, and (3) de-' crease in frictional resistance to slip due to the presence of breccia fragments between the hanging wall and footwall blocks.

STRUCTURAL SETTING OF TETON PASS WITH EMPHASIS ON FAULT BRECCIA ASSOCIATED WITH THE JACKSON THRUST FAULT, WYOMING

by

Ann Marlene Vasko

A thesis submitted in partial fulfillment
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Ann Marlene Vasko

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

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The fault zone of the Jackson thrust fault is defined by a severely deformed cataclastic zone approximately nine meters wide. Thrust-related changes in the hanging wall rock (Gallatin Limestone) are: (1) a severely brecciated zone 0-4 m from the fault plane, (2) a relatively less brecciated zone 4-9 m from the fault plane, (3) a decrease in grain size of breccia fragments as the fault plane is approached, (4) an increase in the degree of sorting of breccia fragments nearer the fault plane, and (5) a loss of well defined bedding planes. Movement along the Jackson thrust fault is interpreted to have been aided by (1) loss of cohesion between hanging wall rock and footwall rock units, (2) decrease in normal stress due to pore fluid pressure, and (3) decrease in frictional resistance to slip due to the presence of breccia fragments between the hanging wall and footwall blocks.

INTRODUCTION

This thesis addresses the deformational mechanism of fault zone cataclasis associated with the Jackson thrust fault, western Wyoming. The objectives are: (1) to investigate cataclastic deformation along the Jackson thrust fault by documentation of the fabric and texture of the cataclastic zone, and (2) to evaluate cataclastic deformation as it relates to the mechanics of thrust faulting.

The long-standing paradox of thrust faulting is that the shear stress required to initiate lateral movement far exceeds the laboratory shear strength of the rock. Smoluchowski (1909) calculated the force necessary to push a 200 km long thrust plate along a horizontal surface to be seven times the crushing strength of granite at the ground surface. Breccia, resulting from cataclasis, is a deformational product commonly associated with thrust faulting, and is a friction-dependent mechanism of brittle deformation involving both fracture and rigid-body rotation (Borg and others, 1960) at low pressures and temperatures (Higgins, 1971). By studying cataclastic deformation along thrust faults, the dynamics of thrust faulting may be better understood.

The first half of this thesis is an introduction and brief review of the contemporary views on the structure and tectonic history of the Idaho-Wyoming foreland fold and thrust belt. This portion of the thesis is designed to familiarize the reader with the study area, and serves to set up a few premises that are used in the latter half of the thesis.

Study Area

The phenomenon of cataclasis was studied in the hanging wall block of the Jackson thrust fault in western Wyoming (Fig. 1). This fault extends from the northwestern Idaho-Wyoming boundary, south into west-central Wyoming, where it becomes known as the Prospect thrust, and continues southward into southwest Wyoming as the Darby thrust, terminating at the Uinta Mountains in northeastern Utah (Figs. 1 and 7). The Jackson thrust fault is the easternmost thrust of the Idaho-Wyoming-northern Utah foreland fold and thrust belt. It is a Late Paleocene-Early Eocene, thin-skinned fault with relative transport from southwest to northeast (Dorr and others, 1977). A more detailed discussion of the Jackson fault will be presented in subsequent sections.

Location and Accessibility

The study area is located in western Teton County, Wyoming (Fig. 1), 22-24 kilometers west of Jackson, Wyoming on State Highway 22 in Range 117 west, Township 41 north. This location was chosen because of good cross-sectional exposures of the Jackson thrust fault, its associated cataclastic zone, and easy accessibility from either Driggs, Idaho or Jackson, Wyoming.

The Jackson thrust fault is exposed in a road cut 3.6-3.7 km west of Teton Pass, or 0.6 km southeast of Coal Creek campground. The study area is bounded to the north by the Teton Range which is a north-trending, Late Cenozoic basin and range structure, and to the south by the Snake River Range which is a northwest-trending foreland fold and thrust belt terrain (Blackstone, 1980).

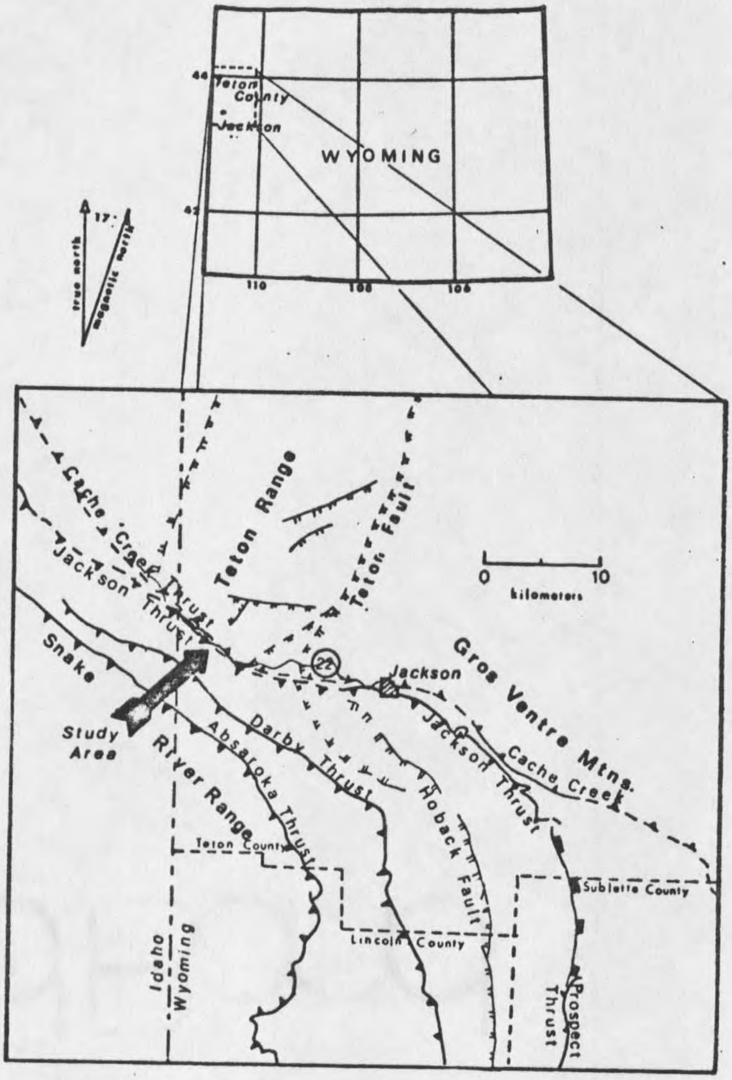


Figure 1. Index map of the study area and major tectonic elements (modified from Ver Ploeg, 1982).

Method of Study

Field study in the Teton Pass area was started in September 1981 and completed in June 1982 with valuable assistance rendered by David Redgrave during this phase of the study. A descriptive approach was used in this study, rather than theoretical modelling. The method of study consisted of: (1) collection and description of fault zone material at measured intervals away from the fault plane at two localities (one 3.6 km and another at 1.5 km west of Teton Pass, Wyoming), (2) detailed mapping of the fault zone with plane table and alidade, and (3) use of thin sections and photographs to examine the mineralogy, grain size, grain characteristics, and overall petrofabric of the cataclastically deformed rocks.

A total of forty-two samples of fault breccia from the hanging wall of the Jackson thrust fault were collected at measured intervals from the fault plane. Thirty-two samples were thin-sectioned and examined to determine mineralogy and textural features. Eight-by-ten black and white photographs of the thirty-two slabbed and polished breccia samples were used to measure and count the size of breccia fragments. A circular template was used to measure fragment diameter, a pin hole through the photograph kept track of the fragments counted, and a record of the number of fragments of each diameter was kept on a tally sheet. Due to the intense weathering of samples at one location (1.5 km west of Teton Pass), only 18 samples (photographs) from one locality (3.6 km from Teton Pass) were used to generate histograms, the cumulative frequency curve, the median grain size versus distance from the fault graph, and the graph of sorting versus distance from fault.

Breccia fragments and cement were differentiated on the photographs. By measuring the area of both the fragments and cement, dilatancy, or an increase in volume, as determined by the relationship:

$$\epsilon_{mean} = 1/2 \ln (A/A_o),$$

where A = area of breccia fragments, and A_o = area of fragments and cement. Dilatancy was determined on 10 samples of fault breccia.

PREVIOUS WORK

Teton Pass Area

Classic papers on the Idaho-Wyoming thrust belt include the regional geology by Rubey and Hubbert (1959) and Armstrong and Oriel (1965), a summary of the orogenic phases in the thrust belt by Eardley (1965), and geologic quadrangle maps by Schroeder (1972, 1973), and Rubey (1973b). The geology of the Jackson Hole area was summarized by Love and others (1973) and mapped by Love and Albee (1972). Geology on Teton Pass was mapped by Zeller (1982). Regional Paleozoic and Mesozoic stratigraphy was described by Wanless and others (1955), and the Late Cretaceous and Tertiary formations were described by Love (1956) and Rubey (1973a).

Cataclastic Deformation

Higgins (1971) classified cataclastic rocks on the basis of cohesion, which is the shear strength of a rock that is not related to interparticle friction. Higgins recognized two types of cataclastic rocks: those with primary cohesion and those without primary cohesion (Table 1).

Primary cohesion refers to the congenital or inherent coherence of a rock, as opposed to that produced by secondary cementation. Cataclastic rocks with primary cohesion are metamorphic rocks and their

Table 1. Cataclastic rock classification (modified from Higgins, 1971).

<table>
<tr><th colspan="2">Rocks without primary cohesion</th><th colspan="3">Rocks with primary cohesion</th></tr>
<tr><th rowspan="2">Volume % fragments</th><th rowspan="2"></th><th colspan="2">Cataclasis dominant over neomineralization-recrystallization</th><th>Neomineralization-recrystallization dominant over cataclasis</th></tr>
<tr><th>Rocks without fluxion structure</th><th>Rocks with fluxion structure</th><th>Rocks with fluxion structure</th></tr>
<tr><td rowspan="2"></td><td rowspan="2">Fault breccia</td><td rowspan="2">Microbreccia</td><td>Protomylonite</td><td rowspan="2">Mylonite gneiss</td></tr>
<tr><td rowspan="2">Mylonite</td></tr>
<tr><td rowspan="2">30%</td><td rowspan="2">Fault gouge</td><td rowspan="2">Cataclasite</td><td rowspan="2">Blastomylonite</td></tr>
<tr><td>Ultramylonite</td></tr>
</table>

cohesion is the product of neomineralization-recrystallization processes. Mylonites, mylonite-gneisses, and blastomylonites are examples of rocks where neomineralization-recrystallization (constructive processes) are dominant over cataclasis (destructive processes) (Higgins, 1971). Cataclastic rocks with primary cohesion are metamorphic rocks and are not to be discussed in this thesis.

Fault breccia and fault gouge are cataclastic rocks without primary cohesion and are generally associated with near-surface faulting, low confining pressures, and low temperatures (Higgins, 1971). The degree of cataclasis depends on the confining pressure, original character of the rock, amount of movement, and the duration of movement (Higgins, 1971). The following definitions proposed by Higgins will be used in this thesis:

> Fault breccia -- rock composed of angular to rounded fragments, formed by crushing or grinding along a fault. Most fragments are large enough to be visible to the naked eye, and they make up more than 30% of the rock. Coherence, if present, is due to secondary processes.
>
> Fault gouge -- pastelike rock material formed by crushing or grinding along a fault. Most individual fragments are too small to be visible to the naked eye, and fragments larger than the average groundmass grains make up less than 30% of the rock. Coherence, if present, is due to secondary processes.

Experimental research on the mechanical behavior of rocks has resulted in quantitative knowledge which can be applied to practical or field situations. Experimental study of the relationships between brittle rock deformation and mechanics of thrust faulting was addressed in the following papers. Jaeger (1959) and Brace and Byerlee (1966) studied the frictional properties of rocks and the relationship to stick-slip faulting. Borg and others (1960), Engelder (1974), Lajtai and others (1974), and Mandl and others (1977) are among the experimentalists who have attempted to generate fault gouge and breccia. However, experiments have failed to simulate the natural stresses that produced the magnitude of cataclastic rock observed in nature. This discrepancy is due in part to the fact that laboratory tests normally give information about the properties of the material itself, but do not determine the properties of the rock as a whole unit. Paterson (1978) provided a summary of the laboratory apparatus, classical views, and recent developments of experimental brittle rock deformation.

Engelder (1974), in an attempt to characterize the texture and fabric of quartz gouge, collected specimens from (1) the Bonita normal fault in New Mexico with gouge in the Cretaceous Mesa Rica Sandstone, (2) the Muddy Mountain thrust fault in southeast Nevada with gouge in the Jurassic Aztec Sandstone, (3) the Hurricane high-angle fault in Utah with the gouge in the Permian Coconino Sandstone, and (4) a high-angle reverse fault on the north flank of the Uinta Mountains, Utah with gouge in sandstones of the Precambrian Uinta Mountain Group. Engelder concluded that natural gouge develops as a result of cataclasis and increases in volume until it reaches a critical value. He also stated that the development of natural gouge involves a decrease in size and sorting which is an important observation that will be discussed with respect to the Jackson fault. Brock and Engelder (1977) reexamined the Muddy Mountain thrust of Nevada and came to the same conclusion that during cataclastic deformation, grain size and sorting decrease with increasing confining pressure and increasing displacement.

Lageson (1980) investigated cataclastic deformation associated with the Absaroka thrust fault of western Wyoming. His study revealed four levels of deformation: (1) a moderately brecciated footwall, (2) a sharply demarcated fault plane, (3) an interval of intensely brecciated rock overlain by (4) a transitional interval of moderately brecciated rock. Lageson (1980) also found evidence for stable-sliding such as striations and steps along the fault plane. He concluded that two different mechanisms of deformation, one producing the breccia zone and one producing the discrete fault plane, occurred at different times along the same fault. He stated that the two mechanisms were probably stick-slip (brecciation) and stable-sliding (discrete fault plane) motion.

Pittman (1981) studied quartz gouge in the Simpson Group of Oklahoma and its effect on permeability and porosity. He concluded that both permeability and porosity decrease in the cataclastically deformed fault zones.

GENERAL GEOLOGY OF TETON PASS

The two major thrust faults in the study area are the Jackson and the Cache Creek. They represent two distinct styles of deformation. The Jackson thrust is a product of foreland fold and thrust deformation during the Latest Paleocene-Early Eocene in which only the Phanerozoic sedimentary veneer was involved in faulting (thin-skinned). In contrast, the Cache Creek is a basement-involved (thick-skinned) foreland fault, which overrode the Jackson thrust from the northeast in Early Eocene time.

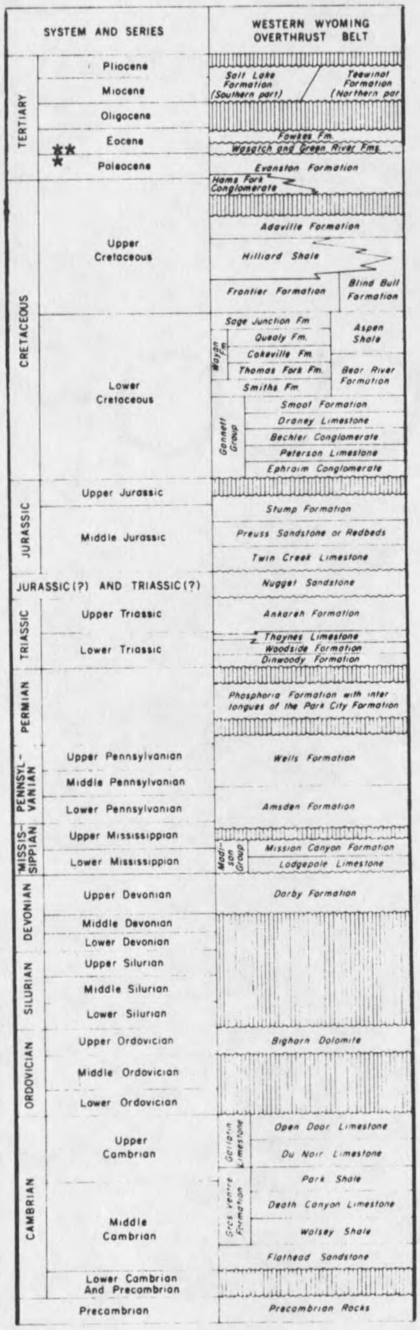
Stratigraphy

Cambrian through middle Upper Cretaceous rocks and extensive Quaternary alluvial and colluvial deposits are present in the Teton Pass area. Figure 2 is the standard stratigraphic section for the Wyoming foreland fold and thrust belt. For a complete stratigraphic description see Wanless and others (1955). Olson (1977) summarized the Triassic through Cambrian. The Mississippian was described by Sando (1977), and the Cenozoic by Warner (1977).

The two major thrust faults in the study area, the Jackson and the Cache Creek, share a common footwall of upper Lower Cretaceous rocks (Fig. 3) (Zeller, 1982). Tectonic transport on the Late Paleocene Jackson fault was from the southwest, whereas transport was from the northeast on the Early Eocene Cache Creek fault (Dorr and others, 1977). Opposing tectonic transport resulted in facies juxtaposition and rapid thickness changes in the present hanging wall sections of the two thrust faults. This will be further discussed in a subsequent section.

Depositional Setting

The study area occupied a transitional position between the Paleozoic and Early Mesozoic miogeocline to the west and the Wyoming shelf to the east (Fig. 4) which influenced placement of the later Sevier and Laramide structures. East of the Wasatch Range and west of the Prospect fault, the crystalline basement passively slopes 2^{o} - 5^{o} west and was not involved in Sevier-style deformation (foreland fold and thrust). East of the Prospect fault the basement rock was involved in Laramide style deformation (foreland) due to the eastward thinning of the



*Skyline Trail Conglomerate, member of the Hoback Formation, which is restricted to the Hoback-northern Green River Basin is time-equivalent to the Upper Evanston Formation (Dorr and others, 1977).

**Pass Peak Formation which is restricted to the Hoback-northern Green River Basin is time-equivalent to the Middle Wasatch Formation (Dorr and others, 1977).

Figure 2. Standard stratigraphic section of the western Wyoming thrust belt (From Ver Ploeg, 1982).

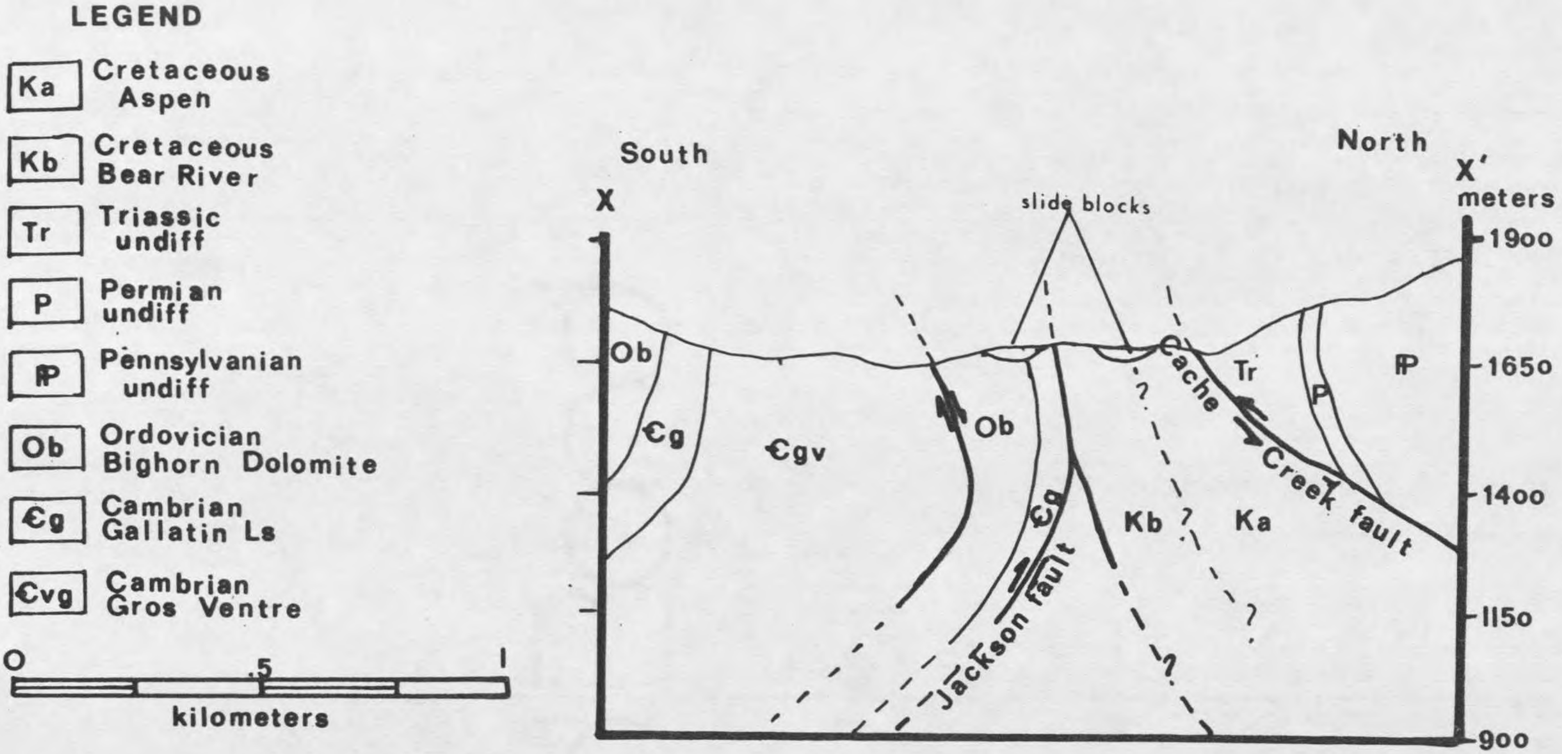


Figure 3. Simplified and reduced cross-section through study area approximately 3.6 km west of Teton Pass, Wyoming. See map in pocket for the location of X-X'. Note that the Jackson fault and Cache Creek fault share a common footwall (modified from Zeller, 1982).

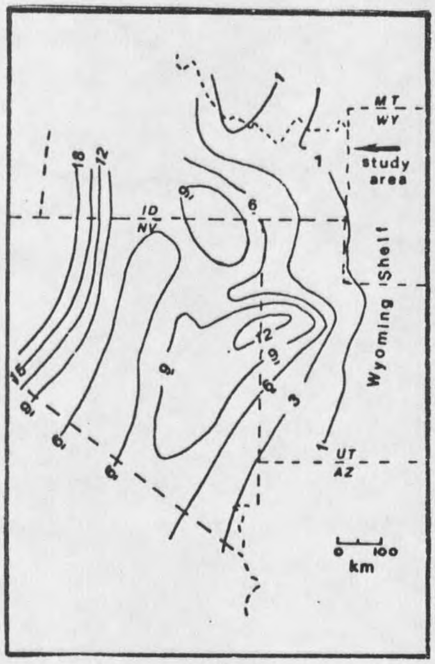


Figure 4. Composite total Paleozoic palinspastic isopach map. Thicknesses in thousands of meters (Modified from Peterson, 1977).

sedimentary veneer and increasing crustal thickness. The present-day foreland fold and thrust belt is roughly coincident with the eastern hinge line of the Paleozoic and Early Mesozoic miogeocline, the depocenter of which was in south-central and southeastern Idaho (Monley, 1971). The total thickness of rocks deposited in the miogeocline has been estimated to be between 15,000 - 30,000 m (Armstrong and Oriel, 1965), whereas time-equivalent shelf rocks deposited to the east in Wyoming are estimated to be 4,800 m thick.

Tectonic Juxtaposition

Monley (1971) illustrated the change from a thick Paleozoic and Mesozoic sedimentary section in the miogeocline to a relatively thin sedimentary section on the western Wyoming shelf by: (1) construction of pre-thrusting isopach maps for the Cambrian through Upper Cretaceous rocks, and (2) comparison of the sedimentary thicknesses of correlative units from west-to-east across the hingeline. Monley's technique of comparing rock thicknesses across the hingeline was used on a smaller scale in this study to compare rock units in the Jackson and Cache Creek thrust sheets.

Comparison of corresponding stratigraphic units in both thrust sheets revealed that similar units are thicker on the Jackson sheet than on the Cache Creek sheet (Fig. 5). For example, the Triassic Woodside Formation is 233 m thick in the hanging wall of the Jackson compared to 116 m in the hanging wall of the Cache Creek. The Pennsylvania Wells Formation, which is 284 m thick in the Jackson hanging wall, is a fine-grained sandstone with intercalated oolitic limestone with chert nodules and stringers (Pattison, 1977). The Wells Formation is structurally juxtaposed against the more clastic and thinner Tensleep Sandstone and Amsden Formation in the Cache Creek hanging wall block. Therefore, rapid thickness changes and sedimentary facies changes over this short distance are a consequence of tectonic juxtaposition by the Jackson and Cache Creek thrust faults.

Regional Tectonic Setting

The Idaho-Wyoming foreland fold and thrust belt is part of a much larger tectonic province, the Cordilleran foreland fold and thrust belt which extends from northern Alaska to southern Mexico (King, 1969), and is divided into nine segments or "salients" (Fig. 6). The study area is located in the Idaho-Wyoming-northern Utah salient which is a 333 km

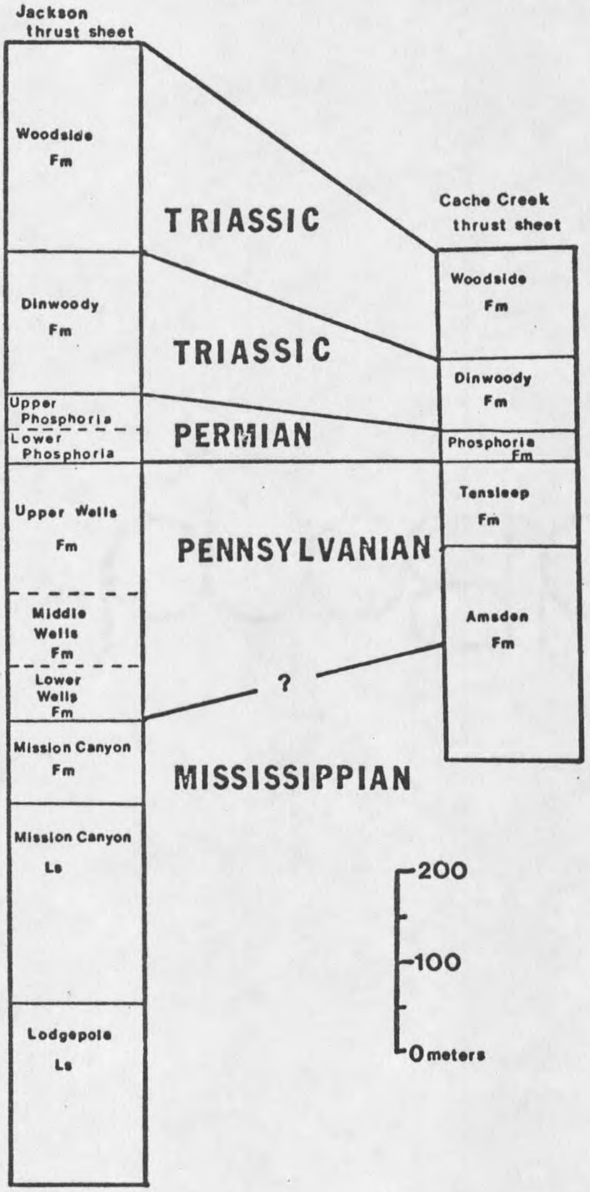


Figure 5. Stratigraphic sections of the Jackson and Cache Creek thrust sheets illustrating the greater thickness of correlative units in the Jackson thrust sheet than in the Cache Creek thrust sheet (measured from maps and x-sections of Zeller, 1982).

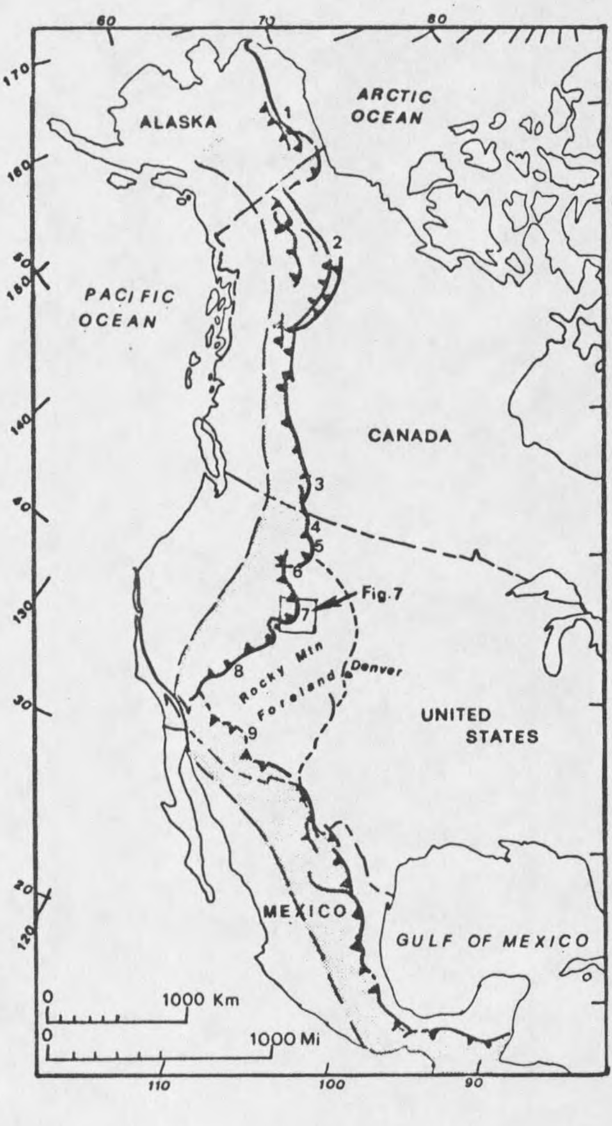


Figure 6. Longitudinal subdivisions of the Cordilleran fold-and-thrust belt. From north to south, subdivisions are (1) Brooks Range, (2) MacKenzie and Franklin Mountains, (3) Canadian Rocky Mountains, (4) Montana Disturbed Belt, (5) central Montana salient, (6) Medicine Lodge thrust system, (7) Idaho-Wyoming-northern Utah salient, (8) Salt Lake City to Las Vegas segment, (9) Las Vegas to Guatemala segment. Stippled area is outline of Cordilleran orogenic belt (modified from Ver Ploeg, 1977, and Drewes, 1978).

long, arcuate, easterly-convex belt of faulted and folded rocks bordered on the north by the Snake River Plain, on the south by the Uinta uplift, on the east by the greater Green River Basin, and on the west by the Wasatch normal fault (Fig. 7).

The structural style of the foreland fold and thrust belt differs from that of the foreland. The basic structural style which typifies the foreland fold and thrust belt province consists of: (1) concentric folds which are asymmetric to the east, (2) major west-dipping thrust faults that are progressively younger to the east and associated imbricate faults, (3) decollement faults in the sedimentary succession, (4) tear faults, (5) overall relative tectonic movement from west to east, and (6) younger, superposed listric normal faults (Royse and others, 1975). The crystalline basement was not deformed in the area east of the Wasatch Mountains and west of the Prospect-Darby fault system, but is structurally detached from the sedimentary veneer by a regional decollement located above the Cambrian Flathead Formation (Royse and others, 1975). Blackstone (1977) indicated that the Precambrian basement in this area slopes gently westward with a regional dip of 2° - 5°, which also must be the maximum dip of the decollement if it is assumed that the basement was not involved in the faulting.

In comparison, foreland-style deformation is characterized by northwest-trending, asymmetrical, Precambrian-cored anticlinal uplifts bounded by high-angle faults with great vertical displacements (Dorr and others, 1977). Precambrian rocks are exposed in foreland structures due to the thin sedimentary veneer and large vertical and horizontal movements along basement-involved faults.

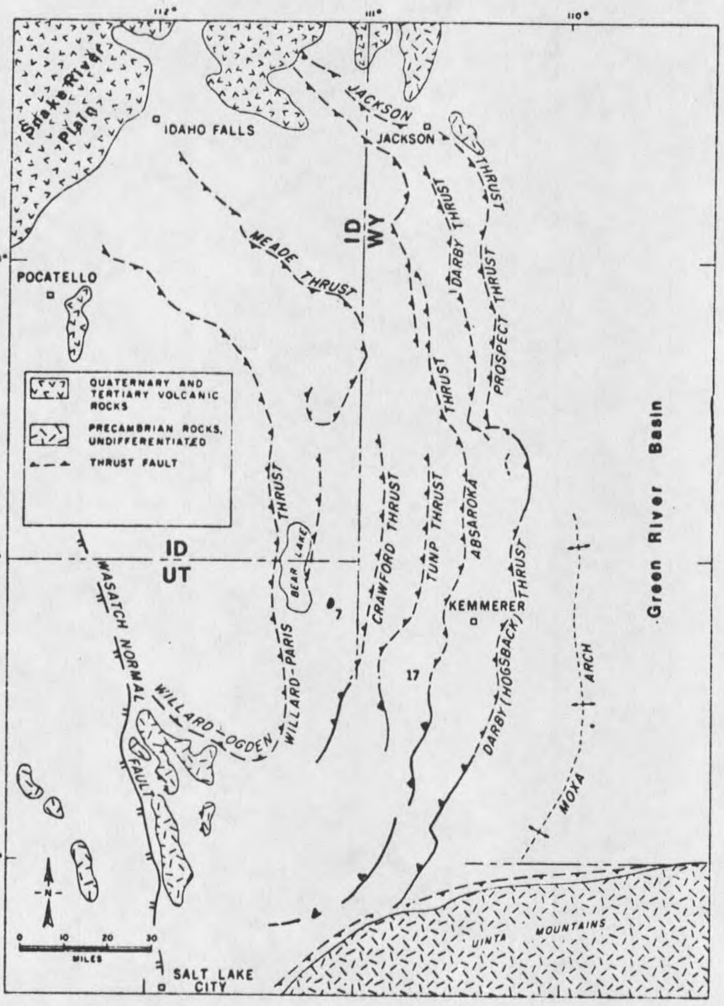


Figure 7. Limits of the Idaho-Wyoming-northern Utah salient. Western limit is the Wasatch normal fault, the eastern limit is the greater Green River Basin, the southern limit is the Uinta Mountains, and the northern limit is the Snake River Plain (modified from Ver Ploeg, 1982).

Structural Setting

Structural Geology of the Teton Pass Area

Folds

Folds on the Jackson thrust sheet in the study area are concentric (class 1B, parallel folds of Ramsey, 1967), trend N 50° W, and are commonly overturned to the southwest (Plate 1). Figure 8 shows an atypical fold in a silty layer in the Ordovician Bighorn Dolomite that is northeast-trending, overturned to the west, tight to isoclinal with second-order disharmonic folds on its east limb.

As previously stated, the foreland fold and thrust belt is characterized by concentric folds that are commonly overturned to the east in opposition to the westward asymmetry observed in the study area. This symmetry reversal is a result of: (1) the elevated Precambrian basement to the north (ancestral Teton-Gros Ventre uplift) which restricted northeast translation of the Jackson thrust sheet during the Late Paleocene (Dorr and others, 1977) and (2) the Early Eocene, southwest-moving Cache Creek thrust sheet which overrode and overturned the Jackson thrust fault (Zeller, 1982).

Thrust Faults

The Jackson thrust is a Late Paleocene, thin-skinned (Sevier-style), listric thrust fault that forms the main frontal (easternmost) thrust of the foreland fold and thrust belt (Dorr and others, 1977). Regionally, the fault surface dips 2° - 5° west (Blackstone, 1977) in a stair-step

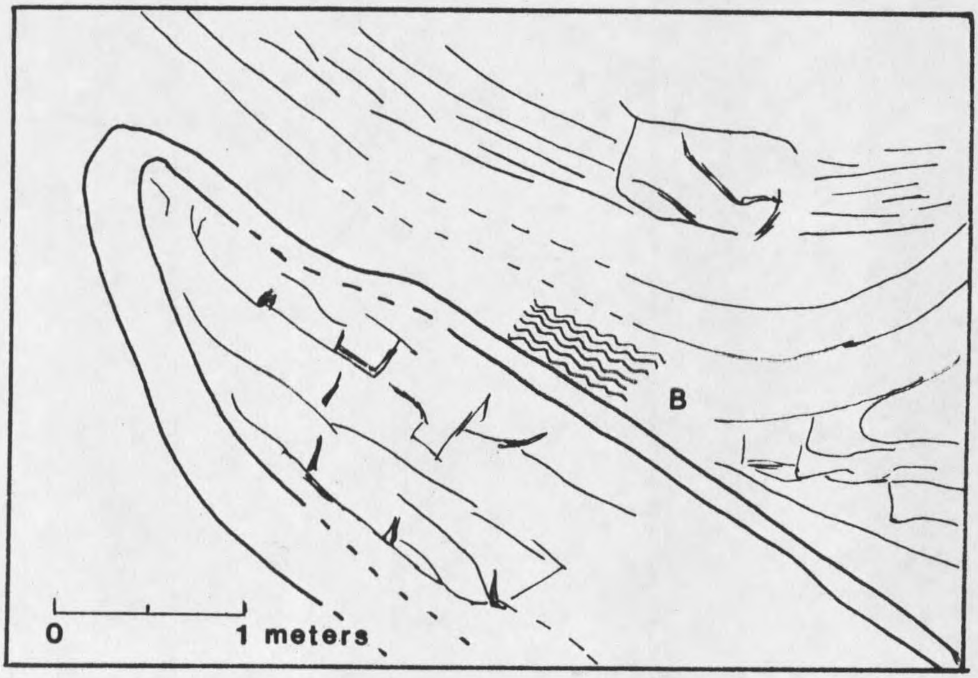
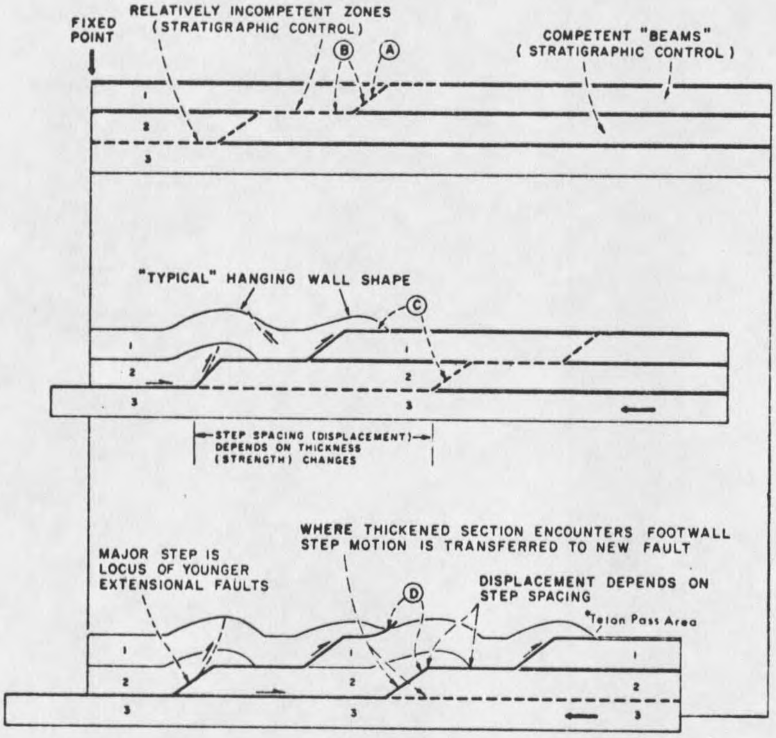


Figure 8. A tight to isoclinal, complex fold in a silty layer of the Ordovician Bighorn Dolomite. It trends northeast and is overturned to the west. Second order, disharmonic folds are located on the east limb of the fold (B).

profile with alternating ramps and treads (Rich, 1934; Royse and others, 1975). Approximately fifty percent shortening of the Paleozoic and Mesozoic rocks in the thrust belt has been achieved by telescoping and resultant doubling of the sedimentary section through motion along low-angle, listric thrust faults and contemporaneous concentric folds (Royse and others, 1975). Figure 11 illustrates Royse's geometric stair-step profile of thrust faults which develops when thrust faults climb up-section through competent rocks to form oblique ramps and glide parallel to stratification in incompetent rocks to form treads. Royse concluded that major anticlinal, concentric folds in the hanging walls of major thrust faults are a result of rocks being rotated over major ramps (Fig. 9); likewise, adjacent synclines form over treads.

In the study area, the Jackson thrust fault trends N 45° W to east-west, is overturned to the south-southwest, but is vertical at the road-cut exposure (Fig. 10). Zeller (1982) mapped the Jackson thrust fault at the contact between the Cambrian Gallatin Limestone in the hanging wall and the Cretaceous Bear River Formation in the footwall (Figs. 11, 12). The Gallatin Limestone in the hanging wall is a dark gray, unfossiliferous, massive dolomitic limestone which shows extensive cataclastic deformation near the fault contact. The Cretaceous Bear River Formation in the footwall is a black shale without observable structural deformation, which may be due to the fact that: (1) shale tends to deform ductily and (2) contemporary landslide deposits in the Bear River Formation may have destroyed or obscured any evidence of deformation.

In contrast, the Cache Creek thrust is an Early Eocene, thick-skinned (Laramide-style), foreland fault that trends N 45° W in the



IDEALIZED THRUST FAULT DEVELOPMENT

Ⓐ FAULTS CUT UP SECTION IN DIRECTION OF TECTONIC TRANSPORT.

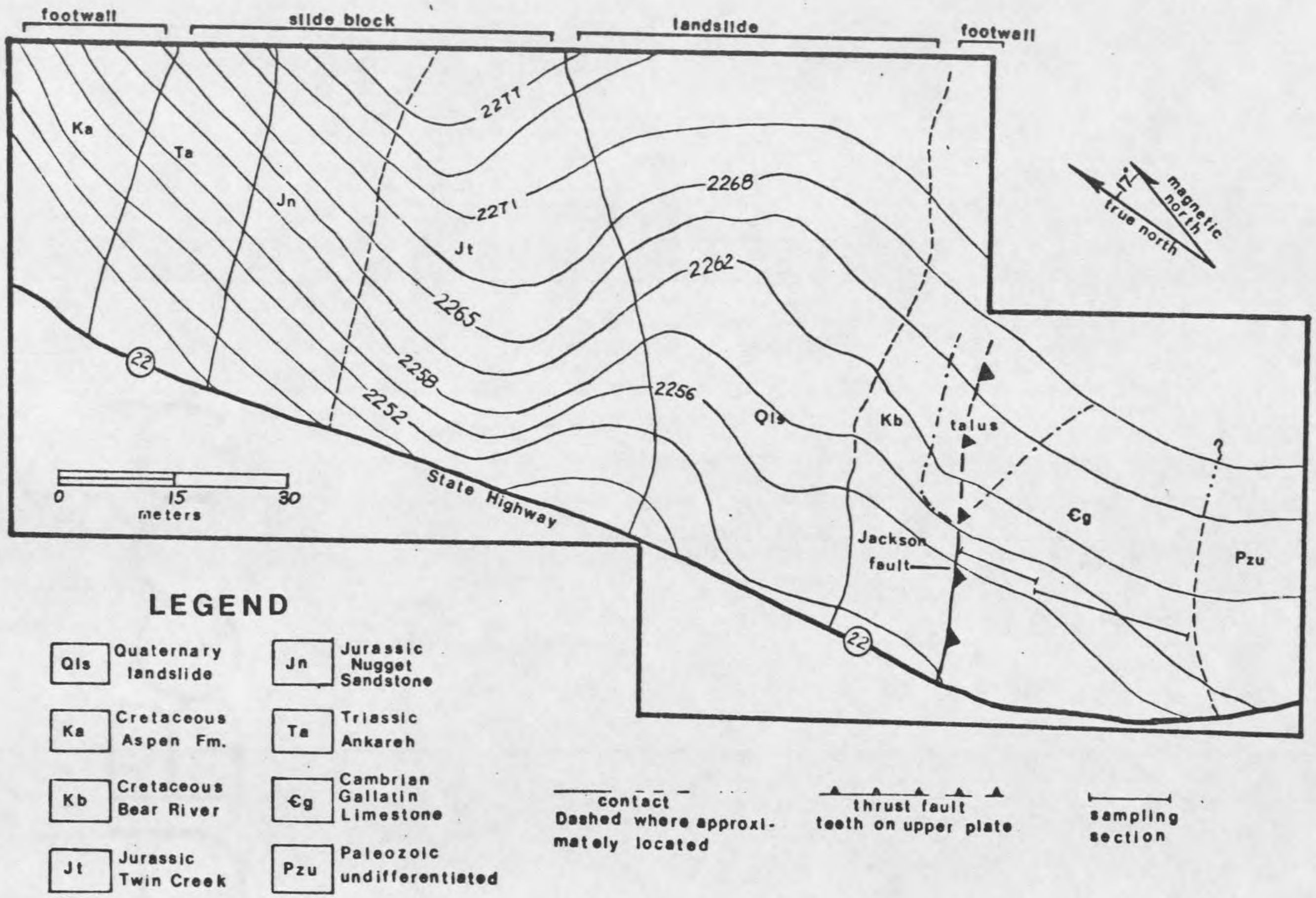
Ⓑ FAULTS TEND TO BE PARALLEL TO BEDDING IN INCOMPETENT ROCKS AND OBLIQUE IN COMPETENT ROCKS.

Ⓒ MAJOR FAULTS ARE YOUNGER IN DIRECTION OF TECTONIC TRANSPORT.

Ⓓ MAJOR THRUST FAULTS DON'T OVERLAP SIGNIFICANTLY.

GENERAL EFFECT IS TO DOUBLE THE FAULTED SECTION, THEREFORE NET SHORTENING ALWAYS APPHOXIMATES 50 %.

Figure 9. Model proposed by Royse and others (1975) to depict idealized thrust fault development. The Jackson thrust on Teton Pass would theoretically have been positioned at the leading edge of the second fault (*) before deformation by the Cache Creek fault.



PLANE TABLE MAP OF STUDY AREA, TETON PASS, WYOMING

Figure 10. Map illustrating the orientation of the Jackson thrust fault, stratigraphic contacts, and the location of the sampling section in the study area 3.6 km west of Teton Pass, Wyoming.

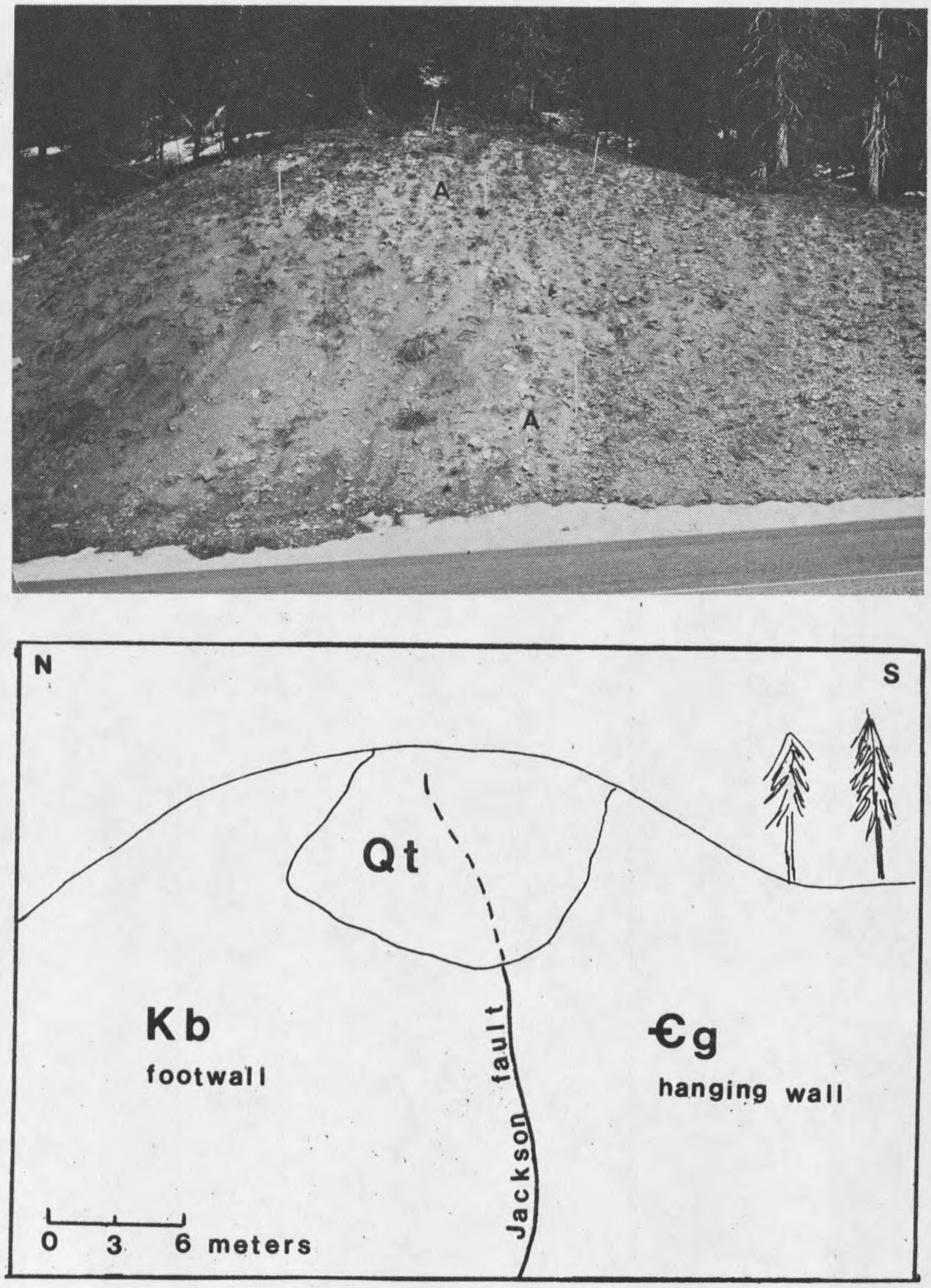


Figure 11. Roadcut exposure (3.6 km west of Teton Pass) of the Jackson thrust fault. The Cretaceous Bear River Formation (black shale) is in the footwall, brecciated Cambrian Gallatin Limestone is in the hanging wall, and talus (Qt) covers the fault in the upper portion of the photo and sketch.

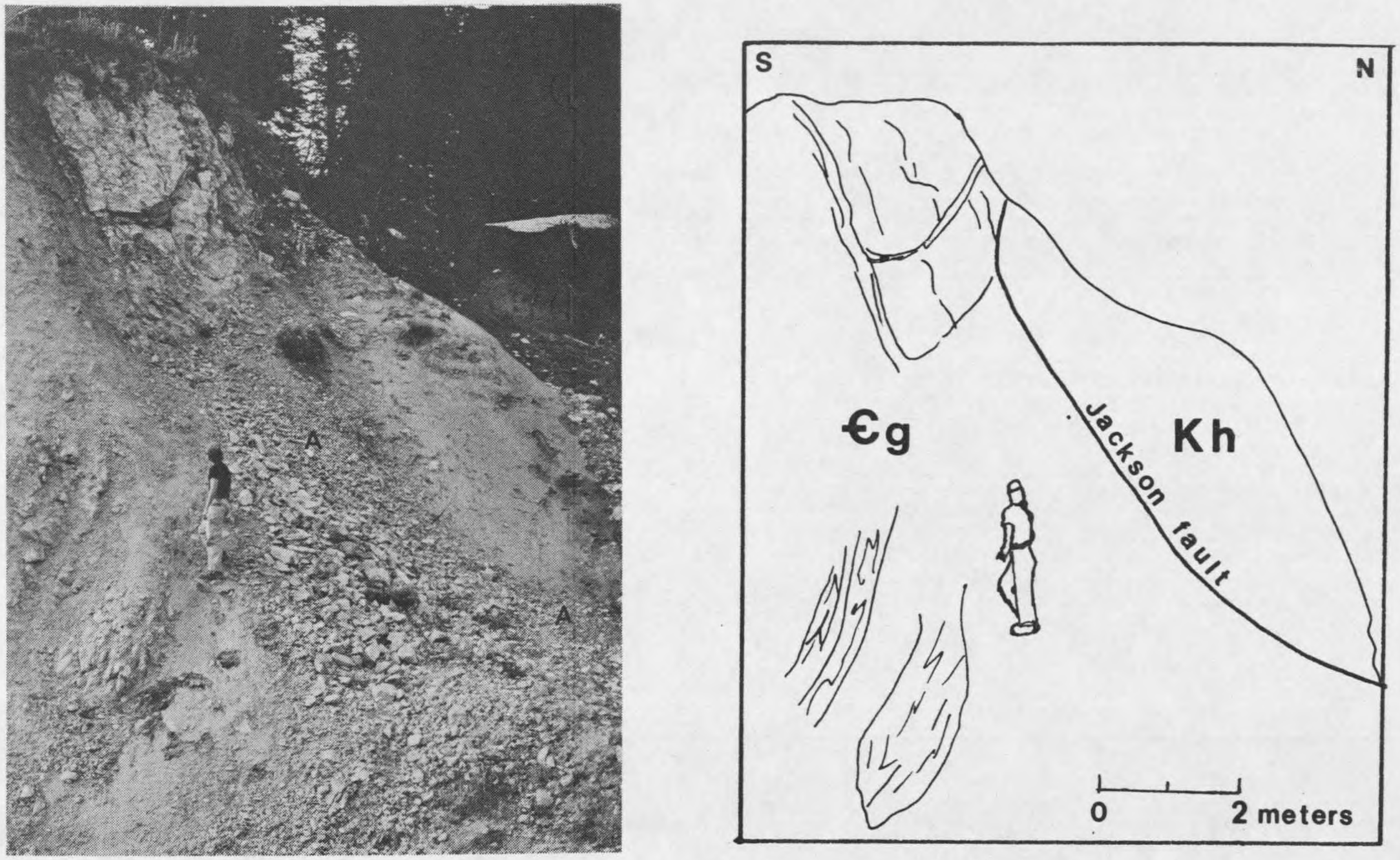


Figure 12. Roadcut exposure (1.5 km west of Teton Pass) of the Jackson thrust fault, which is overturned to the south. Brecciated Cambrian Gallatin Limestone (Cg) is in the hanging wall and Cretaceous Hillard Formation (black shale) is in the footwall (Kh).

study area (see map in pocket). In the study area, Zeller (1982) mapped the Cache Creek thrust fault at the contact between the Triassic Woodside Formation in the hanging wall and the Cretaceous Aspen Formation in the footwall, although the contact is obscured by scree from the Woodside Formation (Fig. 3). Relative movement along the Jackson and Cache Creek thrust faults was determined by Dorr and others (1977) who used displaced Paleocene and Eocene conglomerates suggesting that the Creek fault overrode the Jackson thrust fault from the northeast during the Early Eocene. According to Dorr and others (1977) the Late Paleocene Skyline Trail Conglomerate was displaced eastward by the Jackson thrust fault, followed by displacement of the Early Eocene Pass Peak Formation by the Cache Creek thrust fault. In addition, Zeller (1982) mapped the Jackson thrust fault as overturned to the southwest based on overturned imbricate thrust faults in the hanging wall of the Jackson thrust sheet on Teton Pass. Therefore, displaced Paleocene and Eocene conglomerates and overturned thrust faults document the Cache Creek fault as being an Early Eocene fault that overrode the earlier Jackson fault.

Sevier and Laramide Deformation of the Teton Pass Area

The sequence of events which were most important in determining the present-day structural configuration of Teton Pass began with the Late Jurassic Paris thrust (Armstrong, 1968). In western Wyoming the Late Jurassic through Middle Cretaceous was characterized by eastward thrusting of thick geoclinal rocks over thin cratonal sequences (Armstrong, 1968).

The initial rise of the ancestral Teton-Gros Ventre Mountains at the former shelf edge, uplift of the Wind River Range, and major movement on the Absaroka thrust fault all occurred at approximately the same time in the Late Cretaceous (Fig. 13) (Dorr and others, 1977). The last major episode of eastward thrust displacement occurred along the frontal Jackson-Prospect-Darby fault system at the close of the Paleocene. The Latest Cretaceous-Early Tertiary Laramide orogeny deformed the crust into north-northwest trending basement-cored uplifts such as the Wind River Range (Burchfiel, 1981). Paleozoic and Mesozoic rocks are draped over the flanks of the uplifts that are bounded by low-to high-angle, basement-involved reverse faults, such as the Cache Creek fault (Burchfiel, 1981). To the west, local normal faulting began in the westernmost thrust ranges during Eocene time and continued to the present (Armstrong and Oriel, 1965). Evidence for this includes displacements along the Teton normal fault, the Hoback listric normal fault, and fresh scarplets that cut Pleistocene and Holocene talus along the base of the Teton Range (Dorr and others, 1977).

LAB ANALYSIS AND INTERPRETATION

General Petrography

The hanging wall rock of the Jackson thrust fault at the fault contact is the dark gray, massive, unfossiliferous Gallatin Limestone. Brecciation only occurs in the hanging wall block of the Jackson thrust sheet. Therefore, the following analysis pertains only to the Cambrian Gallatin Limestone. For purpose of discussion, the fault zone in the hanging wall block has been divided into two zones, A and B, based

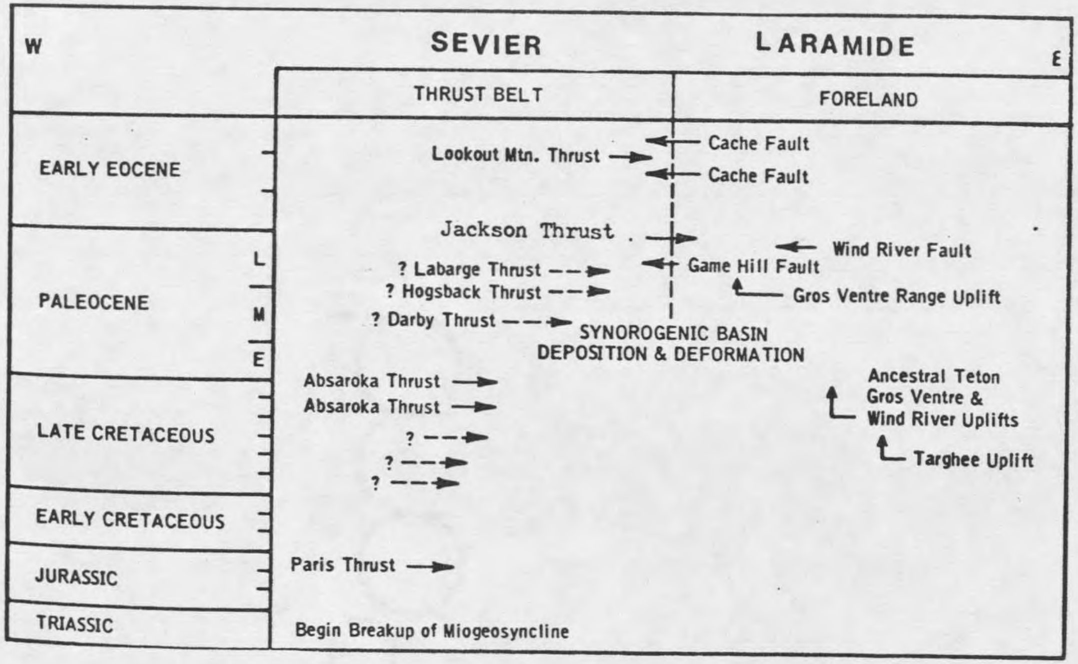


Figure 13. Summary of Sevier and Laramide events, showing ages of faults and progressive impingement of foreland and thrust belt through time (modified from Dorr and others, 1977).

primarily on grain size distribution. Zone A extends from 1 - 4 m from the fault and zone B from 4 m outward (Fig. 14). Due to lack of outcrop exposure the outer limit of zone B was indeterminable. Histograms and other statistical illustrations for the breccia samples are located in the Appendix.

Composition

The fault zone material is composed of crystalline calcite. Breccias in zones A and B consist of large limestone fragments, coarse sparry cement between the fragments, the medium crystalline calcite matrix (Fig. 15). Both zones show evidence of dissolution and recrystallization. The calcite crystals are generally twinned at random orientations and some exhibit strained crystals (slightly undulose extinction).

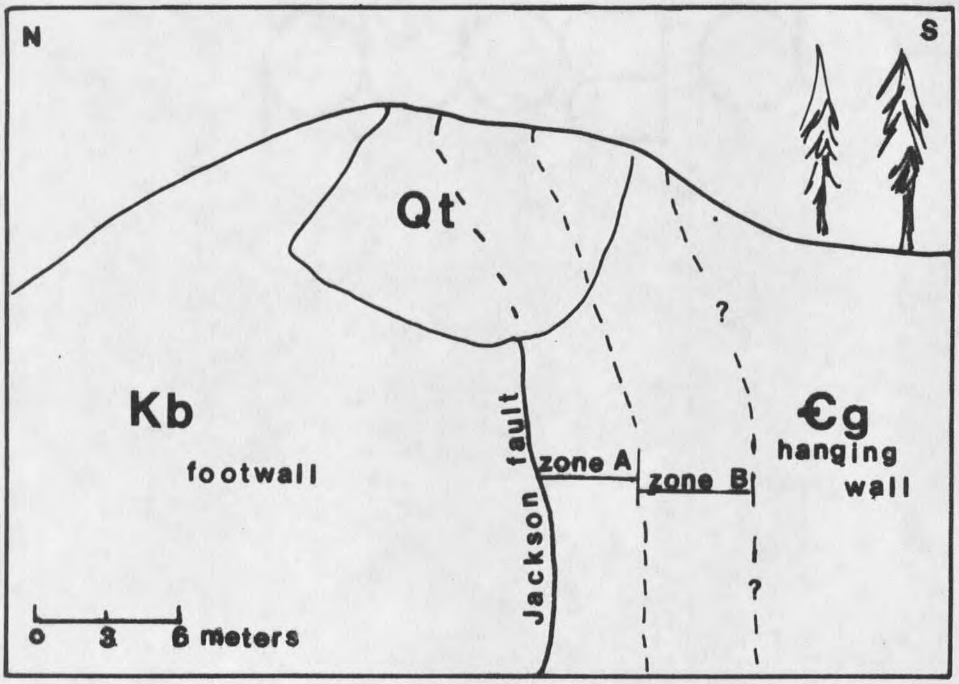


Figure 14. Sketch of positions of zone A and zone B. See Fig. 11.

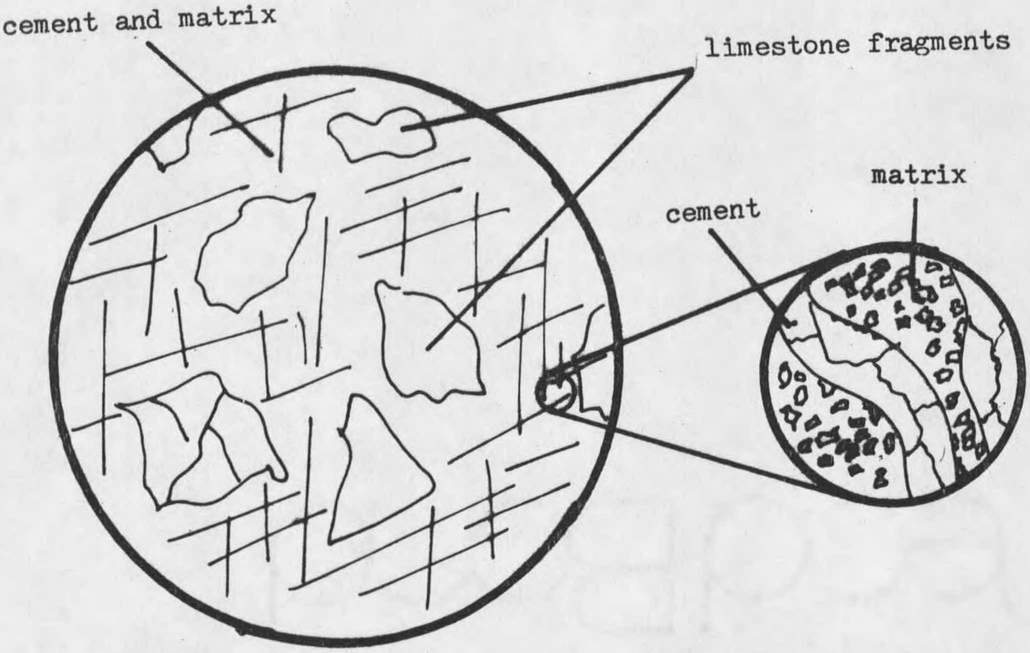


Figure 15. Diagrammatic sketch of the distribution of components which make up the fault zone breccia in the Jackson thrust fault hanging wall

In zone A, medium crystalline calcite matrix is predominant with up to 15% coarsely crystalline sparite cement. Similarly, medium crystalline matrix is predominant in zone B with up to 25% very coarsely crystalline cement.

Size

Zone A contains breccia fragments with an average size of 1.9 mm, coarsely crystalline calcite cement (1 mm), and medium crystalline calcite matrix (0.10 mm) (Fig. 16). A decrease in grain size of the breccia fragments occurs toward the fault plane (Fig. 17). From 0.0 to 0.3 m from the fault, samples have normal size distributions which are

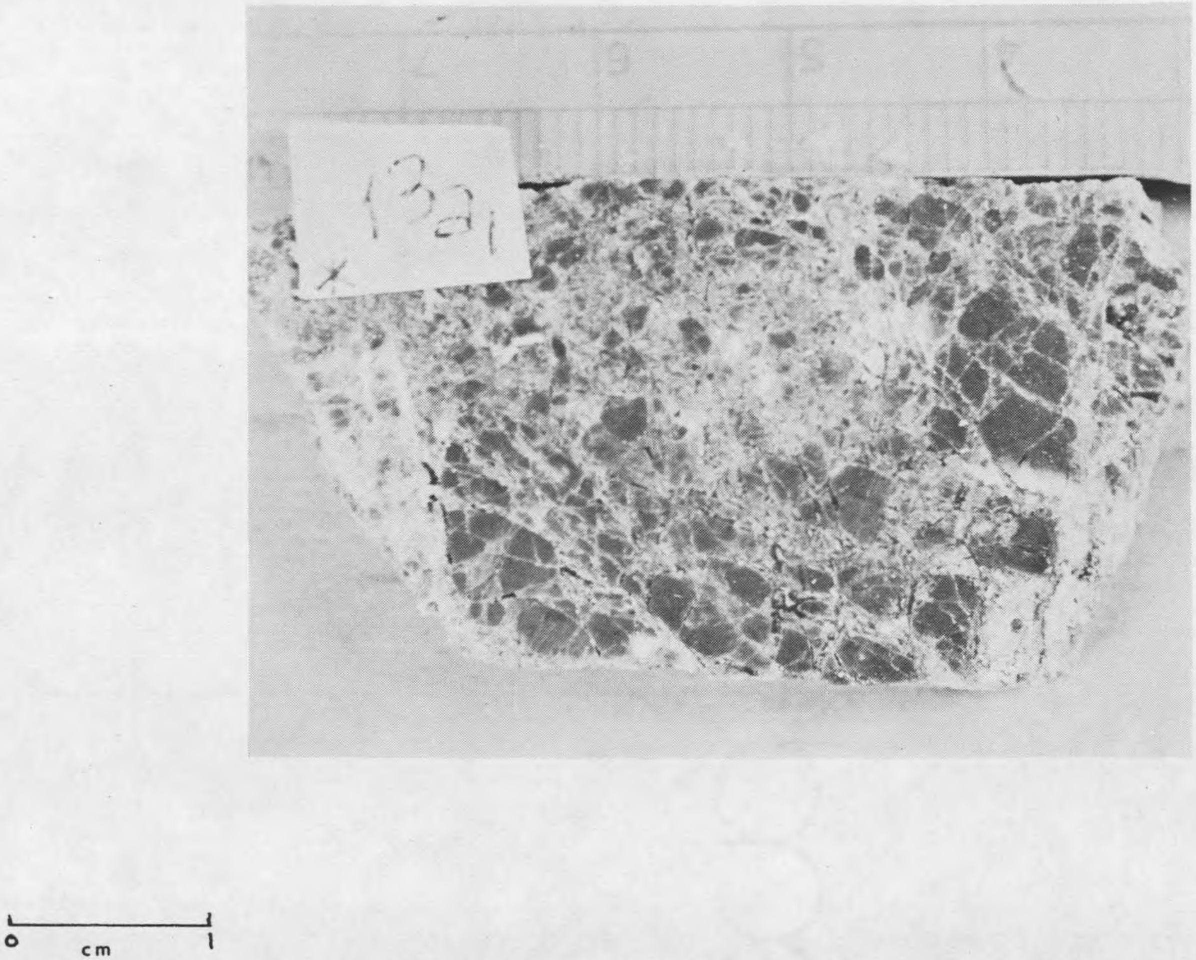


Figure 16. Photograph of the fault zone material 0.15 m from the fault plane (zone A). Dark areas are breccia fragments and light areas are cement.

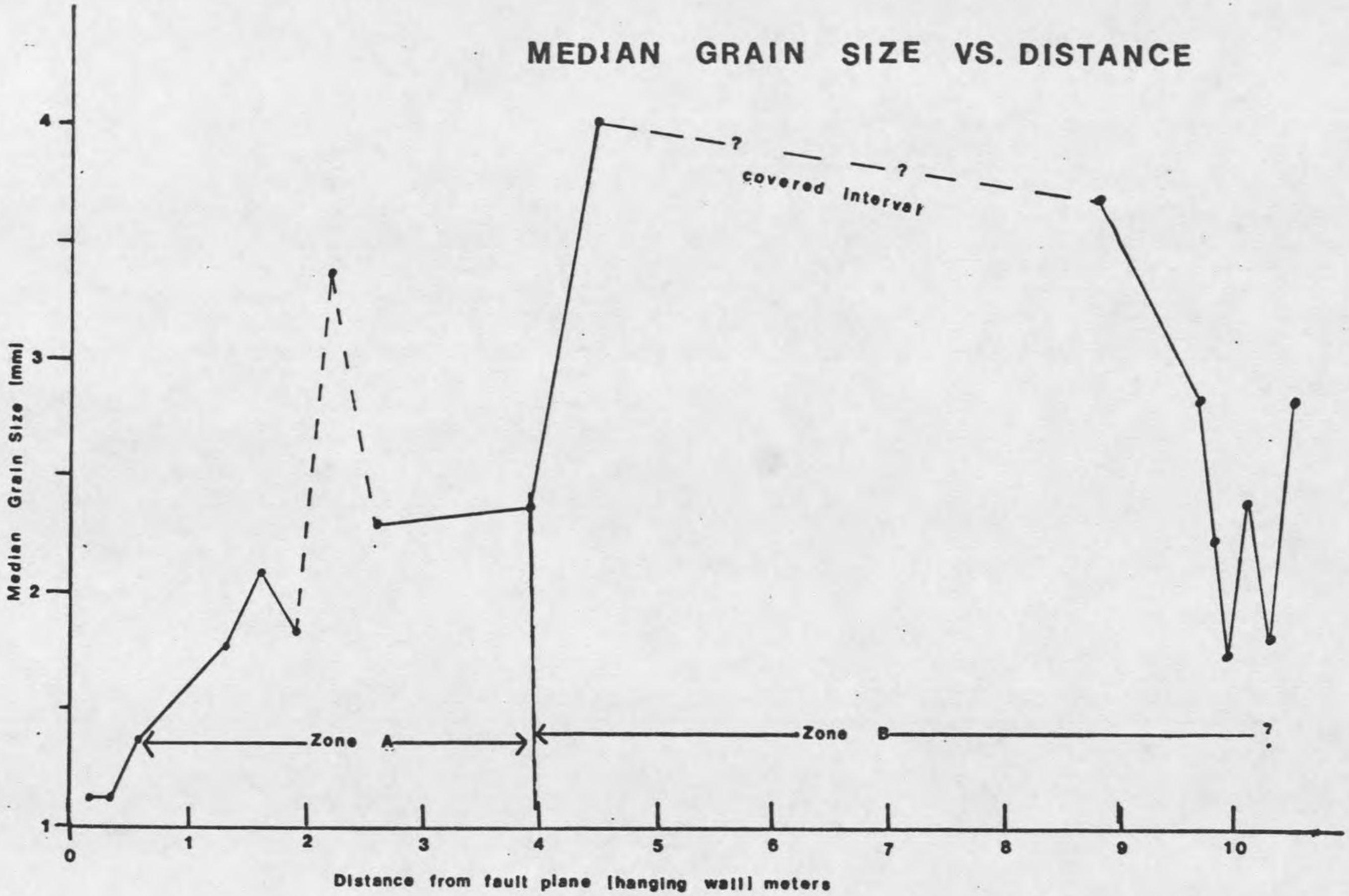


Figure 17. Graph illustrating the decrease in size of the breccia fragments nearer the fault plane.

slightly fine-skewed, with a median fragment size of 1.25 mm, and are mesokurtic.[1] The size distribution of breccia fragments from 1 to 1.25 m from the fault is platykurtic[2] with a mean size of 1.7 mm. Breccia fragments less than 1 mm are absent 2.5 to 4.0 m from the fault plane and the size distribution is strongly coarse-skewed, platykurtic, with a primary mode of 4 mm, and a median size of 3.0 mm.

Zone B contains breccia fragments with an average size of 3.0 mm, very coarsely crystalline calcite cement (1 - 4 mm), and medium crystalline calcite matrix (0.15 mm) (Fig. 18). Size distribution of breccia fragments from 9 to 9.75 m from the fault plane is strongly coarse-skewed, mesokurtic to leptokurtic,[3] with a primary mode of 4.0 mm. Fragments less than 1 mm begin to appear again at about 10 m away from the fault. Samples 10 - 10.6 m from the fault exhibit bimodal size distributions with a primary mode of 4 mm and a secondary mode which varies from 0.3 mm to 1.1 mm.

Sorting

A plot of the graphic standard deviation of breccia fragment size distribution (as computed by Folk, 1974) versus distance from the thrust fault contact is a measure of sorting (Fig. 19). Within the fault zone the breccia fragments closer to the fault (zone A) are moderately well sorted, whereas the fragments farther away (zone B) are more poorly

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[1] Closely resembles a normal frequency-distribution curve.

[2] A frequency-distribution curve that is broad and flat-topped.

[3] A frequency-distribution curve that is narrow and peaked.

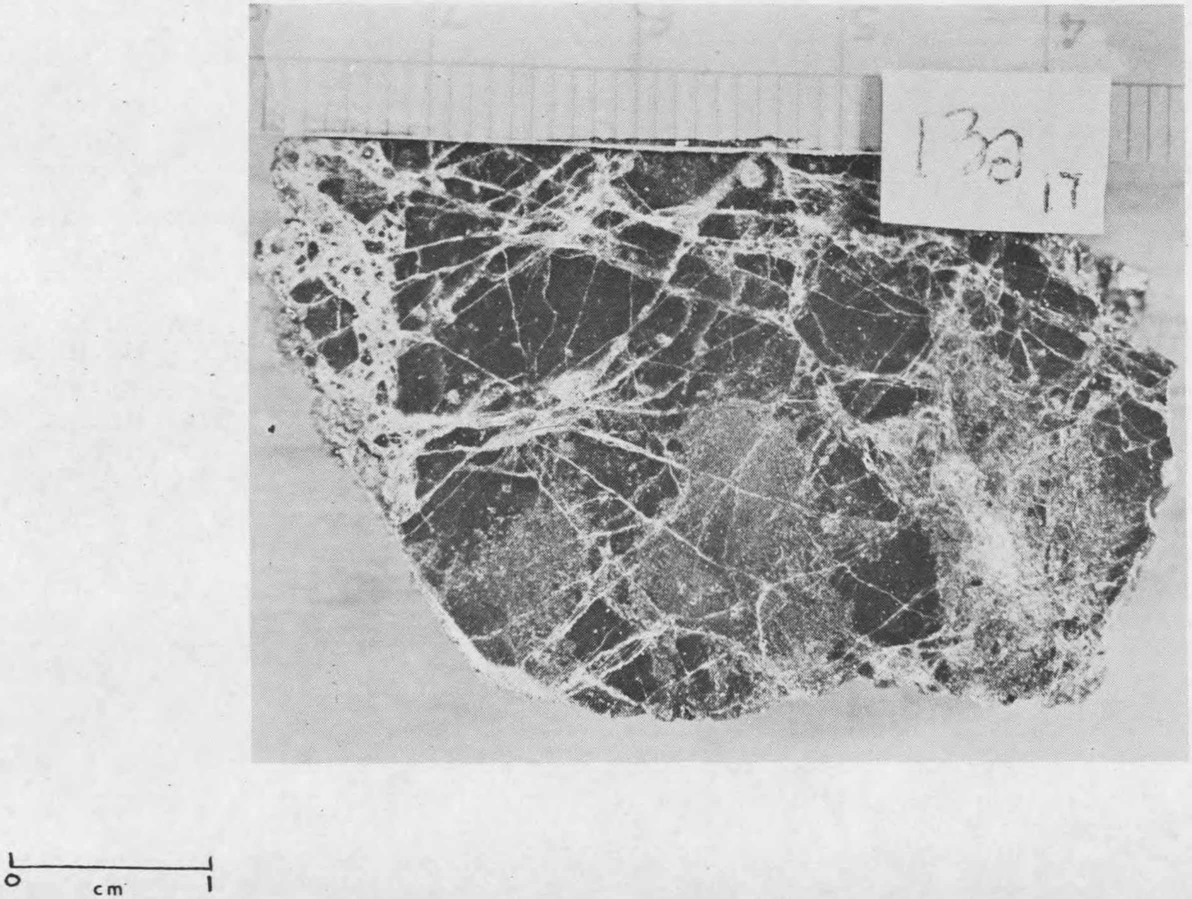

Figure 18. Photograph of the fault zone material 10.3 m from the fault plane (zone B). Darker areas are breccia fragments and lighter areas are cement.

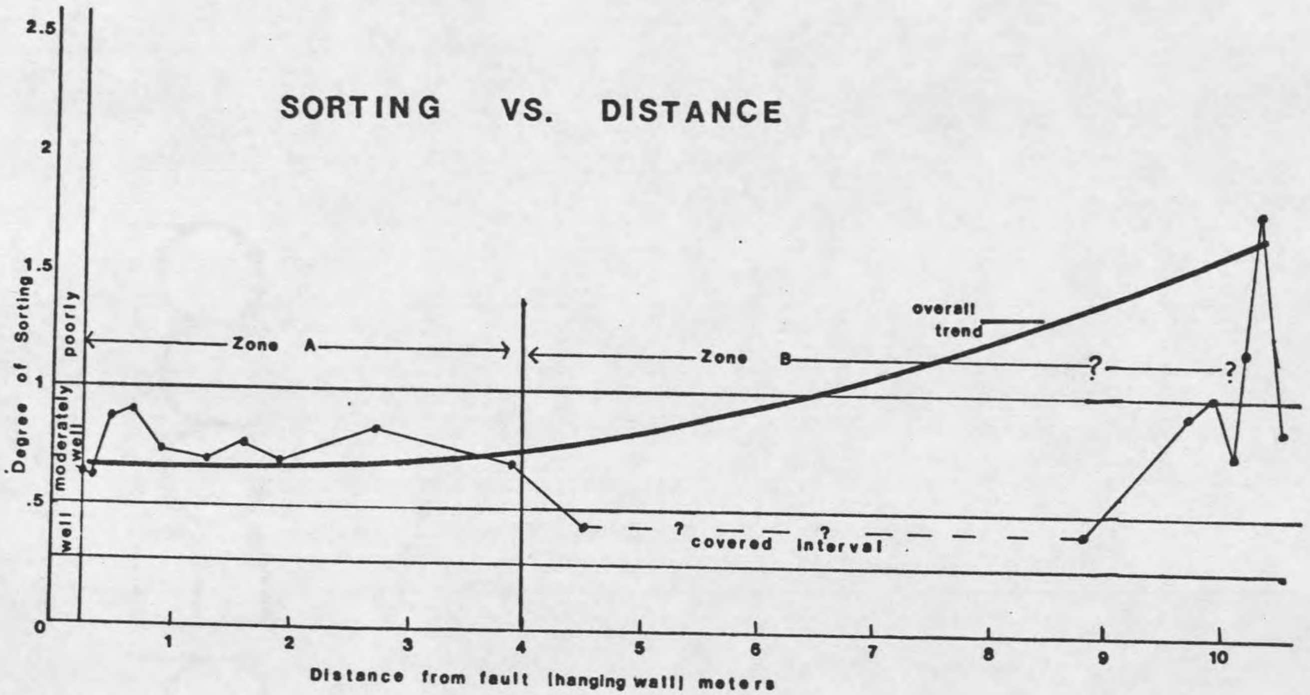

Figure 19. Graph illustrating the overall increase in sorting of breccia fragments nearer the fault plane.

sorted. The breccia fragments in zone A are predominantly subangular, whereas those in zone B are angular.

Interpretation of Data

The decrease in fragment size and increase in sorting as the fault plane is approached is the result of cataclastic deformation associated with movement along the Jackson thrust fault. The smaller average fragment size of zone A suggests a greater intensity of cataclasis than in zone B. Assuming greater intensity of cataclasis nearer the fault, the size differentiation between zones A and B indicates an increase in solid-body rotation of fragments and a higher degree of abrasion in zone A. With the increase in sorting of zone A, it seems unlikely that the breccia fragments of zone B were subjected to an equal amount of abrasion.

Dilatancy, or an increase in volume, is generally associated with brecciation (Spencer, 1977). If dilatancy did occur in the fault zone, then an increase in area would be expected and could be easily determined. The entire area of a sample was compared with the total area of the breccia fragments of that sample (see Method of Study). Samples from the study area show an average dilatancy of only 8%, which implies a volume increase. In addition, there appears to be a high amount of porosity (approximately 15% in the fault zone samples). Whether the porosity is fault related or a diagenetic feature is not known. There is evidence for exsolution and recrystallization, and porosity in other limestones associated with thrust faults in the fold and thrust belt is generally not considered to be fault-related (Wood, 1982).

The origin of the medium crystalline calcite matrix in the fault zone poses an interesting problem of whether it is a crystallization product or the result of extreme pulverization of limestone fragments. If the matrix was truly microfragment, evidence for later or multiple generations of cement enclosing earlier fragments would be expected. This question could not be positively answered in this study, therefore a crystallization origin was assumed.

Mechanics of Thrust Faulting with Application to the Jackson Thrust

Three mechanisms have been advanced to explain lateral transport of rock masses over surfaces of low dip: (1) gravity sliding of the thrust sheet down an inclined surface, (2) lateral compression resulting in movement of the thrust plate horizontally or up an inclined fault surface or basement interface, and (3) lateral spreading of an uplifted rock mass (Spencer, 1977). Variables such as pore fluid pressure, rock type, relative ductility, degree of brecciation, and mode of movement influence the dynamics of thrust faulting. The following discussion illustrates the relationships among these variables, how they affect each other, and which factors have been predominant in the case of the Jackson thrust fault. In addition to these relationships, a comparison of the inferred mechanics of motion of the Jackson thrust fault with the Muddy Mountain thrust in Nevada (Brock and Engelder, 1977), and the Absaroka thrust in Wyoming (Lageson, 1980), makes possible an interpretation regarding the transport mechanism of the Jackson thrust fault.

Mechanical Variables

The major resistance to movement by gravity sliding is friction. Studies have determined that the angle of the inclined surface on which the thrust sheet slides must be approximately 30° to overcome frictional resistance (Spencer, 1977). This angle is not realistic because most thrust fault surfaces are inclined approximately 2° - 5° toward the hinterland (Spencer, 1977). In the case of lateral compression, the stress needed to push the block horizontally far exceeds the strength of the rock. In both cases the coefficient of friction needs to be effectively reduced to allow horizontal displacement.

The detachment or basal decollement of many thrust faults is usually localized along a less competent rock unit, such as shale or an evaporite bed, which reduces the cohesion between the more competent rock units (Gretner, 1972). Shales commonly have high amounts of interstitial fluids, which under compaction due to lithostatic pressure, produce high pore fluid pressure. The increase in pore fluid pressure effectively reduces the normal stress (Hubbert and Rubey, 1959), which reduces the frictional resistance to sliding. Rocks adjacent to the incompetent rock unit must have low permeability to permit the gradual build-up of pore fluid pressure. The rapid advancement of a thrust sheet resulting in additional tectonic overburden also increases the pore fluid pressure. Gretner (1972) postulated that the competent units carry a disproportionately high part of the horizontal load. When the thrust sheet breaks along the competent units the load is suddenly transferred to the incompetent units resulting in the development of high pore fluid pressure in the incompetent units, which effectively reduces the overburden pressure (effective stress). This "pumping effect" of Gretner's (1972) theoretically results in the self-perpetuating process of thrust faulting known as breakaways or piggy-back thrusts.

Dilatancy, or an increase in volume, commonly accompanies brecciation under low confining pressures (less than 1 kb.), but at 1 - 2 kb confining pressure, there may be little or no dilatancy (Spencer, 1977). If, as previously stated, the brecciated zone of the Jackson thrust fault underwent an average of only 8% dilatancy, then movement on the Jackson probably occurred under 1 - 2 kb confining pressure. Furthermore, an increase in volume in the brecciated zone might be expected if pore fluid was present during movement. It seems likely that there would be slightly strained and unstrained calcite crystals (probably spar) between breccia fragments if pore fluid was present during and immediately after movement, respectively. Such is the case with the brecciated zone associated with the Jackson thrust fault. Also, lack of recrystallization products produced by frictional heating, such as pseudotachylite, implies the presence of pore fluid. The confining pressure of 1 - 2 kb is also supported by the known overburden thickness of the Jackson thrust sheet of 4500 - 5500 m (Zeller, 1982). Therefore, it is suggested that the lack of cohesion between hanging wall and footwall blocks and the presence of pore fluid sufficiently reduced the frictional resistance to aid in lateral movement of the Jackson thrust fault.

Mode of Movement

The two general types of fault motion are stick-slip and stable sliding. Stick-slip motion is characterized by alternately high and low slip rates and may be the result of sudden brittle failure of locked portions on the fracture surface, such as thrust ramps. Overall movement is slow, but consists of a series of fast "spurts" and only segments of the thrust sheet move at a given time (Gretner, 1972). Sporadic movement may be aided by Gretner's (1972) "pumping effect", which involves sporadic motion along thrust faults due to transfer of stress between competent and incompetent rock units via pore fluids. Abnormal pore fluid pressures permit brittle behavior at unexpectedly large depths (greater than 6000 m) which would account for stick-slip motion and breccia generation at deeper levels on a thrust fault (Handin and others 1963).

In contrast, stable sliding is characterized by low effective normal stress, higher temperatures, faster, but constant displacement rates (Logan, 1978). Stable sliding implies a discrete sliding surface on which striations, raised steps, and gouge marks occur (Elliot, 1976).

Experimental studies of the mechanical behavior of fault gouge suggest that it may greatly affect the mode of movement along a fault. Logan's (1978) study of various experimentally produced gouges found that calcite gouge at 1 kb becomes very fine, indurated, and compacted, resulting in stick-slip movement. He concluded that a fine-grained limestone should show stick-slip movement and that grain size plays an important role in determining the mode of movement. Gretner (1972) also stated that gouge profoundly lowers frictional resistance to slip for both stick-slip and stable sliding motion. This implies that strain rate plays an important role in determining which mode of movement is dominant.

There was no evidence for stable sliding, such as striations, along the Jackson thrust fault in the study area. Stick-slip motion is generally associated with brittle behavior, as is brecciation. Therefore, the extensive brecciation observed along the Jackson thrust fault suggests that stick-slip motion was the dominant mode of movement.

Factors Influencing Brecciation

The generation of fault breccia is enhanced by brittle rock, low temperatures, shallow crustal depths, and high strain rates (Spencer, 1977). Physical parameters that control the thickness of tectonic breccia (i.e., the thickness of fault zones A and B) are rock type and the associated physical characteristics, distance moved, pore fluid pressure, lithostatic pressure, temperature, and strain rate. These factors are related in the following equation:

$$B_{\text{thickness}} = D \times K_d \times C \qquad (1)$$

B = breccia thickness

D = distance moved

K_d = ductility constant (derived from Donath, 1970)

C = constant = 5×10^{-4} (derived from transport distance and breccia thickness)

The above equation is intended to estimate the thickness of tectonic breccia associated with a thrust fault and was generated from data from three thrust faults with known fault-related breccia: (1) the Muddy Mountain thrust of Nevada (Brock and Engelder, 1977), (2) the Absaroka in western Wyoming (Lageson, 1980), and (3) the Jackson thrust of western Wyoming. Lageson (1980) stated that breccia thickness depends primarily on the material properties of the rock units. The equation (1) includes not only rock characteristics, but incorporates the variable of distance moved.

The ductility (K_d) constant was derived from Donath (1970) (Fig. 20). The three thrust faults studied had 4000 - 5000 m of overburden and movement occurred under 1 - 2 kb of confining pressure. Overburden, in turn, affects the ductility of various rock types and determines K_d (Fig. 20).

Donath's (1970) graph of ductility (percent shortening before fracture) versus confining pressure shows that fracturing (in the generation of fault breccia) is largely a ductile process. Ductile fracture, which occurred in the Jackson thrust sheet as evidenced by the presence of both large folds (ductile deformation) (Fig. 10) and breccia (brittle deformation). For example, at 1.5 kb confining pressure, dolomite strains only 6% while limestone strains 12% before fracture occurs (Fig. 20); dolomite is more dense and brittle than limestone, accounting for its lower ductility. This is substantiated by field observations that show more extensive brecciation in the Bighorn Dolomite than in the Gallatin Limestone.

The constant (C) is the ratio between the measured breccia thickness along each fault and the distance of tectonic transport. For example, Brock and Engelder (1977) determined the transport distance of

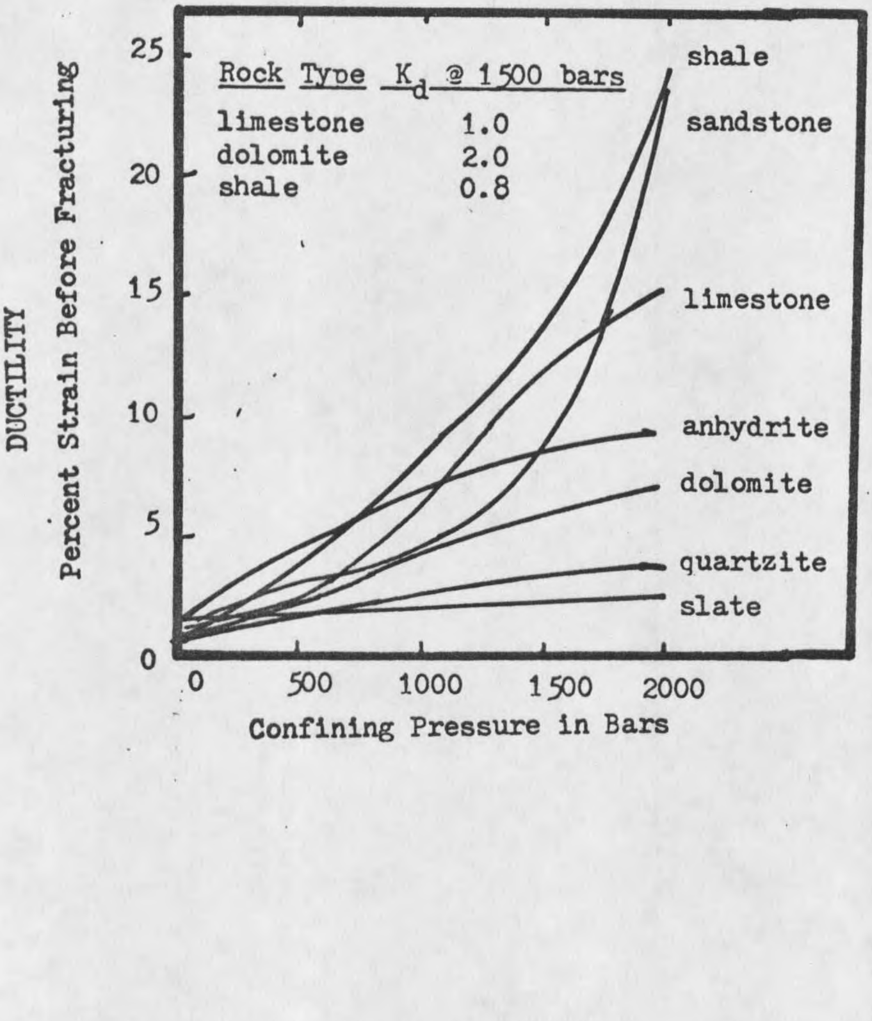

Figure 20. Ductility of common rocks under different confining pressures (Donath, 1970). Using limestone as a reference point, K_d was determined for shale and dolomite at 1500 b; dolomite strains 6% before fracturing and limestone 12% before fracturing. Therefore, K_d for dolomite is twice that of limestone.

the Muddy Mountain thrust sheet to be 24,000 m with 12 m of associated breccia, therefore:

$$(C) = \frac{12 \text{ m breccia}}{24{,}000 \text{ m transport distance}} = 5 \times 10^{-4}.$$

(C) probably is not a linear function at higher (greater than 30 km) transport distances. Breccia thickness probably reaches a critical value in response to surrounding physical parameters, and cannot increase infinitely because the thrust sheet would be reduced to a pile of fragments.

Lack of data regarding thrust faults and associated breccia and the fact that equation (1) was derived from small segments on only three thrust faults limits the validity of (C) and the entire equation. Therefore, in view of the limited area studied it is dangerous to assume that the equation (1) would apply to areas elsewhere along the Jackson fault and that conditions determined or assumed to have existed in the Teton Pass area existed along other areas of the Jackson fault.

Assuming the equation (1) is applicable, an estimation of the thickness of tectonic breccia can be made, assuming the following conditions: low temperatures, high strain rates (probably stick-slip motion), little pore fluid pressure, brittle rock and movement at 4500 - 5500 m depth. Lack of brecciation, or unexpectedly low amounts of it, could be due to a number of factors that invalidate the above equation, such as: (1) high pore fluid pressure reducing the frictional resistance to sliding, (2) an increase in confining pressure due to high amounts of lithostatic pressure, and (3) an increase in confining pressure promoting ductile rather than brittle behavior.

The presence of breccia fragments probably aided in movement along the Jackson thrust fault. The fragments reduce the frictional resistance to slip by acting like ball bearings between the two blocks.

Muddy Mountain and Absaroka Faults Compared to the Jackson Fault

By comparing the Jackson thrust fault with the Muddy Mountain thrust of southeast Nevada, some similarities and differences are revealed. In both cases the breccia fragment size decreases near the fault plane, which is due to the mechanical grinding and breakdown of the rock. The most intense cataclasis on both faults occurs within 4 - 5 m of the fault and decreases or ends 10 - 12 m from the fault surface. Brock and Engelder (1977) found that sorting decreases near the fault plane of the Muddy Mountain thrust, in contrast to the Jackson where sorting increases nearer the fault plane. In the Muddy Mountain thrust, Paleozoic carbonates are thrust over Mesozoic sandstones, whereas with the Jackson, a Cambrian limestone is thrust over a Cretaceous shale. There is cataclastic deformation (breccia) in the footwall of the Muddy Mountain fault but no brecciation appears in the footwall of the Jackson fault. Finally, Brock and Engelder (1977) proposed that the Muddy Mountain thrust sheet slid down a pre-existing slope (gravity slide).

A comparison with Lageson's data (1980) on the Absaroka fault of Wyoming reveals similarities with the Jackson fault, with differences primarily in the details. Zones A and B of both the Absaroka and Jackson thrust faults are at approximately the same distances from the fault plane. The breccia fragments are approximately the same size in zone A, but are larger in zone B on the Absaroka thrust than on the Jackson thrust fault. Sorting in the hanging wall increases as the fault plane is approached in both cases. Minor brecciation occurs in the footwall of the Absaroka fault (Jurassic limestone), but no brecciation occurs in the footwall of the Jackson fault (Cretaceous shale).

From the above review and interpretations, it is suggested that sorting of breccia fragments may be a possible indicator of mode of movement along a thrust sheet. In the case of gravity sliding, where movement may be essentially a one-time event, the sorting of the breccia fragments is poorer relative to the original sorting of the rock unit, such as with the Muddy Mountain thrust fault. On the other hand, thrust faults interpreted to have formed as a result of lateral compression, such as the Jackson and Absaroka faults, tend to have more well sorted fragments nearer the fault plane. It is suggested that the increase in sorting of the fragments nearer the fault, may be due to multiple reworking and milling of the fragments during the spasmodic advancement of the thrust sheet over long priods of time.

SUMMARY

It is interpreted that lateral compression resulted in movement along the Jackson thrust fault, with tectonic transport of the Jackson thrust sheet being accomplished primarily by stick-slip motion. Lack of brecciation in the footwall and an increase in the degree of sorting of the breccia fragments suggests that gravity sliding was not the cause of movement. The 8% average dilatancy is interpreted to represent the presence of pore fluid which probably aided in movement of the Jackson

thrust sheet by reducing the normal stress. Reduced cohesion between the hanging wall rock (Gallatin Limestone) and footwall rock (Cretaceous Bear River Formation) aided in effectively reducing the frictional resistance to slip. Lack of evidence for stable sliding, such as a discrete fault plane, further substantiates the proposition that movement along the Jackson thrust fault was accomplished by stick-slip motion. It is believed that the presence of tectonic breccia effectively lowered the frictional resistance to slip and aided in movement by acting like ball bearings.

ECONOMIC DISCUSSION

Prolonged and intensive mechanical shearing along thrust faults produces drastic changes in the texture of the fault-zone material which affects the shear strength, permeability of fluid flow, capillary properties, and other petrophysical properties (Mandl, 1977). Fault geometry and the characteristics of the fault-zone material are of primary importance in the search for, and analysis of, hydrocarbon accumulation. When faults occur, two economic questions arise: (1) what is the impact of the fault on reservoir porosity and permeability, and (2) does a trap exist? The following is a discussion of two schools of thought concerning the effect of fault-zone cataclasis on hydrocarbon accumulation and migration and its application to the Idaho-Wyoming foreland fold and thrust belt.

Pittman's work (1981) with quartz sandstones of the Simpson Group of Oklahoma (Ordovician) revealed that permeability and porosity was reduced in the cataclastically deformed areas along faults. Granulation caused by cataclasis creates fault zone material that is cellular in nature. The drastic reduction in pore aperture size in the granulated rock creates the potential for fault-sealing traps. When sandstone is faulted against shale, the small pore apertures of the shale create an updip seal regardless of the nature of the fault zone. When sandstone is faulted against sandstone two possibilities exist: (1) the fault may be a seal or (2) the fault may be an updip migratory path for the hydrocarbons.

Mandl and others (1977) found in their experimental work that porosity and permeability increased along cataclastically deformed areas associated with faults. They found that the material closest to the fault zone was much finer than the surrounding material outside the zone, resulting in the pore size of the zone being 1,000 times smaller than the surrounding material. This implies that the capillary pressure of the fault zone is 1,000 times greater than outside the zone. If this is true, the capillary pressure that a non-wetting fluid (oil, gas) has to overcome in replacing a wetting fluid (water) in the fault zone will be approximately 1,000 times greater (Mandl and others, 1977). Pittman observed a bimodal grain size distribution, whereas Mandl reported an increase in the degree of rounding in the shear zone. Mandl concludes that the porosity has increased and the grain surface per unit bulk volume has been reduced. The reduction in the internal surface area increases permeability, since permeability is proportional to the third power of porosity divided by the square of the specific internal surface (Mandl and others, 1977).

Data from the oil and gas fields of the Idaho-Wyoming foreland fold and thrust belt does not support either hypothesis. Hydrocarbon accumulation is dependent on the juxtaposition of a source rock against a reservoir rock. As in the case of Rykman Creek and Table Rock fields, the hydrocarbons are produced from sandstone units (Triassic Woodside Formation and Jurassic Nugget Sandstone) in the hanging wall of a thrust fault that are in fault contact with shales (Lower Cretaceous) or other source rocks in the footwall (Atherton, personal communication, 1982). It appears that the hydrocarbons have migrated across the fault into the reservoir rocks in the hanging wall and have been trapped in the associated hanging wall anticlines.

The examples would tend to support Mandl's hypothesis that permeability is increased in the cataclastically deformed fault-zone material. In the Snakehead Anticline field the producing horizon is the Twin Creek Formation which is a calcareous shale and shalely limestone which owes its porosity to fracturing that is not fault related (Wood, personal communication, 1982). This would imply that faults are sealing features. Many thrust faults are cemented at the surface therefore, it is reasonable to assume that permeability increases during faulting allowing migration of hydrocarbons across the fault into the reservoir rock, and later secondary cementation renders the fault impermeable.

There is no evidence that totally supports either hypothesis, therefore, the relationship between fault breccia and its influence on fault zone characteristics is more likely some combination of both. The complex interaction between fault geometry and the cataclastic deformation associated with thrust faulting greatly complicates the history of hydrocarbon migration and accumulation. Fault geometry and shear zone characteristics are only two variables among many, but further study should reveal some relationships between the two that would aid in economic exploration and exploitation.

CONCLUSIONS

Movement on the frontal Jackson thrust fault occurred in Late Paleocene-Early Eocene time and is interpreted to have been caused by lateral compression from the west-southwest. It is suggested that movement was accomplished by stick-slip motion and was aided by: (1) reduced cohesion between hanging wall and footwall rock units, (2) a decrease in normal stress as a result of an increase in pore fluid pressure, and (3) presence of breccia fragments acting like ball bearings reducing the frictional resistance to slip.

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APPENDIX

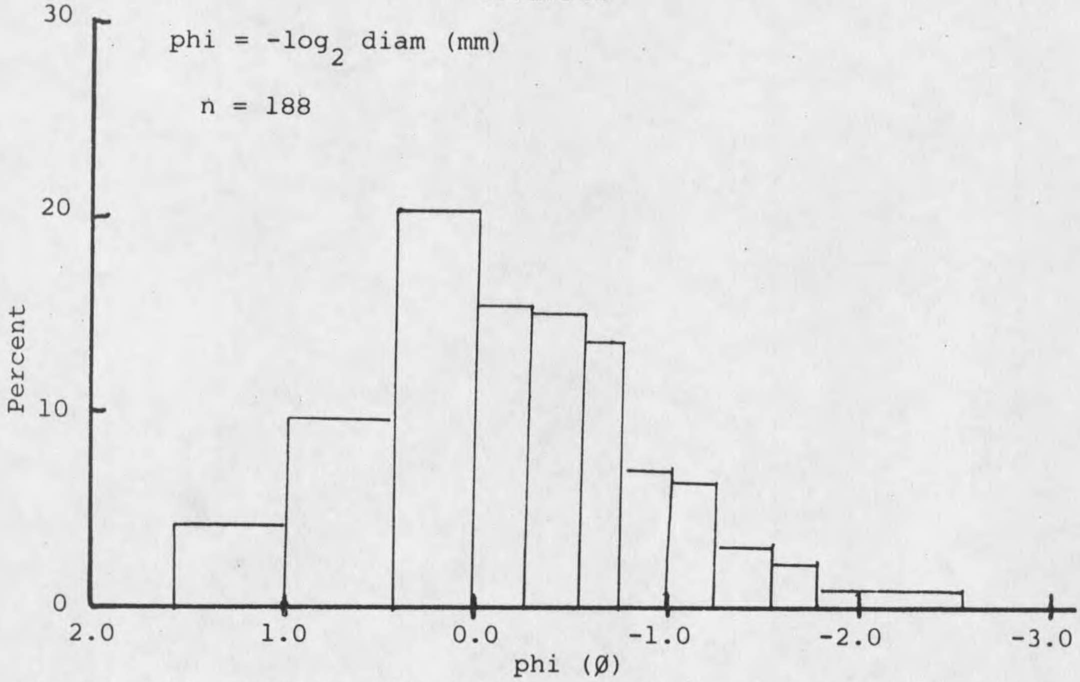

Figure 21. Size distribution of breccia fragments in hanging wall 0.15 m from the Jackson fault.

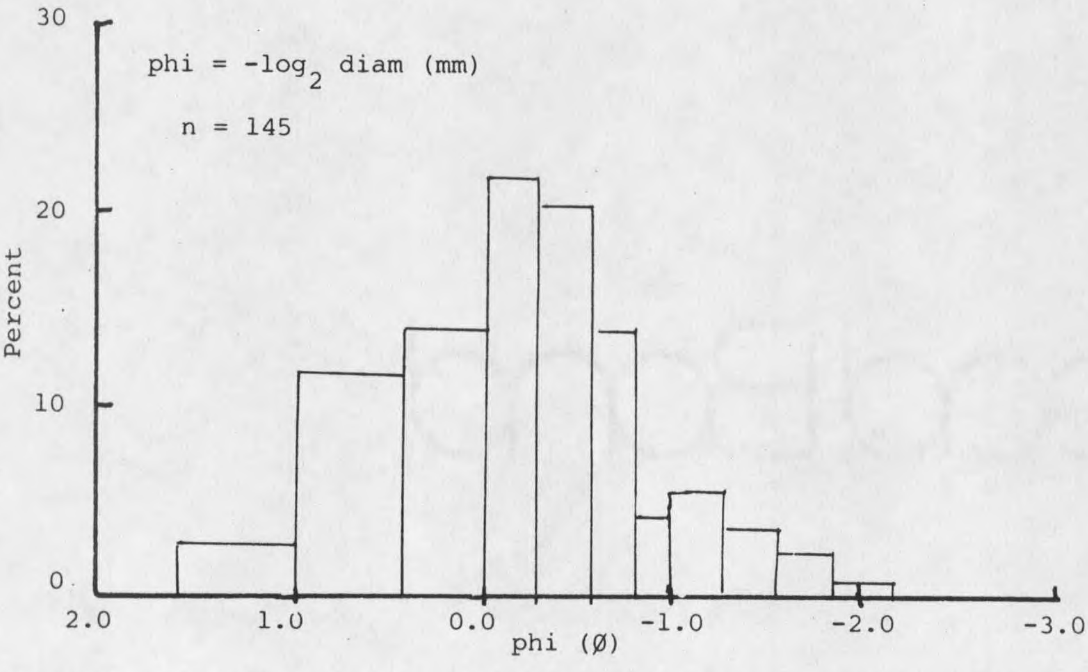

Figure 22. Size distribution of breccia fragments in hanging wall 0.31 m from the Jackson fault.

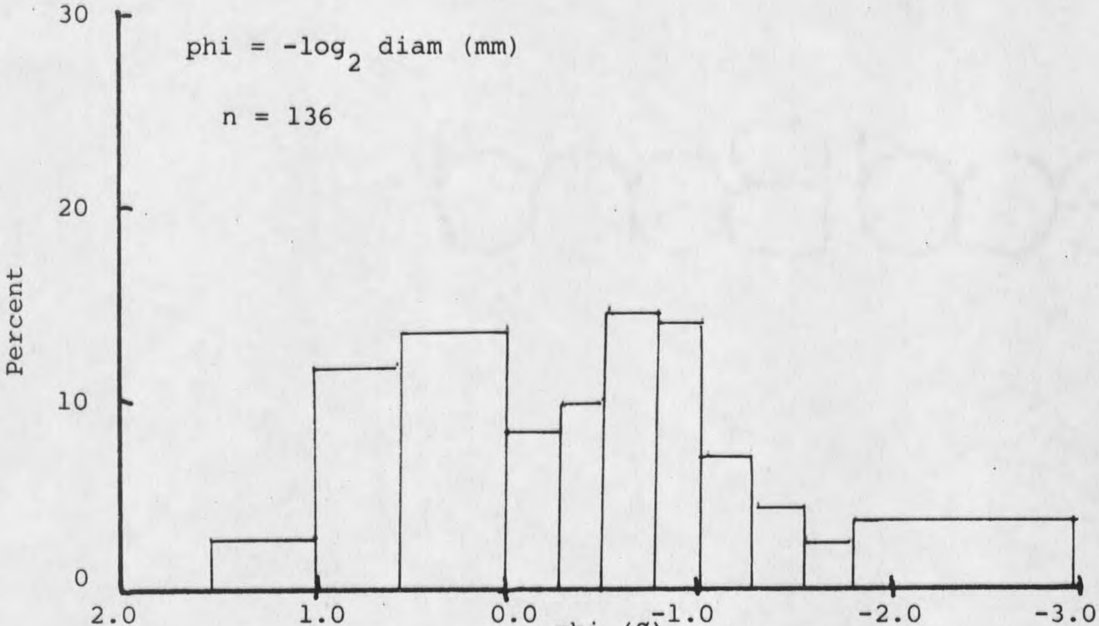

Figure 23. Size distribution of brecca fragments in hanging wall .46 m from the Jackson fault.

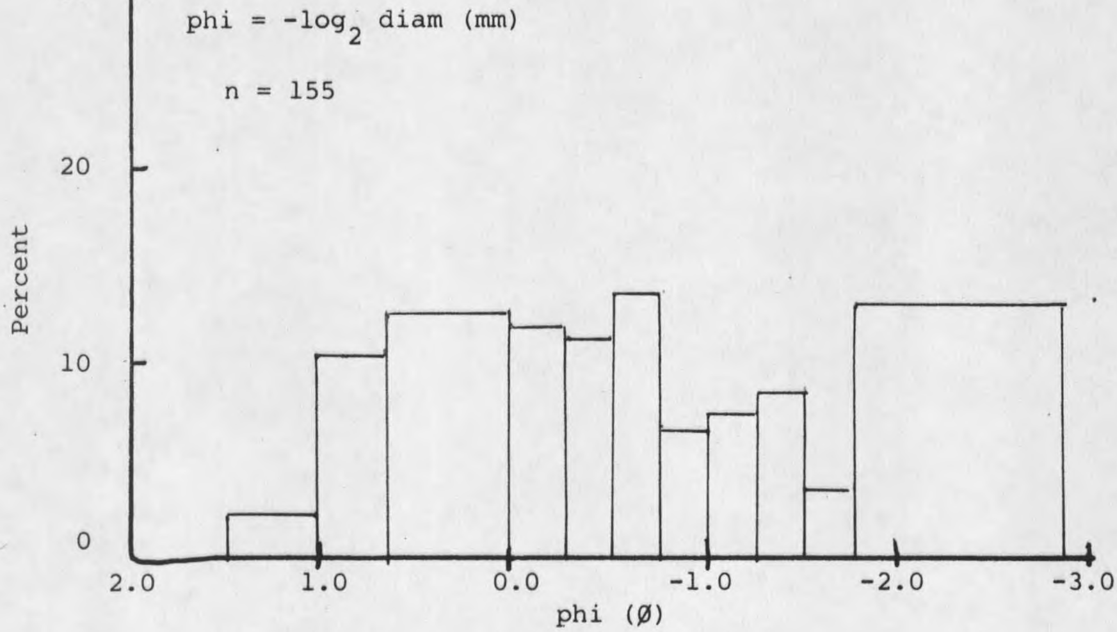

Figure 24. Size distribution of breccia fragments in hanging wall .66 m from the Jackson fault.

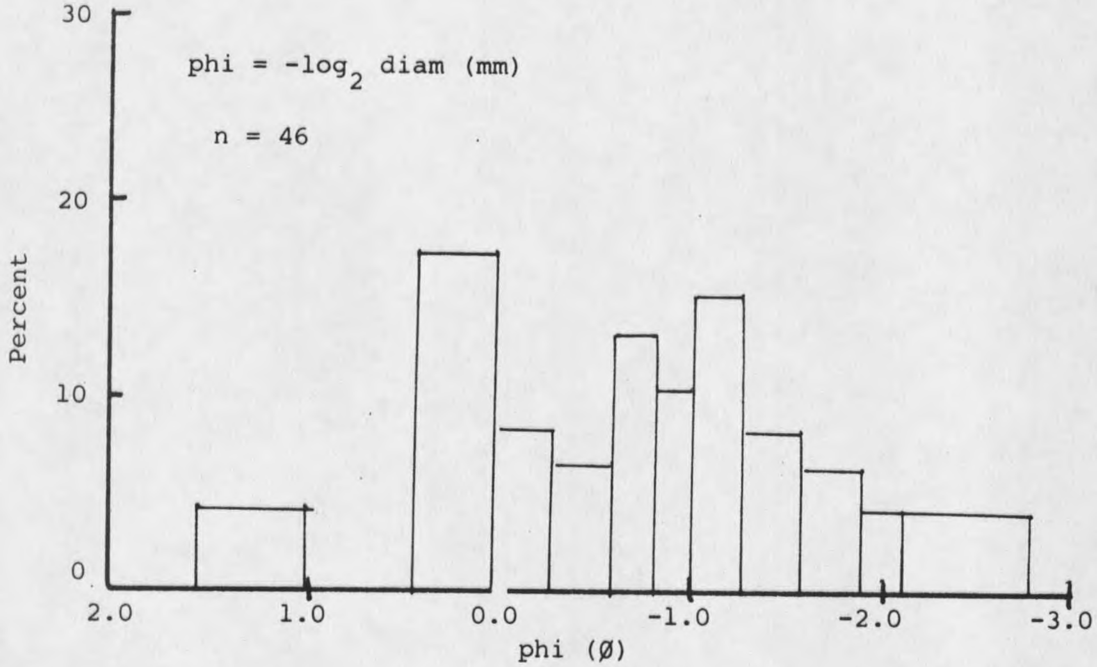

Figure 25. Size distribution of breccia fragments in hanging wall .91 m from the Jackson fault.

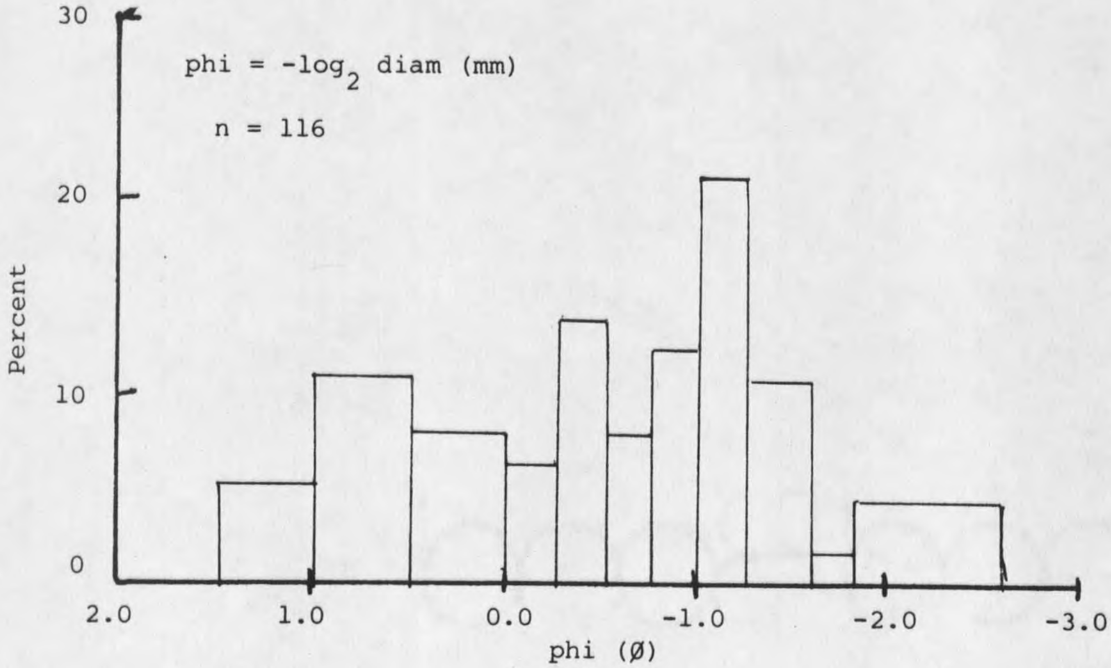

Figure 26. Size distribution of breccia fragments in hanging wall 1.32 m from the Jackson fault.