



Characterization of spaced cleavage, Sawtooth Range, Montana
by Paul A Thorn

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

Montana State University

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Abstract:

The Sawtooth Range is part of the eastern front of the Sevier orogenic belt in northwestern Montana (also called the Montana disturbed belt)(Fig. 1). Spaced cleavage (cleavage comprising discrete domains with a spacing of greater than 1mm) has been identified in the Jurassic Rierdon Formation within this geologic setting. The cleavage forms by the preferential dissolution of calcite as a stress is being applied, allowing relatively insoluble minerals to accumulate along thin domains. Spaced cleavage has been documented in several other areas in similar tectonic settings all over the world. However, cleavage tends to be best developed further back in the fold and thrust belt, decreasing in intensity towards the foreland regions. In contrast the cleavage in the Sawtooth Range has its strongest cleavage in the outermost thrust sheets.

The cleavage in Sawtooth Range has formed in thin limestone beds interbedded with thicker units of mudstone. The cleaved limestone is argillaceous, containing between 4.5% to 44.5% insoluble (non-carbonate) minerals. Insoluble minerals present in the limestone include predominately quartz, clay (about 95% illite, 5% expandable), with minor amounts of pyrite, barite, and apatite. The fossil content within the limestone is variable, containing from less than one percent to over eighty percent fossil fragments.

The cleavage intensity across the Sawtooth Range is highly variable. The intensity ranges from the limestone remaining uncleaved to over 4 domains per centimeter. This variability occurs both regionally and within an individual outcrop. Changes in limestone composition, including the percent insoluble mineral and fossil fragments, play the predominate role in the cleavage variation. Structural position, however, may play a significant influence in the regional cleavage variations.

The percent of shortening accommodated by the formation of spaced cleavage was calculated. In the cleaved units, the shortening accommodated ranged from 2.2% to 24.0% with an average of 13.6%. The amount of shortening accommodated by cleavage formation showed no correlation with cleavage intensity. Cleavage intensity was found to be a function of limestone composition and cleavage domain thickness rather than percent shortening.

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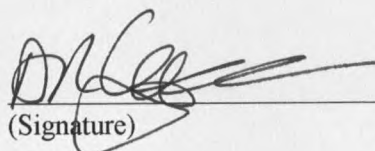
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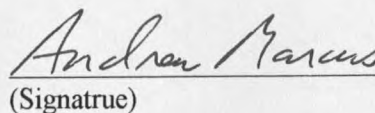
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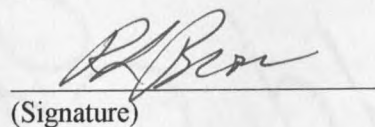
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ABSTRACT

The Sawtooth Range is part of the eastern front of the Sevier orogenic belt in northwestern Montana (also called the Montana disturbed belt)(Fig. 1). Spaced cleavage (cleavage comprising discrete domains with a spacing of greater than 1mm) has been identified in the Jurassic Rierdon Formation within this geologic setting. The cleavage forms by the preferential dissolution of calcite as a stress is being applied, allowing relatively insoluble minerals to accumulate along thin domains. Spaced cleavage has been documented in several other areas in similar tectonic settings all over the world. However, cleavage tends to be best developed further back in the fold and thrust belt, decreasing in intensity towards the foreland regions. In contrast the cleavage in the Sawtooth Range has its strongest cleavage in the outermost thrust sheets.

The cleavage in Sawtooth Range has formed in thin limestone beds interbedded with thicker units of mudstone. The cleaved limestone is argillaceous, containing between 4.5% to 44.5% insoluble (non-carbonate) minerals. Insoluble minerals present in the limestone include predominately quartz, clay (about 95% illite, 5% expandable), with minor amounts of pyrite, barite, and apatite. The fossil content within the limestone is variable, containing from less than one percent to over eighty percent fossil fragments.

The cleavage intensity across the Sawtooth Range is highly variable. The intensity ranges from the limestone remaining uncleaved to over 4 domains per centimeter. This variability occurs both regionally and within an individual outcrop. Changes in limestone composition, including the percent insoluble mineral and fossil fragments, play the predominate role in the cleavage variation. Structural position, however, may play a significant influence in the regional cleavage variations.

The percent of shortening accommodated by the formation of spaced cleavage was calculated. In the cleaved units, the shortening accommodated ranged from 2.2% to 24.0% with an average of 13.6%. The amount of shortening accommodated by cleavage formation showed no correlation with cleavage intensity. Cleavage intensity was found to be a function of limestone composition and cleavage domain thickness rather than percent shortening.

CHAPTER 1

INTRODUCTION

The Sawtooth Range is part of the eastern front of the Sevier orogenic belt in northwestern Montana, also called the Montana disturbed belt (Fig. 1). It lies directly south of Glacier National Park and north of the Helena Salient and consists of a series of imbricate thrust faults with Mississippian through Cambrian strata displaced over Cretaceous mudstones (Mudge, 1972b). Spaced cleavage, characterized by discrete domains with a spacing of greater than 1mm, has been identified in the Jurassic Rierdon Formation within this geologic setting. Spaced cleavage has been identified in foreland fold and thrust belts throughout the world (e.g., Alvarez and others, 1978; Spang and others, 1979; Yonkee, 1983; Marshak and Engelder, 1985; Wright and Henderson, 1992). The cleavage tends to be the best developed in the central portions of fold and thrust belts, decreasing in intensity towards the foreland region, and generally becoming absent in frontal thrust sheets (Yonkee, 1983; Mitra and Yonkee, 1985; Sears, 1988; Protzman and Mitra, 1990). The Sawtooth Range is an exception to this rule in that it exhibits penetrative spaced cleavage within the outermost thrust sheets.

Pressure solution is widely recognized as the principal mechanism in the formation of spaced cleavage, with calcite and dolomite being the dominant minerals removed in carbonate rocks (Wanless, 1979; Engelder and Marshak, 1985; Groshong, 1988; Wright and Henderson, 1992). Under high pressures, calcite and dolomite are dissolved along grain to grain contacts perpendicular to the maximum stress, σ_1 (Engelder and Marshak, 1985; Mitra and Yonkee, 1985; Protzman and

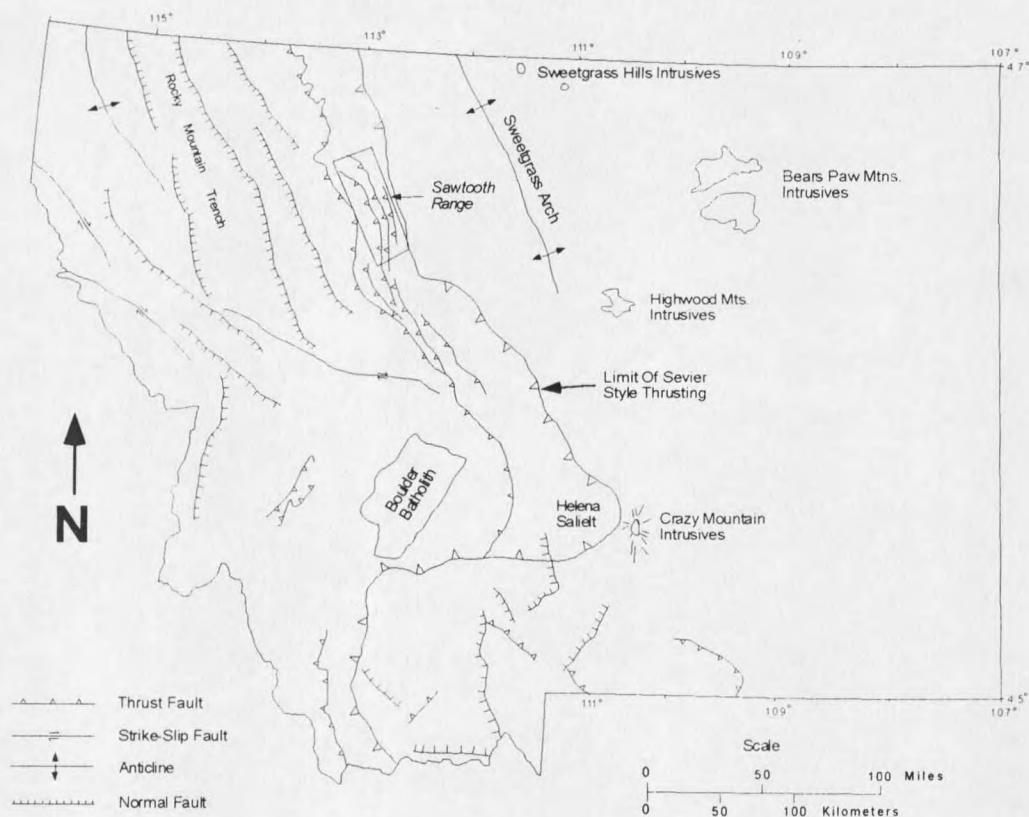


Figure 1. Generalized tectonic map of central and western Montana (Modified from Taylor and Ashley, 1986), illustrating major tectonic features.

Mitra, 1990). As calcite and dolomite are removed, relatively insoluble minerals, such as quartz, hematite and clay minerals, are left behind and concentrated in thin seams to form cleavage domains (Wanless, 1979; Engelder and Marshak, 1985). These domains form perpendicular to the local σ_1 , whereas calcite precipitates at sites of the lowest normal stress (e.g., extensional cracks or pressure shadows) or is carried out of the system via advection in the groundwater system (Wanless, 1979; Carrio-Schaffhouser and Gaviglio, 1990).

The presence of spaced cleavage reveals significant information pertinent to the analysis of internal deformation within fold and thrust belts. Since cleavage forms perpendicular to the local direction of maximum stress (σ_1), the cleavage plane orientation provides a kinematic indicator of the direction of maximum shortening in the thrust system (Engelder and Marshak, 1985; Mitra and

Yonkee, 1985; Soper, 1986). Also, the formation of spaced cleavage in an open system produces significant volume loss (internal strain) within a given unit, adding to the amount of regional shortening calculated from balanced cross-sections (Nickelson, 1986; Protzman and Mitra, 1990; Wright and Henderson, 1992). Previous studies have indicated that internal shortening by this mechanism commonly totals between 20% and 30%, and can reach as high as 50% of the entire formation (Nickelson, 1986; Protzman and Mitra, 1990; Wright and Henderson, 1992). This large degree of internal shortening should be taken into account in balanced cross sections and palinspastic restorations.

This study was undertaken to determine the amount of internal shortening accommodated by the spaced cleavage in the Rierdon Formation of the Sawtooth Range, Montana. Associated goals for the project include: 1) to describe in detail mesoscopic characteristics of spaced cleavage and its distribution within the Sawtooth Range; 2) to describe in detail microscopic characteristics of spaced cleavage; 3) to provide evidence for cleavage initiation, development and timing; 4) to provide a reconnaissance investigation of the stratigraphic variations of cleavage development and how these variations may be important to balanced cross-sections and palinspastic restorations; 5) to compare cleavage development in the Sawtooth Range with cleavage development in other fold and thrust belts in order to determine the reason for cleavage development in the outermost thrust sheets in the Sawtooth Range; and 6) to suggest possible influences that cleavage may have on petroleum and groundwater reservoir qualities.

Study Area

To achieve the defined goals of this thesis project, field studies combined with in-depth laboratory analyses were conducted. The primary area of investigation includes all Rierdon Formation outcrops within the outermost four thrust sheets of the Sawtooth Range, where Paleozoic

rocks have been displaced over Cretaceous strata. The other boundaries are Ford Creek in the south and Swift Reservoir (Birch Creek) to the north (Plate 1). The outermost thrust sheets were selected in order to focus on the question of how much shortening is accommodated by the cleavage formation at the frontal edge of the thrust belt. Additionally, Rierdon outcrops in the Sun River Canyon were studied to provide some constraint on cleavage development in the middle of the Sawtooth Range. A preliminary investigation of Mississippian and Devonian strata in the Teton River area and the Sun River Canyon area was undertaken to determine if cleavage or any other deformational fabric is present in these carbonate units, which provides an indication of the stratigraphic variability of the cleavage in the Sawtooth Range.

CHAPTER 2

BACKGROUND

Geologic Setting

The Sawtooth Range is located along the eastern margin of the Sevier orogenic belt, west of Augusta and Choteau, Montana, and south of Glacier National Park (Figs. 1 and 2). The range forms an arcuate zone, approximately 100 km long and 20 km wide, of closely spaced, north-trending, west-dipping, imbricate thrust faults and related folds, bounded on the west by the Lewis thrust system and on the east by the foothills province of the Rocky Mountains (Mudge, 1972b). Paleozoic carbonate rocks have been thrust over Cretaceous mudstone, with the resistant carbonate strata forming a repeating pattern of asymmetric ridges, similar to the teeth on a rip saw (Fig. 3). The spacing of these ridge-bounding thrust faults varies from 0.8 to 1.5 km (Mudge, 1965; 1966; 1967; 1968). Contractual deformation occurred during the early Tertiary between 56 and 50 Ma (Mudge, 1970; Hoffman and others, 1976; Altaner and others, 1984; Ellison, 1991).

Mudge (1972b; 1982) has divided the northern portion of the Montana fold and thrust belt into four subbelts on the basis of stratigraphic and structural characteristics (Fig. 4). Subbelt I consists of Cretaceous strata with imbricate thrust faults and related folds. Subbelt II contains imbricate thrust faults displacing Paleozoic rocks over Cretaceous strata, and related folds (Mudge, 1972b; 1982). These faults have a much greater displacement than in subbelt I, with stratigraphic separations of up to 1800m (6000 feet) (Mudge, 1982). Subbelt III comprises Mesozoic strata repeated by imbricate thrust faults. These faults contain no Paleozoic strata, and have been

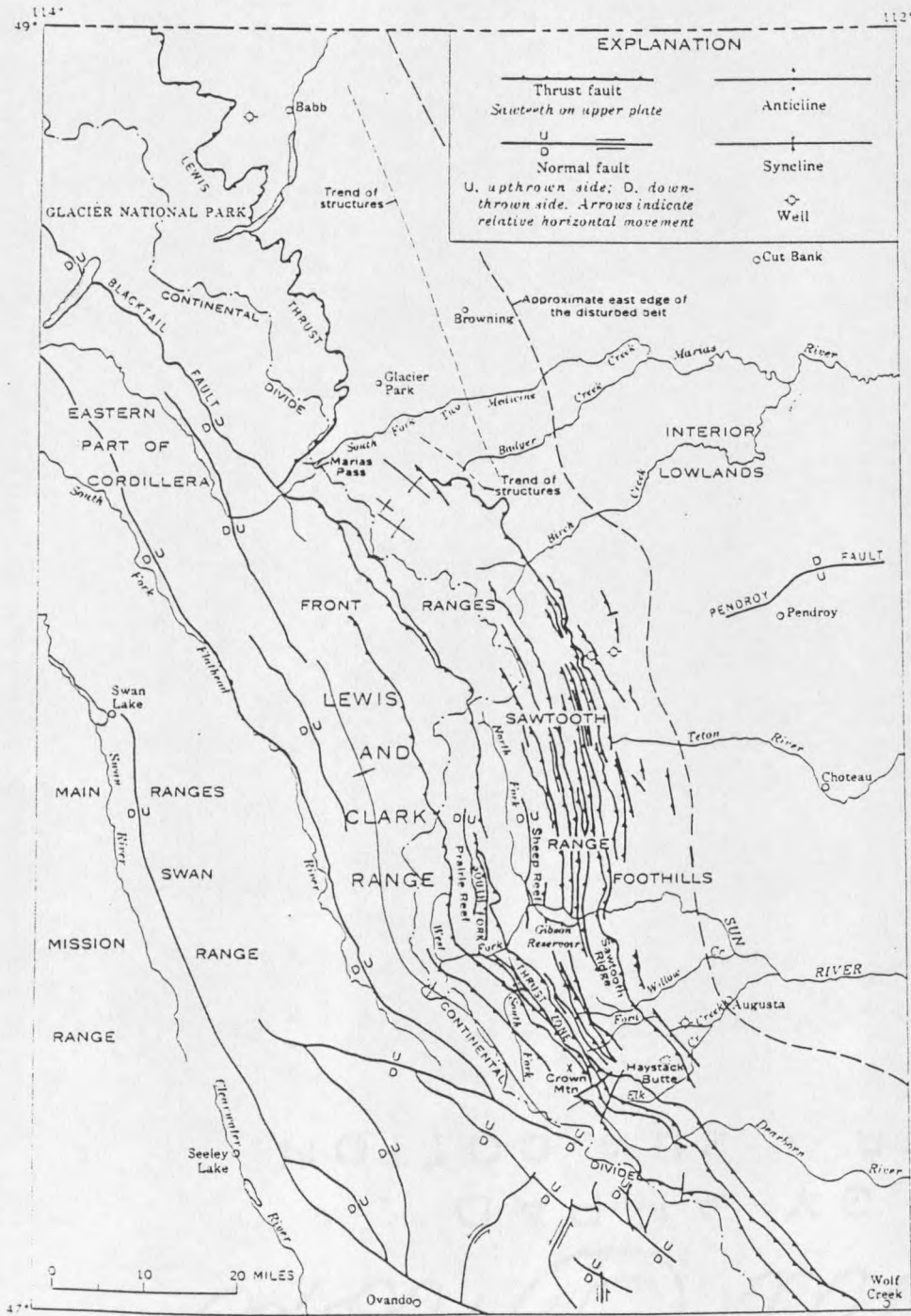


Figure 2. Structural map of the Sawtooth Range and surrounding area (from Mudge, 1972b).



Figure 3. Aerial photograph of the Sawtooth Range. The repeating ridges are composed of Mississippian and Devonian carbonates thrust over Cretaceous strata, which forms the valleys. The view looks north into the Sun River Canyon area, with the Gibson Reservoir on the left.

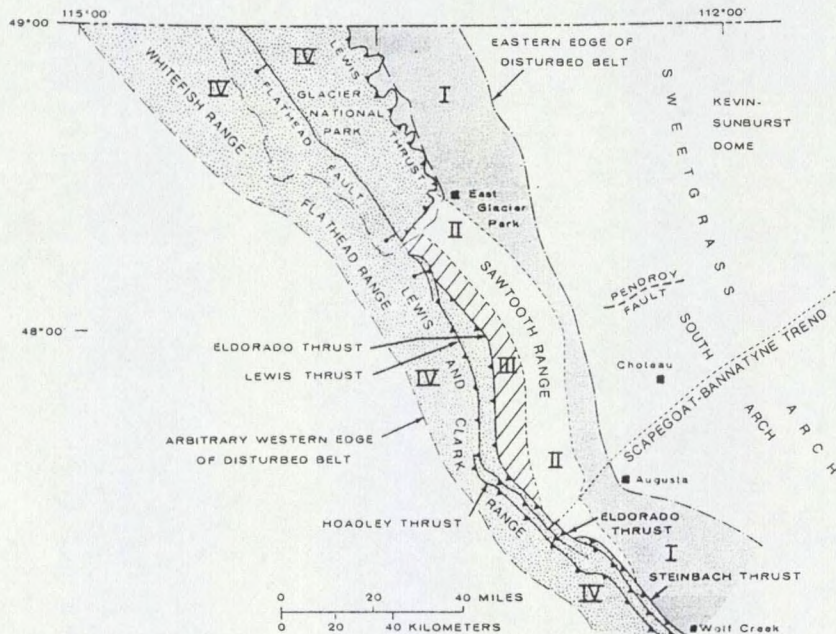


Figure 4. Subbelt division of the Northern Disturbed Belt (From Mudge, 1982).

overridden by the Lewis thrust to the north and Eldorado thrust to the south (Mudge, 1982). Subbelt IV contains thrust and folded Proterozoic and Paleozoic strata. The eastern boundary of the belt is the Lewis/Eldorado/Steinbach thrust system (Mudge, 1972b; 1982). The study area is located within subbelt II.

The imbricate thrust geometry of the Sawtooth Range could have formed either as a trailing imbricate fan or as a hinterland dipping fault duplex fault zone (Boyer and Elliot, 1982). A trailing imbricate fan has repeating thrust faults forming progressively toward the foreland, in front of the thrust with the largest amount of displacement (Fig. 5)(Boyer and Elliot, 1982; McClay, 1992, Fig. 20 on p. 424). The faults of the imbricate fan lose their displacement up-section into fault propagation folds, or by distributing it among several splays (Mitra, 1986). Conversely a hinterland dipping duplex consists of an array of thrust faults bounded by a floor thrust and a roof thrust, with the slip on each imbricate fault transferred to the roof detachment (Fig. 6) (Boyer and Elliot, 1982; Mitra, 1986; McClay, 1992, Fig. 26 on p. 426). In the trailing imbricate fan model (Fig. 5), the thrust with the greatest displacement is the Lewis thrust to the west, with the imbricate thrusts of the Sawtooth Range progressing towards the east (foreland). In the hinterland dipping duplex model, the floor thrust is the basal decollement, and the roof thrust is the Lewis thrust. This roof thrust has been interpreted to have been completely eroded away in the Sawtooth Range (Singdahlsen, 1986; Mitra, 1986). Although both models can theoretically produce the geometry observed, the trailing imbricate fan model is preferred by the author because many of the thrusts die out into folds (blind imbricate complex; McClay, 1992, fig.20 on p. 424), both within the range and at the northern termination of the range (Fig. 6)(Mudge and Earhart, 1983), and due to the fact that the duplex model would require large north-south variations in the amount of shortening on the Lewis thrust system, which are not documented (Mudge and Earhart, 1980).

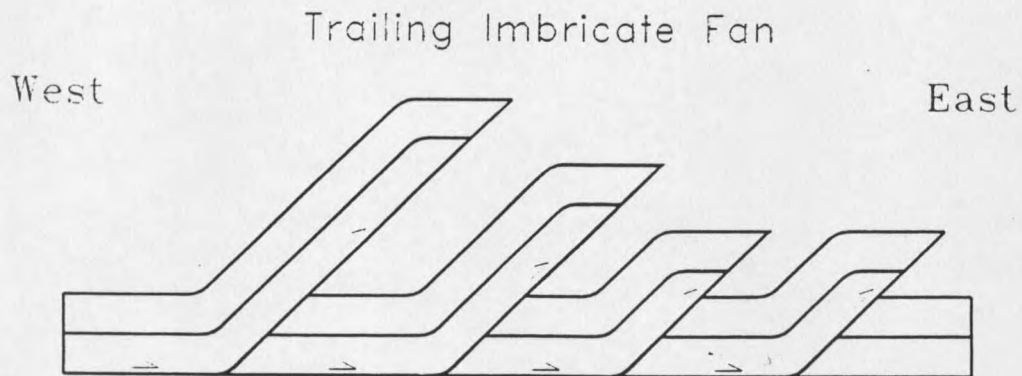


Figure 5. Illustration showing the geometry of a trailing imbricate fan. Note that the largest amount of displacement occurs towards the hinterland portion, with displacement decreasing towards the foreland (modified from McClay, 1992, p. 424).

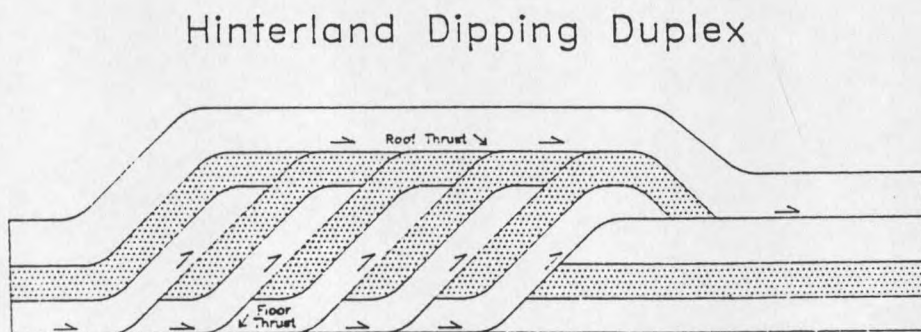


Figure 6. Illustration showing the geometry of a hinterland dipping duplex (modified from McClay, 1992, p. 426). The Lewis thrust would be the roof thrust in the diagram.

The stratigraphy of the Sawtooth Range has been described in terms of its effect on the structural style during contractional deformation. Three dominant lithotectonic zones have been identified in the range (Fig. 7) (Singdahlsen, 1986; Ihle and Lageson, 1987; Ihle, 1988; Lageson and Schmitt, 1994). Zone 1 consists of Cambrian strata, characterized by interbedded limestone and mudstone deformed into tightly spaced, isoclinal, disharmonic folds and imbricate thrust faults (Singdahlsen, 1986; Ihle, 1988; Lageson and Schmitt, 1994). Pressure-solution cleavage and fracturing is present in the thicker limestone beds, while boudinage and pencil cleavage characterize the thin carbonates and mudstones (Ihle, 1988; Lageson and Schmitt, 1994). Zone 2 consists of Devonian dolomite and Mississippian limestone and dolomite (Madison Group). This zone is dominated by massive carbonate units, with kilometer-scale kink and semi-concentric folds (Ihle, 1988; Lageson and Schmitt, 1994). Zone 3 consists of the Jurassic and Cretaceous succession of interbedded sandstone, mudstone, and thin argillaceous limestone. This zone is dominated by closely spaced imbricate thrust faults and tight folds, with strong pencil cleavage in mudstones and pressure solution cleavage in argillaceous limestone beds (Ihle, 1988; Lageson and Schmitt, 1994). A more detailed description of the stratigraphic section in the Sawtooth Range is given by Mudge (1972a).

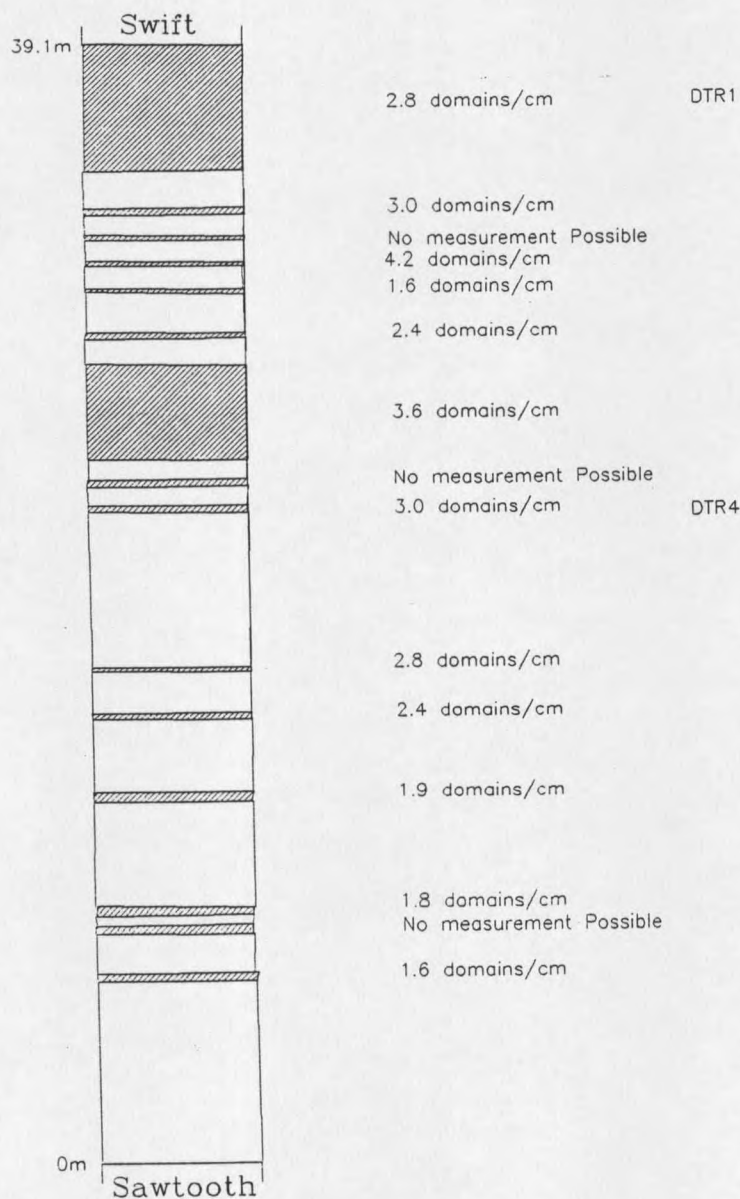
Rierdon Formation

The Rierdon Formation consists of calcareous mudstone interbedded with thin beds of limestone (Cobban, 1945; Mudge, 1972a). The limestone beds are generally between 10cm and 30cm in thickness, but occasionally are as thick as 1m (Figs. 8 and 9). The mudstone beds are often calcareous and commonly contain pencil structures, created by the intersection of closely spaced fractures with bedding. No cleavage development has occurred within mudstone.

The limestone beds are classified as gray to gray brown biomicrites or gray brown micrites (Mudge, 1972a). The argillaceous component varies from 3% to over 40%. The fossil content of the

Stratigraphic Column		Lithotectonic Unit	Stratigraphic Unit				
Cretaceous		ZONE 3 Interbedded limestone, sandstone, shale and mudstone. Style: Closely spaced thrust faults and fold trains. Cleavage is present in argillaceous limestones, with pencil structures in the shales.	Two Medicine Fm	1430–2260m			
			Virgelle Sandstone				
			Telegraph Creek Fm				
			Marias River Shale				
			Blackleaf Formation				
			Kootenai Formation				
Jurassic		Morrison Formation Swift Formation Rierdon Formation Sawtooth Formation					
Devonian/Mississippian			ZONE 2 Massive dolomite and limestone. Style: Kilometer-scale concentric, chevron and box folds, with imbricate thrust faults.		Castle Reef Dolomite	560–880m	
		Allan Mountain Ls					
	Three Forks Formation Jefferson Formation Maywood Formation						
Cambrian	ZONE 1 Interbedded carbonates and shales. Style: Closely spaced disharmonic folds and imbricate thrusts.		Devils Glen Dolomite Switchback Shale Steamboat Limestone Pentagon Shale Pagoda Limestone Damnation Limestone Gordon Shale Flathead Sandstone	350–725m			

Figure 7. Generalized stratigraphic column and lithotectonic divisions for the Sawtooth Range (after Mudge, 1972a; Ihle, 1988; Lageson and Schmitt, 1994).



Shaded areas represent argillaceous limestones.
 Unshaded areas represent shales and silty mudstones.
 Cleavage intensities for the limestones given to the right of the column.
 Sample name indicated if a sample was collected from the bed.

Figure 8. Measured section of the Jurassic Rierdon Formation. The section was measured at station 1 near the souther termination of the Diversion thrust.



Figure 9. Jurassic Rierdon Formation outcrop. Note the repeating, thin, resistant limestone beds separating the less resistant mudstone. Person for scale.

limestone beds range from less than 1% to up to 80% (Mudge, 1972a). The fossils are predominately ammonites, gastropods and *Gryphaea* (Mudge, 1972a). A more detailed description of fossil taxa is provided by Mudge (1972a, p. A47). Sparry calcite occurs only in isolated veins and recrystallized shell fragments. Stained thin sections and SEM results have shown that no dolomitization has occurred (Mudge, 1972a; this study).

Cleavage Classification

The term "cleavage" as used in this thesis, is defined as "...the tendency of a rock to break along surfaces of a specific orientation" (Twiss and Moores, 1992, p. 263). The fabric elements in which the original rock has been altered by deformational processes are commonly referred to as domains, whereas the undeformed matrix lying in between adjacent domains is referred to as microlithons (Fig. 10)(Engelder and Marshak, 1985; Twiss and Moores, 1992, p.263).

There are two principal characteristics that have been used to classify cleavage: the cleavage domain spacing (intensity) and cleavage shape or morphology (Borradaile and others, 1982). A detailed classification scheme based on these parameters is given by Twiss and Moores (1992, p. 263)(Fig. 11). Cleavage is divided into two categories, continuous and spaced (Figure 12).

Continuous cleavage is defined as having a spacing of less than 10 μ m and is generally referred to as slaty cleavage (Engelder and Marshak, 1985; Twiss and Moores, 1992, p.263). Continuous cleavage is further divided on the basis of grain size of the deformed rock. The classification of *spaced* cleavage, with a domain spacing of more than 10 μ m, is more complex. Spaced cleavage is subdivided into three distinct categories: compositional, disjunctive and crenulation (Fig. 11).

Compositional spaced cleavage is marked by layers of different mineralogical composition, where the rock has a tendency to break parallel to these compositional layers (Twiss and Moores, 1992, p. 263). This can either be *diffuse*, with widely spaced, weak concentrations of minerals, or *banded*, with closely spaced, distinct layers (Twiss and Moores, 1992, p. 263). *Disjunctive spaced* cleavage is defined as detached cleavage domains, generally formed by pressure solution in previously unfoliated rocks, and generally cross-cutting pre-existing sedimentary layering within the rock (Engelder and Marshak, 1985; Twiss and Moores, 1992, p. 264). This is further divided into four categories based on domain geometry: *stylolitic*, *anastomosing*, *rough*, and *smooth* (Fig. 12).

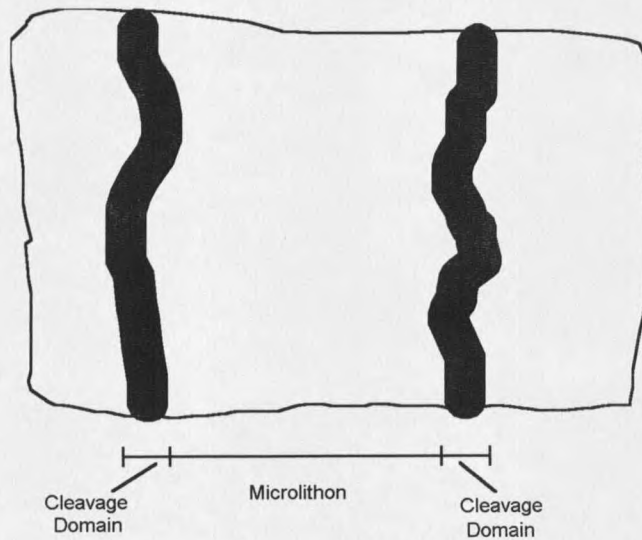


Figure 10. Illustration of domains and microlithons within a cleaved rock. The domain consists of concentrated insoluble minerals and the microlithons are the undeformed rock between the domains.

Cleavage	Spaced	Compositional	Diffuse
			Banded
		Disjunctive	Stylolitic
			Anastomosing
			Rough
			Smooth
		Crenulation	Zonal
			Discrete
	Continuous	Fine	Microcrenulation
			Microdisjunctive
			Microcontinuous
		Coarse	

Figure 11. Cleavage classification based on cleavage morphology and intensity (from Twiss and Morres, 1992, p. 263).

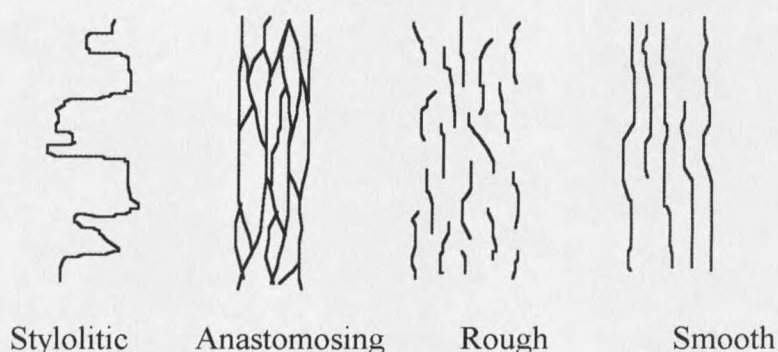


Figure 12. Sketch illustrating the different domain geometries seen in spaced cleavage (after Twiss and Moores, 1992, p. 263).

Crenulation spaced cleavage is defined as small scale harmonic wrinkles or chevron folds that develop in a pre-existing foliation. The cleavage forms on the fold limbs, which become attenuated as platy minerals align, creating a surface for the rock to break along. The microlithons comprise the fold hinges. Crenulation cleavage can either be zonal or discrete based on the angle of the platy minerals to the cleavage domain (Twiss and Moores, 1992, p. 266).

A second classification scheme, developed by Alvarez and others (1978), is used to describe cleavage intensity. This scheme uses four categories of domain spacing as its main criterion: weak, moderate, strong, and very strong (Fig. 13). Classification by intensity is a quick and simple way of describing the cleavage development in hand sample or in outcrop, and is easily applied in the field. It is, however, restricted to the description of spaced cleavage (Engelder and Marshak, 1985). Both classification schemes will be used in this thesis.

Process of Cleavage Formation

The development of disjunctive spaced cleavage in sedimentary rocks deformed at shallow depths has been shown in laboratory and field studies to be primarily a result of rock-water

<i>Spaced Cleavage</i>			<i>Slaty Cleavage</i>
Weak	Moderate	Strong	Very Strong
10 cm	1 cm	1 mm	0.1 mm

Domain Spacing

Figure 13. Cleavage classification scheme based on domain intensity (Alvarez and others, 1978).

interactions (i.e. Alvarez and others, 1976; Borradaile and others, 1982; Engelder and Marshak, 1985; Bhagat and Marshak, 1990; Wright and Henderson, 1992). There are predominately four modes of rock-water interaction: pressure solution, free face dissolution, diffusion in fluid films, and advection by bulk fluid circulation (Engelder and Marshak, 1985). Pressure solution is generally thought to be the principal mechanism in the formation of disjunctive spaced cleavage, with diffusion and advection directly aiding in the process (Engelder and Marshak, 1985; Carrio-Schaffhauser and Gaviglio, 1990; Wright and Henderson, 1992).

Pressure solution is defined as the dissolution of a mineral or minerals at grain-to-grain contacts when a stress is applied to the system (Engelder and Marshak, 1985; Carrio-Schaffhauser and Gaviglio, 1990). At shallow depths tectonic stresses produce a difference in chemical potential along grain boundaries within the rock. This change in chemical potential allows dissolution to occur along grain faces subjected to the highest normal stress, with the ions migrating via diffusion along faces subjected to the lowest normal stress (Carrio-Schaffhauser and Gaviglio, 1990). Diffusion along the grain faces is restricted to distances on the scale of a few grain diameters (Engelder, 1984;

Knipe, 1989; McCraig and Knipe, 1990). The dissolved material will either precipitate along low stress grain boundaries, or pass into the pore fluid where fluid film diffusion and/or advection in the groundwater system takes over (Carrio-Schaffhauser and Gaviglio, 1990). In carbonate rocks calcite and dolomite are the minerals preferentially dissolved by pressure solution (Alvarez and others, 1976; Mitra and Yonkee, 1985). Clays, quartz and other "insoluble minerals" have been shown to play a passive role in the process, and are preferentially enriched in the cleavage domains as carbonate minerals are removed (Durney, 1972; Mitra and Yonkee, 1985; Engelder and Marshak, 1985; Protzman and Mitra, 1990). The evidence for pressure solution includes the truncation of grains (e.g. ooids, peloids and fossil fragments) along cleavage domains, the offset of oblique veins which formed prior to cleavage development, and offset bedding along cleavage domains (Durney, 1972; Alvarez and others, 1976; Yonkee, 1983; Protzman and Mitra, 1990).

In order to maintain the chemical potential gradient so that pressure solution can continue, the dissolved calcite must precipitate in areas undergoing the least compressive stress (Engelder and Marshak, 1985). However, these precipitation points must occur within a few grain diameters from the source. Studies have suggested that 20% - 30% of the original rock is commonly dissolved or lost during pressure solution (Nickelson, 1986; Bhagat and Marshak, 1990; Protzman and Mitra, 1990; Wright and Henderson, 1992). With such a large volume of rock being dissolved, these precipitation sinks would quickly fill up with calcium carbonate, causing the pressure solution process to prematurely stop (Engelder and Marshak, 1985). Therefore, in order to dissolve 20% - 30% of the rock, calcium carbonate must be carried away from the source. Fluid film diffusion and advection are the modes by which this is accomplished, allowing pressure solution to proceed (Wanless, 1979; Engelder and Marshak, 1985).

Diffusion involves the transfer of material, via fluid films attached to grains, away from zones of relatively high normal stress in the direction of the lowest normal stress (Bayly, 1987;

Knipe, 1989). The distance which this can occur depends on the chemical potential gradient produced by the stress being applied, and the amount and interconnectiveness of the fluid films (Wanless, 1979). Like the pressure solution process described above, the fluid films can become saturated with dissolved ions leading to precipitation in pressure sinks such as extensional veins, gash fractures, or in strain shadows behind more resistant grains (Carrio-Schaffhouser and Gaviglio, 1990; Bayly, 1987; Mitra and Yonkee, 1985). Once the sinks become filled, however, the saturated water must be removed by advection, or the pressure solution process will effectively shut down (Carrio-Schaffhouser and Gaviglio, 1990; Engelder and Marshak, 1985).

Advection is the circulation of ground water through the system, which generally follows Darcyian laws and is indicative of an open system (Geiser and Sansone, 1981). As "fresh" waters are circulated through the system, the dissolved ions are leached out of the fluid films into the larger groundwater system. For every ion that leaves the fluid film into the groundwater system, one more can theoretically be dissolved to take its place, leaving the fluid film at or near saturation (Engelder and Marshak, 1985). The distance material is carried away via advection is dependent on the size of the groundwater flow regime, volume of water flowing through the system, and availability of sinks for reprecipitation (Engelder, 1984). Redeposition can occur anywhere from several centimeters to several kilometers from the source area (Engelder, 1984).

The rate of the pressure solution process is controlled by the rate of diffusion of the dissolved ions through the pore water system (Engelder and Marshak, 1985). Pressure solution cannot take place without a liquid phase supporting the ion exchange process (Carrio-Schaffhauser and Gaviglio, 1990). The rate of diffusion through the pore waters is controlled primarily by two factors: the chemical potential and water chemistry. The variation of the chemical potential in the rock is produced from differences in the stress field (Engelder and Marshak, 1985; Knipe, 1989). The more stress applied on the rock body in one direction, the larger the chemical potential gradient

becomes, allowing ions to diffuse more quickly through the liquids. There are two factors which influence the water chemistry: pH and trace element concentration. Calcite solubility increases as the pH of the water decreases, resulting in higher diffusion rates with lower pH values and vice versa (Lasaga, 1984). The trace elements present in the pore waters may impede the ion exchange during the pressure solution process, thus slowing the rate down (Nabelek, 1987).

The rate of large scale water advection will also influence the rate of pressure solution. As described above, once the pressure sinks have been filled, the fluid films become over saturated and ions must be removed from the fluid films or the process will shut down (Engelder and Marshak, 1985). In order for pressure solution to continue, the system must be replenished with "fresh" waters. If the replenishment of the fresh waters via advection is slower than the rate of diffusion through the pore fluids, then advection becomes the rate controlling step in the pressure solution process.

Clay minerals and other insoluble grains, such as quartz, feldspar, oxides, and sulfides play a critical role in the pressure solution process. Cleavage distribution is strongly controlled by limestone composition (Marshak and Engelder, 1985). Impure limestones (>10% insoluble residue) develop spaced cleavage, whereas pure limestones (<10% insoluble residue) develop only isolated tectonic stylolites (Wanless, 1979; Yonkee, 1983; Marshak and Engelder, 1985; Protzman and Mitra, 1990). Clay particles within the matrix attract water films, creating a path for the diffusion of dissolved ions (Weyl, 1959; Wanless, 1979). Engelder and Marshak (1985) state further that any insoluble grain, not just clay, which is small relative to the soluble clasts, can attract a water film and will act in a similar manner as that of the clays. In order for the insoluble matrix to be able to provide a diffusion pathway, an interconnecting network of fluid films on the insoluble particles must exist to link the sites of dissolution with the free-fluid of the system (Engelder and Marshak, 1985).

CHAPTER 3

METHODS

Field Techniques

Cleavage orientation and intensity were recorded at every exposure of the Rierdon Formation within the study area. Cleavage intensity was measured by counting the number of cleavage domains which cross a five centimeter long transect perpendicular to the orientation of the cleavage, and is given in domains per centimeter (d/cm). In addition to cleavage measurements, orientation of other deformational fabrics, predominately joints and pencil structures, were recorded where observed. Oriented samples were collected wherever possible using the technique of Prior and others (1987). The collection of these samples was very difficult due to the fragile nature of the cleaved limestones and therefore it was not possible to sample all outcrops.

Laboratory Techniques

Laboratory techniques include petrographic microscope observations, insoluble mineral determination (sample dissolution), SEM observations, and X-ray diffraction. The sample preparation and methodology of each technique and its relevance to the project will be described below.

Thin Section Preparation

Thin sections were cut from all oriented samples. Two orientations were sampled: one

perpendicular to both cleavage surfaces and bedding surfaces (denoted by a "-1" in the sample name), and the other parallel to bedding surfaces and perpendicular to cleavage surfaces (denoted by a "-2" in the sample name). The sections were cut to a large format (50 x 75 mm), finished with a microprobe quality polish, and left uncovered for SEM analysis.

Petrographic Microscope

Petrographic studies were conducted from 20x to 400x to characterize the morphology of spaced cleavage and to determine the composition of microlithons and cleavage domains. Microstructures, such as gash fractures and extensional veins, were identified and described. In addition to the characterization of the cleavage domains and microlithons, widths of the microlithons and cleavage domains were measured across transects perpendicular to the cleavage. These measurements were used to calculate the amount of shortening accommodated by the spaced cleavage.

Insoluble Mineral Determination (Sample Disolution)

The determination of the percentage of insoluble minerals within samples collected was accomplished by dissolving out carbonate minerals. A representative sample with at least 3 cleavage domains was cut cleanly on all sides to produce fresh (unweathered) surfaces. It was washed in distilled water to avoid contamination and ground into a powder with a porcelain mortar and pestle to speed up the dissolution process. The powder was dried at 50°C to drive off any remaining water, and weighed until the weight remained constant. Either acetic or hydrochloric acid was added to the sample, and dissolution was allowed to proceed at room temperature. A concentration of 20% was used for the acetic acid and a 0.19M solution was used for the hydrochloric acid as suggested by Ostrom (1961). Such acid concentrations, while high enough to dissolve calcite and dolomite, are not high enough to affect any other minerals which may present (Ostrom, 1961). Once all of the

calcite had been dissolved, indicated by no reaction occurring when fresh acid was added to the sample, the residual minerals were collected by passing the solution through filter paper. The residuum was then rinsed 3-5 times with distilled water to cleanse the sample of any remaining acid, dried at 50°C for over 24 hours and weighed. The difference in the pre- and post-dissolution weights represents the amount of insoluble minerals present within the samples. This quantity, expressed as a percentage ($\text{post-weight/pre-weight} \times 100$), was given the label "Is". This value was then used in the formulas to calculate the amount of shortening that has occurred.

Scanning Electron Microscopy (SEM)

The SEM was used in order to characterize the morphology, composition and structure of cleavage domains using magnifications from 15x to 6000x in order to compliment observations with the petrographic microscope. The microscope used was a JEOL-6100 SEM with NORAN Voyager energy dispersive analysis (EDS) system, running at 15 kV. Samples (polished thin sections) were prepared by sputter coating with carbon and analyzed using back-scattered electron detector. Backscattered electron images, area and spot specific X-ray analyses, and the X-ray maps were used to determine the chemistry and mineralogy of the samples and to provide a check for the assumptions made in the calculation of the amount of shortening accommodated by spaced cleavage.

Density images were obtained to analyze the structure and texture of the cleavage domains, and the geometry of minerals both within the domains and microlithons. Area specific and spot specific X-ray analyses were conducted on individual minerals within the microlithons and cleavage domains in order to determine the elements present and the mineralogy. The relative percentage of cations present in the X-ray analysis, using their simple oxides (e.g. CaO, FeO, and MgO), were determined using EDS. X-ray maps showing the relative intensity of the elements present were constructed in order to determine how the elements vary across the cleavage domains.

X-ray Diffraction (XRD)

Diffraction data were collected with an automated Scintag XGEN 4000 diffractometer, using $\text{CuK}\alpha$ radiation with 2.0 x 4.0 mm beam slits and 0.5 x 0.3 mm detector slits. Random powder diffraction scans were performed on the insoluble minerals left over from the dissolved samples. The samples were ground into a fine powder with a mortar and pestle, lightly packed into sample holders, and then analyzed from 2° to 70° 2θ with a count time two degrees per minute. The software package PC Diffraction Management System was used in the measurement of the d-values. Identification of the minerals present was based on the correspondence of the experimental d-values and d-values published on the JCPDS card files.

Samples for clay analysis were obtained from both the insoluble minerals directly from cleavage domains and dissolved samples. To obtain the clay material from the domains, samples of cleaved limestone were broken up along cleavage domains and soaked overnight in one liter distilled water. 10 grams of sodium hexametaphosphate was added to the distilled water to help dislodge the clays from the domains. For the dissolved samples, 10 grams of the sample was suspended into 500ml of distilled water using an ultrasonic probe. The $<2.0\mu\text{m}$ size fraction for all samples was separated by centrifugation. The $<2.0\mu\text{m}$ fraction was separated from the solution using a vacuum filter apparatus. The minerals were then transferred on to a glass using the filter transfer method outlined by Moore and Reynolds (1989; p. 192 - 195) in order to create an oriented sample. The samples were treated with ethylene glycol at 60°C for 12 hours. Diffraction data was collected from 2° to 50° 2θ , using steps of 0.1° 2θ for three seconds at each step.

CHAPTER 4

OBSERVATIONS

Cleavage Domain Orientation

The orientation of cleavage is consistent across the entire Sawtooth Range. The strike of spaced cleavage is sub-parallel to the strike of bedding in all areas, with the difference in strike varying by no more than 20° (see stereonet in Appendix 1). The strike of spaced cleavage and bedding ranges from N-S to NW-SE across the range. In addition, the strike of the cleavage is also sub-parallel to the trend of the major thrust faults and fold axes. Using the orthogonal coordinate system for folds, the cleavage represents a b-c surface (Fig. 14) (Twiss and Moores, 1992, p. 49). The cleavage is at high angles to bedding, with bedding/cleavage intersections ranging between 70° and 90° (Appendix 1).

Cleavage Domain MorphologyMacroscopic Scale

The spaced cleavage within the Rierdon Formation forms a distinct weathering pattern. Sharp crevices occur along cleavage domains where they are exposed to the atmosphere (at the weathering surface), making the rock appear fractured; hence, the term "fracture cleavage" was used by early workers (Alvarez and others, 1976). These crevices gradually taper off into the domain away from the weathering surface (Fig. 15).

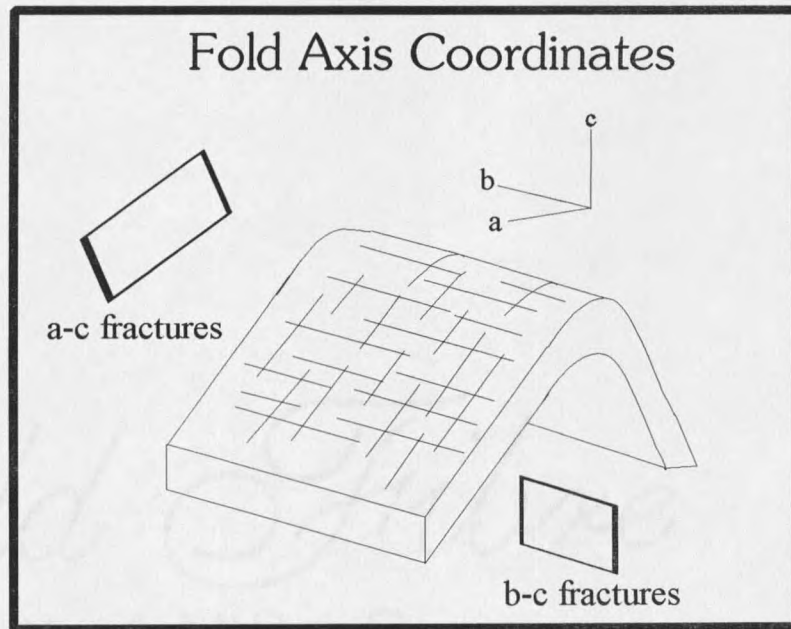


Figure 14. Illustration of fold axis coordinates (modified from Twiss and Moores, 1992, p. 49). Cleavage is sub-parallel to the b-c plane.

When viewed at the outcrop scale, cleavage has two distinct morphologies. The cleavage domains occur both as nearly parallel and anastomosing domains, with the trace pattern identical on both bedding surfaces and mutually perpendicular joint surfaces (Fig. 15). When the limestone contains anastomosing limestone domains, it produces a tapered, sharp edged block up to 2cm in diameter and 5cm long. When the domains are parallel, weathering produces square corners on blocks of about the same dimension (Fig. 15). The anastomosing geometry in the outcrop is predominate, with the parallel geometry only occurring at stations 10, 22, 23, 24, 25, 26, and 31 (Plate 1). At every station, however, only one type of domain geometry was observed; the two geometries did not occur together at any one station.

Cleavage Morphology and Outcrop Weathering Pattern

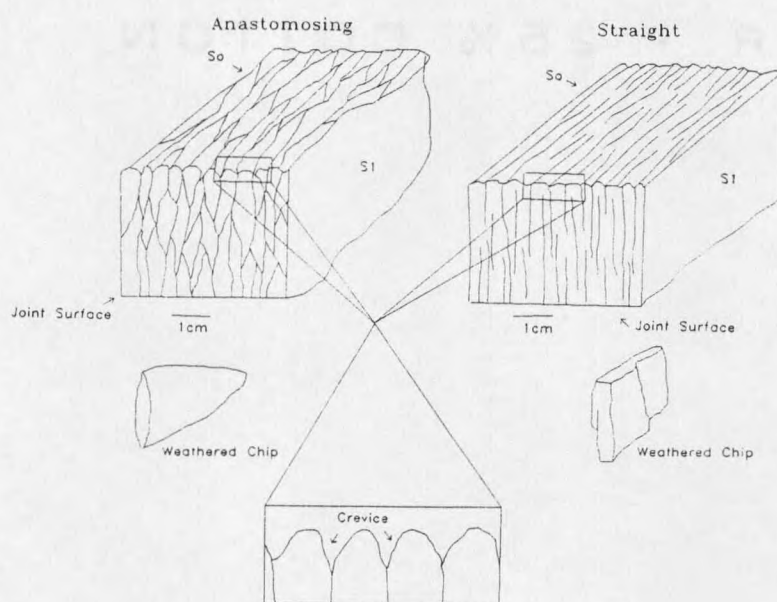


Figure 15. Block diagram illustrating the outcrop weathering pattern of anastomosing and parallel straight cleavage geometries.

Microscopic Scale

Due to the detailed nature of microscopic scale observation techniques, more features of the cleavage domains were described than at the macroscopic scale. The features described at the microscopic scale include: domain shape, domain boundaries, terminating geometries, domain thickness, domain length, and the internal structures of domains.

The shape of individual domains varies from slightly wavy to an irregular, almost sutured pattern (Figs. 16 and 17). The slightly wavy pattern typically occurs within more homogeneous limestones, and the more irregular pattern occurs within more fossiliferous portions of limestone beds (Fig. 16). The fossil fragments appear to have been a barrier that deflected the cleavage domains around them (Fig. 17). Thicker domains (greater than about 0.10 mm) do not appear to be as influenced by fossils, and develop a more straight pattern. In addition, gastropods, unlike other

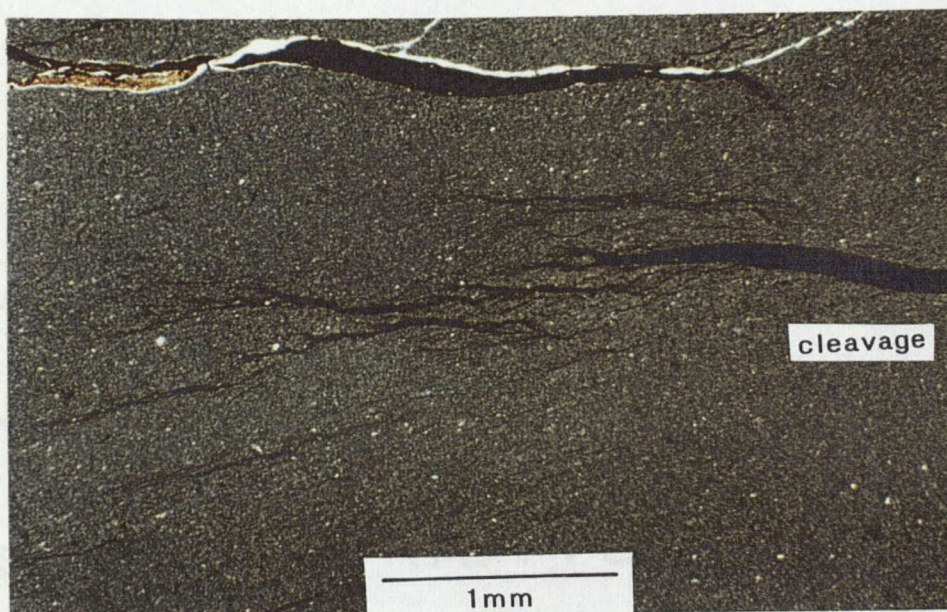


Figure 16. En echelon pattern of cleavage domains in thin section. Note the slightly wavy geometry, distinct boundaries, and horsetail termination of the domains. Photomicrograph was taken under plain polarized light.

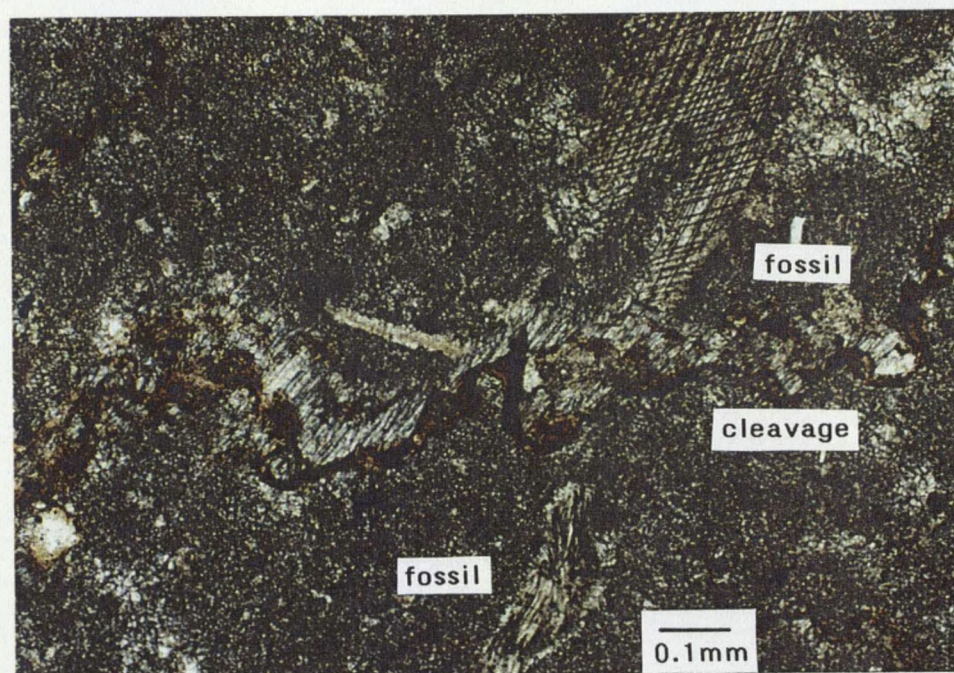


Figure 17. Very wavy, irregular cleavage domain geometry. Note the presence of fossil fragments which have been replaced by calcite. Photomicrograph was taken under plain polarized light.

fossil fragments, appear not to have created a barrier to dissolution and were readily dissolved (Fig. 18). When there were no obstacles to cleavage development, the cleavage domains developed in a straighter and more regular pattern.

The boundaries of cleavage domains range from very distinct to very diffuse (Figs. 19 and 20). In general, the thicker domains (greater than 0.05mm) have very sharp boundaries, whereas thinner domains (less than 0.05mm) have about an equal number of sharp and diffuse boundaries. In the thinner domains, the boundaries tend to be diffuse towards the terminations and are more distinct in the middle. There are exceptions to these observations (larger domains having diffuse boundaries, terminating domains with sharp boundaries, etc.), but these anomalies are only occasionally observed.

Two terminating geometries of cleavage domains - tapering and horsetailing - are seen throughout the study area. A domain with tapering geometry gradually becomes thinner until it tails out (Fig. 21). The length of the tapering, measured from the point where the domain consistently thins out, varies from tens of microns to up to three millimeters. A horsetailing geometry consists of several smaller domains splitting off of the main domain stem until the domains become small enough that they taper out (Figs. 16 and 22). Neither termination pattern appears to be dominant between samples. However, one type will be dominant within an individual sample.

The thickness of cleavage domains ranges from less than 0.01mm to up to 0.4mm in diameter. The domains tend to be the thickest in the center, becoming thinner as they terminate. Only minor pinching and swelling occurs in the center of the domains, with notable exceptions when fossils disrupt the continuity of the domains. The frequency of the domain distribution is dominated by the thinner domains, with the highest number being less than 0.03mm in thickness, and two thirds being less than 0.06mm in thickness (Fig. 23). No sample, however, is completely dominated by the smaller domains, where in every case there are domains at least 0.10 mm in thickness, but more

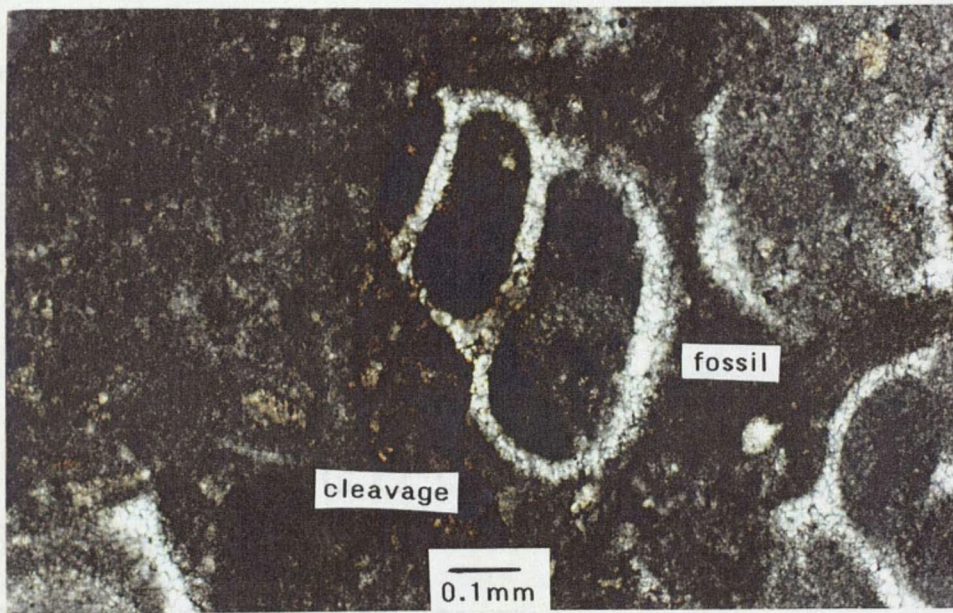


Figure 18. Gastropod partially dissolved along a cleavage domain. Photomicrograph was taken under plain polarized light.

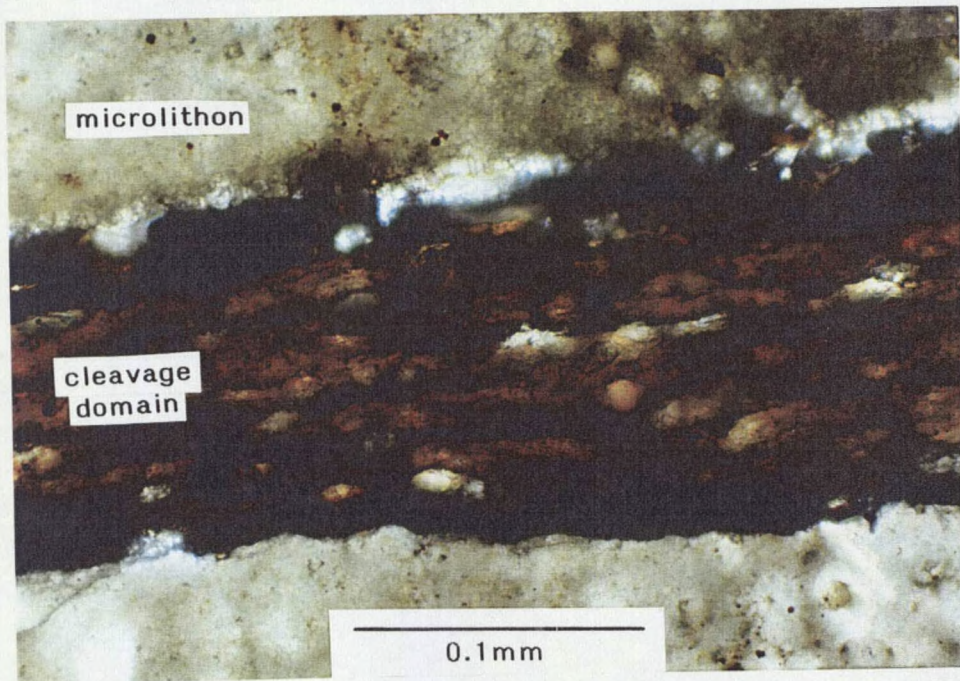


Figure 19. Cleavage domain with very distinct boundaries. Note the alignment of platy minerals sub-parallel to the domain boundaries. Photomicrograph was taken under plain polarized light.

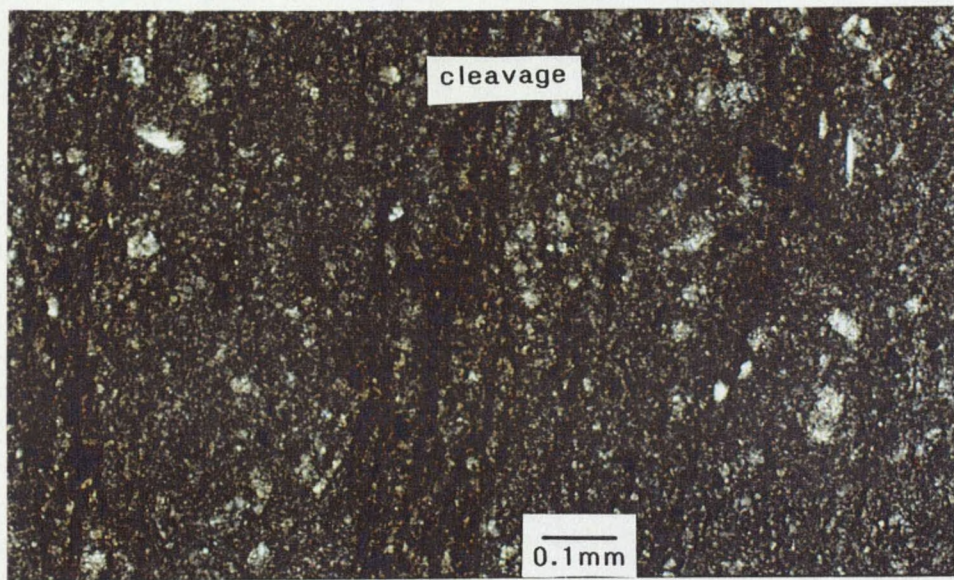


Figure 20. Cleavage domains with very diffuse boundaries. Photomicrograph was taken under plain polarized light.

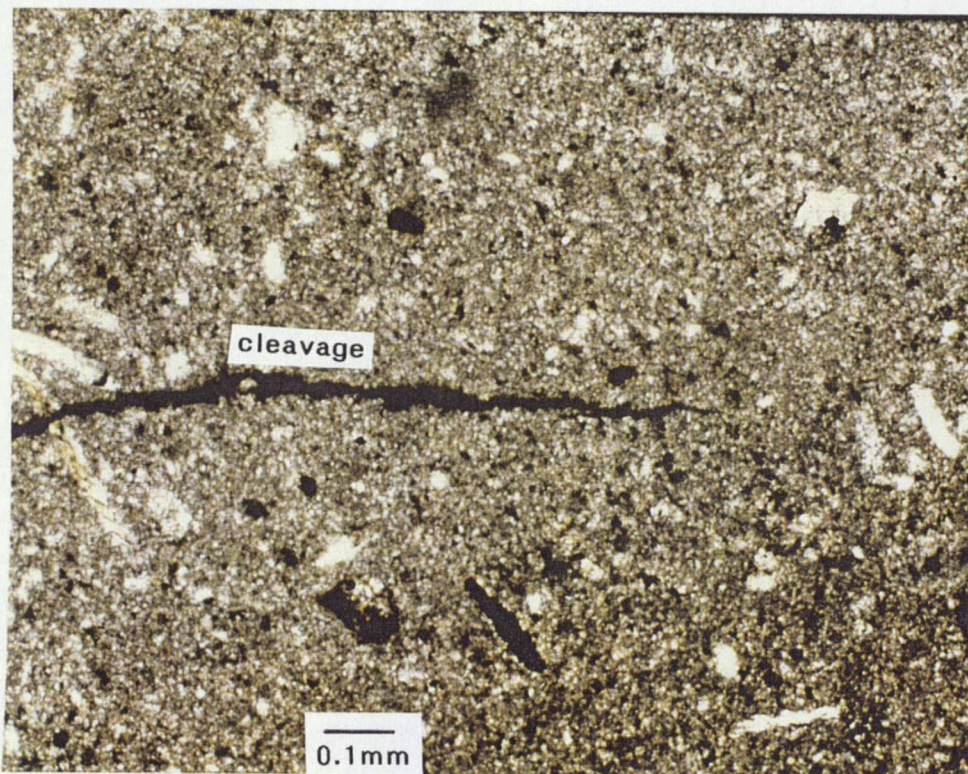


Figure 21. Cleavage domain with a tapering terminating geometry. Note how the domain gradually becomes thinner until in ends, and does not split. Photomicrograph was taken under plain polarized light.

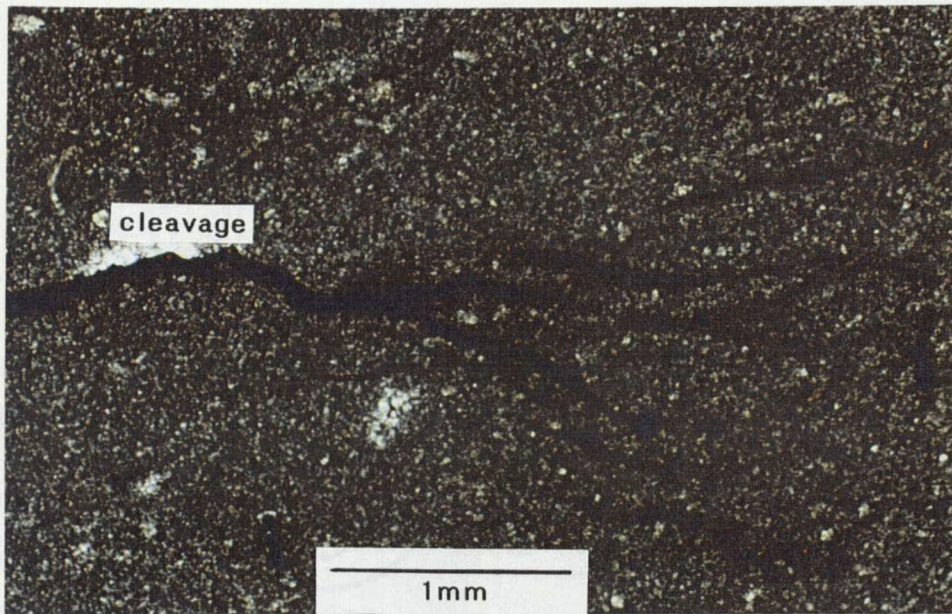


Figure 22. Cleavage domain with horsetailing termination geometry. Photomicrograph was taken under plain polarized light.

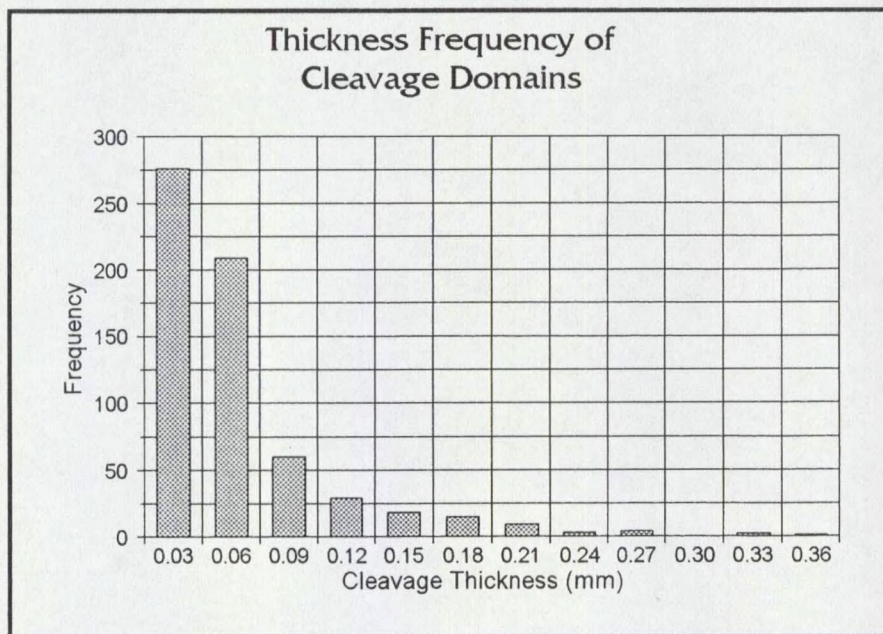


Figure 23. Thickness frequency of cleavage domains. Domain thicknesses were measured on a petrographic microscope at 100x magnification.

commonly reaching to greater than 0.20mm in thickness (Table 1). The average domain thickness, between 0.03mm and 0.04mm, is about the same in all the samples, with the exception of SRR1-1 and DCR1-2, which have averages of 0.10 and 0.09 respectively. The thickness of the domains is never seen to be more than 0.4mm.

The cleavage domains have a finite length, and therefore must be linked together in some manner in order to accommodate shortening throughout the rock. Within the samples studied, anastomosing and parallel domains were the predominate geometry observed at both the microscopic and outcrop scale. An anastomosing geometry consists of individual domains that split and rejoin (Fig. 24). These anastomosing domains are seen to occur either penetratively or in discrete zones.

Table 1. Maximum and average thickness of the cleavage domains, measured with a petrographic microscope at a magnification of 100x.

Thickness Statistics of Cleavage Domains		
Sample	Maximum Thickness (in mm)	Average Thickness (in mm)
BTR1-1	0.31	0.04
BTR1-2	0.35	0.04
DCR1-1	0.22	0.05
DCR1-2	0.26	0.09
DCR2-1	0.21	0.06
DCR2-2	0.16	0.04
DTR1-1	0.31	0.04
DTR4	0.20	0.05
DTR5	0.10	0.03
GRR1-1	0.11	0.03
GRR1-2	0.24	0.03
PTR1-3	0.15	0.03
SRR1-1	0.25	0.10
TRR2	0.10	0.04

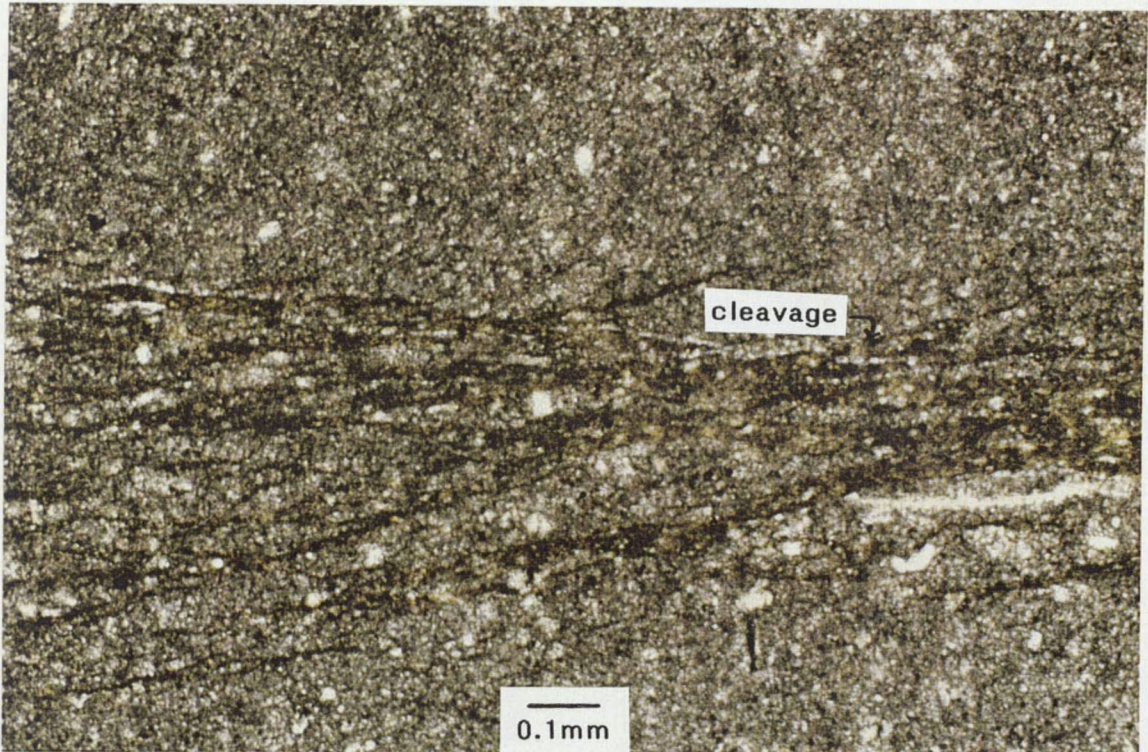


Figure 24. Cleavage domain with an interlinking or anastomosing geometry. Photomicrograph was taken under plain polarized light.

Samples that contain penetrative anastomosing domains have the anastomosing linking geometry throughout the entire sample. When the anastomosing occurs in zones, there is a distinct boundary within which smaller domains also divide and rejoin in an anastomosing fashion, with undeformed limestone domains in between the zones. The anastomosing geometry typically terminates in the horsetail fashion. In contrast to the anastomosing geometry, the domains with parallel geometry do not intersect. The distribution of domains across the sample is predominately random; no distribution pattern is evident. However, there are a few instances where a definite en echelon pattern occurs (Fig. 16). The parallel cleavage domains terminate in both a tapering and horsetailing geometry. Within the samples studied, both geometries are observed, with one pattern or the other dominating.

Within the individual domains, there is a definite internal structure present, with the

alignment of clay minerals predominating. This alignment, in all cases, is sub-parallel to the domain boundaries (Fig 19). In addition to mineral alignment, there is some subtle s-c fabric present within the domains. This fabric was faint where observed, and only present in a few of the domains of each individual sample.

Cleavage Intensity Variations

Macroscopic Scale Variations

Variations in the cleavage intensity within the limestone beds of the Rierdon Formation at the macroscopic scale occurs in three ways: 1) between the average intensity of the individual outcrops (regional variations), 2) within the outcrops, and 3) within the stratigraphic section. The average cleavage intensity between the outcrops ranges from uncleaved to an average of 3.0d/cm (Plate 1, Table 2). Two specific areas provide excellent examples of how the cleavage intensity varies greatly over short distances. Limestone beds cropping out about 750m east of Choteau Mountain are uncleaved, whereas outcrops about 2.5 kilometers to the north may have a cleavage intensity of between 1.0 and 2.0 d/cm (Fig. 25). The Swift Reservoir area also shows a large variation in cleavage intensity, ranging from an intensity of 3.0 d/cm in the southern outcrop, decreasing to uncleaved limestones only 2 kilometers to the north on the northern edge of the Swift Reservoir (Fig. 26).

Variations in cleavage intensity in the Rierdon Formation also occur at the outcrop scale. The variation in cleavage intensity within an individual outcrop is as much as 4.8 d/cm at station 20, with an average outcrop variation of 1.8 d/cm (Table 2). These cleavage variations occur both within a single traceable limestone bed and between the beds. Two transects along an individual limestone bed were conducted: one at station 3 (Wagner Basin) and one at station 5 (Cutrock Creek) (Figs. 27 and 28). At station 3, two beds separated by 1m of mudstone were traced for 110m (Fig. 27). The

Table 2. Maximum, minimum, and average cleavage intensities within the Rierdon Formation. Stations at which the limestone has remained uncleaved are not listed. The intensities are given in domains per centimeter.

Maximum, Minimum and Average Cleavage Intensity Within the Rierdon Formation			
Station	Maximum Intensity (d/cm)	Minimum Intensity (d/cm)	Average Intensity (d/cm)
1	4.8	1.2	2.6
2	3.0	2.0	2.2
3	3.4	0	1.7
4	3.8	1.6	2.9
5	2.2	0	1.0
6	1.8	0.6	1.3
8	2.2	0.4	0.8
9	4.2	1.4	2.9
10	0.6	0.4	0.5
12	1.6	0.4	1.1
13	1.8	0.2	1.2
15	1.6	1.0	1.3
16	1.8	1.2	1.5
17	2.8	0.8	1.7
19	3.6	0.6	1.9
20	4.8	0	3.0
22	0.8	0	0.4
23	1.6	0.6	1.2
24	0.8	0	0.2
25	2.8	0	0.9
26	2.0	1.0	1.3
27	2.0	0.4	1.0
28	1.6	0.4	0.7
29	2.8	0.4	1.3
30	3.6	0	1.5
31	1.6	0	0.9
32	4.6	1.0	2.1
33	3.8	1.4	2.5
34	4.0	0	2.1
35	0.8	0.4	0.7

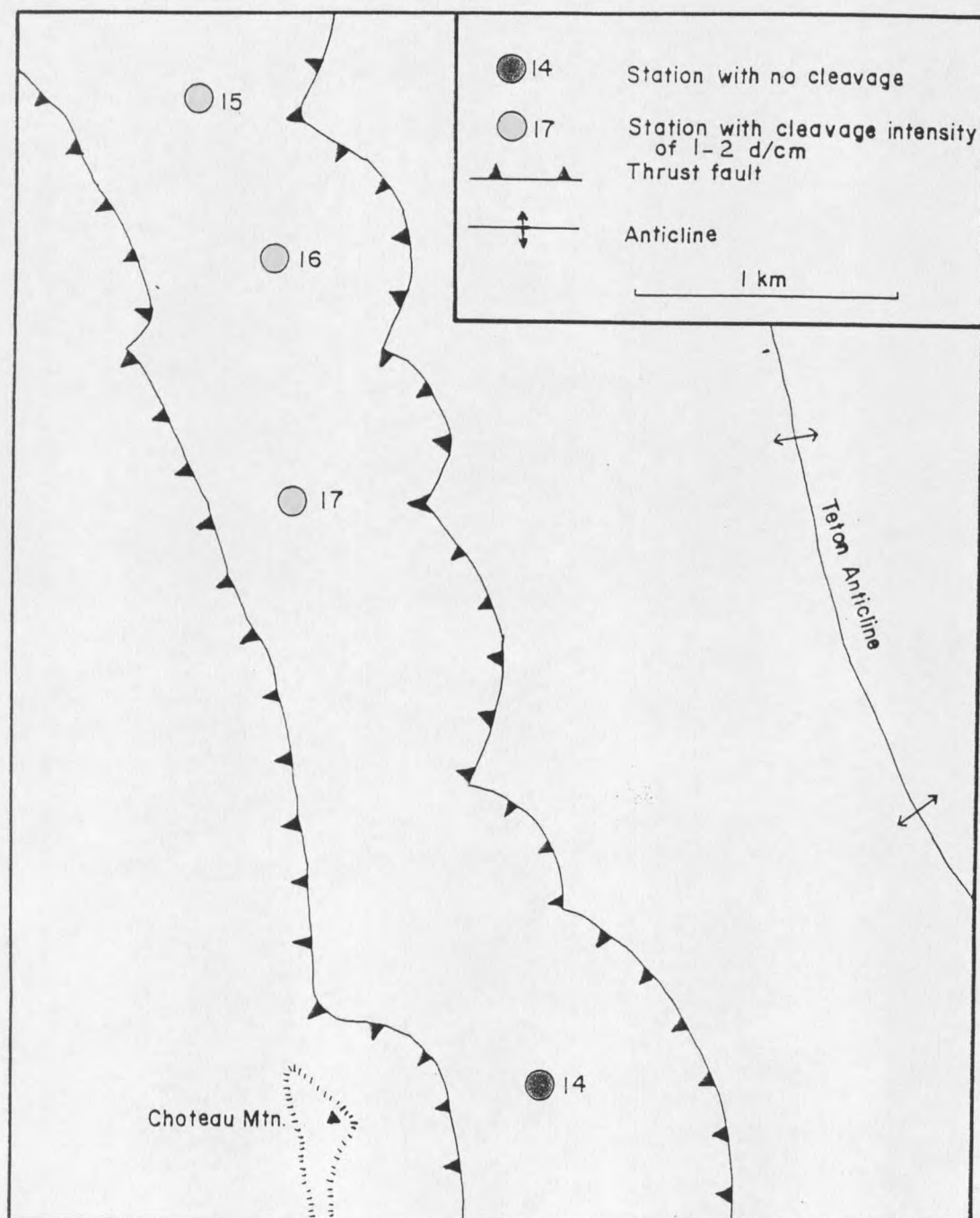


Figure 25. Average cleavage intensity variations between four outcrops in the vicinity of Choteau Mountain. All outcrops are in the hangingwall of the frontal thrust.

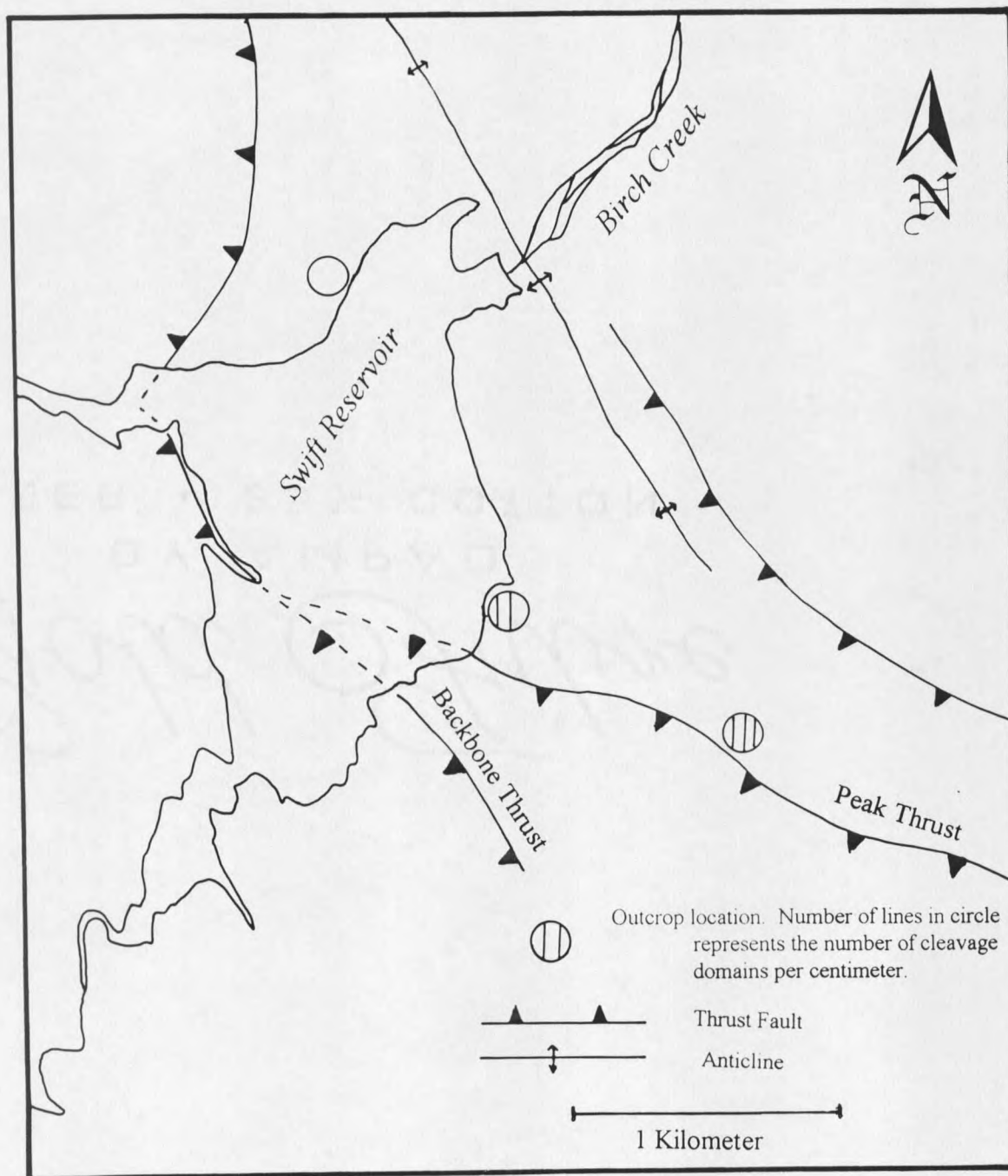


Figure 26. Average cleavage intensity variations between three outcrops in the vicinity of the Swift Reservoir. Note how the frontal thrust dies out into a fold to the north.

Cleavage Intensity Variation

At the Wagner Basin Outcrop

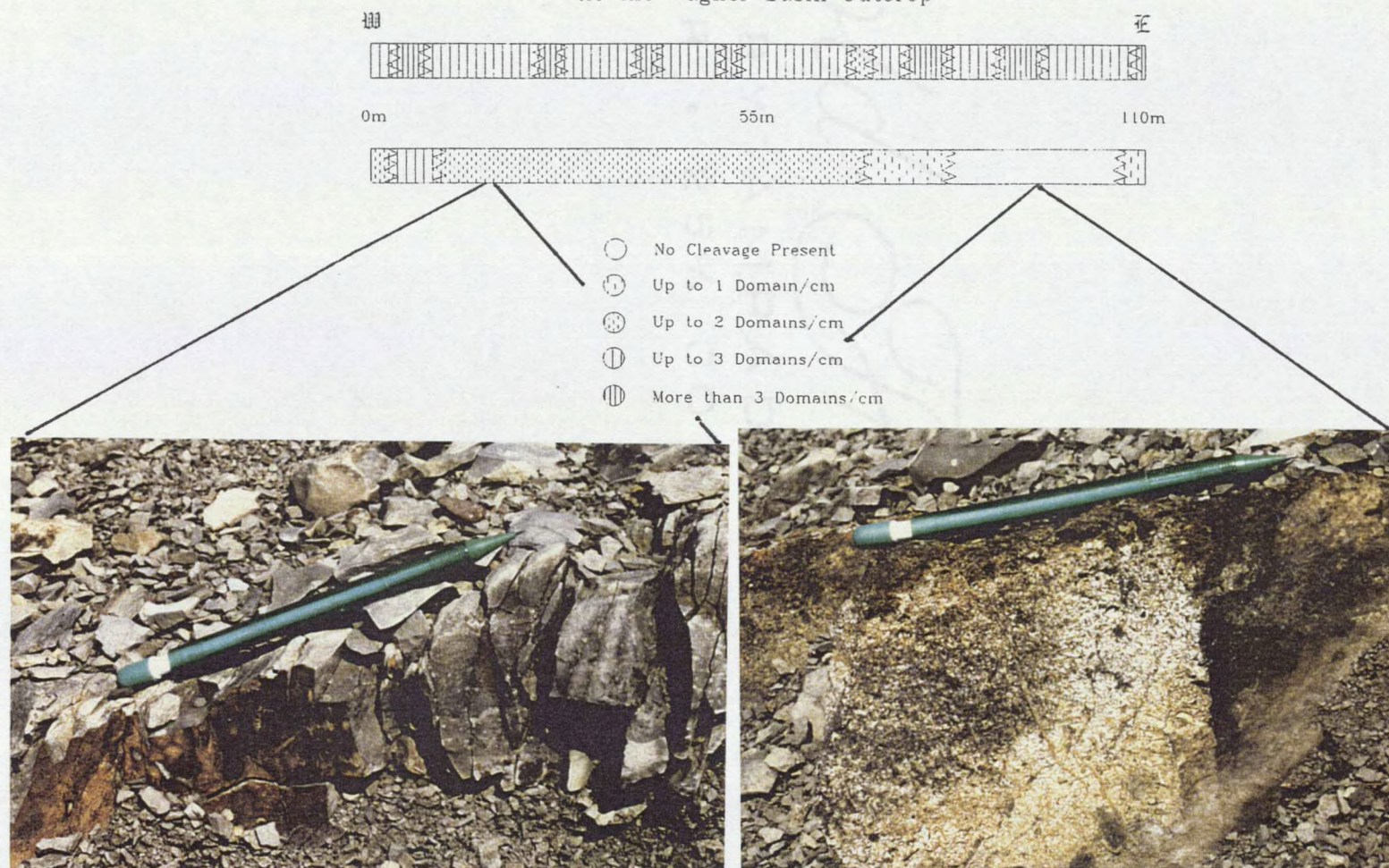


Figure 27. Measured cleavage intensity variations in two limestone beds at station 3 (Wagner Basin). The two beds are 10 - 15 thick and separated by 95cm of mudstone. Pencil is 15cm in length.

Cleavage Intensity Variation At the head of Cutrock Creek

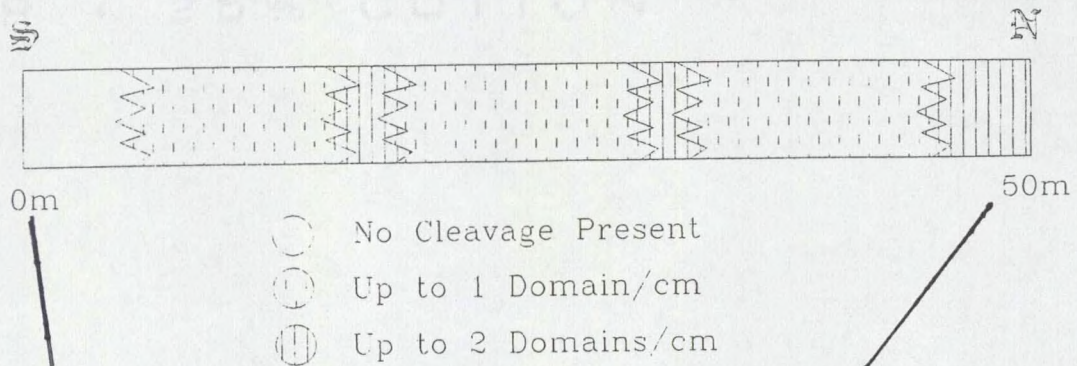


Figure 28. Measured cleavage intensity variations along a single limestone bed at station 5 (the head of Cutrock Creek). Note how the cleavage intensity increases from south to north.



Figure 29. Goniote, 14cm in diameter, which has remained uncleaved within a intensely cleaved limestone. The surrounding limestone has a cleavage intensity of 4.1 d/cm. Compass clinometer for scale.

lower bed shows the largest variation in intensity, ranging from 2.2 d/cm at the 5m mark to the bed being uncleaved at around the 90m mark (Fig. 27). At station 5, the cleavage intensities in the same bed varies from uncleaved to the south to 1.2 d/cm to the north (Fig. 28). There are also variations in the cleavage intensity within the same bed, where large goniotites (greater than 10cm in diameter) are uncleaved within an intensely cleaved matrix (Fig. 29). These fossils have remained uncleaved in every case, and were observed both in situ and as float resting on top of the Rierdon outcrops.

The cleavage intensity variation between beds was measured in detail at stations 1 and 3. The Rierdon section was measured at station 1, with the cleavage intensity measured on every limestone bed present (except where it was not possible to obtain a representative measurement) (Fig. 8). Here the intensity varied from 1.6 d/cm to 4.2 d/cm. At station 3, the transects described above show that the cleavage intensity in the upper bed is consistently over 1 d/cm higher than the lower bed, and is as much as 3 d/cm higher (around 90m into the transect)(Fig. 27).

Microscopic Scale Variations

In addition to the macroscopic cleavage intensity variations observed, there are also variations observed at the microscopic scale. Since the measurements were conducted with the petrographic microscope, the figures are reported as the average length, or spacing, between the cleavage domains. The spacing variation between the minimum and maximum within an individual sample is as high as 6.0mm (in sample DCR2-2), with a 4 to 5mm difference being the most common (Table 3). The average spacing between the samples ranged from 0.85mm to 2.42mm (Table 3). These spacings are two to three times less than those measured in the field (Table 3).

Table 3. Spacing of the cleavage domains on the microscopic and macroscopic scale.

Microscopic and Macroscopic Scale Cleavage Intensity					
in the Rierdon Formation					
Sample	Station	Microscopic Spacing (mm)			Macroscopic Spacing
		Max.	Min.	Ave.	
BTR1-1	4	4.20	0.02	0.99	3.4
BTR1-2	4	5.52	0.10	1.44	3.4
DCR1-1	29	5.10	0.03	1.47	7.7
DCR1-2	29	5.48	0.11	1.56	7.7
DCR2-1	30	4.52	0.32	1.51	6.7
DCR2-2	30	6.21	0.20	2.42	6.7
DTR1-1	1	4.49	0.08	1.65	3.8
DTR4	1	4.90	0.28	1.57	3.8
DTR5	3	4.49	0.02	1.37	5.9
GRR1-1	32	5.85	0.08	1.53	4.8
GRR1-2	32	4.05	0.03	1.07	4.8
PTR1-3	34	3.90	0.10	0.85	4.8
SRR1-1	20	3.60	0.32	1.13	4.8
TRR2	17	4.42	0.48	1.50	5.9

Stratigraphic Variations

An initial reconnaissance of carbonate units (other than the Rierdon limestone) was conducted to determine if spaced cleavage is present in other formations within the study area. Only the carbonate units were studied.

Spaced cleavage has been observed in Cambrian limestones in the Sawtooth Range (Singdahlsen, 1986; Ihle, 1988). The cleavage has been described in the Swift Reservoir area, where cleavage with an intensity of 1 d/cm to 1 domain per 5 cm (0.2 d/cm) is present in the Steamboat Limestone. Since Cambrian rocks do not crop out in the study area except in the Swift Reservoir, these units were not studied in this project. However, massive carbonates of Devonian and Mississippian age are present throughout the study area. No spaced cleavage was observed in the

Devonian carbonate units, the Mississippian Allan Mountain Limestone, or the lower member of the Mississippian Castle Reef Dolomite. In the upper member of the Mississippian Castle Reef Dolomite, there are fractures with a strike parallel to the b-c plane of the fold coordinates (Fig. 13; Fig. 30), which is also parallel to the strike of the cleavage in the Rierdon Formation. These fractures have a similar outcrop weathering pattern and orientation as the spaced cleavage in the Rierdon Formation. They have an intensity of 1 d/cm to 1 domain per 10 cm, which is moderate to weak on the scale by Alvarez and others (1978). However, thin sections from samples show no pressure solution fabric present along the fractures, such as insoluble minerals or partially dissolved fossils, with the fractures filled with calcite. Due to the lack of features associated with spaced cleavage, it is presumed that the fractures are not spaced cleavage (they may be syntectonic, open, extension fractures).



Figure 30. Fractures sub-parallel to the b-c plane of the fold axis coordinates in the upper (Sun River) member of the Mississippian Castle Reef Dolomite. Note how the fractures have a similar outcrop weathering pattern as spaced cleavage in the Rierdon Formation. The fractures, however, are not spaced cleavage.

In Mesozoic units (other than the Rierdon Formation) there are no significant carbonate beds present, with the exception of a thin limestone bed near the base of the Swift Formation (Mudge, 1972a). Where this bed is exposed (observed only at stations 1 and 3), it contains spaced cleavage with an average intensity of 1.4 d/cm. Like the Rierdon Formation, the orientation of cleavage is parallel to the b-c fold coordinates (Fig. 13).

Composition

Domain Composition

The cleavage domains are composed of predominately non-carbonate minerals, with only a small fraction of calcite remaining within the domain boundaries. Petrographic microscope observations reveal that domains are composed predominately of quartz and clay minerals. Compositional analyses using the SEM confirm this, with quartz the dominate mineral present. Pyrite and barite grains also are present (Fig. 31), but they tend to be very small ($<10\mu\text{m}$) and only occasionally reached 1mm in diameter. The quartz grains within the domains range from less than $2\mu\text{m}$ to up to 2mm in diameter. XRD was used to determine the clay mineralogy within the domains. The clays present in the mineral fraction extracted from the domains are kaolinite and R >3 ordered, 5% - 10% expandable illite/smectite (I/S) (Appendix 2).

Microlithon Composition

The microlithons, as identified with a petrographic microscope, are composed predominately of fine grained calcite, with approximately 10% to 25% other minerals, most commonly quartz and clay. Sparry calcite is present within extensional veins and fossil fragments, and no dolomite is present within the samples. Compositional analysis using SEM corresponds to the minerals found using the petrographic microscope. Small diameter grains of pyrite and barite are also identified

within the microlithons similar to the domains. Apatite is found in the microlithons, but only in small quantities. Quartz and clay minerals are still the dominant non-carbonate minerals present in the microlithons.

Fossils and ooids are common within the microlithons. The fossil content within the observed samples range from less than 1% to approximately 60%, with between 10% and 20% the most common. Shells have predominately been replaced with sparry calcite, with only a small number retaining their original structure. Ooids are also present, but comprise at most only about 1% of the total limestone. The original fabric (concentric layering) of the ooids is generally absent, having been replaced with sparry calcite, but the core of an ooid is occasionally observed.

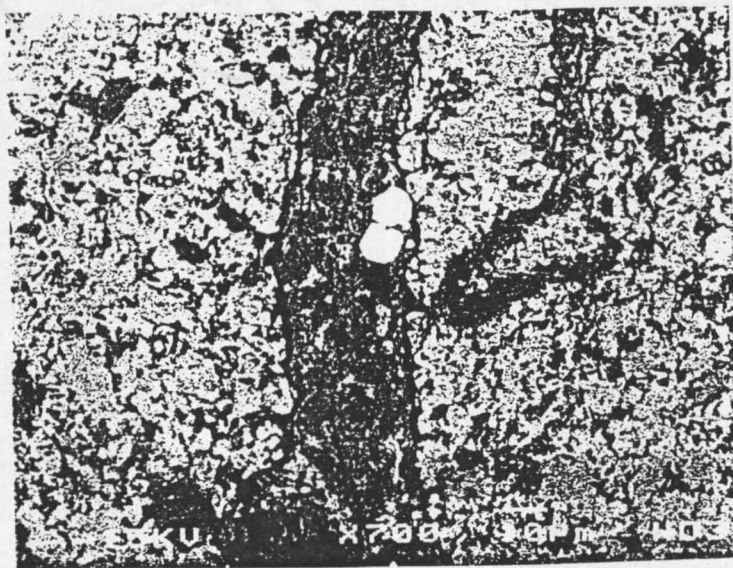


Figure 31. Backscattered electron image, from the SEM, of a cleavage domain. The darker shades represent lighter minerals, such as quartz and clay, the intermediate shades represent calcite, and the bright grains are the heavy minerals such as barite and pyrite. The cleavage domain is the dark band in the middle of the picture.

Whole Rock Insoluble Mineral Analysis

Whole rock insoluble mineral analysis of samples of cleaved limestones, including both the microlithons and domains, show that the deformed rock contains between 13.2% and 25.7% insoluble minerals, with an average of 19.2% for the samples containing spaced cleavage (Table 4). The uncleaved samples from the Rierdon had a wider range of insoluble mineral content, from a high of 33.8% to a low of 4.8% (Table 4). Samples collected from Devonian and Mississippian carbonates have a much lower insoluble mineral content, ranging from 1.6% to 11.7% (Table 4). XRD was used to determine the mineralogy of insoluble minerals using the whole rock dissolution process. Quartz and clay minerals are the predominant constituents, indicated by the strongest diffraction peaks (See appendix 2). In addition, pyrite and barite are present within the insoluble mineral samples (Appendix 2). Possible additional minerals include orthoclase, glauconite, phillipsite, and chlorite (Appendix 2). These minerals are very difficult to positively identify due to low concentrations (making it difficult to identify smaller peaks) and peak interference from a multi-compositional sample. An analysis of the $>1\mu\text{m}$ size fraction reveals that clay minerals include kaolinite and R >3 ordered, 5%-10% expandable I/S). There are no differences in the insoluble mineralogy between the cleaved samples and the uncleaved samples from the Rierdon Formation. However, the insoluble mineral content from the Mississippian and Devonian carbonate units contains almost 100% quartz (Appendix 2).

Table 4. Percent insoluble minerals within the samples of both cleaved and uncleaved units.

Percent Insoluble Minerals				
Unit	Sample	Location (Station #)	Cleavage	% Insoluble Minerals
Rierdon Formation	BTR1	4	Y	25.7
	DCR1	29	Y	15.2
	DCR2	30	Y	15.0
	DTR1	1	Y	13.2
	DTR4	1	Y	13.7
	DTR5	2	Y	21.6
	GRR1	32	Y	14.6
	PTR1	34	Y	16.0
	SRR1	20	Y	22.5
	STR2	13	Y	23.3
	TRR2	17	Y	15.6
	BCR1	18	N	20.5
	DTR6	2	N	6.5
	DTR7	2	N	6.8
	DTR12	1	N	4.5
	STR1	5	N	33.8
	TRR1	14	N	44.5
Castle Reef Dolomite	DTC1	3	N	12.5
	DTC2	32	N	11.0
Allan Mtn. Lmst.	TRA2	14	N	7.7
Devonian (Undiff)	PTD1	34	N	1.6

Associated Deformational Fabric

In addition to the cleavage present within limestone beds of the Rierdon Formation, there are other deformational fabrics present which may be associated with, or unrelated to, cleavage development. The following section describes these deformational fabrics in the Rierdon Formation, both at the microscopic and macroscopic scales. A preliminary description of the macro- to

megascopic scale deformation in the other units of the Sawtooth Range is also provided.

Deformational Fabric in the Rierdon Formation

Extensional fractures are prevalent throughout the limestones of the Rierdon Formation. These fractures are filled with sparry calcite and range in thickness from less than 0.01mm to 0.8mm. The fractures are up to 4cm in length and are at 70° to 90° to the cleavage and bedding surfaces. Cross-cutting relationships observed in thin sections show the fractures both cutting and being cut by the cleavage domains (Fig. 32). In total, approximately 70% of the fractures cut cleavage domains, and 30% of the domains cut fractures. The calcite fill was analyzed using cathodoluminescence on the SEM, and the CL images showed a distinct difference in luminescence intensity between the calcite infilled veins and the microcrystalline calcite matrix (Fig. 33)

Microscopic shear zones are commonly observed in thin sections taken from the Rierdon limestones (Fig. 34). These zones generally occur within the cleavage domains, and are recognized by the displacement of calcite veins which cut across or have been cut by cleavage domains (Fig. 34). The displacement along the shear zones ranges from 0.1mm to between 2mm and 3mm, as measured in thin section. Mineral alignment within the cleavage domains may provide additional evidence for shearing. There was only slight development of s-c fabric within the thicker domains. No other structural fabric related to shearing was observed. The shear zones have developed solely within the boundary of the cleavage domains, with no shear zones observed that cut through the limestone matrix.

The Rierdon limestones throughout the Sawtooth Range contain a conjugate set of joints, with one set nearly parallel to spaced cleavage and the other perpendicular (see stereonet in Appendix 1). The spacing of the joints ranges from between 5cm and 30cm. The joints in every instance cut across cleavage (Fig. 35).

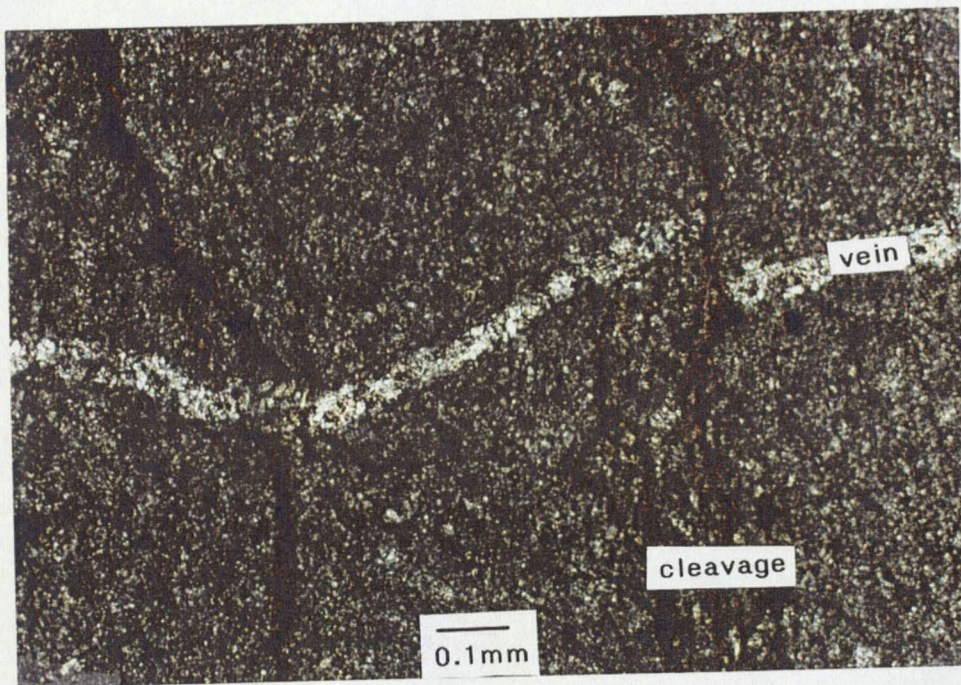


Figure 32. Secondary calcite vein both cutting and being cut by cleavage domains. This shows that the calcite vein was filled during deformation. Photomicrograph was taken under plain polarized light.

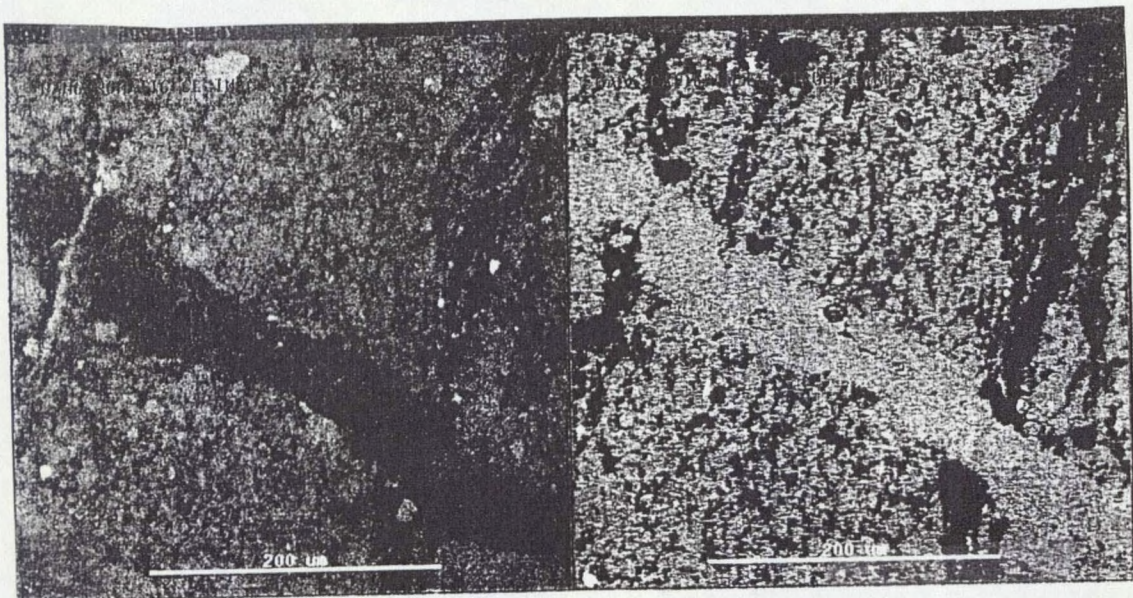


Figure 33. On the right is a backscattered electron image of a secondary calcite vein cutting two cleavage domains. On the left is a CL image of the same area. Note how the calcite vein (dark band) has a much lower luminescence than the calcite matrix. This suggests that the calcite precipitated in the vein came from an external source.

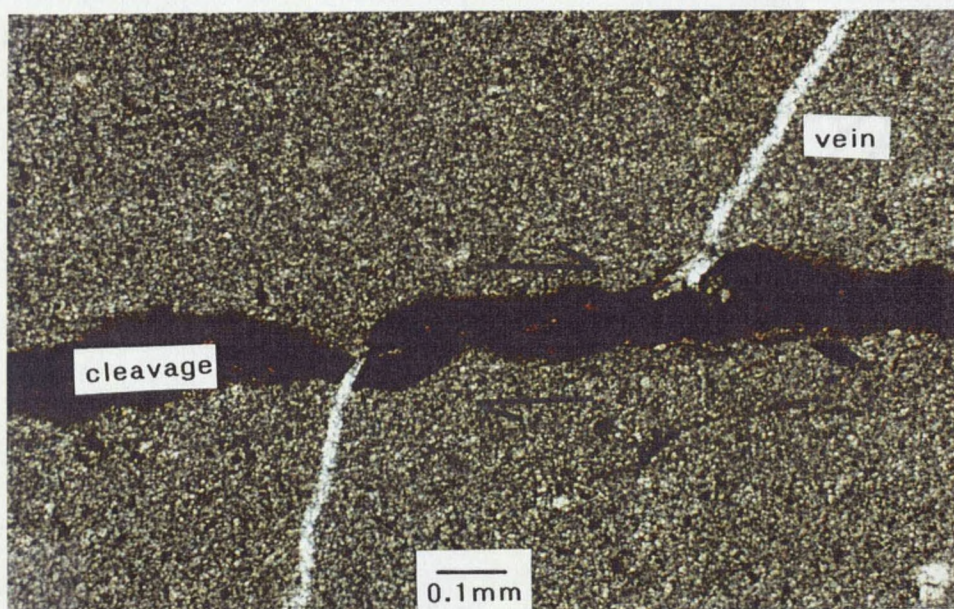


Figure 34. Cleavage domain off-setting a secondary calcite vein, showing that right-lateral shearing has taken place along the cleavage domain. Photomicrograph was taken under plain polarized light.



Figure 35. Cross-cutting relationships between joints and spaced cleavage. Note how the joint face (facing the camera) is smooth with the domain traces vertical and perpendicular to the joint face. This shows that the joints cut cleavage and must post date cleavage development.

The mudstone units within the Rierdon Formation contain pencil structures, formed by cleavage-bedding intersections creating enlongate "pencil-like" fragments when weathered at the outcrop (Engelder and Geiser, 1979; Reks and Gray, 1982). The cleavage which forms the pencil structures is created by the alignment of platy minerals (Engelder and Geiser, 1979; Reks and Gray, 1982). This fabric with a spacing between 0.5cm and 1.5cm. Pencil structures are predominant in the more calcareous mudstones.

Deformation within Other Formations

The Cambrian succession includes units having interbedded carbonates and mudstone. Structures in this lithotectonic zone were described by Singdahlsen (1986) and Ihle (1988) in the vicinity of the Swift Reservoir. Here, the rocks were highly deformed and contain closely spaced imbricate thrusts, disharmonic folds, spaced cleavage and pencil structures. These structures have accommodated up to 60% shortening within the Cambrian strata (Ihle, 1988). However, with the exception of the Swift Reservoir area, the Cambrian units are not involved in the deformation within the outer three to four thrust sheets of the Sawtooth Range (the area of this study), and thus this part of the section is beyond the realm of this investigation.

Devonian and Mississippian strata consists of massively bedded carbonates which contain kilometer-scale concentric folds, box folds, chevron folds and imbricate thrust faults (Mudge, 1972b; Mudge, 1982). Chevron and box folds tend to occur several thrust sheets back, (west) from the front of the range, and are completely absent in the outermost three to four thrust sheets (Mudge, 1982). Concentric folds occur throughout the entire range, especially in the frontal thrusts (Fig. 36), commonly involving Jurassic and Cretaceous strata. No small scale structures were observed in this zone, except for fractures. Near the basal decollement zone (the area most affected by cataclasis) (Holl, 1991). They do not extend outside the basal decollement zone, leaving the upper portion of



Figure 36. Large concentric fold of Mississippian carbonates in the frontal thrust between Ford Creek and Sawtooth Mountain. Note how the less resistant Jurassic and Cretaceous strata have been eroded off the crest of the fold.



Figure 37. Small scale folds in Cretaceous Kootenai Formation along Ford Creek. The fold amplitude is approximately 1.5 meters.

carbonates in the hanging wall relatively undeformed (Holl, 1991).

The Cretaceous and Jurassic units are composed of interbedded limestone, sandstone and mudstones (Fig. 7) (Mudge, 1972a). The internal deformation style of these units was observed in the Sun River Canyon, North Fork of the Teton River and at Ford Creek. They have been deformed by small-scale folds and faults, spaced cleavage, and pencil structures. No folds or faults were observed within the Rierdon, Swift, or Sawtooth Formations, but small-scale folds and faults were observed in the Kootenai Formation in the Sun River Canyon and at Ford Creek (Fig. 37). The faults have displacements of less than 3m and the folds have amplitudes from 3m to less than 20cm. Spaced cleavage has developed in thin argillaceous limestone beds near the base of the Swift Formation, at an average intensity of 1.2 domains per centimeter. It was not possible, due to the fragile nature of these limestone beds, to collect a sample from this unit. Pencil structures are prevalent in mudstone units of the Kootenai and Blackleaf Formations, with a spacing between 0.5cm and 2.0cm. The deformation within the Morrison Formation is unknown because it is not exposed.

CHAPTER 5

INTERPRETATIONS

Morphological Observations

Two types of domain geometries are present: 1) anastomosing and 2) sub-parallel, non-connecting. These geometries occur both at the microscopic and macroscopic scale. In all cases, the observed geometries at the microscopic scale mimic the macroscopic scale, and thus the interlinking geometry appears to be scale independent. The two geometries never occur together in the same sample, or at the same outcrop. There is no correlation between the interlinking geometry and the sample composition (insoluble mineral content, insoluble mineral amount, and fossil content). The samples with the sub-parallel, non-connecting geometries, in every case have an intensity of less than 1.5 d/cm. However, there are samples with anastomosing geometries that have domain intensities less than 1.5 d/cm (e.g. at station 3). In addition, at outcrops with intensities that range from less than 1 d/cm to over 2 d/cm, the interlinking geometry is anastomosing in every case. The fact that the sub-parallel geometry is restricted to intensities of less than 1.5 d/cm suggests that the interlinking geometry is at least partially related to cleavage intensity. However, there are other factors, possibly including variations in the stress field, which may have a role in determining the interlinking geometry at an individual outcrop.

The shape of the cleavage domains appears to be directly related to the fossil content within the sample. In the samples with few fossil fragments, the cleavage domains form in a slightly wavy pattern. When fossils become more abundant, the domains become deflected around the fossil

fragments and take on a more irregular pattern (Fig. 17). However, the thicker domains (>10 mm) do not appear to be as affected by fossil fragments. This is interpreted to be due to the amount of shortening accommodated within an individual cleavage domain. As the domain becomes thicker, more shortening is accommodated by the individual domain. Continued shortening overwhelms the barrier posed by the fossil, causing it to dissolve, allowing the domain to develop in a more regular fashion. However, not all fossil fragments appear to pose a barrier for cleavage development. Gastropods, for instance, are rarely seen to deflect cleavage domains, and are usually partially dissolved along the domain boundaries.

The domain boundaries range from being very distinct to diffuse, with thicker domains containing distinct boundaries and thinner domains containing more diffuse boundaries. This suggests a dependent relationship on the amount of shortening within the cleavage domain. The initial stages of development result in diffuse domains. As shortening continues along an individual domain, the boundaries become more distinct. The exceptions to this observation may be related to very localized variations in composition.

Cleavage Initiation

The processes that initiate spaced cleavage remain relatively unknown because once cleavage has formed, the feature that controlled the initiation site of the cleavage domain has been either altered or completely destroyed (Engelder and Marshak, 1985). The fact that the rock does not deform homogeneously during the formation of spaced cleavage suggests that there must be some feature in the rock that initiates preferential dissolution. Two ideas have been put forth concerning where cleavage will preferentially develop within the rock: 1) along pre-existing macroscopic discontinuities, and 2) at sites controlled by grain-scale inhomogeneities in the rock (Engelder and Marshak, 1985). Macroscopic discontinuities include sedimentary structures such as bedding or mud

cracks, and structural features such as fractures or joints. These discontinuities may be significant because they could provide a large-scale advection pathway for the removal of the dissolved ions (Geiser and Sansone, 1981). The rapid replenishment of fresh waters circulating through the discontinuities allows calcite to diffuse into the waters quicker, thus initiating cleavage development along fractures (Geiser and Sansone, 1981). Grain scale inhomogeneities include variation in the clay concentration at the microscopic level, or the presence of large, rigid grains within a fine-grained matrix. Since clay interconnectivity is important for dissolution within limestones, slight variations in the clay content could increase the diffusion rate of dissolved ions and cause dissolution to initiate at these sites (Engelder and Marshak, 1985). Large, rigid grains may alter the stress field, concentrating stress on a very small area. Because calcite solubility is directly related to the amount of stress, this would cause the calcite to dissolve at this point before the rest of the matrix (Engelder and Marshak, 1985). These two ideas were tested on the cleaved limestone of the Rierdon Formation to determine if they have any influence on the cleavage initiation within the Sawtooth Range.

Macroscopic Discontinuities

Within the cleaved limestones of the Rierdon Formation, bedding was the only sedimentary structure observed. Cleavage has formed nearly perpendicular to bedding, making it an unlikely discontinuity which controlled cleavage initiation. Therefore, sedimentary structures may be eliminated as possible controls for cleavage initiation.

The Rierdon Formation is well jointed with a conjugate joint set prevalent throughout the entire range. The joint and bedding orientation within the Rierdon were plotted on stereonets to determine if there is a relationship between the strike of joints and cleavage. In several outcrops one of the conjugate joint sets correlates with the cleavage orientation, with station 1 and Choteau Mountain outcrops being the best examples (see Appendix 1 for the stereoplots). There are,

however, three outcrops that have no correlation between the joints and cleavage: station 3 (the northern termination of the Diversion thrust), station 6 (Benchmark Road) and station 19 (Swift Reservoir). The joints, however, cut across and off-set the cleavage in every case. These cross-cutting relationships demonstrate that the joints post-date the cleavage surfaces, and thus cannot have played a role in cleavage initiation. Since no other discontinuities were observed, it is interpreted that macroscopic discontinuities do not play a role in the cleavage initiation.

Grain Scale Discontinuities

Clay discontinuities are a reasonable source for the nucleation of cleavage domains within the Rierdon Formation. Areas with relatively higher clay concentration at the microscopic level could create enough of an increase in the diffusion rate at that point to initiate pressure solution earlier than the rest of the surrounding matrix (Wanless, 1979; Engelder and Marshak, 1985). However, these areas are impossible to identify within the sample because when the cleavage forms, these concentrations of clay became incorporated into the cleavage domain, thus losing the original distribution at the point of cleavage initiation.

Relatively large, rigid grains are also likely to have a strong influence on cleavage initiation sites in the Rierdon limestone beds. Large grains of quartz and pyrite are observed within the cleavage domains with both the scanning electron and petrographic microscopes (Figs. 21 and 33). These grains are up to $50\mu\text{m}$ in diameter and would have originally been surrounded by a microcrystalline calcite matrix. The quartz and pyrite grains are observed in approximately 10% of the cleavage domains, with the rest of the domains remaining relatively void of any large insoluble grains. This percentage, however, may be skewed by the sampling process. Since a cleavage domain is a three dimensional feature, and the thin sections only represent a two dimensional view of the domain, it is probable that thin sections will have missed the grain that could have been responsible

for the initiation of that particular cleavage domain. Therefore, it is possible that all domains have, at some point, a large grain incorporated within, that may represent the initiation site for the domain.

Fossil fragments may also play the same role as quartz and pyrite fragments in acting as large, rigid fragments along which cleavage initiates. The shells of fossils are commonly composed of sparry calcite and are found within an argillaceous micritic matrix. These fossils may act as a rigid barrier, resisting pressure solution and concentrating stress along their boundaries.

Occasionally a cleavage domain is seen to be well developed along a fossil fragment, where the domain is deflected around its boundaries. In these cases, the cleavage may have been initiated by the fossil fragment. However, most of the cleaved samples contained less than 3% fossil fragments, with only a very limited number actually coming in contact with a domain. In these samples, fossil fragments are thought to only play a minor role in the selection of initiation sites.

Not all rigid grains observed in thin section were within the cleavage domains. Quartz and pyrite grains up to $50\mu\text{m}$ in diameter were also observed in the micritic calcite matrix, away from the individual cleavage domains. These grains obviously did not initiate a cleavage domain, so it is also possible that the grains observed in the domains did not initiate the cleavage, but were incorporated within the domain as the calcite around the individual grains was removed. It is not evident what would cause one grain to initiate pressure solution, while another does not. Other influences, such as grain shape could play a significant role in the selection process.

Random Control on Cleavage Initiation

It is possible that the cleavage initiation process is completely random. Each site in a rock could have an equal chance of forming a cleavage domain at any given moment during deformation. This hypothesis cannot be tested. It seems likely, given all of the inhomogeneities present within the limestones, that inhomogeneities play some role in the cleavage initiation process. However, as

deformation progresses and domains continue to form, there will be fewer discontinuities remaining to focus the initiation of the cleavage domains, reducing their role in cleavage initiation. It is therefore possible that random formation may predominate later in the deformation process.

Cleavage Development

Once a cleavage domain has been established at the initiation point, the cleavage domain will propagate outward in three dimensions in what has been termed an "anticrack" (Fletcher and Pollard, 1981). This propagation of the domain takes place in the same fashion as a crack developing in rock or glass, except that the unit is being shortened rather than extended. As the limestone continues to be dissolved, the insoluble residues accumulate along this "anticrack", allowing the cleavage domain to propagate outward as deformation progresses (Fletcher and Pollard, 1981).

There appears to be a maximum thickness in the cleavage domains of the Rierdon Formation, in that domain thickness does not exceed 0.35mm. However, there is still a wide variance in thickness seen between the domains. The variance in domain thickness occurs both between the samples and within individual samples. The variances between the samples is best illustrated by comparing samples SRR1-1 and GRR1-1 (Table 1). SRR1-1 has an average domain thickness of 0.10mm and a maximum of 0.25mm, where as GRR1-1 has an average of 0.03mm and a maximum of 0.10mm. Individual samples have a large variance as well. This is illustrated by the sample BTR1-2, which has a range from a thickness of less than 0.01mm to 0.35mm. These variances in domain thickness suggest differences in the timing of abandonment of cleavage domains. It is uncertain what would cause one domain to develop a relatively larger thickness, while another is abandoned while still very thin. Since the thickness variations take place in the same sample and no mineralogic or textural differences were observed in the thin sections (either in the domains or the microlithons), it is unlikely that the abandonment is due to changes in the composition of the

limestone. One possibility is that the domain was abandoned when the thin concentrations of clay and other insoluble minerals acted as a glide plane for lateral shear, with the stress accommodated by the shearing (Wanless, 1979). Since evidence for shearing (c-s fabric) is not observed in 90% of the domains, especially the thinner ones, this cannot be the primary method for domain abandonment.

Domain abandonment, however, could be caused by rotating, compacting, and dewatering of insoluble minerals within the domain as deformation continues (Alterman, 1973). This will shut off the pathway for diffusion to occur and effectively choke off the cleavage domain (Weyl, 1959; Alterman, 1973; Wanless, 1979). This appears to be the likely method for domain abandonment in the Sawtooth Range.

There are not enough voids in the Rierdon formation to allow all of the dissolved calcite to reprecipitate in, and extensional fractures and primary porosity within the cleaved Rierdon limestone represent less than 1% of the entire rock volume. Therefore, the spaced cleavage in the Rierdon Formation must have developed in an open system. This is supported by observations using cathodoluminescence (CL) on the SEM. The CL images of the calcite matrix and secondary calcite veins in the cleaved limestones all have different luminescence intensities (Fig. 33). The difference in luminescence intensity in calcite is a function of trace element composition of calcite, indicating a different source for the calcite in the veins (Marshall, 1988). Since the veins are seen to both cut and be cut by cleavage domains, the veins must have developed synchronously with cleavage. Thus, the fluids that brought in the calcite that was deposited in the extensional veins were circulating through the rock at the same time as deformation occurred, indicating that cleavage did form in an open system. This circulation of fluid is the most likely means of removing the dissolved ions from the dissolution sites.

Timing

In the Sawtooth Range, cleavage forms at high angles ($>70^\circ$) to bedding almost without exception. When the cleavage is plotted on stereonet, no fanning is observed. This, however, could be a result of outcrop position, since the outcrops of the Rierdon Formation are present in only isolated patches on the flanks of the folds. The cleavage in the Sawtooth Range consistently forms at high angles to bedding and is therefore presumed to have formed during an early event of layer-parallel shortening, before thrust faulting occurred. This is similar to the findings in other studies (Groshong, 1975; Yonkee, 1983; Mitra and others, 1984; Ihle, 1988; Protzman and Mitra, 1990)..

Cleavage Intensity Variations

Regional Variations

Two ideas are suggested to explain the wide variation in cleavage intensity (from uncleaved units to 3.0 d/cm) observed across the Sawtooth Range. The first idea is that the cleavage intensity variation is due to structural position, and the second is that cleavage intensity variation is due to limestone composition. The effect these two variables have on cleavage intensity is analyzed below.

The effects of structural position on cleavage intensity variations may be subdivided into three categories: 1) outcrop position in regard to the frontal thrust (i.e., the number of thrust sheets from the frontal-most thrust); 2) outcrop position related to the thrust termination; and 3) outcrop position in relation to the crest of the fault propagation fold in an individual thrust sheet. It has been suggested from previous studies that the cleavage intensity tends to increase towards the hinterland (Mitra and Yonkee, 1985; Sears, 1988; Protzman and Mitra, 1990). In order to test this idea, the cleavage intensity was plotted against the number of thrust faults back from the frontal thrust (Fig. 38). The strongest intensities occur in the outermost thrust sheets, with uncleaved units occurring as

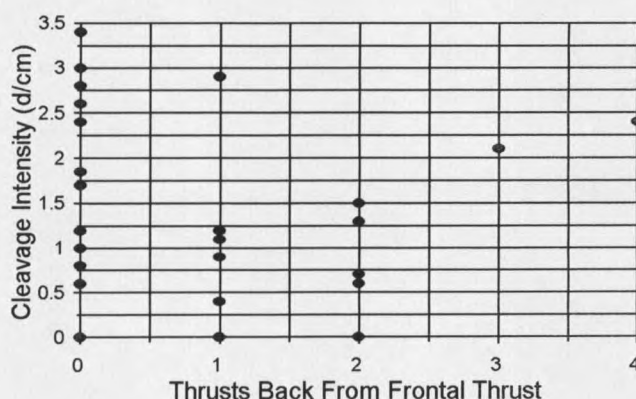


Figure 38. Plot of cleavage intensity versus the number of thrusts from the frontal thrust. Note how the intensity ranges from uncleaved to just under 3.5 d/cm in the frontal thrust.

little as two thrusts back. Therefore, in the Sawtooth Range, this relationship for spaced cleavage is not supported. However, strong cleavage intensities were observed as far back as the Palmer thrust (four thrust faults back) along Gibson Reservoir, which suggests that an inverse relationship is not generally true either.

The greatest amount of displacement along an individual thrust sheet generally occurs towards the center of the sheet (Boyer and Elliot, 1982). This relationship may also hold true for the cleavage intensity. An idealized illustration was developed to show this hypothetical relationship (Fig. 39). This relationship seems to apply on an unnamed thrust near Swift Reservoir, with the strongest cleavage intensities occurring towards the center of the thrust, with intensity decreasing towards the north and becoming completely absent just outside the termination of the thrust sheet (Figs. 26 and 39). This relationship, however, does not hold true along the Diversion thrust in the Sun River Canyon, where the outcrop right near the termination of the thrust fault has a greater cleavage intensity than the outcrop in the center of the thrust fault (Figs. 39 and 40). The

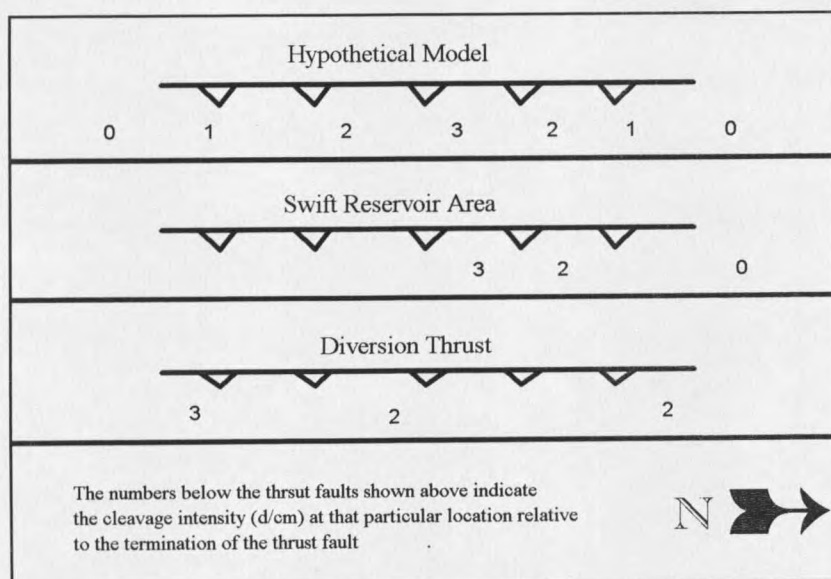


Figure 39. Hypothetical model on how cleavage intensity could vary in relation to the thrust termination. The lower two diagrams show application of the model to the Swift Reservoir area and the Diversion thrust. Note how the model does not hold up on the Diversion thrust.

relationship is also not supported in Lime Gulch near Choteau Mountain, in the Blackleaf Canyon area, and along the French thrust. In these areas uncleaved outcrops are in the center of the thrust sheet and cleaved outcrops are closer to the thrust fault's termination. Therefore, it is evident that this relationship is not universally true in the Sawtooth Range.

The third possible structural relationship is outcrop position in relation to the crest of the fault propagation fold in an individual thrust sheet. It is hypothesized that cleavage intensity will increase towards the crest of a fold where the units may be undergoing local compression related to folding (Fig. 41). Unfortunately, in the Sawtooth Range the Rierdon Formation has been eroded along the crests of folds or is covered over this interval, making it impossible to determine whether this relationship exists in this area. However, assuming that the bedding angle increases with distance from the fold axis, the outcrop's position in relation to the crest of a fold can be estimated. Bedding angles were plotted against cleavage intensity to determine if such a relationship exists

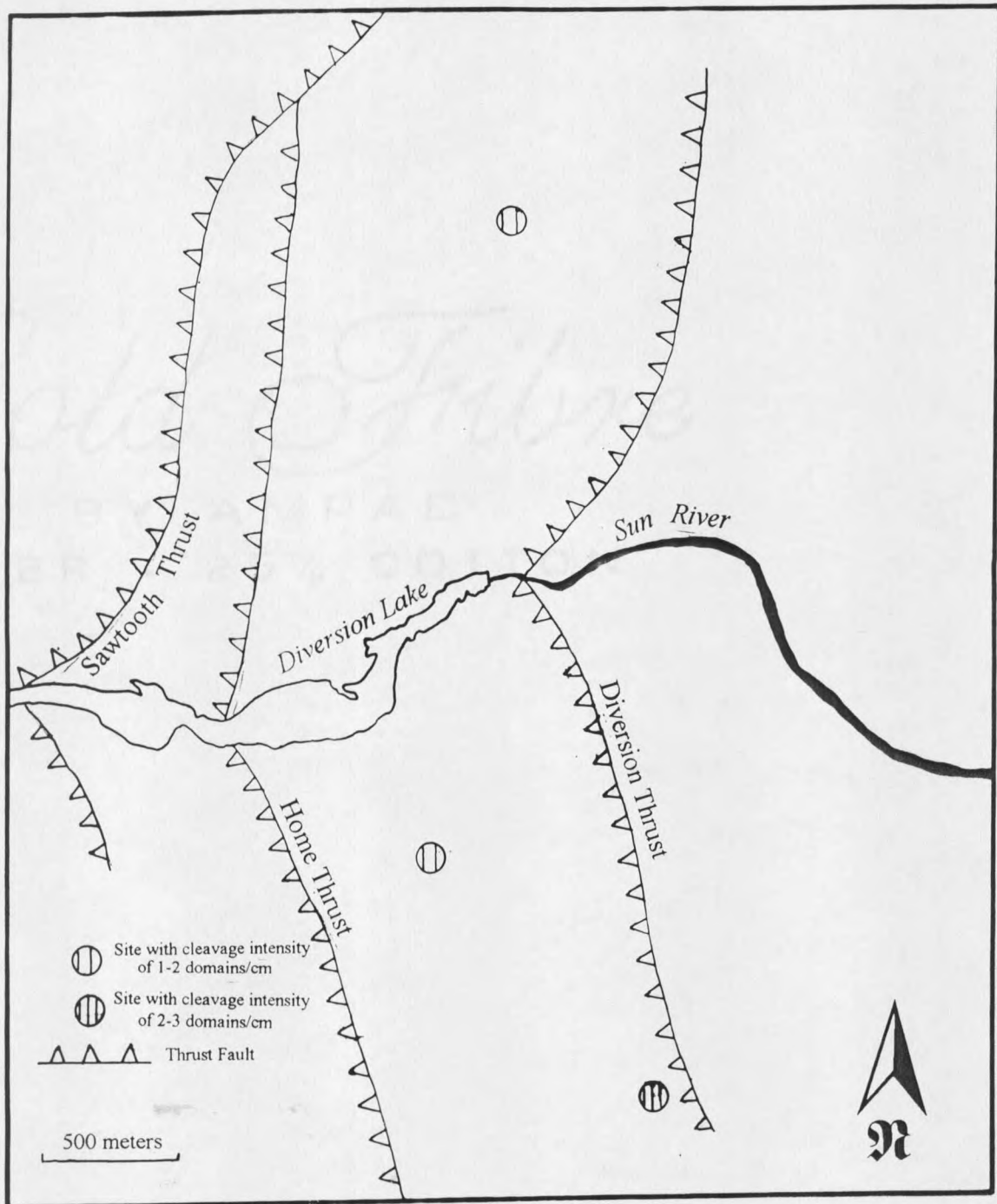


Figure 40. Celavage intensity variations in the Diversion thrust Area.

(Fig. 42). The correlation had an r-squared value of 0.05, and when combined with the plot, it is evident that there is no correlation present between the bedding angle and intensity. Therefore, the third structural hypothesis is not supported.

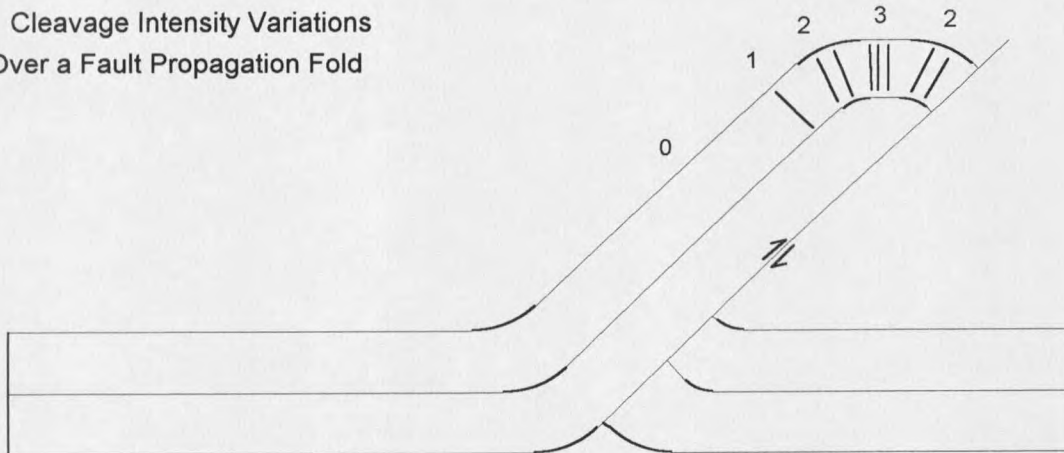
Since the pressure solution process is dependent on the insoluble mineral fraction within limestone (Wanless, 1979; Engelder and Marshak, 1985), cleavage intensity variations could be due to differences in limestone composition between individual outcrops. It is, however, impossible to determine whether or not this relationship exists on a regional scale due to large compositional differences in limestone beds at an individual outcrop. The best example of this change in composition is at station 3 (Wagner Basin outcrop), where the insoluble mineral fraction ranges from 6.5% to 21.6% and fossil content ranges from less than 1% to over 60%, all within 100m. Similar observations were made at other outcrops, but not studied in detail. With such a wide range of values seen in individual outcrops, it is not practical or reliable to apply an average composition to an individual outcrop.

It is uncertain exactly what role that structural position plays on the variation in cleavage intensity. Results of this study show that intensity is not related to the position relative to the frontal thrust, to the horizontal distance from the thrust termination, or to the position relative to the fold axis. It is impossible to determine the role that limestone composition plays in the cleavage intensity variation on a *regional* scale due to the large variation in composition at individual outcrops. It is possible, and most likely, that cleavage intensity may be related to a combination of some or all of the above factors, in addition to some unknown factors as well. However, it is still unknown what the primary cause for the regional cleavage intensity variation is.

Outcrop-scale Variations

It is evident that the cause of cleavage intensity variation at the outcrop scale is a result of

Hypothetical Model of the
Cleavage Intensity Variations
Over a Fault Propagation Fold



The numbers over the fold represent the theoretical cleavage intensities at that position on the fold, and are given in domains/cm.

Figure 41. Hypothetical model on how cleavage intensity could vary in relation to fault propagation folds. Note how the cleavage intensity increases towards the crests of the folds.

Cleavage Intensity Vs. Bedding Angle

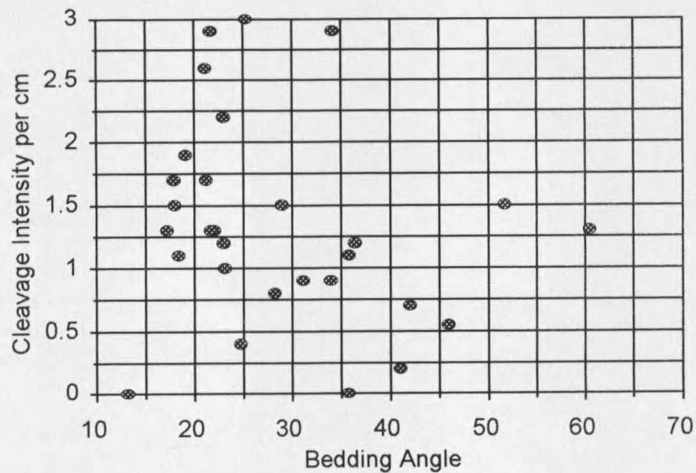


Figure 42. Plot of cleavage intensity versus bedding angle. Note how there is no correlation between the two variables.

local changes in the limestone composition. The role that composition had on cleavage intensity is illustrated at station 3 (Wagner Basin), where it is apparent that fossil content within the limestone indirectly influenced cleavage intensity. At this station, areas with low fossil content (less than 10%; sample DTR5) have the highest cleavage intensity (over 2 d/cm) and areas with high fossil content (greater than 60%; sample DTR7) remained uncleaved (Fig. 27). The percent fossil content directly influences insoluble mineral content, where limestone with low fossil content have higher insoluble mineral content and vice versa (e.g. sample DTR5 at 21.6% versus DTR7 at 6.8%; Table 4). The variability in insoluble mineral content produced by changing fossil content subsequently alters the cleavage intensity. This is supported further at station 1, where large goniatites (up to 30cm in diameter) contain only 4.5% insoluble minerals (sample DTR12, Table 4), and have remained uncleaved in a limestone matrix with a cleavage intensity of 4.1 d/cm (Fig. 29). No limestone in the Rierdon Formation with an insoluble mineral content below 10% or above 30% was cleaved (Table 4). Similar results were found in other studies (Alvarez and others, 1978; Wanless, 1979; Yonkee, 1983; Mitra and others, 1984; Marshak and Engelder, 1985).

It is apparent that the insoluble mineral content directly impacts the cleavage intensity, although it may not be the only factor influencing it. Other influences on cleavage intensity may include localized variations in the stress field or changes in the groundwater flow (that will influence rock-water interaction) during deformation. Unfortunately, there is no evidence of these influences remaining in the rock to determine what role they may have played. However, their possible role should not be ignored in more theoretical studies.

Shortening

The loss of calcite during the formation of spaced cleavage represents a volume of the total rock that has been removed during deformation. It is unclear, however, how much has been removed

from the system, and how much shortening has resulted. Due to this volume loss, it is impossible to restore the beds to their original length or volume in the construction of balance cross-sections. Previously, the amount of shortening accommodated by spaced cleavage has only been roughly estimated and never quantified. There is, however, enough evidence preserved within the domains and microlithons of the cleaved limestones to quantify the amount of shortening that is accommodated via the pressure solution process.

Formulas

To calculate the amount of shortening, the following formula was used:

$$\% \text{ Shortening} = [(L_o - L)/L_o](100) \quad (1)$$

where L_o is the undeformed length and L is the deformed length of a limestone bed. The variable L can be calculated simply by adding the length of the microlithons and domains together. Since deformation occurred in an open system with volume loss, there is no direct method to calculate L_o ; thus, it must be reconstructed by using three measured features of the samples as described previously: the percentage of insoluble minerals in the deformed sample (I_s), the length of the microlithons (L_M), and the length of the domains (L_D).

Two assumptions are made in the following calculation: 1) the percent of insoluble minerals in the microlithons is the same as the sample total *before* deformation; 2) the domains have no calcite remaining within their boundaries and the domains contain 100% insoluble minerals. The validity of these assumptions will be discussed later.

The ultimate goal is to solve for L_o , which is the width of the microlithons (L_M) and the width of the domains *before* deformation (D), which then can be input into equation (1) to calculate the amount of shortening. Since no insoluble minerals have been removed during deformation, and are preserved within the cleavage domains, there is a direct relationship between the domain (its

length and insoluble mineral fraction) and the original width of the rock it represents. This relationship is shown in the following equation:

$$(L_D)(100)=(I_o)(D) \quad (2)$$

where I_o is the original insoluble mineral fraction present in the sample before deformation, D is a reconstruction of the width of the rock that the domain represents before deformation began, and the 100 represents the percent of insoluble minerals within the domain boundaries. This equation states that the width of the domain which contains 100% insoluble minerals is equal to the initial width containing the original insoluble mineral percentage. This smaller insoluble residue percentage was present before deformation occurred.

Using the assumption that the percent insoluble minerals of the sample before deformation is the same as in the microlithon ($I_o=I_M$), the equation to determine the variable I_o can be solved. The amount of insoluble minerals in the microlithons cannot be directly measured by chemical analysis. It is, however, possible to calculate it using the three known variables, L_D , L_M , and I_S . Within the sample, the total insoluble mineral content is equal to the sum of the insoluble minerals present in the domains and the insoluble mineral fraction in the microlithons. Therefore:

$$(L_D)(100)+(L_M)(I_M)=(I_S)(L_D+L_M) \quad (3)$$

where L_D is the length of the domains across the transects, 100 is the percent of insoluble minerals present within the domain boundaries, L_M is the length of the microlithons, I_M is the percentage of insoluble minerals within the microlithons, and I_S represents the percentage of the insoluble minerals in the sample. From equation (3), I_M can subsequently be calculated using the known values of L_D , L_M , and I_S .

In summary, the calculation of shortening within the Rierdon limestones takes place in three steps: 1) equation (3) is used to calculate I_M using the known values for L_M , L_D , and I_S ; 2) assuming that I_M is equal to I_o , the value for I_M is used in equation (2) with L_D to calculate for D ; and 3) D is

summed with L_M to yield L_O , which is used in equation (1) to determine the percent internal shortening that is accommodated by the cleavage.

Discussion of Assumptions

The calculations shown above are based on two assumptions: the domains are 100% enriched with insoluble minerals (or have 100% calcite depletion) and that the insoluble mineral content within the microlithon is representative of the sample as a whole *before* deformation occurred. The assumption that the domains contain 100% insoluble minerals within their boundaries has a direct impact on the shortening calculations. If there is calcite remaining within a domain, the amount of shortening that has occurred will be overestimated by these calculations. The amount of overestimation is shown in Table 5, where calculations were performed at 100, 90, 80, and 70 percent insoluble mineral content. The values were calculated by substituting the representative percent for 100 used in equations (2) and (3). In all of the samples, the difference in the amount of shortening was overestimated by 10% to 15% per each 10% increment less than 100%. This large potential error makes it imperative that no calcite is remaining in the cleavage domains for the shortening calculation to be accurate.

From observations using the scanning electron microscope it is evident that there is still calcite present in most of the domains (Fig. 43), which makes the calculations at 100% insoluble mineral within the domains invalid. Elemental analyses were conducted on the domains using the SEM. This gave an estimation of the percent calcite present within the domains, reducing the amount of error present within the shortening calculations. The estimations were based on the weight percent of the simple oxides present (e.g. CaO for calcium and MgO for magnesium)(Appendix 2). The results showed that the percent insoluble minerals in the domains ranged from 84% in DTR4 to 95% in DTR1-1, with an average of 92% for all of the samples (Table 6). These values can subsequently

Table 5. Illustration on how the amount of calcite remaining in cleavage domains affect the percent shortening within a given sample. The numbers across from the sample name are the amount of shortening for each percentage of calcite depletion within a domain. Note how, as the percent calcite depletion decreases, so does the amount of shortening.

Variations in Shortening Related to Percent Calcite Depletion in Cleavage Domains				
Sample	Percent Calcite Depletion			
	100%	90%	80%	70%
BTR1-1	10.5	9.3	8.0	6.7
BTR1-2	7.7	6.8	6.1	5.3
DCR1-1	17.0	15.0	13.0	11.0
DCR1-2	26.4	23.3	20.2	17.1
DCR2-1	17.9	15.8	13.7	11.6
DCR2-2	21.0	18.5	16.1	13.6
DTR1-1	23.3	20.8	18.2	15.7
DTR4-1	16.3	14.4	12.5	10.6
DTR4-2	13.6	12.1	10.5	8.9
DTR5	2.4	2.1	1.8	1.5
GRR1-1	10.6	9.4	8.1	6.9
GRR1-2	20.5	18.1	15.7	13.3
PTR1-3	18.2	16.1	13.9	11.7
SRR1-1	28.4	24.7	21.0	17.4
TRR2	4.7	4.1	3.6	3.0

replace the 100% used in equations (2) and (3), resulting in more representative values for shortening. The second assumption, that the microlithon insoluble mineral percentage is representative of the total sample before deformation cannot be verified. This is because the formation of the cleavage destroyed what was previously present, making it impossible to ascertain the original (pre-deformation) insoluble mineral percentage. If the assumptions are not valid, the

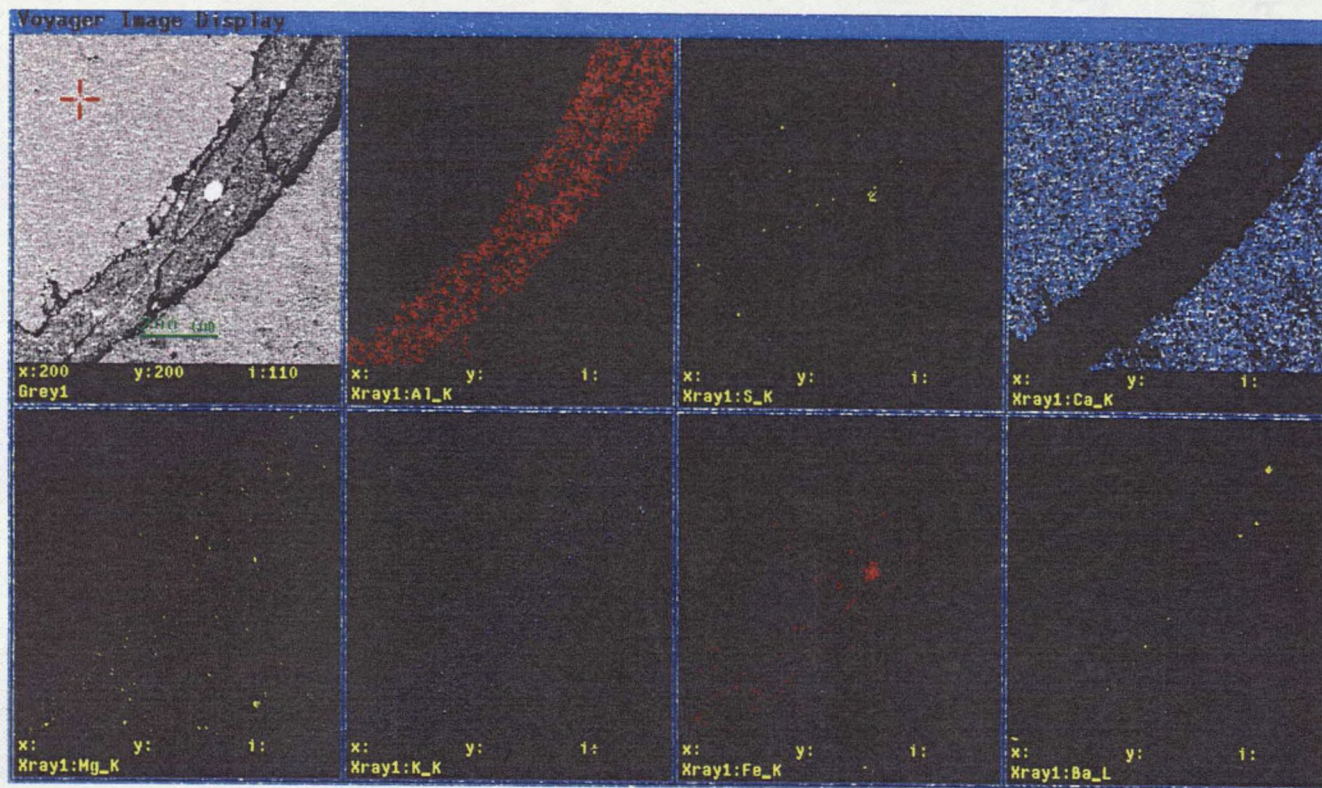


Figure 43. SEM backscattered image (upper left) and element maps of a cleavage domain (center of each picture). The relative brightness of a color on the maps indicates the relative intensity of a particular element. Note how the cleavage domain is nearl 100% depleted in Ca, but still has some Ca remaining, suggesting that calcite is still present within the domain.

Table 6. Estimated percent calcite depletion within the cleavage domains.

Calcite Depletion Within the Cleavage Domains	
<u>Sample</u>	<u>% Calcite Depletion</u>
BTR1-3	90
DCR1-1	94
DCR1-2	92
DTR1-1	95
DTR1-2	93
DTR4	84
GRR1-2	94
PTR1-3	94
SRR1-1	88
TRR2	90
<i>Average</i>	<i>92</i>

implications are as follows: 1) if the insoluble mineral content was greater in the original sample than the microlithon, then the amount of shortening is overestimated, or 2) if the insoluble mineral content was less in the original sample, then the shortening is underestimated. The amount of over or under estimation depends on the degree of difference between the regions. No significant mineralogic differences were observed using either the petrographic microscope or SEM. Therefore, it is likely that the microlithons are close and representative of the original insoluble mineral content.

Calculated Shortening

Using the formulas derived above, shortening values were calculated on samples collected for the Rierdon Formation across the entire Sawtooth Range. The variables used in the calculations are shown in Table 7. In addition, the estimated values for the insoluble mineral enrichment in the domains, shown in Table 6, were substituted for the 100% shown in equations (2) and (3). The amount of shortening ranges from 2.2% in sample DTR5 to 24.0% in SRR1-1, with an average of 14.2%.

The shortening values are dependent upon the total domain widths across a given distance and the insoluble mineral percentage. The total widths of the domains across a given distance is a function of the domain thickness and intensity. This is evident in samples DCR1-2 and DCR2-1, where both samples have a similar insoluble mineral content, yet DCR1-2 has a cleavage intensity of 1.2 domains per centimeter and DCR2-1 has an intensity of 2.0 domains per centimeter. However, the total domain thickness is greater in DCR1-2 (Table 7), which results in a greater amount of shortening (Table 4). The reason that DCR1-2 has a greater amount of strain accommodated through a lower domain intensity is because more strain has taken place in each individual domain, which adds up to more than in DCR2-1. The shortening values are also dependent upon the percentage of insoluble minerals present. This concentration dictates how much calcite must be dissolved in order to create a certain intensity; the higher the insoluble mineral percentage, the less

Table 7. Calculated shortening for the cleaved limestone in the Rierdon Formation. The variables which contain length measurements (Ld, Lm, Lo and L) are given in total millimeters across the transect in which the measurements were taken.

Calculated Shortening						
Sample	Ld (mm)	Lm (mm)	Is	Lo (mm)	L (mm)	% Shortening
BTR1-1	3.0	82.4	25.7	94.0	85.4	9.1
BTR1-2	1.6	60.4	25.7	66.4	62.0	6.6
DCR1-1	2.2	72.0	15.2	88.2	74.2	15.8
DCR1-2	2.8	59.1	15.2	81.4	61.9	23.9
DCR2-1	2.2	69.5	15.0	85.6	71.7	16.2
DCR2-2	2.6	70.1	15.0	89.8	72.7	19.0
DTR1-1	1.5	71.1	13.2	83.5	72.6	13.1
DTR4-1	1.5	58.1	13.7	68.7	59.6	13.2
DTR4-2	1.1	50.8	13.7	58.4	51.9	11.1
DTR5	0.3	46.3	21.6	47.6	46.6	2.2
GRR1-1	1.5	82.5	14.6	93.2	84.0	9.9
GRR1-2	2.2	62.8	14.6	80.3	65.0	19.1
PTR1-3	1.6	46.1	16.0	57.4	47.7	16.9
SRR1-1	4.1	49.8	22.5	70.9	53.9	24.0
TRR2	0.5	57.7	15.6	60.7	58.2	4.1
Average						13.6

calcite that has to be dissolved to create a given domain intensity. This is illustrated by comparing samples DTR1-1 and BTR1-2, both of which have similar outcrop intensities. In sample BTR1-2, the domain to microlithon width ratio is 3 to 100 and in sample DTR1-1 it is 2 to 100. Because BTR1-2 has a higher domain to microlithon ratio, it would appear that sample BTR1-2 should also have the higher shortening value. However, because BTR1-2 has an insoluble mineral content of 25.7% compared with 13.2% in DTR1-1, the cleavage in BTR1-2 has one third the shortening as DTR1-1 (Table 7).

Many authors have suggested that the cleavage intensity increases as the amount of strain increases (Alvarez and others, 1978; Wanless, 1979; Marshak and Engelder, 1985; Mitra and Yonkee, 1985). When the cleavage intensity is plotted against the calculated shortening, it is evident that there is no correlation between shortening and average cleavage intensity for an outcrop (Fig. 44). However, in the Sawtooth Range, it is apparent that the cleavage intensity is related to a combination of insoluble mineral content and total widths of the domains across a given transect.

It is uncertain what will cause the variation in domain thickness. The samples DCR1 and DCR2 illustrate this point. Both have similar mineralogy, percent insoluble minerals, and fossil content. Yet, DCR1 has developed much thicker domains while having a lower domain intensity than DCR2. The answer lies somewhere in the cleavage development process. In DCR1, pressure solution may have occurred for a longer duration along each individual domain, while in DCR2 the domains may have been abandoned at an earlier stage. Possibilities which could cause these localized variations include differences in the groundwater flow or degree of compaction within the individual domains while pressure solution is taking place. Since the answer is most likely in the differences of the conditions during cleavage development, there is no way to test for these.

There is a substantial variation in the amount of calculated shortening across the Sawtooth Range; values range from 0% in the uncleaved units to as high as 24% in SRR1. The large variation

% Shortening vs. Cleavage Intensity

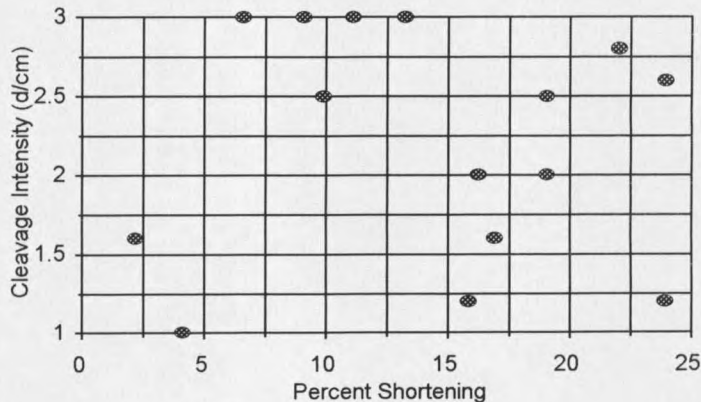


Figure 44. Plot of calculated shortening versus cleavage intensity, as measured in the field. Note how there is not predictive trend in the plot.

in the shortening values greatly impacts how the strain was accommodated during deformation in the Sawtooth Range. Because of the large variation, it is not appropriate to apply an average amount of shortening across the entire range. The amount of internal strain accommodated by the cleavage formation is variable enough that it cannot be predictive with a reasonable amount of uncertainty. Thus, the amount of shortening accommodated through the cleavage remains to be a local effect, and must be analyzed as such. This directly influences the ability to use this information in balanced cross-sections and palinspastic reconstructions. Like small scale folds on a regional cross-section, the amount of shortening accommodated through cleavage formation must be ignored, being variable enough that it can not be averaged out. However, if a regional study on the variation in internal strain accommodated by cleavage were conducted, these data can be included in balanced cross-sections across the region.

Stratigraphic Variations in Cleavage Development

As previously described, cleavage has formed in the limestone beds of the Rierdon Formation, whereas the Devonian and Mississippian carbonates have remained uncleaved. The Devonian-Mississippian carbonates were given a cursory examination in order to investigate the origin of this phenomenon. Three possible explanations for this difference include: differences in the mineralogy, differences in insoluble mineral percentage, and stratigraphic relationships. These results, however, are only preliminary, since the Paleozoic units were only studied at the two locations, rather than across the entire Sawtooth Range.

The mineralogy of the carbonates, namely calcite versus dolomite, may play a role in the pressure solution process, and in turn, the formation of spaced cleavage. The matrix in limestone beds of the Rierdon Formation is composed of micritic calcite, with no dolomite present. In contrast, the mineralogy of all the other carbonates ranged from dolomitic limestones to pure dolomite. Since dolomite is less soluble than calcite (Weyl, 1959), the presence of dolomite may be enough to prevent pressure solution from occurring. This could explain the differences observed in the Sawtooth Range, but only if tectonic stress was insufficient to dissolve dolomite as well as calcite. This stress cannot be quantitatively measured to determine if it reached a threshold where dolomite would have begun to dissolve.

The insoluble mineral fraction will also play a significant role in cleavage development. As previously discussed, a carbonate unit must have at least 10% insoluble minerals present in order to form pressure solution cleavage (i.e. Protzman and Mitra, 1990; Mitra and Yonkee, 1985; Engelder and Marshak, 1985; Wanless, 1979). The Devonian carbonates and the Allan Mountain Limestone are below this cut-off point (Table 4), and are uncleaved. However, the Sun River Member of the Castle Reef Dolomite contains an average insoluble mineral content of 11.7% (Table 4). X-ray

diffraction analysis on the insoluble minerals from this interval show that it is composed of nearly 100% quartz. Even though the insoluble mineral content is high enough for cleavage to take place, the lack of clay within the Sun River Dolomite may be enough to prevent pressure solution from occurring.

Lithology may also be an influencing factor as to whether or not spaced cleavage will form. The difference in lithology is illustrated in the lithotectonic zones (fig. 7), where zone two contains massively bedded carbonates of the Devonian and Mississippian section, and zone three contains argillaceous limestone interbedded with mudstone of the Jurassic. The presence of mudstone between the limestone beds is the critical point in this case. Where mudstone is present between the limestone beds, there is cleavage, and when it is absent, the rocks are uncleaved. When stress is applied to the unit such as this, limestone and dolomite tend to act more rigidly, whereas mudstone tends to deform more plastically (Mitra, 1986; Jamison, 1992; Lageson and Schmitt, 1994). In this case, when a stress is applied to the Rierdon Formation, the mudstones deform plastically, with the bulk of the shortening concentrating in the more competent limestones. This is in contrast to the Devonian and Mississippian carbonates, which have no mudstone between the individual beds, thus the stress is dispersed along the entire thickness. The concentrated stress in the individual limestone beds of the Rierdon may be enough to cause cleavage to form, whereas in more massive carbonate units, the stress never builds up high enough for pressure solution to begin.

Implications for Cleavage Development on Uncleaved Units

The formation of spaced cleavage within the Rierdon Formation has resulted in up to 24% layer-parallel shortening. No other formation in the outermost four thrust sheets has developed this cleavage, which creates a discrepancy in the amount of internal shortening which has taken place between adjacent formations. When this is interpreted using balanced cross-sections, it violates the

assumption "preservation of bed-lengths and area" (Woodward and others, 1986; Hossack, 1979). Since there can be no gaps in the rock left by the calcite which has been removed, this volume loss must be accommodated for by other units in the Sawtooth Range, and within the mudstone of the Rierdon Formation. Therefore, an initial reconnaissance was conducted in other units in order to understand how volume loss in the Rierdon Formation is accommodated in other lithologies. The following are only suggestions on how the internal strain may be accommodated; no quantitative field data were collected. These descriptions are meant to provide a basis to see how the cleavage relates to cross-sections and palinspastic restorations across the Sawtooth Range.

Rierdon Formation Mudstone

Mudstone within the Rierdon Formation is thought to accommodate internal shortening in two ways: flexural flow and the formation of pencil structures. Unlike limestone, pressure solution is not the predominate mechanism for the development of pencil structures within mudstone (Engelder and Geiser, 1979). Studies on the formation of pencil structures have indicated that the development of pencil structures accommodates between 5% and 26% shortening (Reks and Gray, 1982). This is on the same order as the cleavage development in limestone of the Rierdon Formation. Flexural flow is thought to accommodate the shortening in mudstone which does not contain pencil structure. Mudstone tends to act more ductily when being deformed (Lageson and Schmitt, 1994), and thus, will internally thicken as the limestone is shortened by the cleavage. With the combination of pencil structures and flexural flow, mudstone beds will stay consistent with the shortening accommodated by the cleavage within adjacent limestone beds.

Other Formations

The other formations will remain in balance with the shortening in the Rierdon Formation by either internal strain or fault geometry. The Mesozoic strata contain abundant small-scale

intraformational faults and folds (Fig. 37), as well as pencil structures. Although no quantitative field work was conducted on these units, internal strain in the Mesozoic strata likely balances out with the internal strain present in the Rierdon Formation. Devonian and Mississippian strata contain no small scale structures except for extensional fractures and fractures associated with the basal detachment zone of thrust faults (the area affected by cataclasis) (Holl, 1991). However, no significant shortening has been accommodated by these structures (Holl, 1991), which leaves a large difference in the amount of internal strain present between Devonian-Mississippian and Mesozoic strata.

In order to explain the internal strain discrepancy between Devonian and Mississippian and the Mesozoic strata, a more regional view must be taken. A balanced cross-section was drawn from A to A' on Plate 1, across structural zone two (Mudge, 1972b and 1982) starting in structural zone three near the splitting of the Sun River, continuing east along the Sun River Canyon into structural zone one (Fig. 4; Plate 2). The cross-section was balanced within the Mississippian and Devonian units since they lacked significant internal deformation. The Jurassic and Cretaceous units could not be balanced with the Paleozoic strata because of geometric constraints (fault and bedding dips) from the surface data and internal deformation which is at a scale too small to be taken into account. The cross-section shows that deeper into the thrust slices, Devonian is placed directly over Mississippian strata for distances over 2km, with no Mesozoic strata present, with similar geometries obtained by Mudge (1982), Cannon (1979), and Mitra (1986). This suggests that when the Paleozoic strata are displaced over Paleozoic strata, the less competent Mesozoic units have been pushed forward and internally deformed with pencil structures, small scale fold and faults, and spaced cleavage. When the internal deformation is taken into account, the Mesozoic units are then in balance with the Devonian and Mississippian strata.

CHAPTER 6

DISCUSSION

Comparisons of Cleavage Development in Other Fold and Thrust Belts

Spaced cleavage, formed by the same processes and with similar geometries as the cleavage in the Rierdon Formation, has been documented in fold and thrust belts throughout the world (i.e., Carrio-Schaffhauser and Gaviglio, 1990; Bhagat and Marshak, 1990; Mitra and Yonkee, 1985; Spang and others, 1979; Alvarez and others, 1976). In all cases, the spaced cleavage has been observed to decrease in intensity towards the foreland portions of the fold and thrust belts, becoming absent in the outermost thrust sheets. In the Sawtooth Range, however, spaced cleavage is observed with very strong intensities on the frontal-most thrust sheets. Therefore, there must be something unique in the Sawtooth Range for cleavage to develop in a structural setting where it does not develop anywhere else in the world. In order to explain this, comparisons are made of the structural development and lithology of the Sawtooth Range with other fold and thrust belts around the world.

Structural Development

Spaced cleavage has been documented in fold and thrust belts of different ages throughout the world. Because of this, each individual fold and thrust belt has been eroded to a different structural level, which makes comparisons difficult. However, the Idaho-Utah-Wyoming (IUW) fold and thrust belt is nearly the same age as the Montana fold and thrust belt (late Cretaceous to early Tertiary), with neither being deeply eroded (Mudge, 1972b; Mudge, 1982; Mitra and Yonkee, 1985).

Therefore, cleavage development in the two areas are observed at relatively the same structural level. It is for this reason, along with the availability of information on the IUW fold and thrust belt, that comparisons on structural development will focus on the IUW and Montana fold and thrust belts.

The cleavage development in the IUW fold and thrust belt on the macro- and micro-scopic level is very similar to the Sawtooth Range. As in the Rierdon Formation, it is present in argillaceous limestone with insoluble minerals comprising over 10% of the rock by weight (Mitra and others, 1984; Yonkee, 1983). The cleavage forms closely spaced, parallel domains at high angles to bedding, reaching intensities of up to 2 domains per centimeter (Yonkee, 1983), and yielding a moderate to strong intensity in the classification scheme of Alvarez and others (1978). It has also developed a very similar domainal morphology to what is observed in the Sawtooth Range (Yonkee, 1983). However, there is a drastic difference in the cleavage intensity relative to the structural position within each of the belts. In the IUW fold and thrust belt, the cleavage is most intense in the Crawford and Meade thrusts and decreases in intensity towards the foreland, and becoming completely absent in the frontal Hogsback and Prospect thrusts (Figs. 45 and 46) (Mitra and Yonkee, 1985). This is in contrast with the Sawtooth Range, where the strongest cleavage intensities, with domain spacings as high as one every 0.2 cm, are documented in the outermost thrust sheets. The cleavage intensity pattern in the IUW fold and thrust belt fits the generally accepted idea of intensities decreasing towards the foreland (Sears, 1988; Engelder and Marshak 1985; Alvarez and others, 1978).

The difference in the mechanics of the tapered wedge model is one possible reason for the differences in cleavage development in the two belts. Theoretical models on the tapered wedge have been developed and refined by several authors (e.g., Chapple, 1978; Davis and others, 1993; Dahlen, 1984; and Platt, 1986). These theoretical models state that orogenic wedges develop taper towards the undeformed foreland, with the angle of the tip of the taper (θ) equal to the angle of the basal

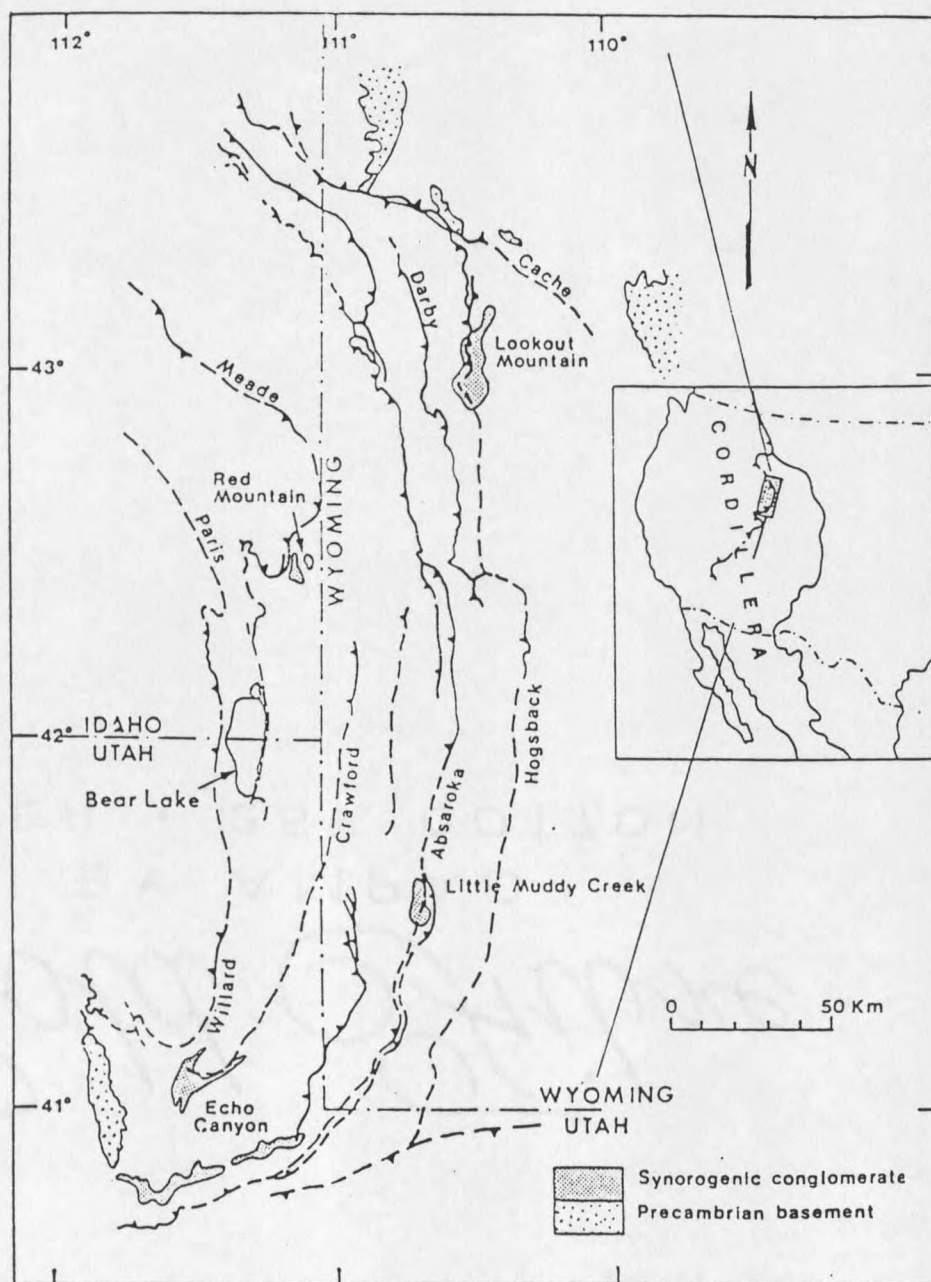


Figure 45. Generalized geologic map of the Idaho-Utah-Wyoming fold and thrust belt (from Mitra and Yonkee, 1985).

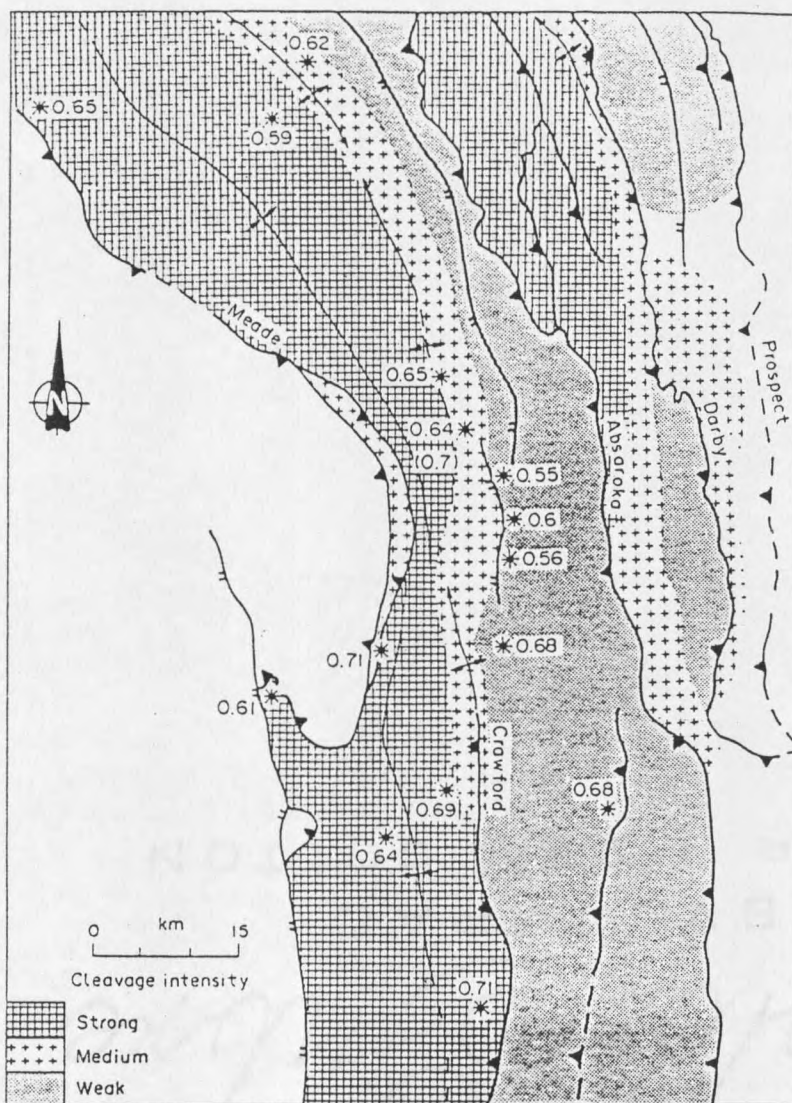


Figure 46. Map showing cleavage intensity variation within the Idaho-Utah-Wyoming fold and thrust belt (from Mitra and Yonkee, 1985). Note how cleavage intensity decreases to the east (towards the foreland).

decollement (β) added with the angle of the upper slope (α) (Fig. 47). When θ equals critical taper, the taper required for the wedge to overcome the basal friction, the wedge will advance in a stable manner towards the foreland (Davis and others, 1983; Dahlen, 1984). If θ is less than critical taper, the wedge will not propagate forward, but will internally thicken towards the rear of the wedge to build up α and subsequently raise θ towards the critical taper (Davis and others, 1983; Dahlen, 1984). If θ becomes greater than critical taper, then the wedge will tend to lengthen by propagating out in front of the wedge by imbrication lowering α , thus θ becomes closer to critical taper (DeCelles and Mitra, 1995).

In the IUW fold and thrust belt, the tapered wedge went through four major episodes of thrusting: 1) Crawford thrusting from 89 to 84 Ma, 2) Absaroka thrusting from 84 to 75 Ma, 3) a second stage of Absaroka thrusting from 69 to 62 Ma, and 4) Hogsback thrusting from 56 to 50 Ma (Lamerson, 1982; Armstrong and Oriel, 1986; DeCelles and Mitra, 1995). Each episode of thrusting occurred in a three stage cycle as follows: 1) wedge imbricating forward with the wedge in a critical to supercritical state, 2) advancement of the wedge along the decollement with the wedge in a supercritical state, and 3) erosion out pacing uplift, stalling the wedge, creating a subcritical state (Fig. 48) (DeCelles and Mitra, 1995). During stage three, the wedge deforms internally to thicken the wedge towards a critical state, and thus back towards stage one (DeCelles and Mitra, 1995). Strata from Precambrian basement rocks through Cretaceous have been involved in the thrusting (Oriel and Platt, 1980; Armstrong and Oriel, 1986). Precambrian basement rocks and Proterozoic sedimentary rocks are involved in and to the west of the Wasatch culmination, with Phanerozoic strata comprising the frontal 50km of the fold and thrust belt in the imbricate fan. Horizontal displacement in the fold

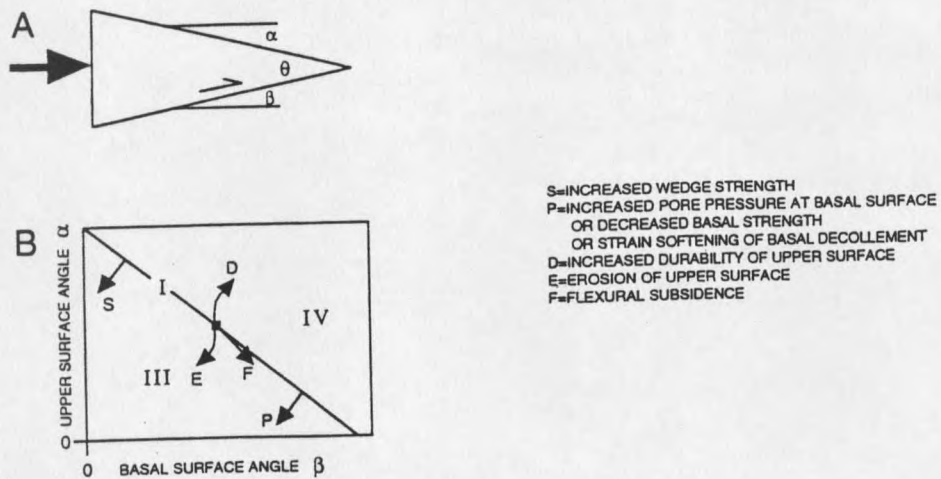


Figure 47. A) Schematic diagram illustrating the geometry of a tapered wedge. B) Illustration showing the behavior of a tapered wedge to influences of the different parameters. I indicates a wedge in a critical state, III is the region where the wedge is in a subcritical state, and IV is the region where the wedge is in a supercritical state. Diagram from DeCelles and Mitra (1995).

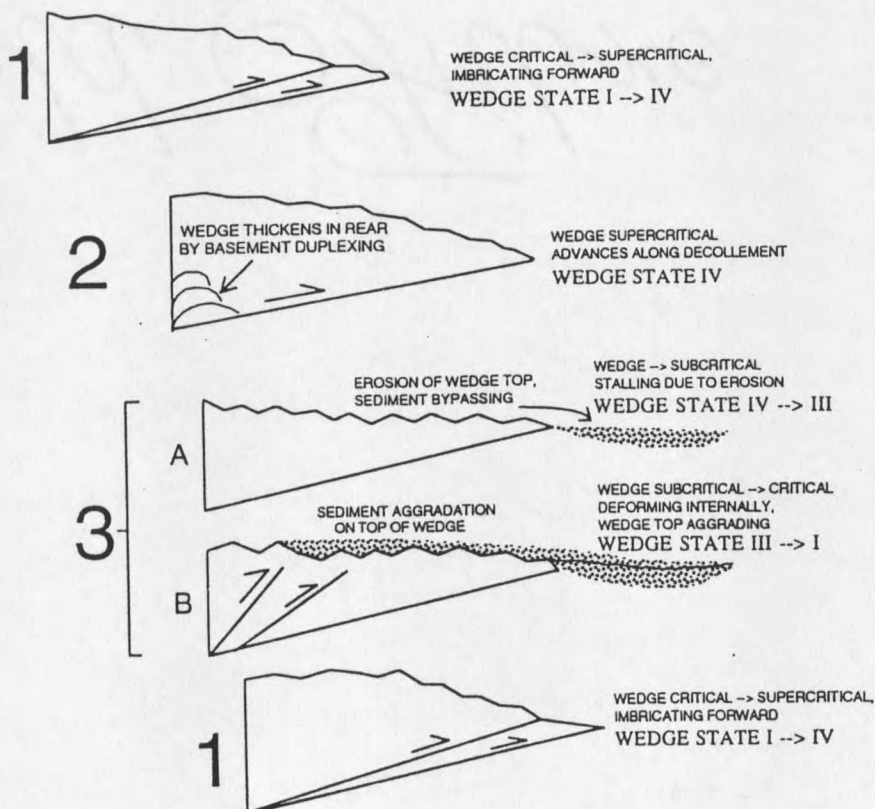


Figure 48. Schematic diagram illustrating the three stage cycle present within the Idaho-Utah-Wyoming fold and thrust belt (from DeCelles and Mitra, 1995).

and thrust belt ranges from 80 - 100 km (Armstrong and Oriel, 1986), with between 16 - 20 km on each fault.

This development is in contrast with the Montana fold and thrust belt, which extends from the Idaho Batholith east to the Rocky Mountain front (where the Sawtooth Range is located). Here, thrusting occurred in two major events: the thrusting of the western thrust sheet from 78 to 72 Ma, and the thrusting of the eastern sheet from 56 to 50 Ma (Hoffman and others, 1976; Mudge, 1982; Sears, 1988; Ellison, 1991). The emplacement of the western thrust sheet involved Proterozoic Belt Supergroup sediments thrust over Mesozoic strata (Sears, 1988). Although total displacement of the western thrust sheet has yet to be accurately determined, it has been estimated that up to 24km of shortening has occurred. The second stage of thrusting took place along the Lewis-Eldorado-Steinbach thrust systems (Sears, 1988). These thrusts carried Proterozoic Belt Supergroup strata out of the Belt Basin more than 65km to the east (Mudge and Earhart, 1980; Sears, 1988). The thrusting over the eastern margin of the Belt Basin created a frontal ramp in the thrust system. The western thrust sheet was displaced over this ramp, and created the Purcell Anticlinorium (Sears, 1988). The Belt Supergroup strata were thrust out to the leading edge of the tapered wedge, overrunning the frontal imbricate fan of Paleozoic and Mesozoic sediments at Glacier Park and Rogers Pass (Mudge, 1972b; Mudge and Earhart, 1980; Mudge, 1982; Sears, 1988). The Sawtooth Range represents a portion of the wedge in which the Proterozoic sediments did not thrust over the leading imbricate fan (Mudge, 1972b; Mudge, 1982). The thickness of the wedge ranges from 25km in the Purcell Anticlinorium to 4km at the Rocky Mountain Front (Sears, 1988).

The two main differences between the IUW fold and thrust belt and the Montana Cordillera is the involvement of the Proterozoic and Precambrian basement rocks, and the time frame in which thrusting took place in. In the IUW salient, the basement rocks and the Proterozoic strata are restricted to the rear of the wedge, where as in the Montana Cordillera, the thick sections of

Proterozoic sediments are thrust to the front edge of the tapered wedge (Mudge and Earhart, 1980; Armstrong and Oriel, 1986; Sears, 1988; DeCelles and Mitra, 1995). The thrusting within the IUW fold and thrust belt occurred in four separate intervals, with each event having between 10km and 20km horizontal displacement and lasting about 7 million years (Armstrong and Oriel, 1986; DeCelles and Mitra, 1995). In the Montana Cordillera, only two events were recorded, with most displacement (65km) taking place along the Lewis-Eldorado-Steinbach thrust system and a duration of about 6 million years (Mudge and Earhart, 1980; Sears, 1988; Elison, 1991). For most of its development, the IUW tapered wedge has been going from a supercritical to subcritical state, resulting in episodic movement (DeCelles and Mitra, 1995). However, the Montana Cordillera tapered wedge was able to maintain a critical to supercritical wedge for six million years, allowing the Proterozoic Belt Supergroup to be displaced over 65km to the east (Mudge and Earhart, 1980; Sears, 1988; Elison, 1991). This is the same amount of time in which each episode of thrusting took place in the IUW fold and thrust belt, but only recording 10km to 20km of horizontal displacement each time (Armstrong and Oriel, 1986). This relatively rapid progression of thick sequences of Belt Supergroup strata may have created a situation of increased stress at the tip of the wedge, which could have allowed cleavage development to take place this close to the front edge of the tapered wedge. This situation did not occur in the IUW fold and thrust belt, which restricted the cleavage development to further back in the wedge.

Lithologic Differences

Comparisons of the lithology of the Rierdon Formation are made with cleaved units from fold and thrust belts from IUW, southern Alberta, New York, northern Italy and southeastern France. The Jurassic Twin Creek Formation in the IUW fold and thrust belt is composed of almost 100% argillaceous limestone, with a minor amount of mudstone present near the base in the Gypsum

Springs Member (Imlay, 1967). In southern Alberta, cleavage is present in the Mississippian Banff Formation (equivalent to the Allan Mountain Limestone) which is composed predominately of thinly to thickly bedded limestones and dolomites, with only a minor amount of mudstones at the base (Spang and others, 1979; Richards and others, 1993). The cleavage present in the Hudson Valley, New York, is seen to develop in the Kalkberg and New Scotland formations, which are composed of gray thin to thickly bedded argillaceous limestones (Laporte, 1967; Murphy and others, 1980; Marshak and Engelder, 1985). Like the formations above, the cleaved formations in Italy and France are also composed of predominately limestones (Alvarez and others, 1976; Carrio-Schaffhauser and Gaviglio, 1990). All of the above are positioned in foreland fold and thrust belts.

When the lithology of these formations is compared with the lithology of the Rierdon Formation, there is a striking difference. The Rierdon Formation consists of mudstone interbedded with numerous thin argillaceous limestone beds, commonly 10 to 15 cm thick, but reach up to 2 m in thickness (Fig. 8)(Mudge, 1972a). In total, about 75% of the formation is composed of mudstone. The formations in the other fold and thrust belts, on the other hand, are composed of almost 100% limestone. It is apparent that the Rierdon Formation has a very different lithology from other cleaved formations.

The difference in the lithology possibly plays an important role in cleavage formation because of the relative strength of mudstone versus limestone. When a stress is applied limestone will tend to act as rigid beams, whereas mudstone will deform more ductilely (Lageson and Schmitt, 1994). Over the total interval of the Rierdon the stress is concentrated within 25% of the total thickness (on the limestone beds), which may end up being enough to allow pressure solution to occur in the outermost thrust sheets. In the other formations, where the limestone is the dominant composition, the stress is dissipated over nearly the entire interval and therefore never reaches a level to start pressure solution in the outermost thrust sheets. In addition, this scenario is further

illustrated within the Sawtooth Range itself where massive carbonate units of the Mississippian and Devonian have remained uncleaved in the outermost thrust sheets, and the Rierdon Formation was intensely cleaved.

Conclusions

Three ideas have been put forth to explain the intense cleavage development in the outermost thrust sheets within the Sawtooth Range: 1) differences in the mechanics of the tapered wedges, and 2) the presence of mudstone in between the limestone beds. The evidence present suggests that both of the above may play an important role in concentrating the stress within the formation. Studies must be conducted on the mechanics of each scenario in order to truly ascertain the role each plays. It is not within the scope of this project to produce such models. However, it is believed that both may have some role in the intense cleavage development within the Sawtooth Range.

Potential Influences on Reservoir Qualities

Reservoir characterization involves describing the spacial distribution of the porosity and permeability within a given unit (Lucia, 1995). The distribution of porosity is dependent on both primary depositional fabric such as grain size and shape (i.e. Lucia, 1995; Choquette and Pray, 1970), and diagenetic processes such as fracturing, mesogenetic dissolution, and cementation (i.e., Mazzullo and Harris, 1992; Kerans, 1989; Choquette and Pray, 1970). Permeability is dependent on the interconnectivity of pore spaces and pore throat size (Pittman, 1971). Deformation, both diagenetic and tectonic, plays a significant role in both the enhancement and degradation of porosity and permeability (Mitra, 1988). Enhancing mechanisms include fracturing and brecciation, whereas reducing mechanisms include cataclasis and pressure solution (Mitra, 1988). Spaced cleavage in limestone of the Rierdon Formation was created by pressure solution and has formed a penetrative

fabric within limestone. This fabric has a significant impact on the reservoir characteristics of the cleaved unit. The following chapter discusses the impact that the formation of the cleavage will have on porosity and permeability of the unit.

Permeability Reduction

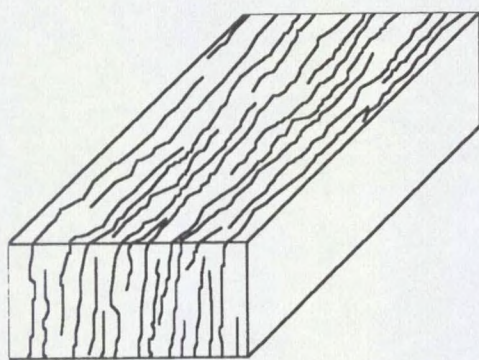
Permeability within a reservoir is greatly affected by the formation of spaced cleavage. During pressure solution calcite is dissolved, allowing clays, quartz, and other relative insoluble minerals to accumulate along thin seams, or domains. As deformation and pressure solution continues, minerals within the domain become compacted, and platy minerals aligning sub-parallel to the domain boundary (Fig. 19)(Marshak and Engelder, 1985). The porosity is significantly reduced within the domain boundary, and forms an effective barrier to fluid migration between the microlithons.

Cleavage tends to form perpendicular to the direction of maximum stress (Soper, 1986; Mitra and Yonkee, 1985; Durney, 1972). The Rierdon Formation illustrates this with cleavage forming an interconnected network of sub-parallel surfaces parallel to the trend of thrust faults, and perpendicular to the regional transport direction (Fig. 49)(Mudge, 1972b; Mudge and Earhart, 1983). Domain intensities within the range vary from one domain to over four domains per centimeter. With such an intense spacing, fluid migration within this unit is severely reduced perpendicular to cleavage, resulting in essentially two dimensional flow regime within the system (Fig. 50).

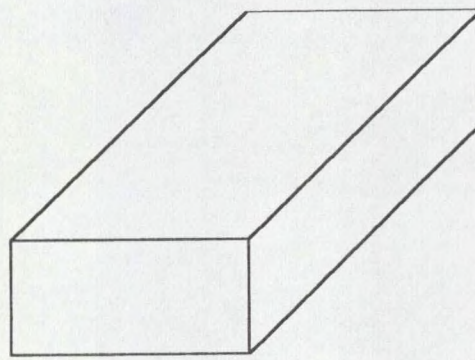
The extent of reservoir anisotropy within cleaved units is influenced by two factors: 1) domain interconnecting geometry and 2) domain spacing. The domain interconnecting geometry determines the extent to which microlithons are separated from each other. Within the Rierdon Formation, there are two domain geometries observed: discontinuous parallel (straight) and anastomosing (Figs. 15, 16, and 24). Domains within a discontinuous parallel geometry are not



Figure 49. Spaced cleavage at station #1 in the Rierdon Formation. Cleavage intensity is 3.4 d/cm. Hammer is 30 cm in length.



Cleaved Limestone



Uncleaved Limestone

Lines Represent Fluid Flow Directions

Figure 50. Schematic diagram showing the difference in flow path between an uncleaved and a cleaved limestone. Note that the cleaved limestone will have only two dimensional flow.

joined with one another, leaving connection between microlithons, which in turn allows fluid migration between microlithons to occur. The anastomosing geometry, however, has domains connecting with each other, thus isolating the microlithons and restricting fluid migration between them. The discontinuous parallel geometry will slow fluid migration perpendicular to the trend, but because it does not form a complete barrier, the fluid migration will be significantly faster than in the anastomosing geometry (Fig. 51). The spacing of the domains will determine how fast fluid can flow in the direction perpendicular to the trend of the domains with a discontinuous parallel geometry. In general, the closer the domain spacing, the longer the fluid flow path has to be in order to travel the same horizontal distance (Fig. 51). In addition, if there is some fluid flow across the domains, cleavage intensity will also affect the velocity. Since fluid migration is considerably slower across the domains, the more domains a fluid has to cross, the slower it will proceed perpendicular to the cleavage trend.

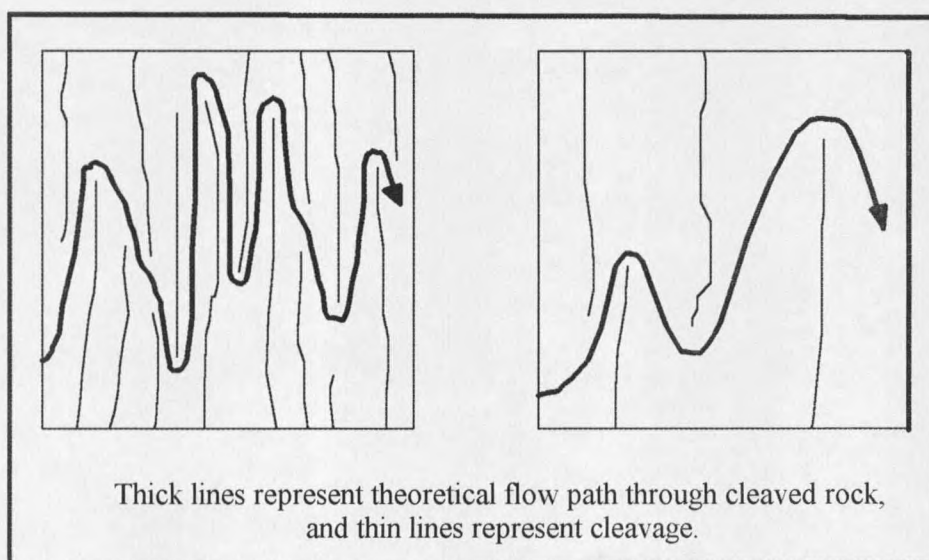


Figure 51. Schematic diagram showing how cleavage spacing will affect the length of the flow path for a fluid migrating perpendicular to the cleavage trend. The flow path is indicated by the thicker line, with the cleavage domains being the thinner lines.

In order to predict reservoir anisotropy, one must determine two things: 1) trend of the cleavage and 2) intensity. The trend will reveal the direction of reservoir anisotropy. In the case of the Sawtooth Range, cleavage trend is fairly consistent in a north-south direction, sub-parallel to the mapped thrust faults (Mudge and Earhart, 1983). Therefore, in the Sawtooth Range, fluid migration would be greatest in a north-south direction, and restricted in an east-west direction. The intensity of the cleavage will determine the extent of anisotropy; the more intense cleavage development is, the more pronounced reservoir anisotropy will be. In the case of the Sawtooth Range, intensity varies widely, with no predictable pattern. However, in the Idaho-Utah-Wyoming fold and thrust belt, cleavage tends to follow a developmental pattern, enabling a prediction of the relative cleavage intensity (Fig. 46)(Mitra and Yonkee, 1985). Therefore, if a regional pattern develops (unlike in the Sawtooth Range), it would be possible to predict the extent of reservoir anisotropy.

Permeability Enhancement

Instead of being a permeability barrier, spaced cleavage could possibly also directionally enhance permeability on the crests of folds within a reservoir. Spaced cleavage has been documented to form in an early stage of layer parallel shortening, before folding and faulting occurred (Mitra and Yonkee, 1985; Engelder and Marshak, 1985; this study). If the unit was later folded, localized extension would have taken place at the crest of the fold (Fig. 52)(Mitra, 1988). Since, by definition, cleavage represents a weakness in limestone, it is likely that open fractures will have formed along these surfaces. Fractures have been documented to increase permeability in the direction of trend by up to two orders of magnitude (Mitra, 1988). Therefore, along the fold axis, permeability could be greatly enhanced parallel to the trend of cleavage. However, the increase in permeability is directly influenced by the aperture of the fractures (Mitra, 1988). If they did not

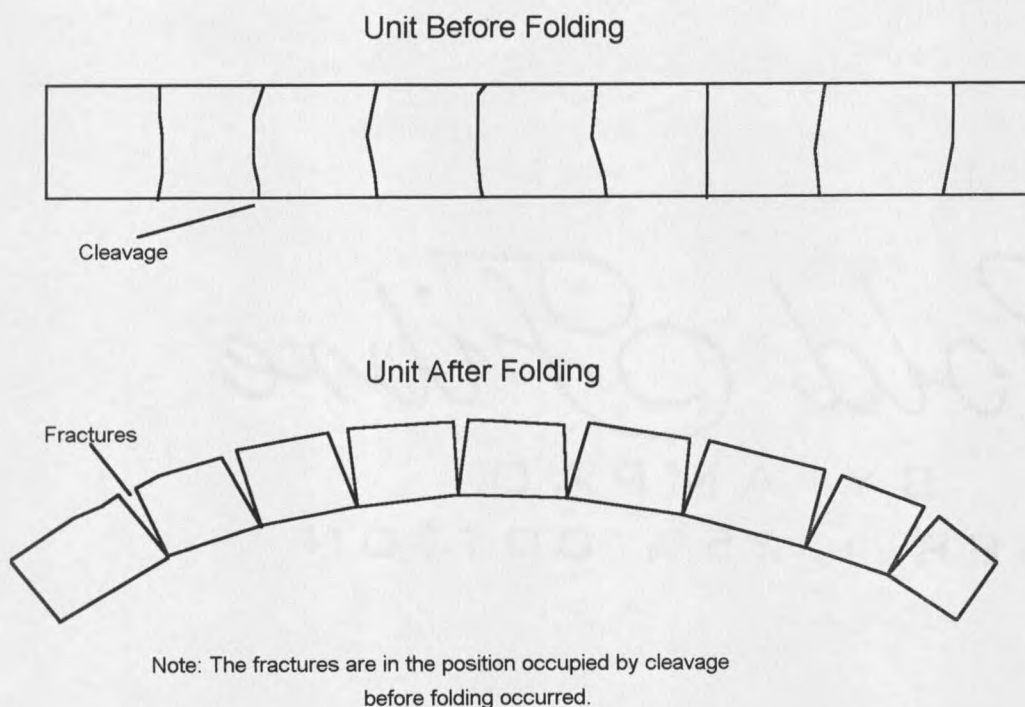


Figure 52. Schematic diagram illustrating how cleavage domains may open up and form fractures at the crest of folds.

open up to an aperture which allows fluid to flow through, they will remain a barrier to fluid migration.

Cementation

The formation of spaced cleavage could also provide a source for secondary calcite cement (Choquette and Pray, 1970; Bhagat and Marshak, 1990), which would reduce the porosity present within the immediate formation and in nearby units (Bhagat and Marshak, 1990; Marshak and Engelder, 1985). In the Rierdon Formation, pressure solution has removed between 2% and 24% of the limestone by volume. This creates a large volume which has to be re-precipitated nearby, or carried out of the system (Engelder and Marshak, 1985; Wanless, 1979; Durney, 1972). Secondary calcite deposition occurred concurrently with cleavage formation, predominately in extensional

fractures. However, when these fractures were analyzed using cathodoluminescence, they showed that the secondary calcite was derived from outside the system (Marshall, 1988)(Fig. 33). This suggests that cleavage in the Sawtooth Range formed in an open system (Marshall, 1988). However, if cleavage forms in a closed system the calcite must be re-deposited in pore spaces and pressure sinks for pressure solution to continue (Engelder and Marshak, 1985; Wanless, 1979). It has been documented in other regions that 50% of the calcite dissolved has been redeposited in the immediate vicinity (Bhagat and Marshak, 1990). This would significantly reduce the porosity adjacent to the domains.

If the dissolved calcite is not deposited near the domains where it dissolved, it will be carried out of the formation into the groundwater regime. This could significantly reduce porosity in nearby units. With relatively saturated waters flowing through the pores of the nearby formations, the calcite might precipitate out, occluding reservoir porosity. This may have occurred in the Castle Reef Dolomite just below the Rierdon Formation, where a conjugate joint set has been completely cemented shut. Other units in the Sawtooth Range which may have been affected by the cleavage formation include the sandstones of the Swift, Sawtooth, and Kootenai Formations. Therefore, the effect cleavage development has on the surrounding rocks can not be overlooked.

CHAPTER 7

CONCLUSIONS

Spaced cleavage has developed at very high intensities within the Rierdon Formation of the Sawtooth Range. This cleavage was formed by pressure solution, indicated by partial dissolution of fossil fragments and calcite veins along cleavage domains, and by accumulation of relatively insoluble minerals within cleavage domains. The interconnecting geometry varied from anastomosing to parallel smooth domains. Initiation of these domains is not clearly understood since the initiation site was destroyed with continuing pressure solution, however, grain scale inhomogeneities such as relatively large, rigid grains, and microscopic clay concentrations are likely to play a role in determining the initiation site for each domain. Since the cleavage trend is consistently at high angles to bedding, it appears to have formed in an early event of layer parallel shortening, before thrusting and faulting occurred. These observations are similar to those of other studies on spaced cleavage development in argillaceous limestones around the world (Durney, 1972; Alvarez and others, 1976; Yonkee, 1983; Marshak and Engelder, 1985; Carrio-Schaffhouser and Gaviglio, 1990).

The cleavage intensity observed varied widely across the entire range, both between individual outcrops and within the same outcrop. Cleavage intensity between outcrops varied from remaining uncleaved to an average intensity of over four domains per centimeter. The reason for this regional intensity variation is most likely a combination of the outcrop's position with respect to the major fault propagation folds within each thrust sheet and local variation in limestone composition. Variations of cleavage intensity within individual outcrops have reached up to a three

domain per centimeter difference, with a 1.5 domain per centimeter difference being most common. These differences in cleavage intensity are related to composition of the limestone (insoluble mineral content).

The amount of internal strain associated with the cleavage development was calculated from samples collected at various intervals across the Sawtooth Range. The values of shortening obtained ranged from 2% to 24%. These values, however, had no correlation with the cleavage intensity observed at the outcrop. This suggests that the cleavage intensity is not higher with increasing strain.

Spaced cleavage appears to have been restricted to developing within the Rierdon Formation. Although there are thick sequences of carbonate present within the Paleozoic section, none of these units in the outermost thrusts contained cleavage. This creates an internal strain accommodation problem between these units and the Rierdon Formation. This is, however, resolved by other forms of internal deformation in the Mesozoic section, and by regional fault displacement patterns in the Paleozoic section.

Spaced cleavage with the intensity observed in the Rierdon Formation has not been documented this close to the foreland edge of the fold and thrust belt anywhere else in the world. It is believed the reason this unique situation in the Sawtooth Range involves the presence of mudstone interbedded with the cleaved limestones. Mudstone, when a stress is applied, tends to deform more plastically, whereas limestone will deform more brittly. This results in concentrated stress in the thin limestone beds, allowing pressure solution to take place.

Spaced cleavage could have a significant impact on the reservoir characteristics. The domains, composed of compacted insoluble minerals of clays, quartz, and pyrite, will form a permeability barrier. This in effect creates a two dimensional flow pattern and results in reservoir anisotropy. However, if these cleavage domains are present over the crest of a fold, they may open

up (fracture), allowing increased fluid migration parallel to the cleavage trend. The formation of spaced cleavage will also provide a source of calcite cement, which may precipitate out both within the formation itself, and in the adjacent units, reducing porosity in those units.

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APPENDICES

APPENDIX 1

STEREOPLOTS

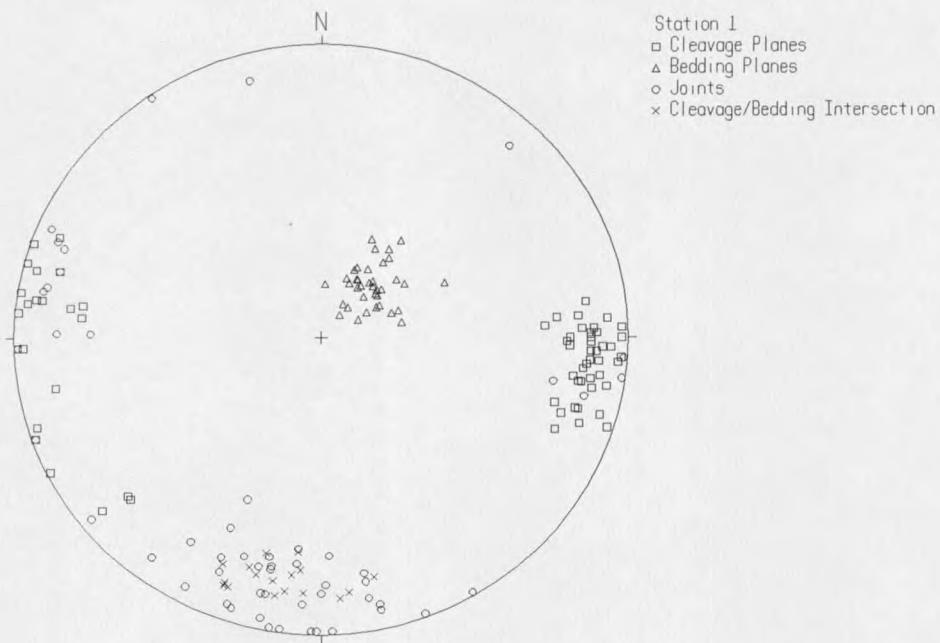


Figure 53. Equal area stereoplot at station 1, on the southern termination of the Diversion thrust.

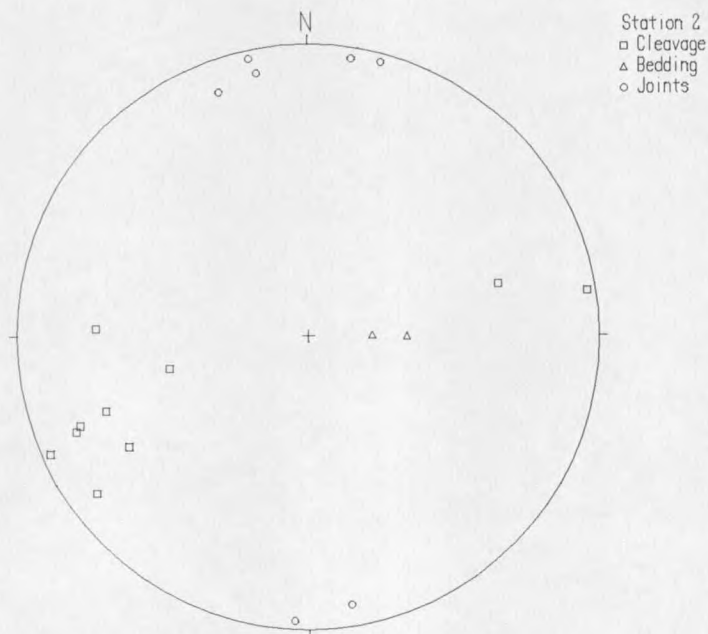


Figure 54. Equal area stereoplot at station 2, just south of the Diversion Reservoir.

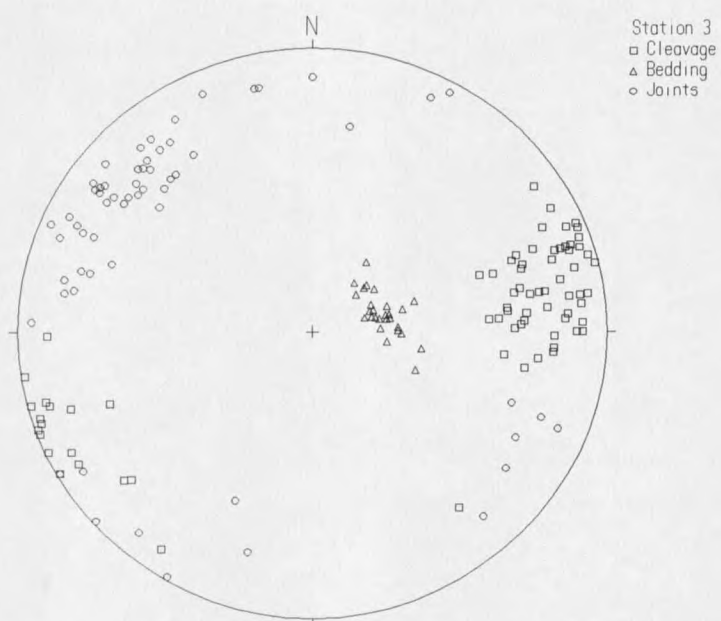


Figure 55. Equal area stereoplot at station 3, in Wagner Basin.

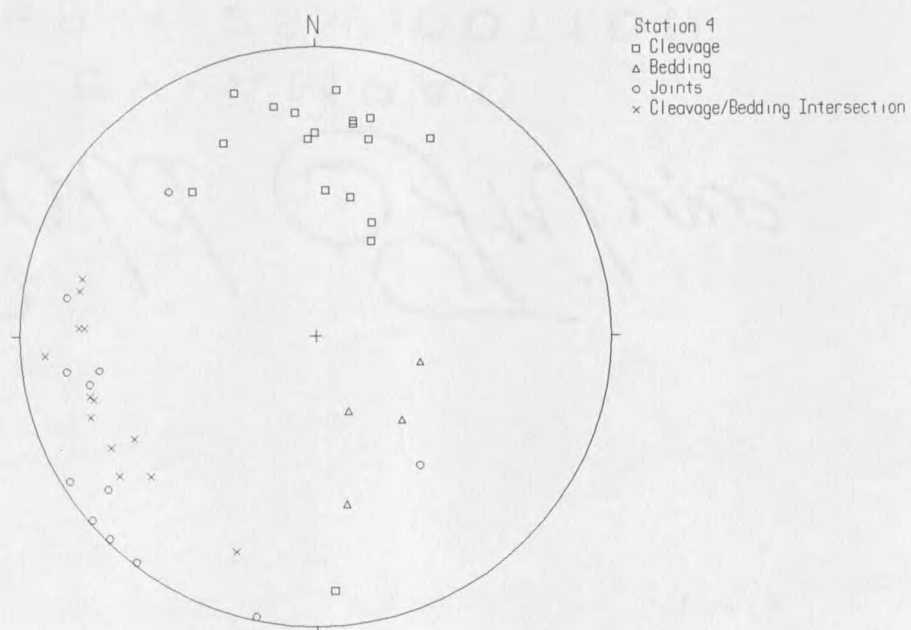


Figure 56. Equal area stereoplot at station 4, just north of Sawtooth Mountain.

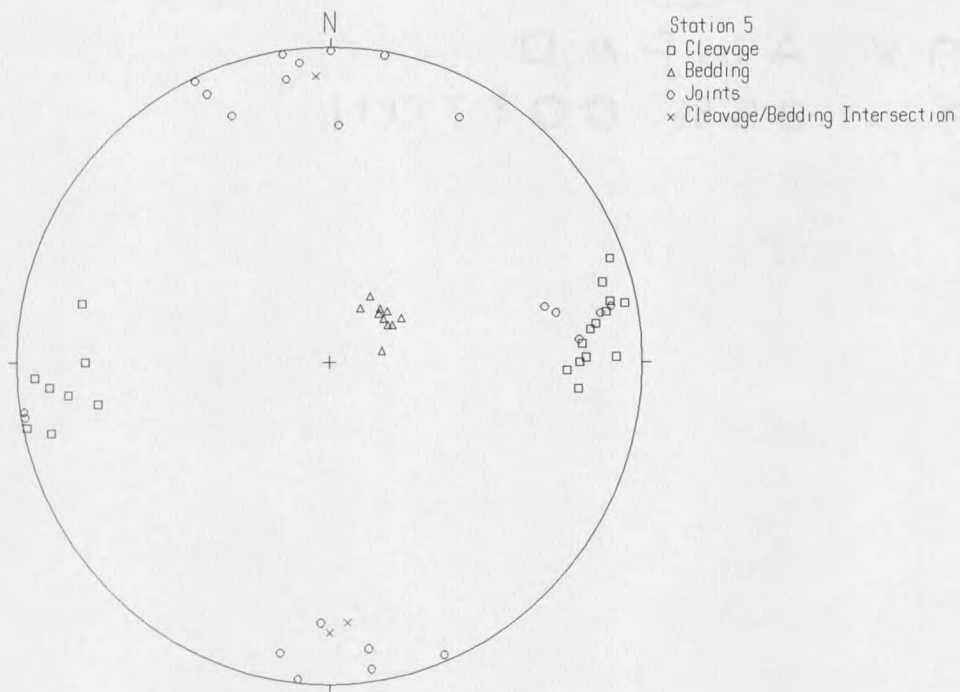


Figure 57. Equal area stereoplot at station 5, on the southern divide of Cutrock Creek.

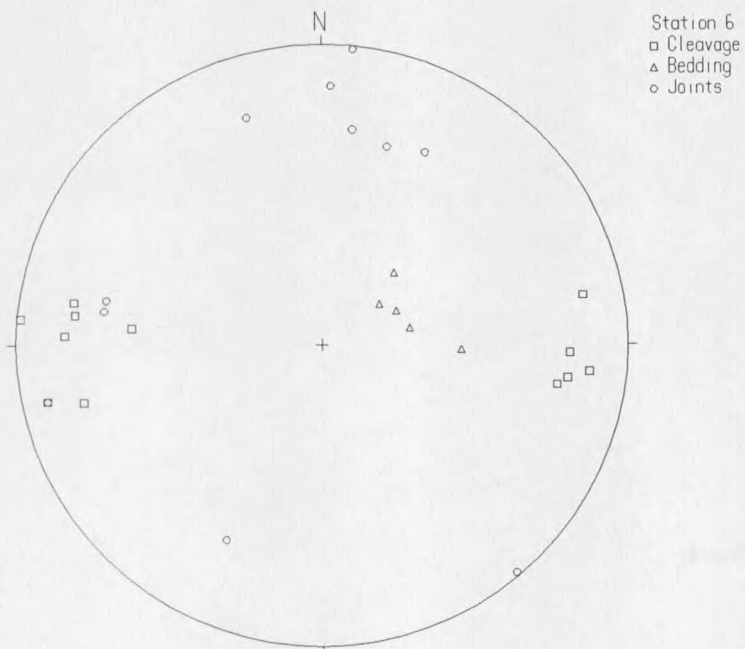


Figure 58. Equal area stereoplot at station 6, on the northern divide of Cutrock Creek.

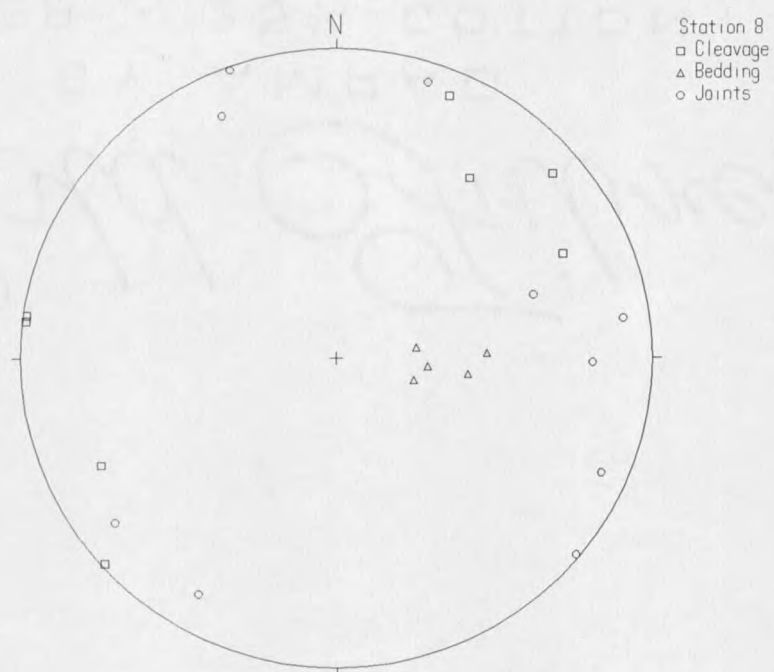


Figure 59. Equal area stereoplot at station 8, along Benchmark Road near Ford Creek.

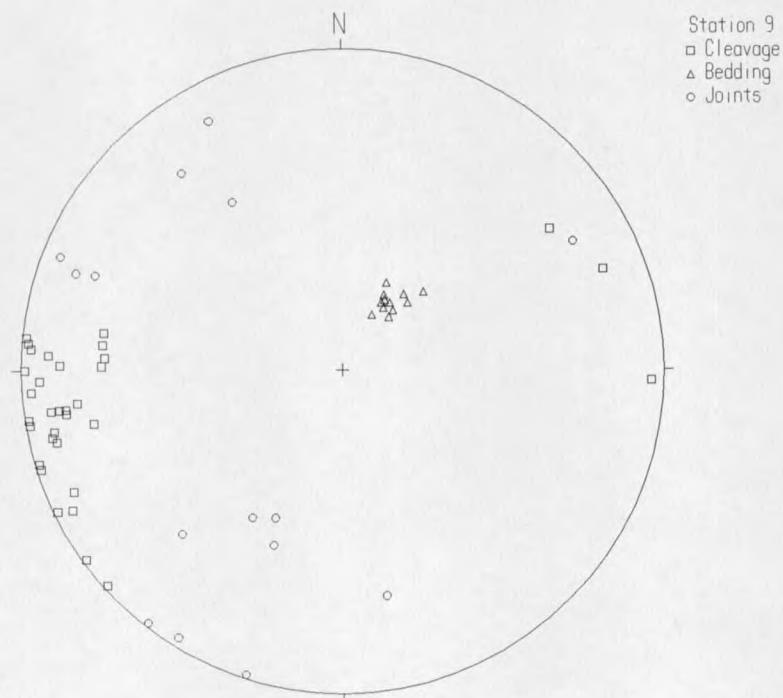


Figure 60. Equal area stereoplot at station 9, along Benchmark Road near Ford Creek.

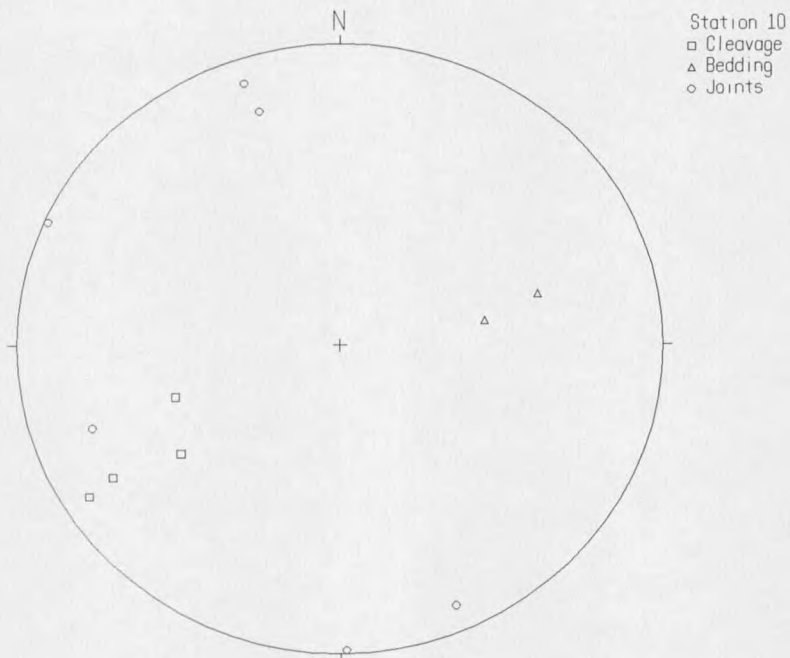


Figure 61. Equal area stereoplot at station 10, near the saddle in French Gulch.

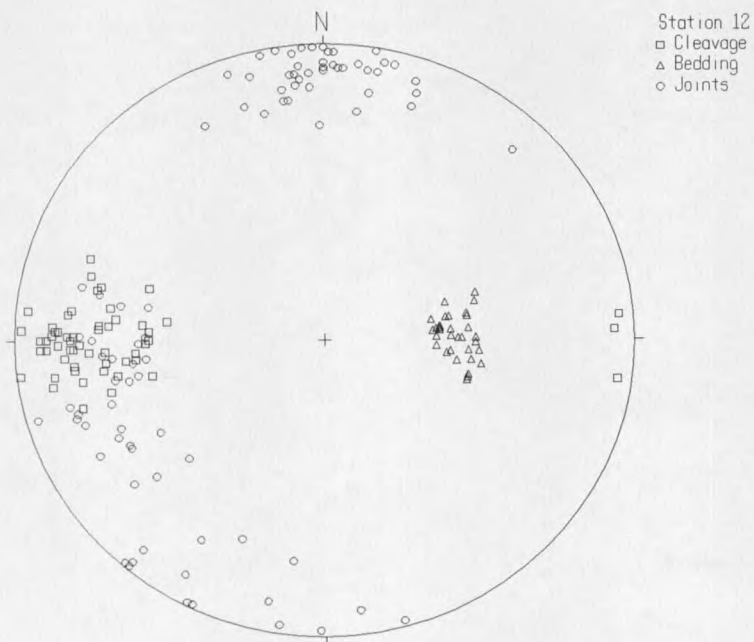


Figure 62. Equal area stereoplot at stations 12 and 13, near the head of Hannon Gulch.

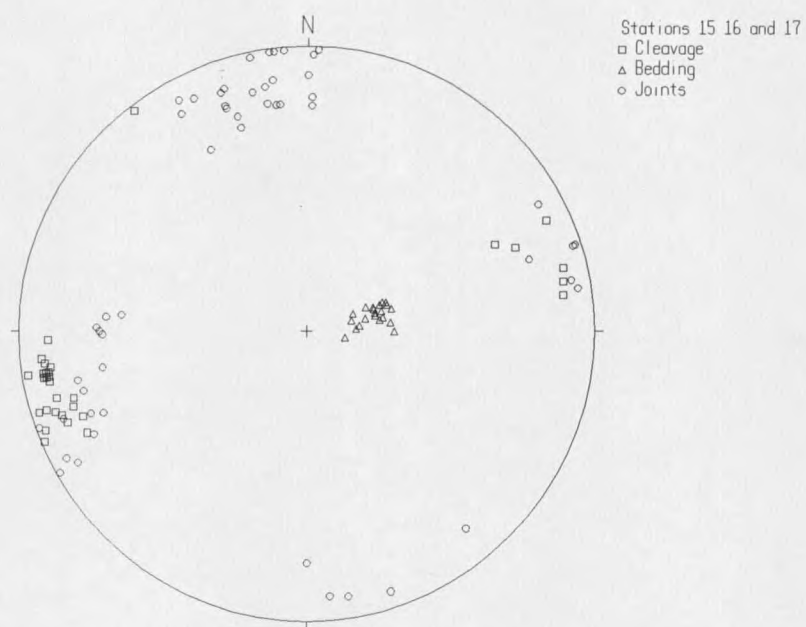


Figure 63. Equal area stereoplot at stations 15, 16, and 17, near Choteau Mountain.

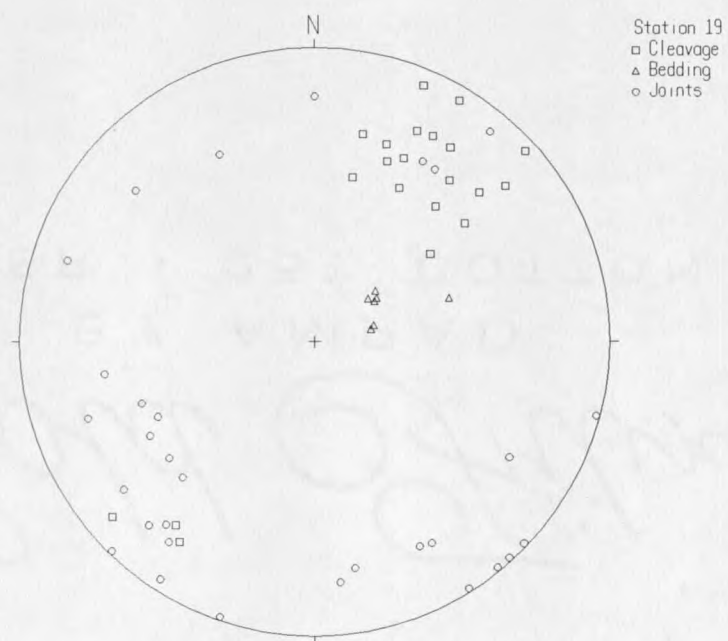


Figure 64. Equal area stereoplot at station 19 on the southern side of Swift Reservoir.

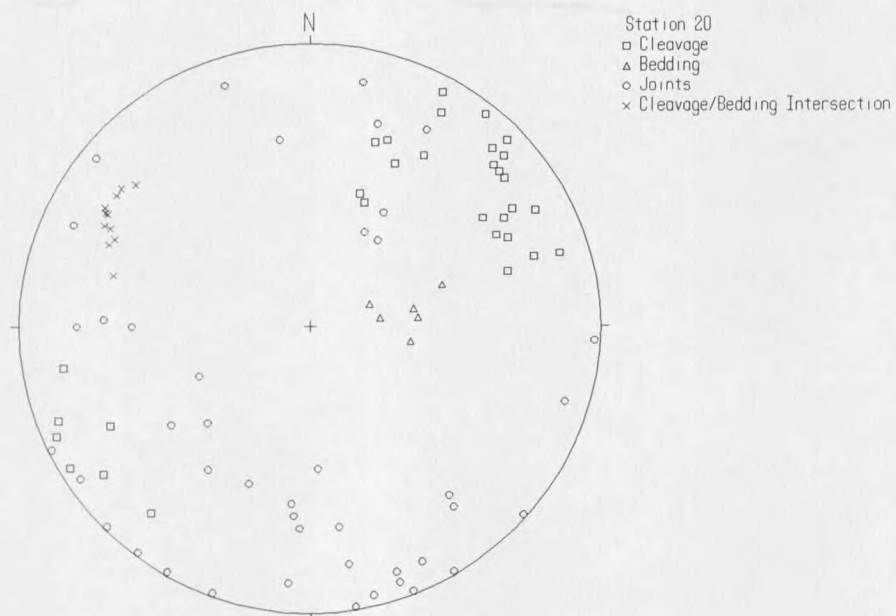


Figure 65. Equal area stereonet at station 20, 1/3 of a mile south of Swift Reservoir.

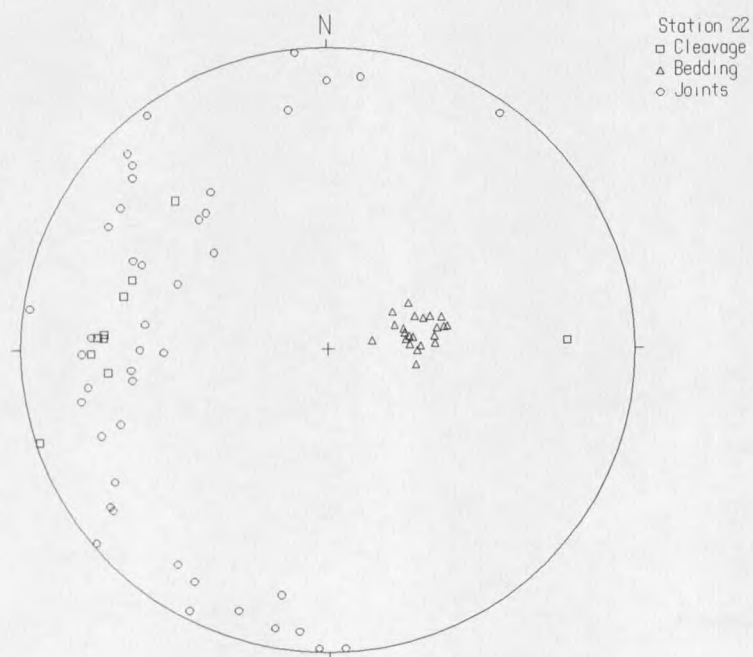


Figure 66. Equal area stereonet at station 22, at the head of Rierdon Gulch.

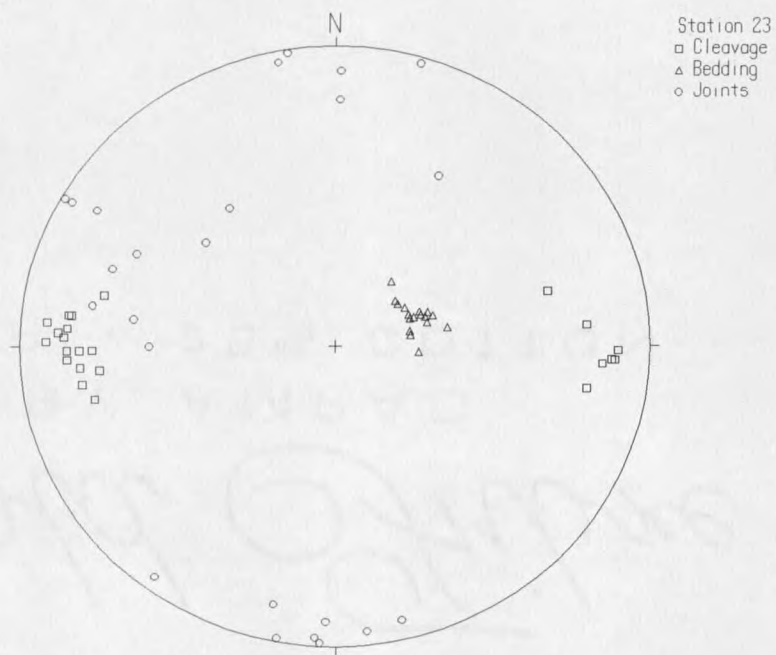


Figure 67. Equal area stereoplot at station 23, near the head of Rain Creek.

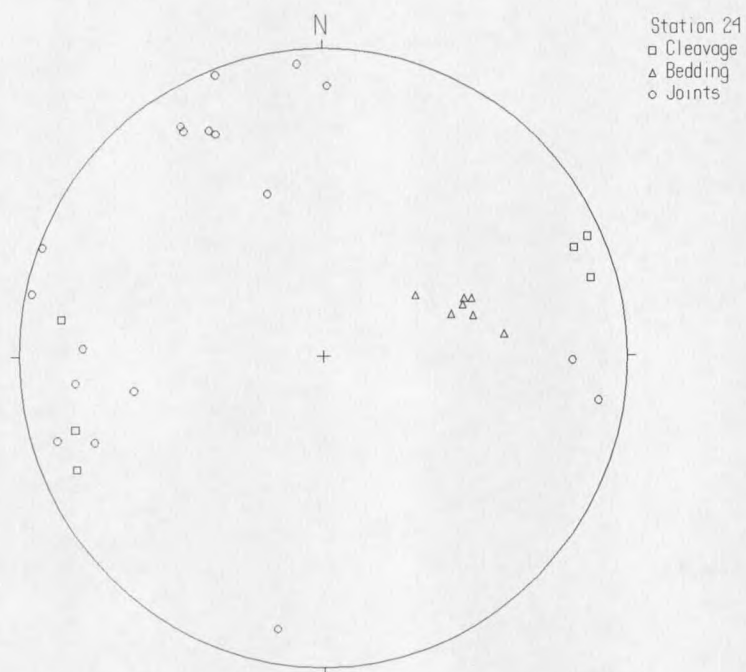


Figure 68. Equal area stereoplot at station 24, along the North Fork Deep Creek.

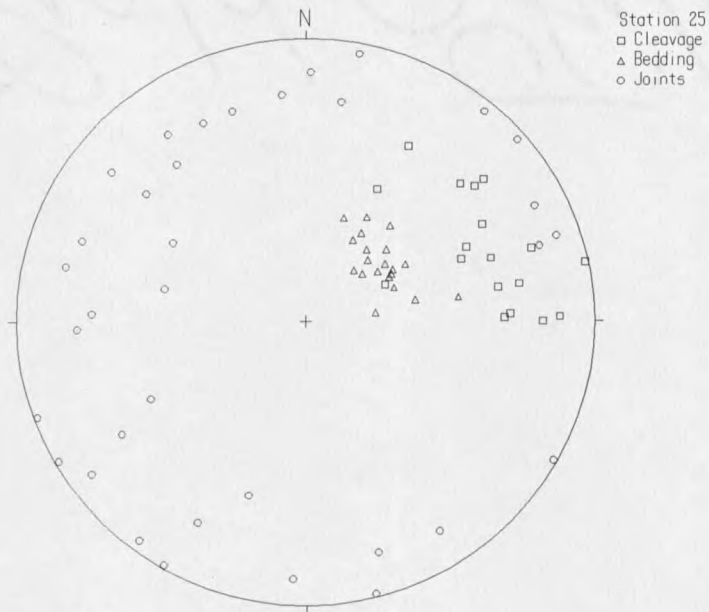


Figure 69. Equal area stereoplot at station 25, in Billie Creek.

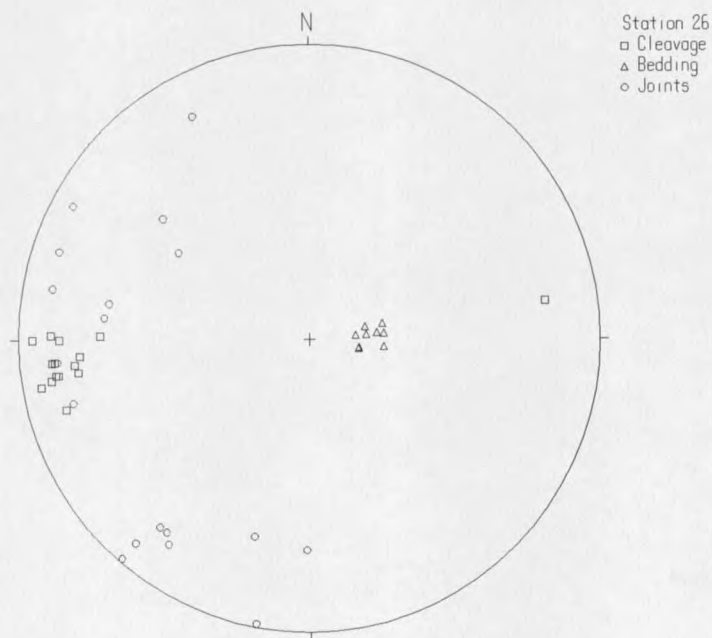


Figure 70. Equal area stereoplot at station 26, at the head of Billie Creek.

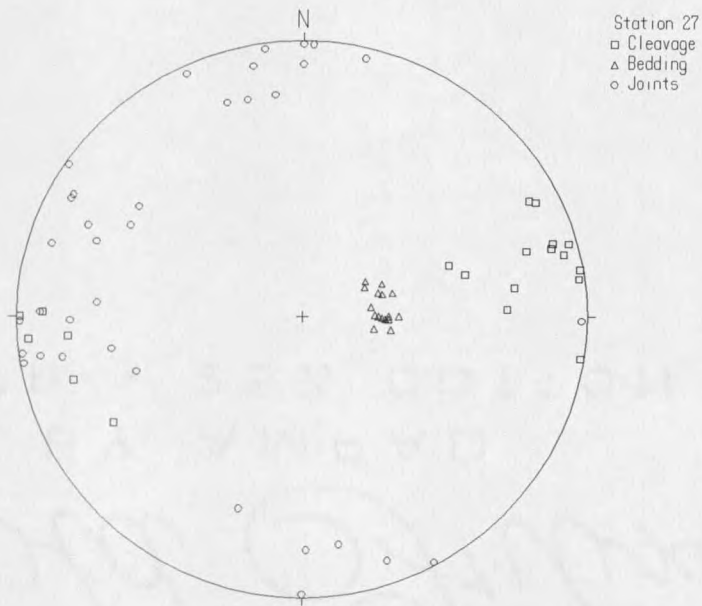


Figure 71. Equal area stereoplot at station 27, to the southwest of Ear Mountain.

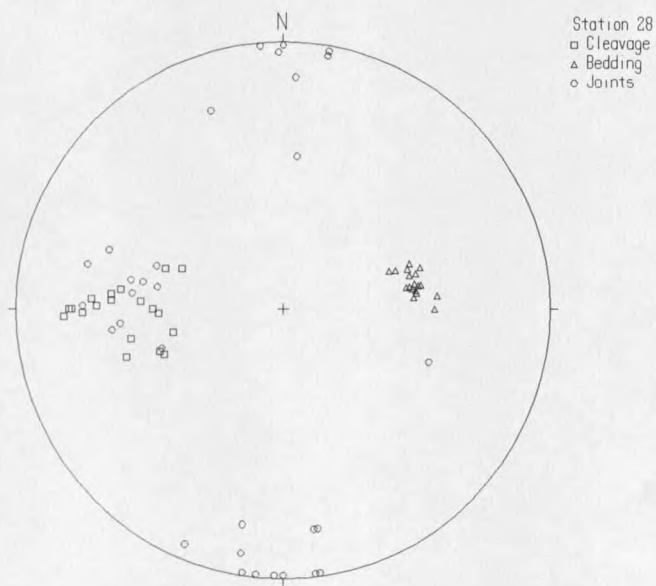


Figure 72. Equal area stereoplot at station 28, at the head of Sheep Gulch.

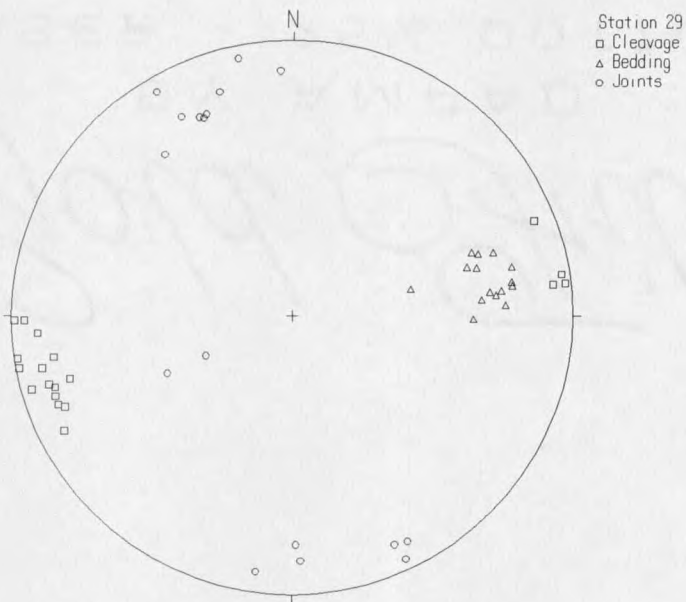


Figure 73. Equal area stereoplot at station 29, between the North and South Forks of Deep Creek.

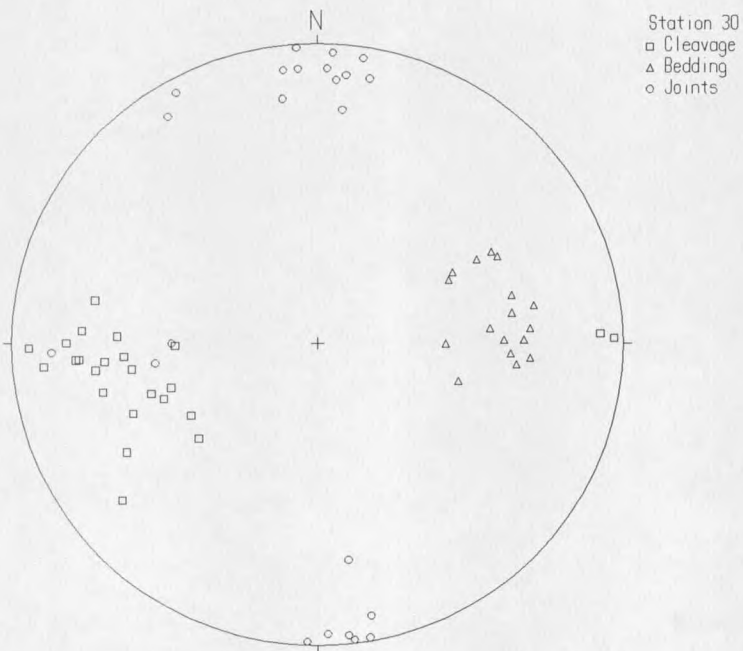


Figure 74. Equal area stereoplot at station 30, along North Fork Deep Creek.

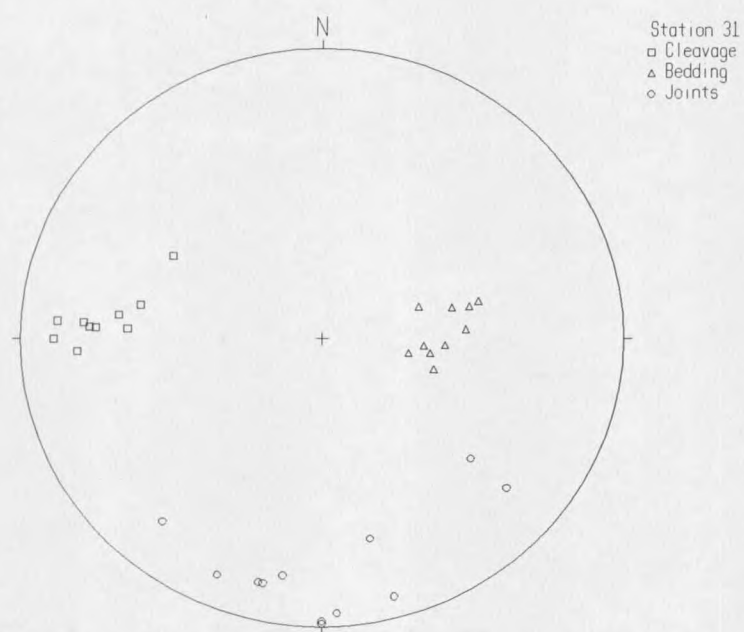


Figure 75. Equal area stereoplot at Station 31, in Rierdon Gulch.

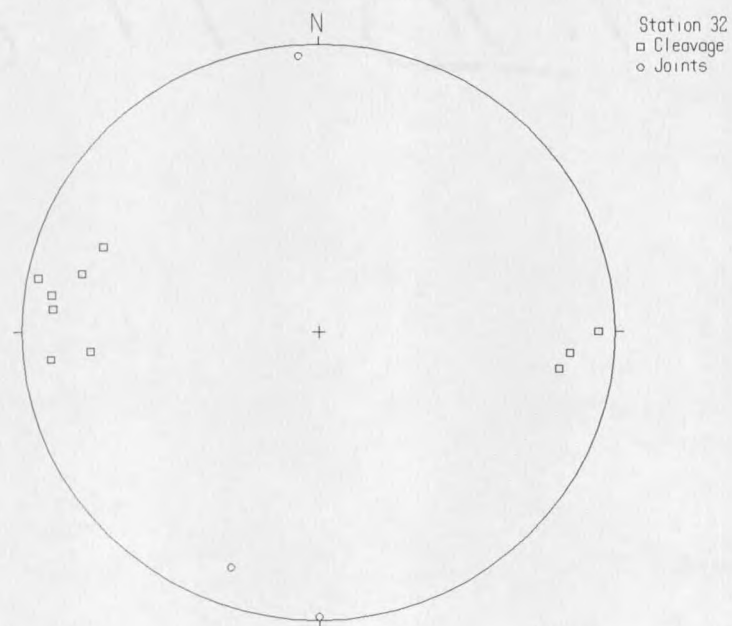


Figure 76. Equal area stereoplot of station 32, at Blacktail Creek.

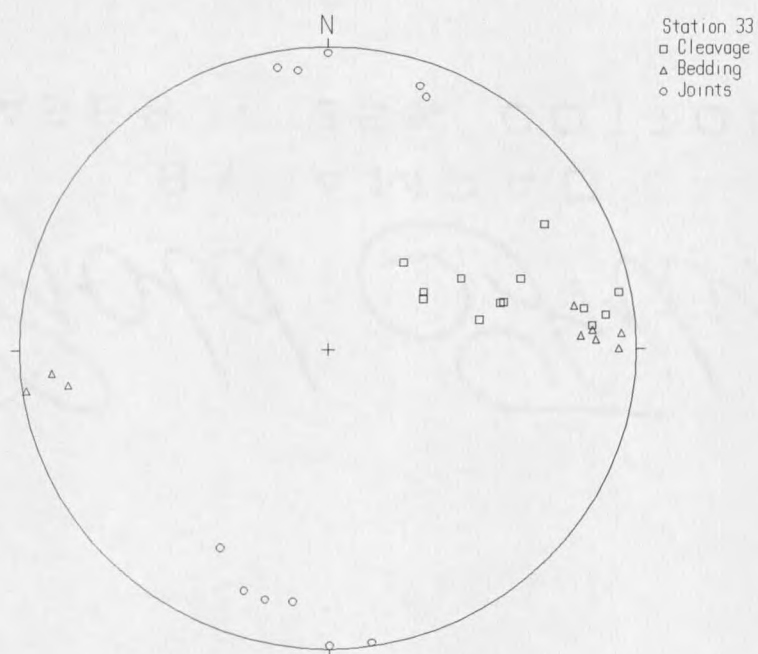


Figure 77. Equal area stereonet at station 33, on the eastern shore of Gibson Reservoir.

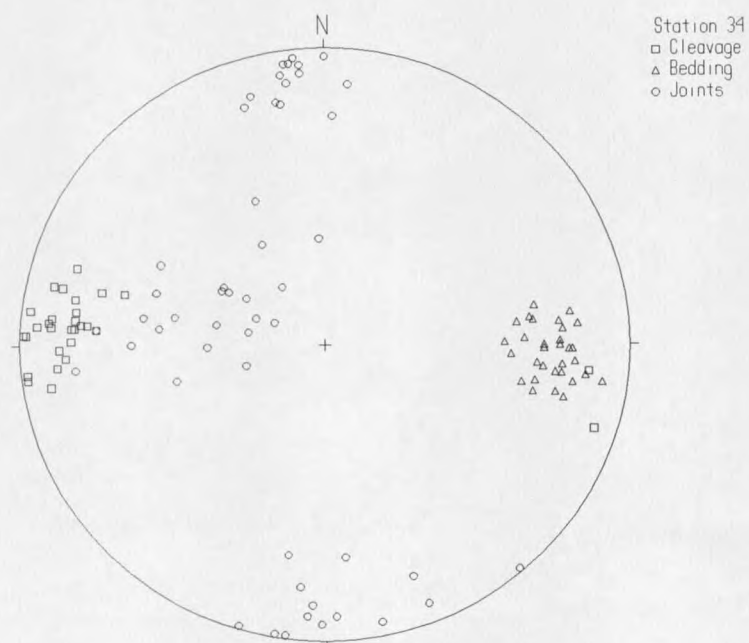


Figure 78. Equal area stereonet at station 34, on the north shore of Gibson Reservoir.

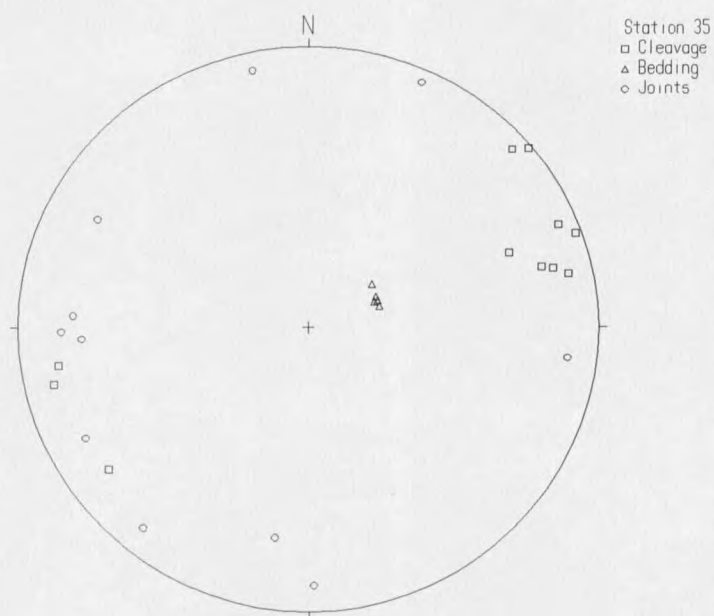


Figure 79. Equal area stereoplot at station 35, on the east side of Walling Reef.

APPENDIX 2

SCANNING ELECTRON MICROSCOPE AND X-RAY DIFFRACTION DATA

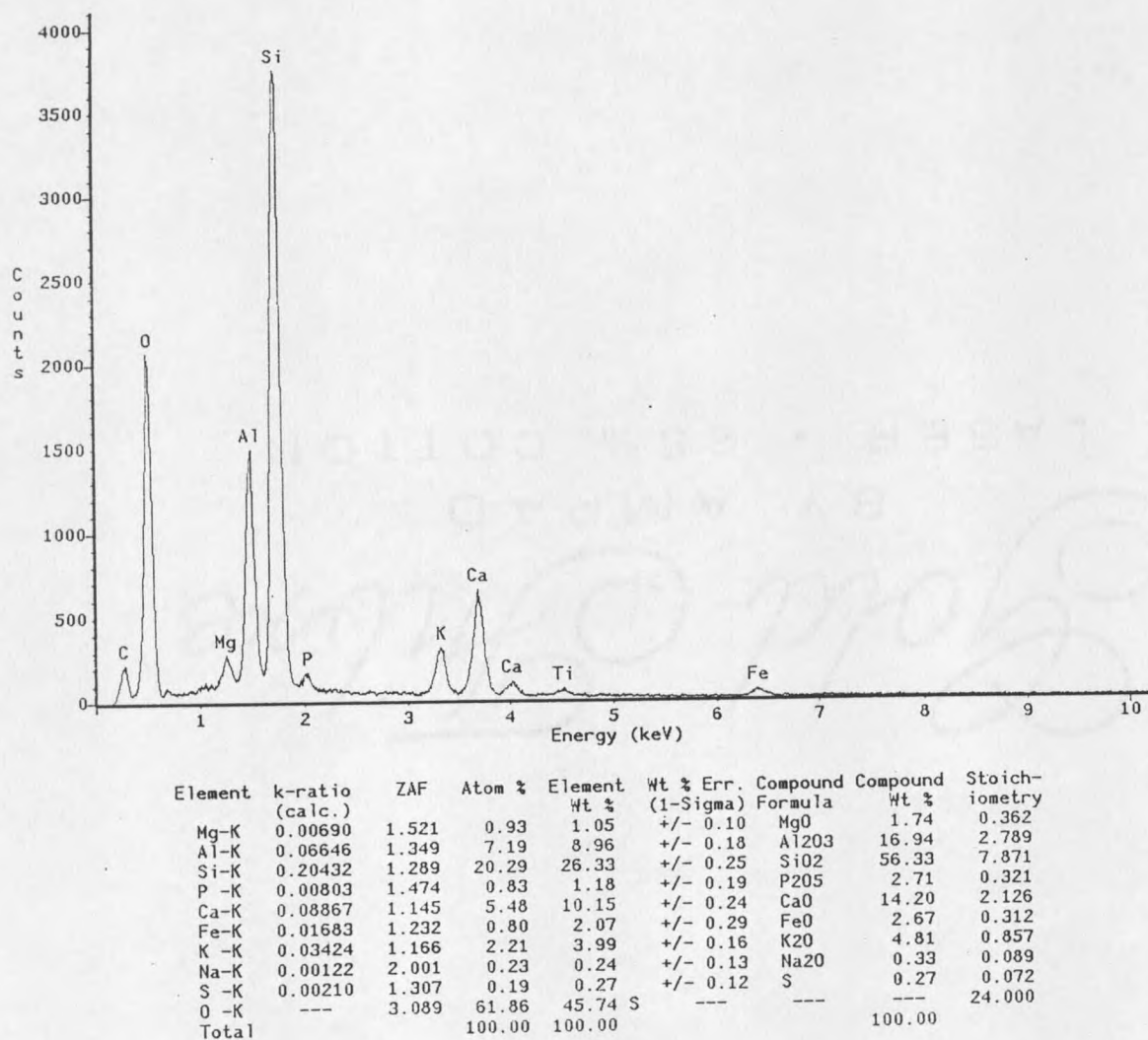
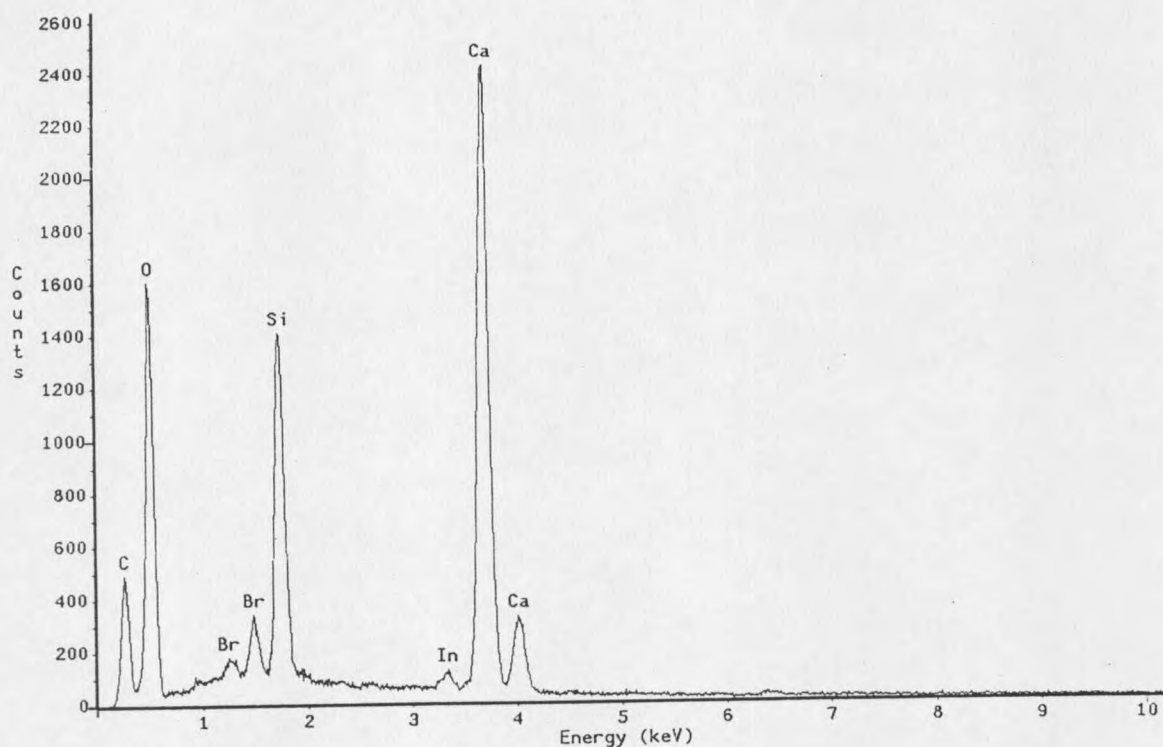


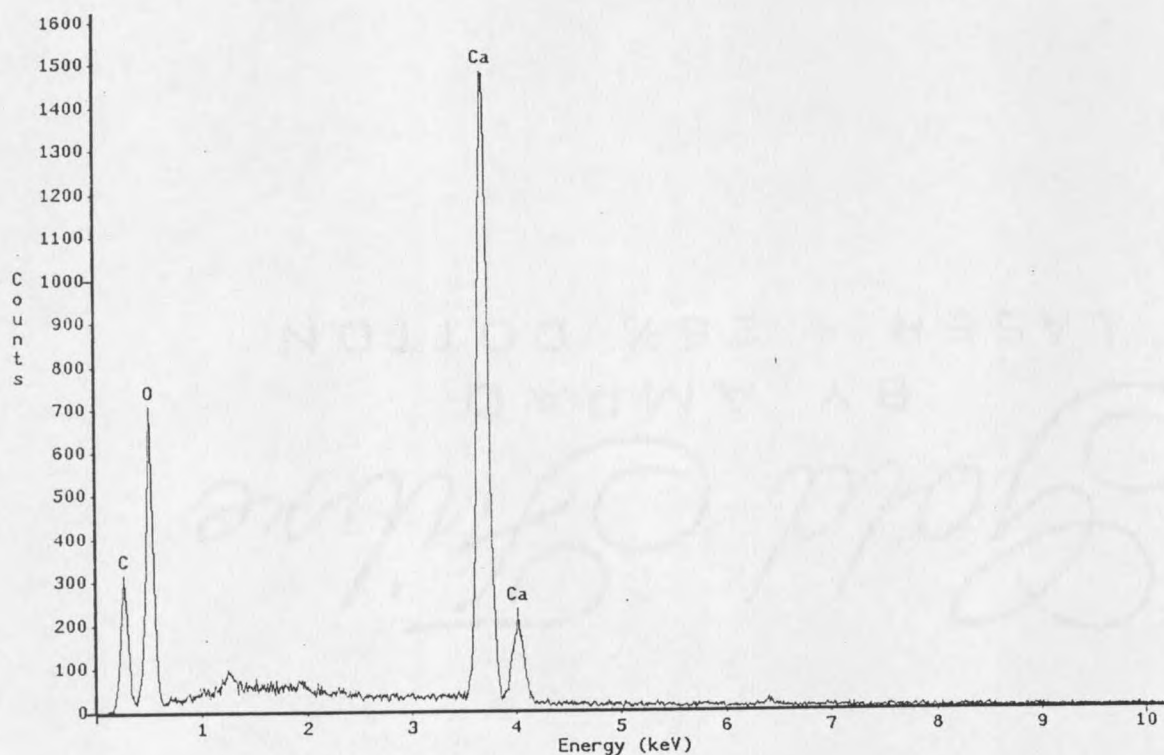
Figure 80. EDS elemental analysis on the cleavage domain in sample BTR1-3. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00347	1.651	0.60	0.57	+/- 0.06	MgO	0.95	0.261
Al-K	0.01163	1.414	1.55	1.65	+/- 0.06	Al ₂ O ₃	3.11	0.674
Si-K	0.08775	1.235	9.78	10.84	+/- 0.10	SiO ₂	23.19	4.263
P -K	0.00072	1.268	0.08	0.09	+/- 0.06	P ₂ O ₅	0.21	0.033
Ca-K	0.46501	1.075	31.61	49.97	+/- 0.43	CaO	69.91	13.774
Fe-K	0.00754	1.219	0.42	0.92	+/- 0.18	FeO	1.18	0.182
K -K	0.00863	1.014	0.57	0.88	+/- 0.07	K ₂ O	1.05	0.247
Na-K	0.00077	2.249	0.19	0.17	+/- 0.16	Na ₂ O	0.23	0.083
S -K	0.00140	1.145	0.13	0.16	+/- 0.06	S	0.16	0.055
O -K	---	5.792	55.08	34.76	---	---	---	24.000
Total			100.00	100.00			100.00	

Stoichiometry results are based upon 24 Oxygen atoms

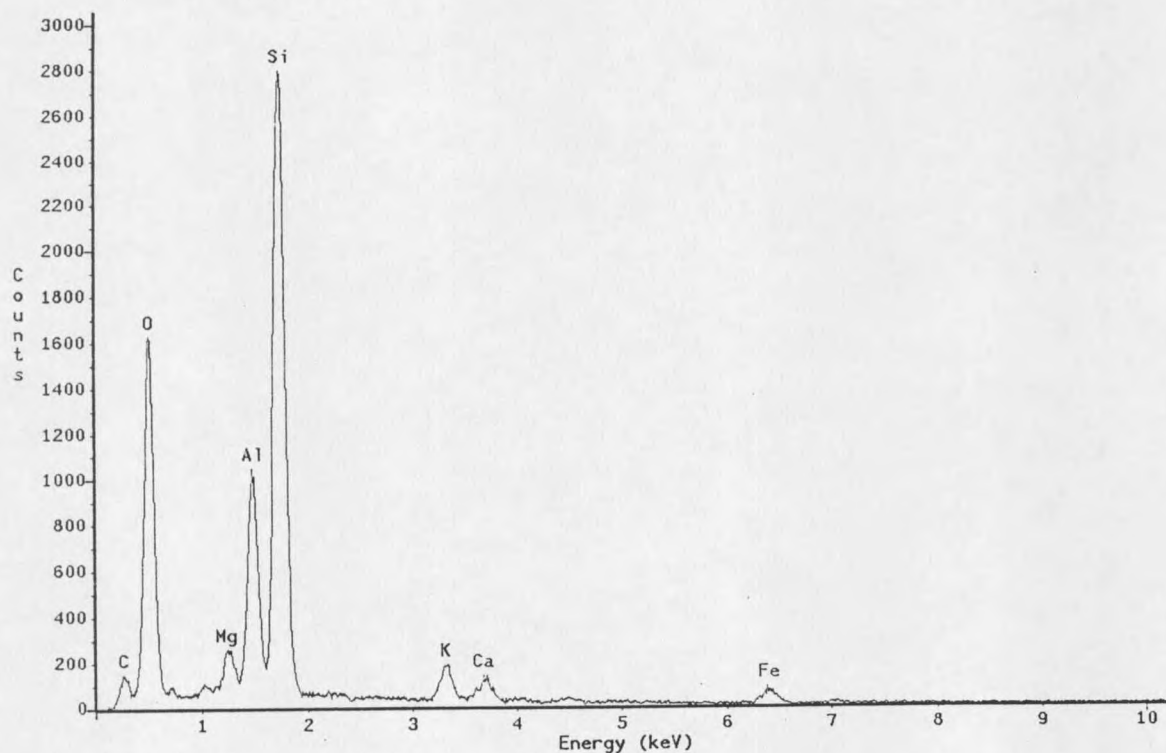
Figure 81. EDS elemental analysis on the microlithon in sample BTR1-3. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00454	1.721	0.90	0.78	+/- 0.08	MgO	1.30	0.433
Al-K	0.00003	1.451	0.00	0.00	+/- 0.08	Al ₂ O ₃	0.01	0.002
Si-K	0.00000	1.231	0.00	0.00	+/- 0.00	SiO ₂	0.00	0.000
P-K	0.00000	1.162	0.00	0.00	+/- 0.00	P ₂ O ₅	0.00	0.000
Ca-K	0.65921	1.041	47.97	68.62	+/- 0.72	CaO	96.01	23.098
Fe-K	0.01397	1.209	0.85	1.69	+/- 0.31	FeO	2.17	0.408
K-K	0.00078	0.919	0.05	0.07	+/- 0.10	K ₂ O	0.09	0.025
Na-K	0.00065	2.380	0.19	0.16	+/- 0.15	Na ₂ O	0.21	0.091
S-K	0.00204	1.063	0.19	0.22	+/- 0.09	S	0.22	0.091
O-K	---	6.908	49.85	28.46	---	---	---	24.000
Total			100.00	100.00			100.00	

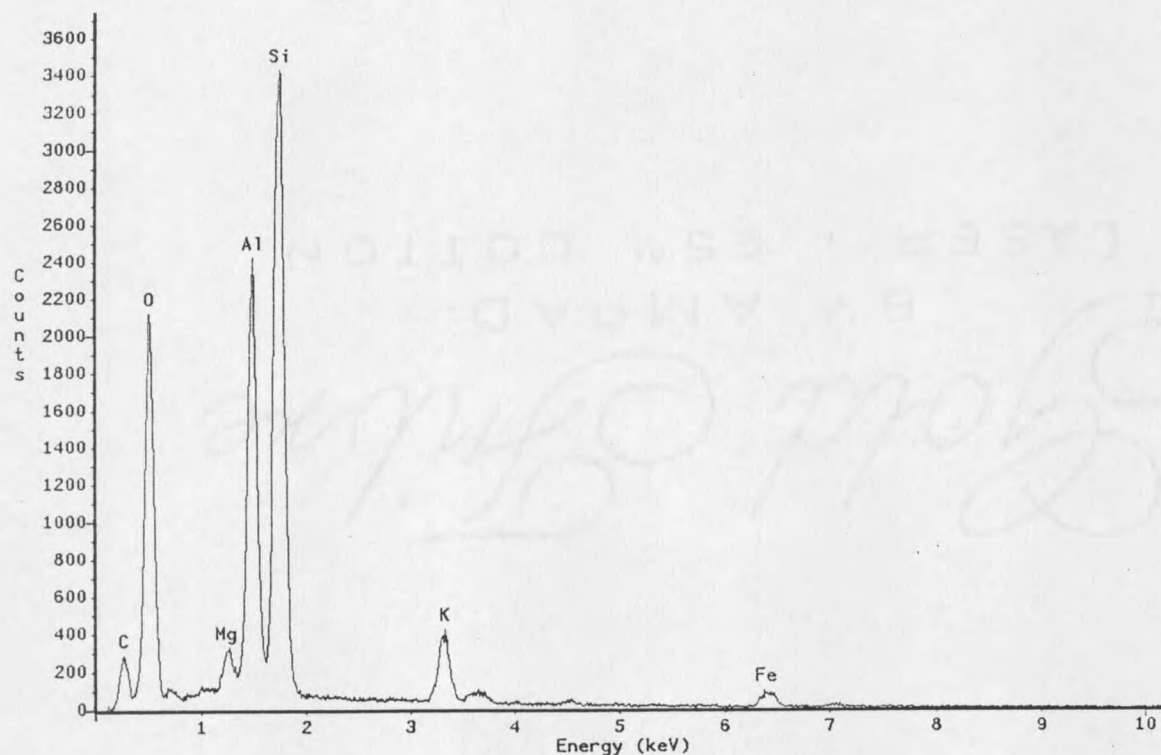
Stoichiometry results are based upon 24 Oxygen atoms

Figure 82. EDS elemental analysis on a calcite vein in sample BTR1-3. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00975	1.376	1.17	1.34	+/- 0.07	MgO	2.23	0.449
Al-K	0.07067	1.296	7.22	9.16	+/- 0.22	Al ₂ O ₃	17.31	2.760
Si-K	0.24418	1.257	23.23	30.69	+/- 0.28	SiO ₂	65.65	8.884
P-K	0.00000	1.408	0.00	0.00	+/- 0.00	P ₂ O ₅	0.00	0.000
Ca-K	0.01895	1.186	1.19	2.25	+/- 0.11	CaO	3.14	0.456
Fe-K	0.03988	1.282	1.95	5.11	+/- 0.27	FeO	6.58	0.744
K-K	0.02954	1.218	1.96	3.60	+/- 0.18	K ₂ O	4.34	0.748
Na-K	0.00237	1.656	0.36	0.39	+/- 0.07	Na ₂ O	0.53	0.139
S-K	0.00184	1.285	0.16	0.24	+/- 0.06	S	0.24	0.060
O-K	---	1.817	62.76	47.23	---	---	---	24.000
Total			100.00	100.00			100.00	

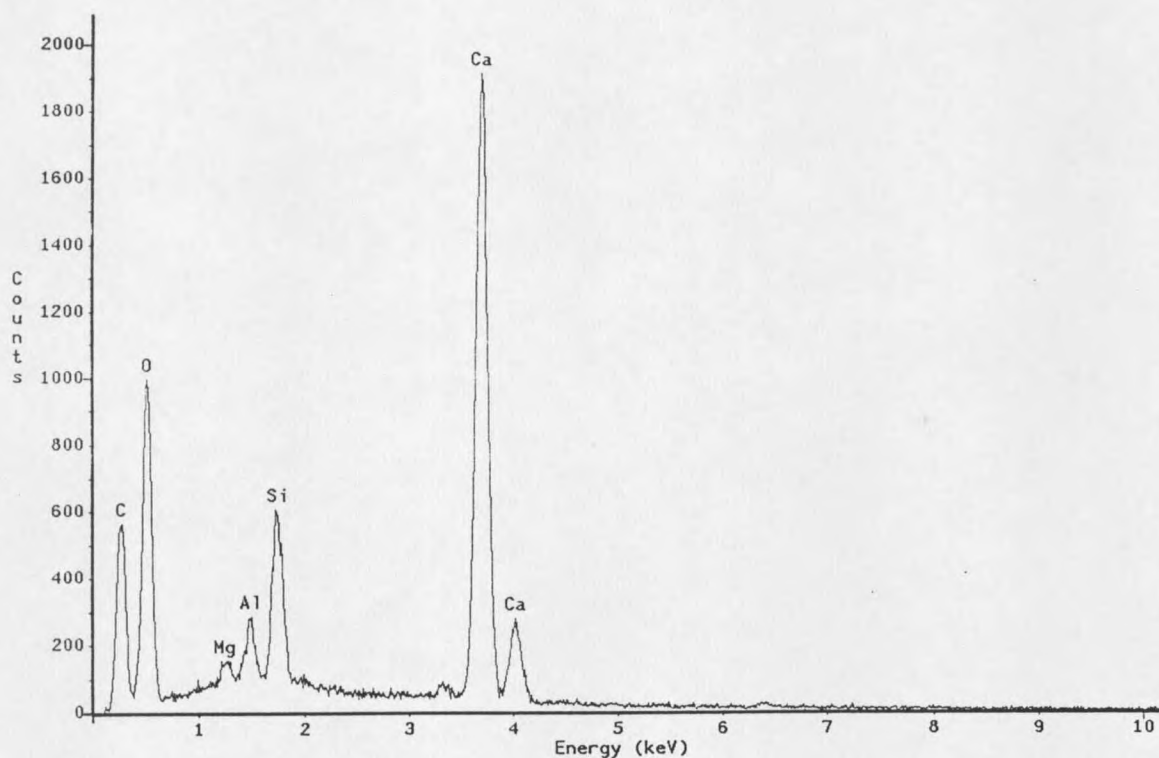
Figure 83. EDS elemental analysis on the cleavage domain in sample DCR1-1. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00802	1.366	0.96	1.10	+/- 0.05	MgO	1.82	0.372
Al-K	0.11387	1.290	11.61	14.69	+/- 0.19	Al ₂ O ₃	27.75	4.499
Si-K	0.20237	1.286	19.75	26.02	+/- 0.23	SiO ₂	55.66	7.657
P-K	0.00020	1.402	0.02	0.03	+/- 0.06	P ₂ O ₅	0.06	0.007
Ca-K	0.00651	1.186	0.41	0.77	+/- 0.07	CaO	1.08	0.159
Fe-K	0.03824	1.279	1.87	4.89	+/- 0.22	FeO	6.29	0.724
K-K	0.04574	1.217	3.04	5.57	+/- 0.17	K ₂ O	6.71	1.177
Na-K	0.00254	1.640	0.39	0.42	+/- 0.10	Na ₂ O	0.56	0.150
S-K	0.00054	1.280	0.05	0.07	+/- 0.05	S	0.07	0.018
O-K	---	1.810	61.91	46.46	---	---	---	24.000
Total			100.00	100.00			100.00	

Stoichiometry results are based upon 24 Oxygen atoms

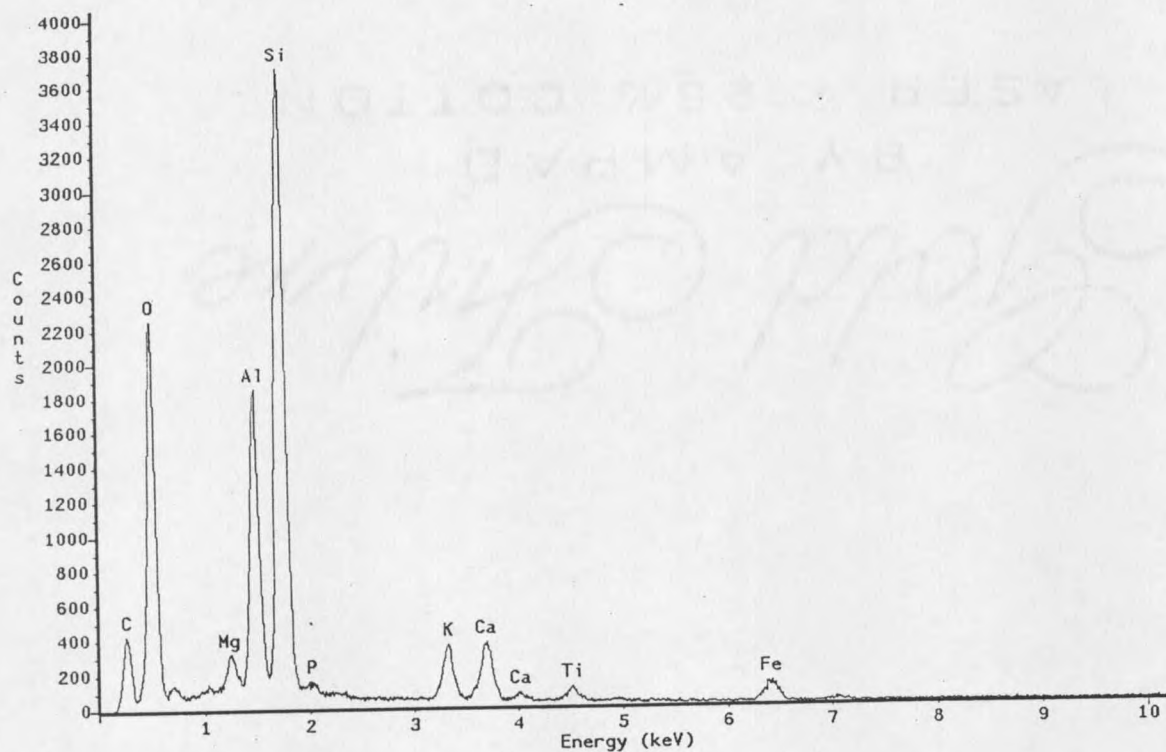
Figure 84. EDS elemental analysis on the cleavage domain in sample DTR1-1. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00349	1.460	0.55	0.51	+/- 0.06	MgO	0.85	0.249
Al-K	0.01348	1.336	1.76	1.80	+/- 0.07	Al ₂ O ₃	3.40	0.792
Si-K	0.04911	1.213	5.58	5.96	+/- 0.16	SiO ₂	12.75	2.518
P-K	0.00184	1.220	0.19	0.23	+/- 0.07	P ₂ O ₅	0.52	0.086
Ca-K	0.50966	1.128	37.73	57.48	+/- 0.55	CaO	80.43	17.022
Fe-K	0.00680	1.262	0.40	0.86	+/- 0.43	FeO	1.11	0.183
K-K	0.00634	1.026	0.44	0.65	+/- 0.08	K ₂ O	0.78	0.197
Na-K	0.00020	1.817	0.04	0.04	+/- 0.08	Na ₂ O	0.05	0.019
S-K	0.00106	1.136	0.10	0.12	+/- 0.07	S	0.12	0.045
O-K	---	3.889	53.20	32.35	---	---	---	24.000
Total			100.00	100.00			100.00	

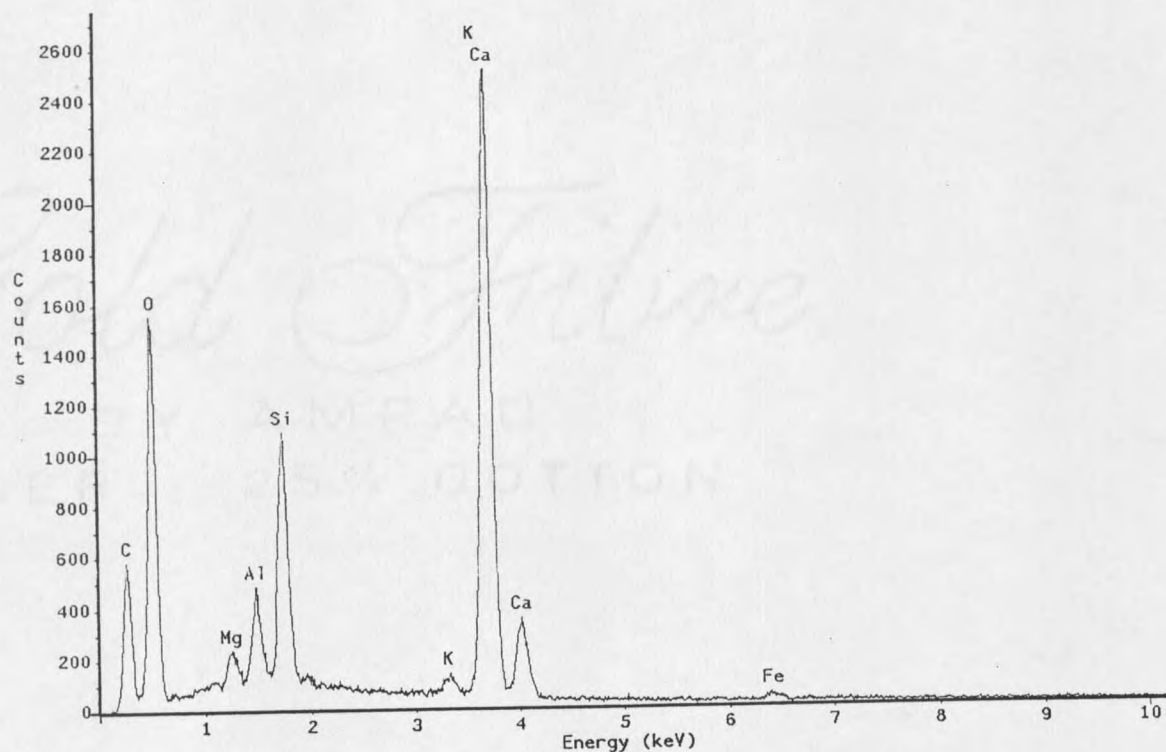
Stoichiometry results are based upon 24 Oxygen atoms

Figure 85. EDS elemental analysis on the microlithons in sample DTR1-1. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



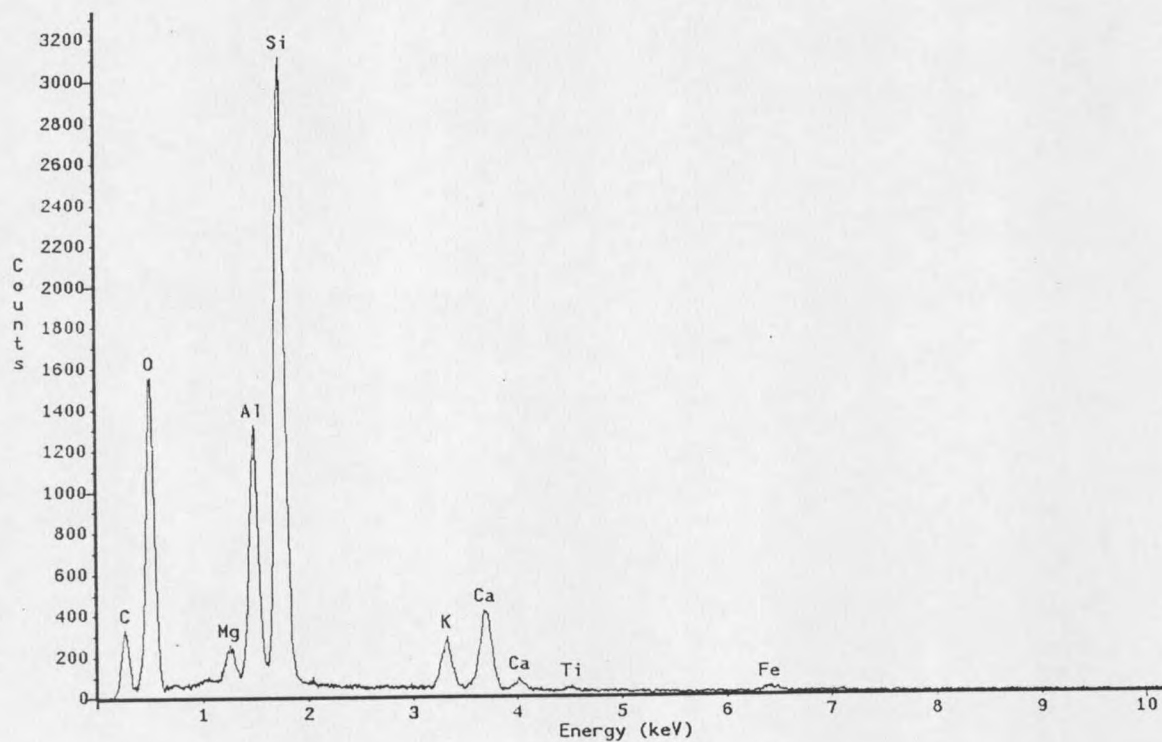
Element	k-ratio (calc.)	ZAF	Atom %	Element	Wt %	Err.	Compound	Compound	Stoich-
						(1-Sigma)	Formula	Wt %	ometry
Mg-K	0.00755	1.563	1.05	1.18	+/- 0.11		MgO	1.96	0.409
Al-K	0.07956	1.377	8.82	10.96	+/- 0.19		Al ₂ O ₃	20.71	3.423
Si-K	0.19213	1.330	19.76	25.55	+/- 0.27		SiO ₂	54.66	7.668
P-K	0.00595	1.501	0.63	0.89	+/- 0.17		P ₂ O ₅	2.05	0.243
Ca-K	0.04643	1.144	2.88	5.31	+/- 0.20		CaO	7.43	1.117
Fe-K	0.04889	1.224	2.33	5.98	+/- 0.36		FeO	7.70	0.903
K-K	0.03526	1.173	2.30	4.14	+/- 0.16		K ₂ O	4.98	0.892
Na-K	0.00126	2.077	0.25	0.26	+/- 0.14		Na ₂ O	0.35	0.096
S-K	0.00125	1.321	0.11	0.17	+/- 0.09		S	0.17	0.043
O-K	---	2.722	61.87	45.56	---	---	---	---	24.000
Total			100.00	100.00				100.00	

Figure 86. EDS elemental analysis on the cleavage domain in sample DTR1-2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



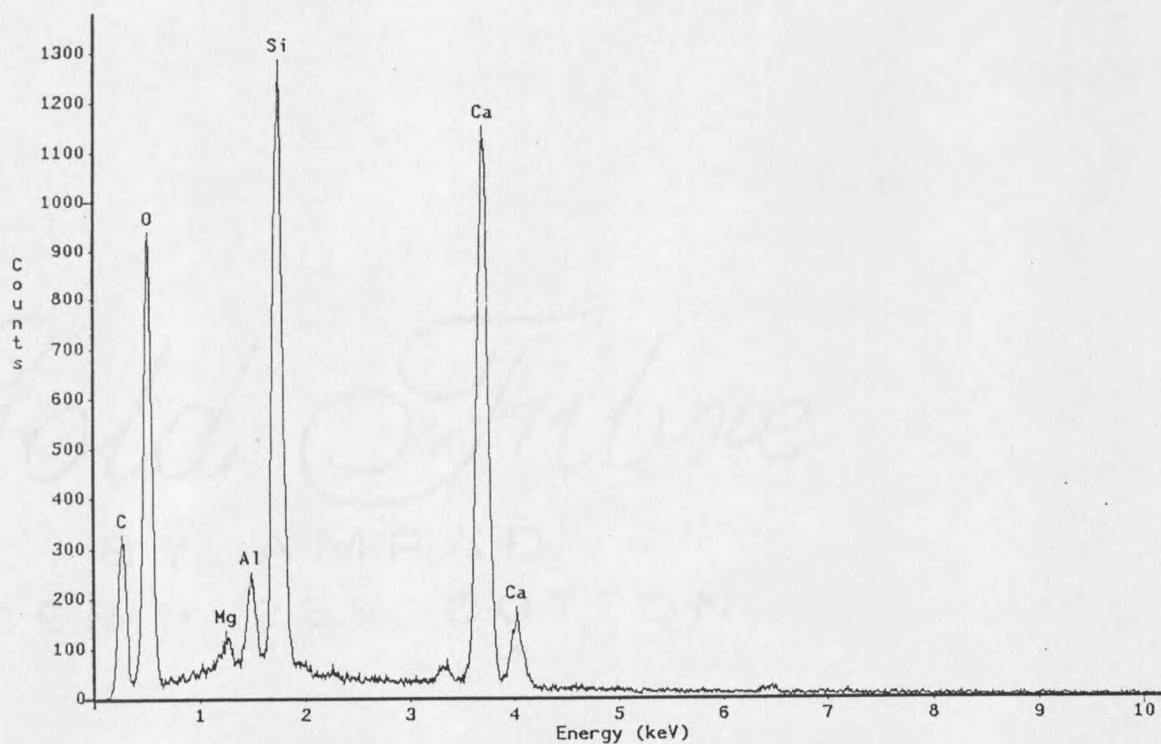
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00646	1.678	1.14	1.08	+/- 0.07	MgO	1.80	0.504
Al-K	0.01996	1.438	2.72	2.87	+/- 0.17	Al2O3	5.42	1.203
Si-K	0.06577	1.261	7.55	8.29	+/- 0.19	SiO2	17.74	3.338
P-K	0.00211	1.264	0.22	0.27	+/- 0.16	P2O5	0.61	0.097
Ca-K	0.46873	1.072	32.07	50.23	+/- 0.43	CaO	70.28	14.171
Fe-K	0.01437	1.217	0.80	1.75	+/- 0.19	FeO	2.25	0.354
K-K	0.01128	1.010	0.75	1.14	+/- 0.16	K2O	1.37	0.329
Na-K	0.00145	2.294	0.37	0.33	+/- 0.17	Na2O	0.45	0.164
S-K	0.00068	1.142	0.06	0.08	+/- 0.06	S	0.08	0.027
O-K	---	5.943	54.31	33.96	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 87. EDS elemental analysis on the microlithons in sample DTR1-2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



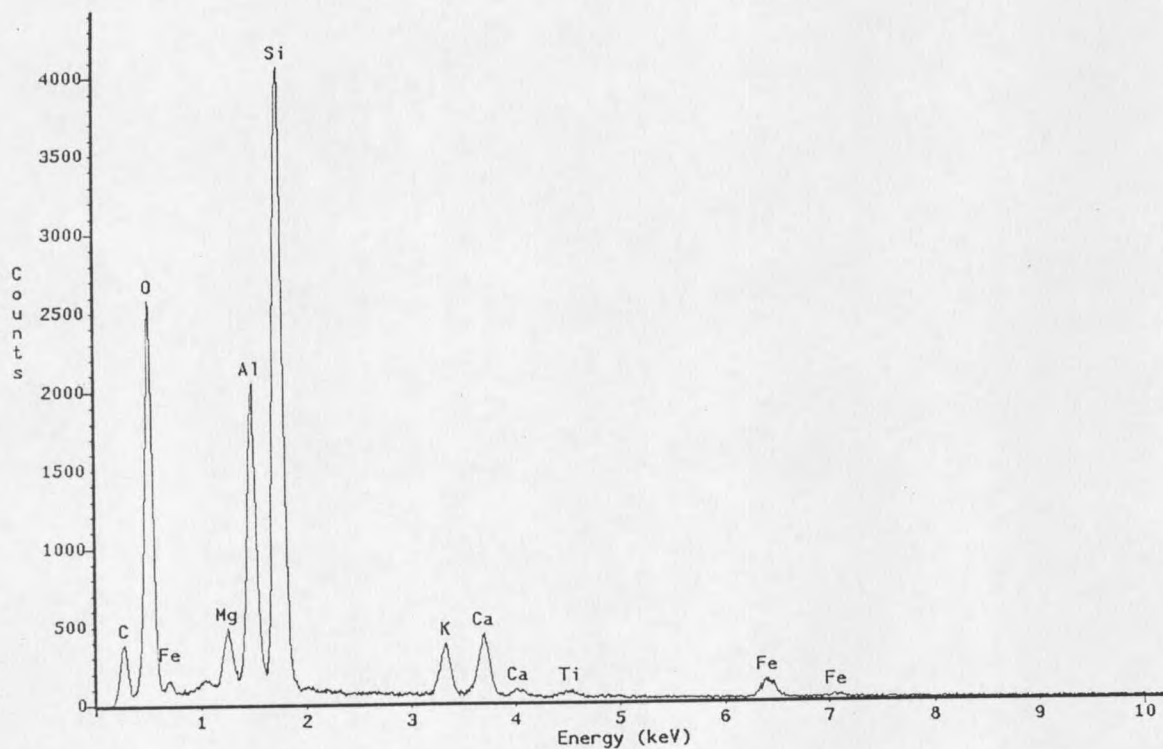
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00896	1.511	1.20	1.35	+/- 0.12	MgO	2.24	0.463
Al-K	0.07383	1.348	7.92	9.95	+/- 0.20	Al ₂ O ₃	18.80	3.065
Si-K	0.20963	1.300	20.83	27.26	+/- 0.25	SiO ₂	58.31	8.063
P-K	0.00118	1.493	0.12	0.18	+/- 0.07	P ₂ O ₅	0.40	0.047
Ca-K	0.07449	1.146	4.57	8.54	+/- 0.25	CaO	11.95	1.770
Fe-K	0.01306	1.233	0.62	1.61	+/- 0.17	FeO	2.07	0.240
K-K	0.03429	1.170	2.20	4.01	+/- 0.18	K ₂ O	4.83	0.853
Na-K	0.00152	1.981	0.28	0.30	+/- 0.09	Na ₂ O	0.41	0.109
S-K	0.00000	1.306	0.00	0.00	+/- 0.00	S	0.00	0.000
Ti-K	0.00475	1.245	0.26	0.59	+/- 0.08	TiO ₂	0.99	0.102
O-K	---	2.993	62.00	46.21	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 88. EDS elemental analysis on the cleavage domain in sample DTR4-2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



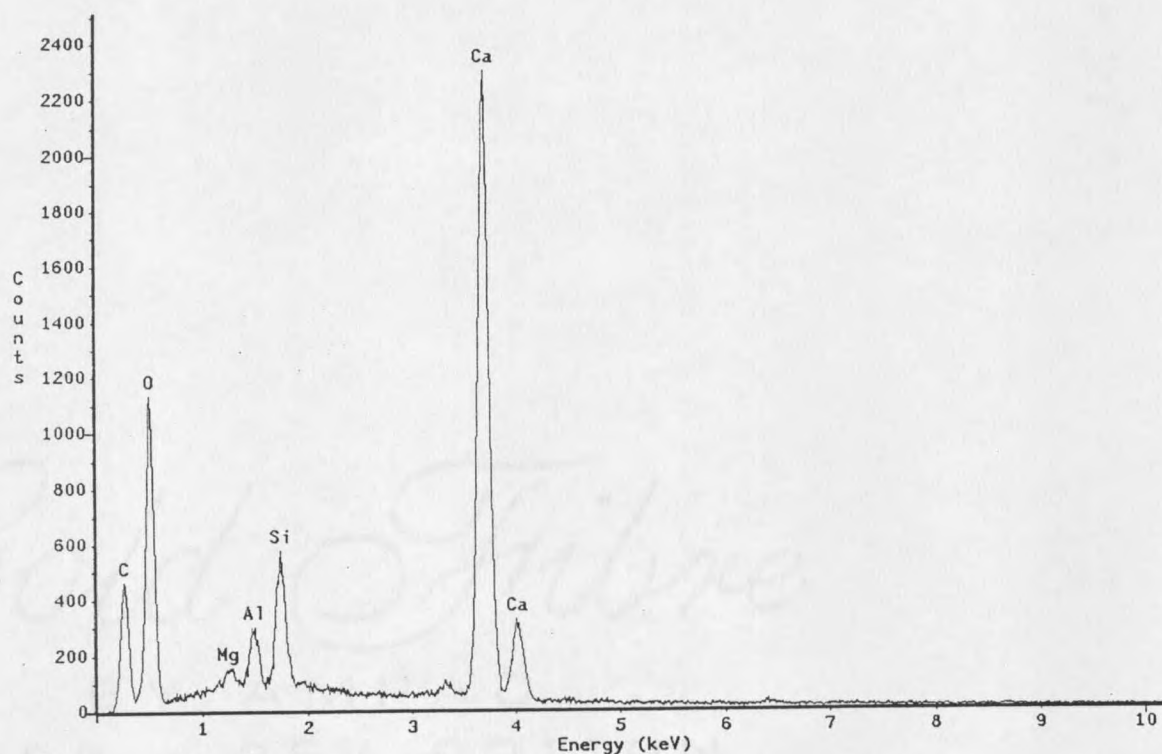
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00422	1.616	0.68	0.68	+/- 0.07	MgO	1.13	0.280
Al-K	0.01615	1.396	2.01	2.26	+/- 0.09	Al ₂ O ₃	4.26	0.835
Si-K	0.13770	1.236	14.59	17.01	+/- 0.24	SiO ₂	36.40	6.049
P-K	0.00215	1.330	0.22	0.29	+/- 0.09	P ₂ O ₅	0.66	0.092
Ca-K	0.35799	1.093	23.50	39.11	+/- 0.50	CaO	54.72	9.745
Fe-K	0.00901	1.224	0.48	1.10	+/- 0.23	FeO	1.42	0.197
K-K	0.00740	1.061	0.48	0.79	+/- 0.09	K ₂ O	0.95	0.201
Na-K	0.00000	2.204	0.00	0.00	+/- 0.00	Na ₂ O	0.00	0.000
S-K	0.00065	1.193	0.06	0.08	+/- 0.08	S	0.08	0.024
Ti-K	0.00184	1.272	0.12	0.23	+/- 0.23	TiO ₂	0.39	0.049
O-K	---	5.034	57.87	38.45	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 89. EDS elemental analysis on the microlithons in sample DTR4-2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



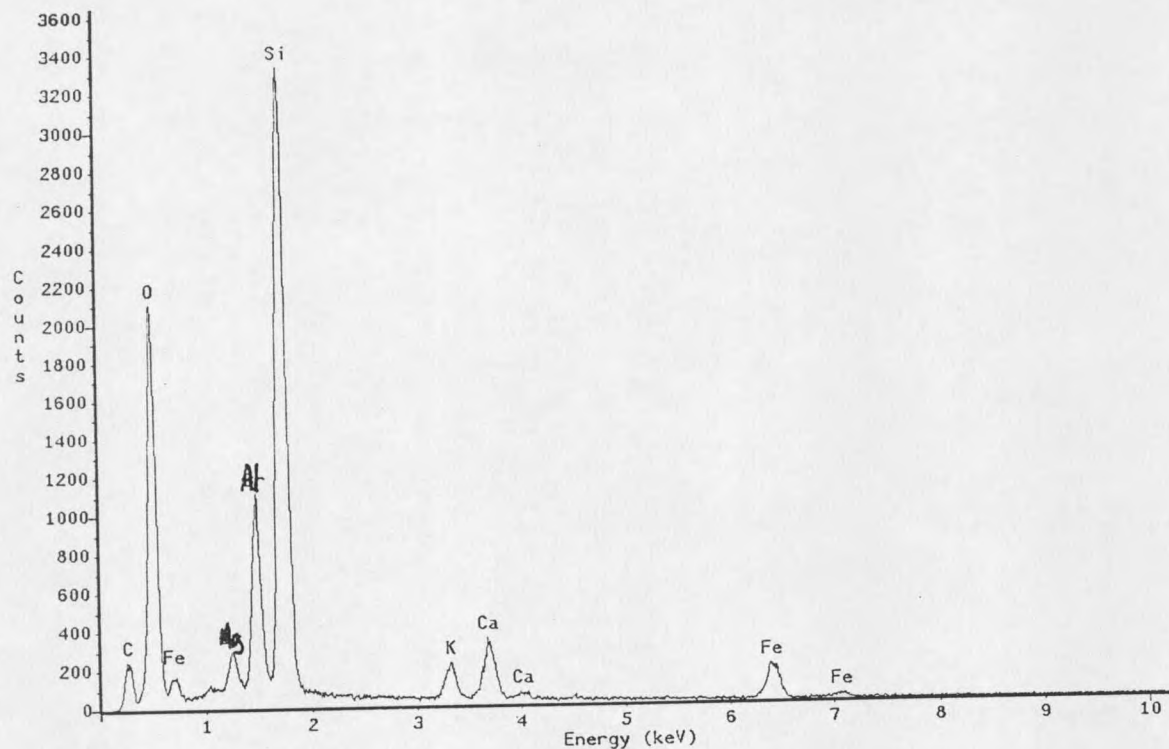
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.01200	1.550	1.66	1.86	+/- 0.06	MgO	3.08	0.645
Al-K	0.07991	1.380	8.85	11.03	+/- 0.18	Al ₂ O ₃	20.83	3.443
Si-K	0.19464	1.332	19.98	25.93	+/- 0.21	SiO ₂	55.47	7.777
P-K	0.00157	1.505	0.17	0.24	+/- 0.06	P ₂ O ₅	0.54	0.064
Ca-K	0.04757	1.143	2.94	5.44	+/- 0.10	CaO	7.61	1.143
Fe-K	0.04487	1.225	2.13	5.50	+/- 0.21	FeO	7.07	0.829
K-K	0.03398	1.173	2.21	3.99	+/- 0.14	K ₂ O	4.80	0.859
Na-K	0.00204	2.047	0.39	0.42	+/- 0.07	Na ₂ O	0.56	0.153
S-K	0.00019	1.319	0.02	0.03	+/- 0.05	S	0.03	0.007
O-K	---	2.697	61.67	45.58	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 90. EDS elemental analysis on the cleavage domain in sample GRR1-2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



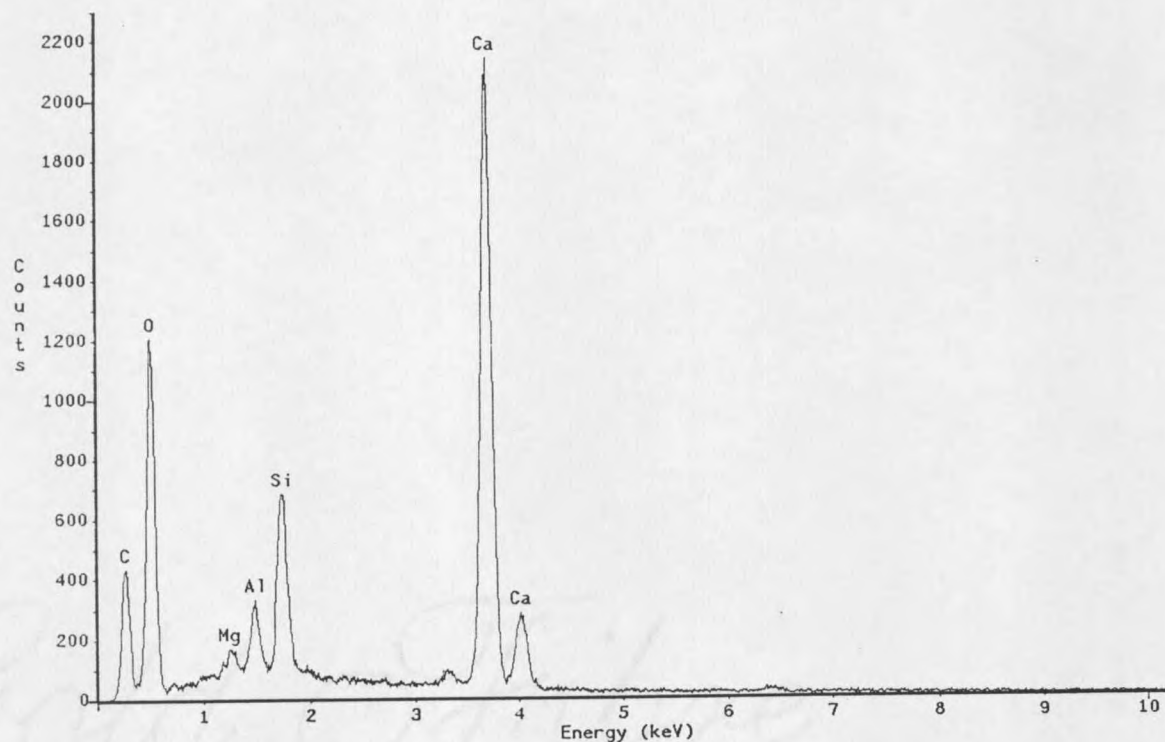
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00362	1.674	0.66	0.61	+/- 0.07	MgO	1.00	0.300
Al-K	0.01590	1.428	2.23	2.27	+/- 0.17	Al ₂ O ₃	4.29	1.013
Si-K	0.03972	1.245	4.66	4.94	+/- 0.18	SiO ₂	10.58	2.119
P-K	0.00045	1.219	0.05	0.05	+/- 0.07	P ₂ O ₅	0.13	0.021
Ca-K	0.55335	1.059	38.71	58.62	+/- 0.52	CaO	82.02	17.606
Fe-K	0.00684	1.215	0.39	0.83	+/- 0.21	FeO	1.07	0.179
K-K	0.00699	0.973	0.46	0.68	+/- 0.08	K ₂ O	0.82	0.209
Na-K	0.00000	2.312	0.00	0.00	+/- 0.00	Na ₂ O	0.00	0.000
S-K	0.00090	1.107	0.08	0.10	+/- 0.07	S	0.10	0.037
O-K	---	6.355	52.76	31.90	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 91. EDS elemental analysis on the microlithons in sample GRR1-2. The upper diagram shows the counts per second for each respective element. The lower table shows each element's relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



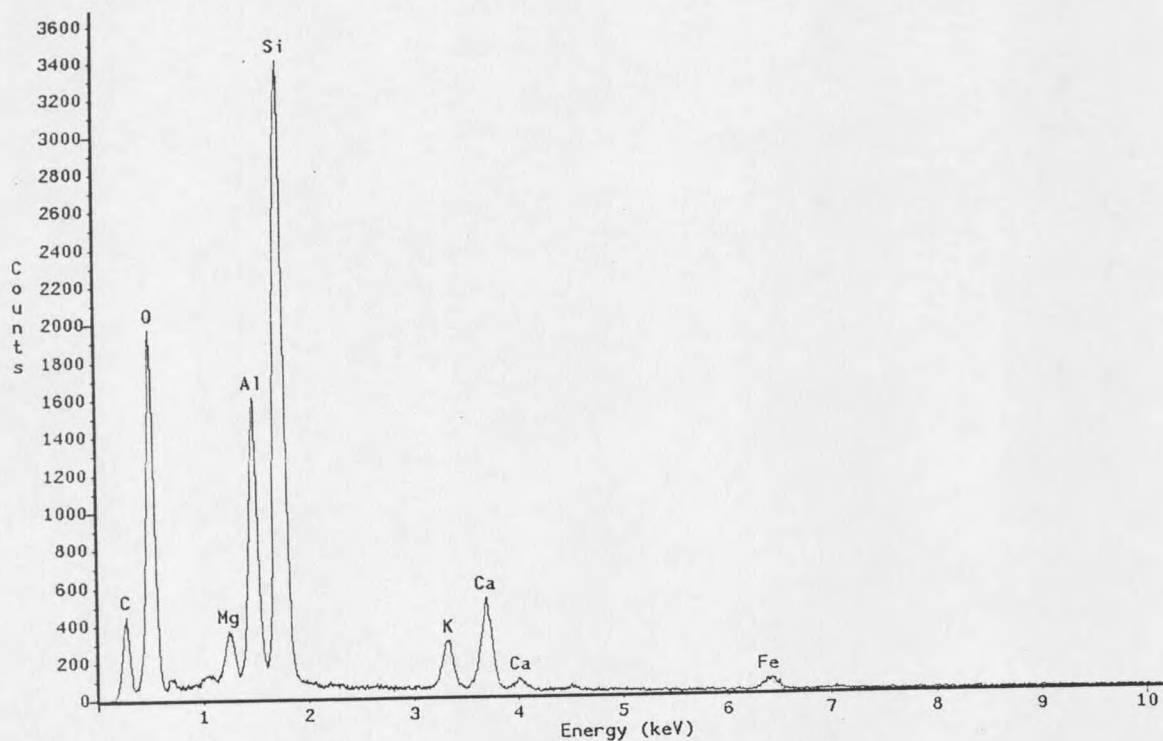
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00822	1.624	1.23	1.34	+/- 0.12	MgO	2.21	0.477
Al-K	0.05160	1.415	6.04	7.30	+/- 0.19	Al ₂ O ₃	13.80	2.348
Si-K	0.20292	1.310	21.12	26.59	+/- 0.28	SiO ₂	56.87	8.214
P-K	0.00228	1.487	0.24	0.34	+/- 0.17	P ₂ O ₅	0.78	0.095
Ca-K	0.04877	1.127	3.06	5.50	+/- 0.21	CaO	7.69	1.190
Fe-K	0.09360	1.212	4.53	11.35	+/- 0.44	FeO	14.60	1.763
K-K	0.02479	1.161	1.64	2.88	+/- 0.15	K ₂ O	3.47	0.639
Na-K	0.00153	2.183	0.32	0.33	+/- 0.16	Na ₂ O	0.45	0.126
S-K	0.00097	1.305	0.09	0.13	+/- 0.10	S	0.13	0.034
O-K	---	2.550	61.72	44.25	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 92. EDS elemental analysis on the cleavage domain in sample PTR1-3. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



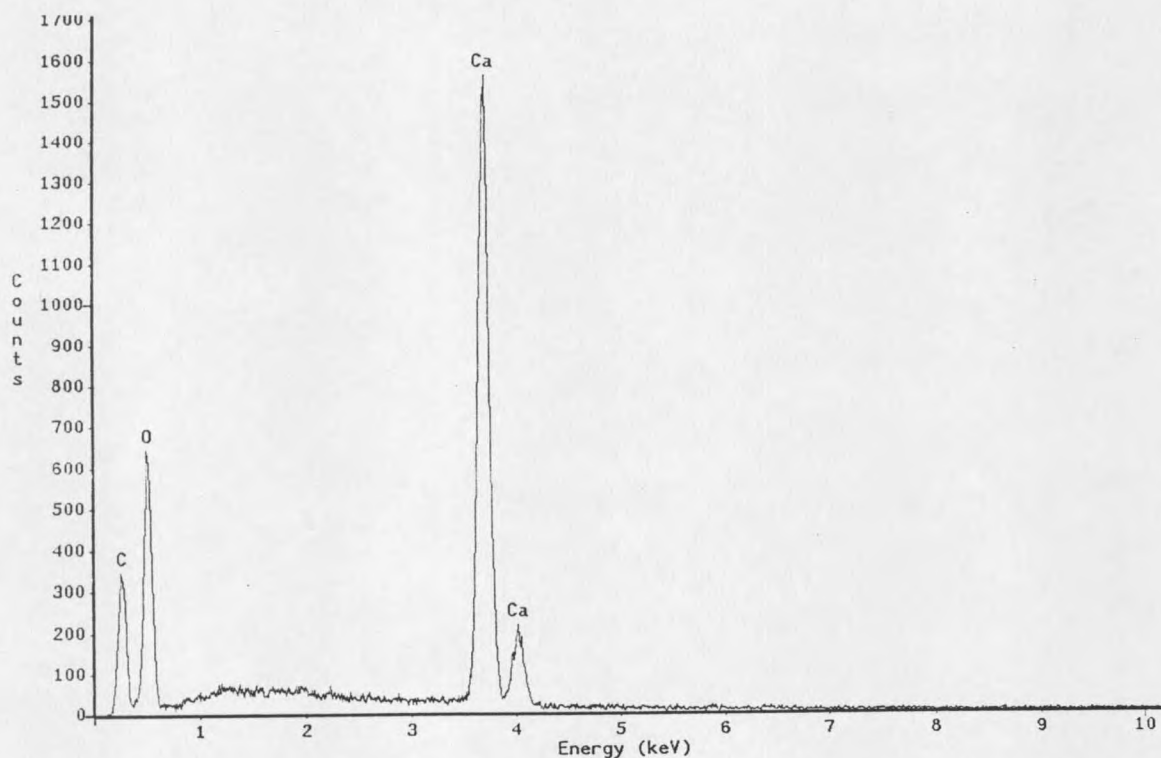
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00624	1.668	1.11	1.04	+/- 0.14	MgO	1.72	0.497
Al-K	0.01633	1.431	2.25	2.34	+/- 0.09	Al ₂ O ₃	4.41	1.005
Si-K	0.05419	1.249	6.25	6.77	+/- 0.20	SiO ₂	14.48	2.797
P-K	0.00260	1.240	0.27	0.32	+/- 0.17	P ₂ O ₅	0.74	0.121
Ca-K	0.50676	1.066	34.97	54.02	+/- 0.50	CaO	75.59	15.644
Fe-K	0.01025	1.216	0.58	1.25	+/- 0.22	FeO	1.60	0.259
K-K	0.00864	0.993	0.57	0.86	+/- 0.08	K ₂ O	1.03	0.255
Na-K	0.00121	2.277	0.31	0.27	+/- 0.12	Na ₂ O	0.37	0.139
S-K	0.00041	1.125	0.04	0.05	+/- 0.07	S	0.05	0.017
O-K	---	6.069	53.65	33.08 S	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 93. EDS elemental analysis on the microlithons in sample PTR1-3. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



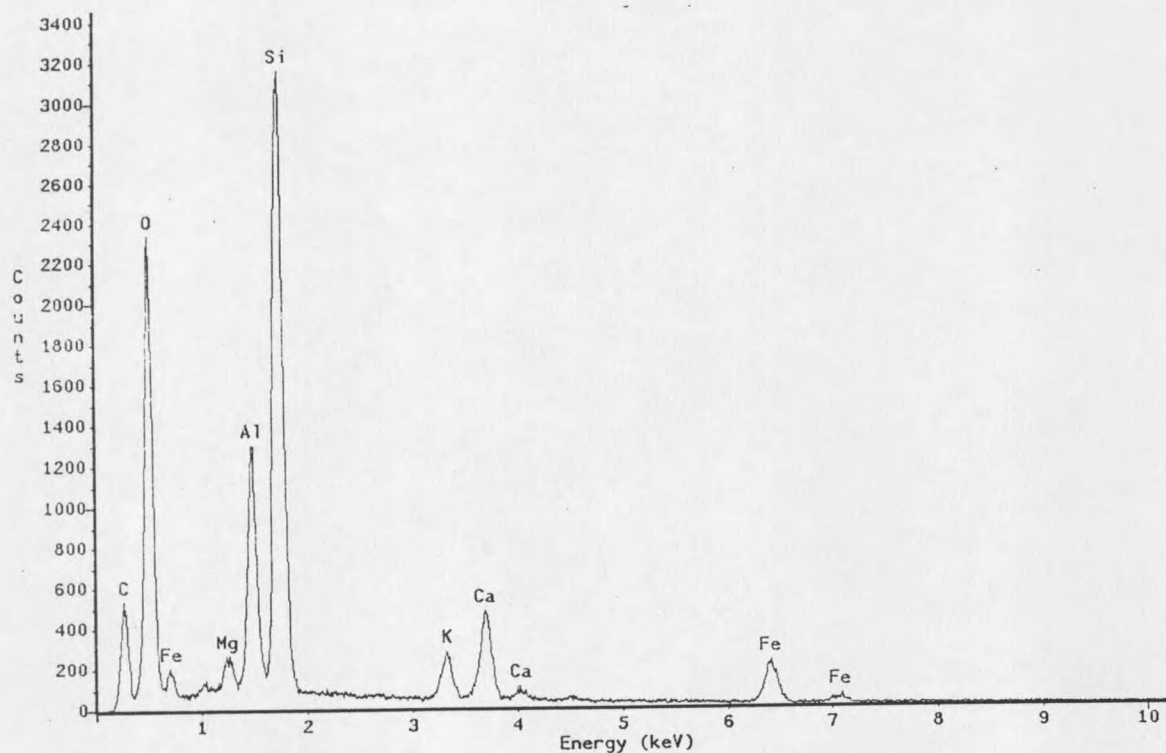
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.01154	1.548	1.59	1.79	+/- 0.12	MgO	2.96	0.622
Al-K	0.07477	1.377	8.28	10.30	+/- 0.19	Al ₂ O ₃	19.45	3.232
Si-K	0.19480	1.323	19.90	25.77	+/- 0.24	SiO ₂	55.14	7.771
P-K	0.00149	1.499	0.16	0.22	+/- 0.06	P ₂ O ₅	0.51	0.061
Ca-K	0.07188	1.143	4.45	8.22	+/- 0.23	CaO	11.50	1.736
Fe-K	0.03209	1.228	1.53	3.94	+/- 0.33	FeO	5.07	0.598
K-K	0.03324	1.169	2.15	3.88	+/- 0.16	K ₂ O	4.68	0.841
Na-K	0.00214	2.045	0.41	0.44	+/- 0.09	Na ₂ O	0.59	0.161
S-K	0.00076	1.314	0.07	0.10	+/- 0.05	S	0.10	0.026
O-K	---	2.949	61.46	45.34	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 94. EDS elemental analysis on the cleavage domain in sample SRR1-1. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



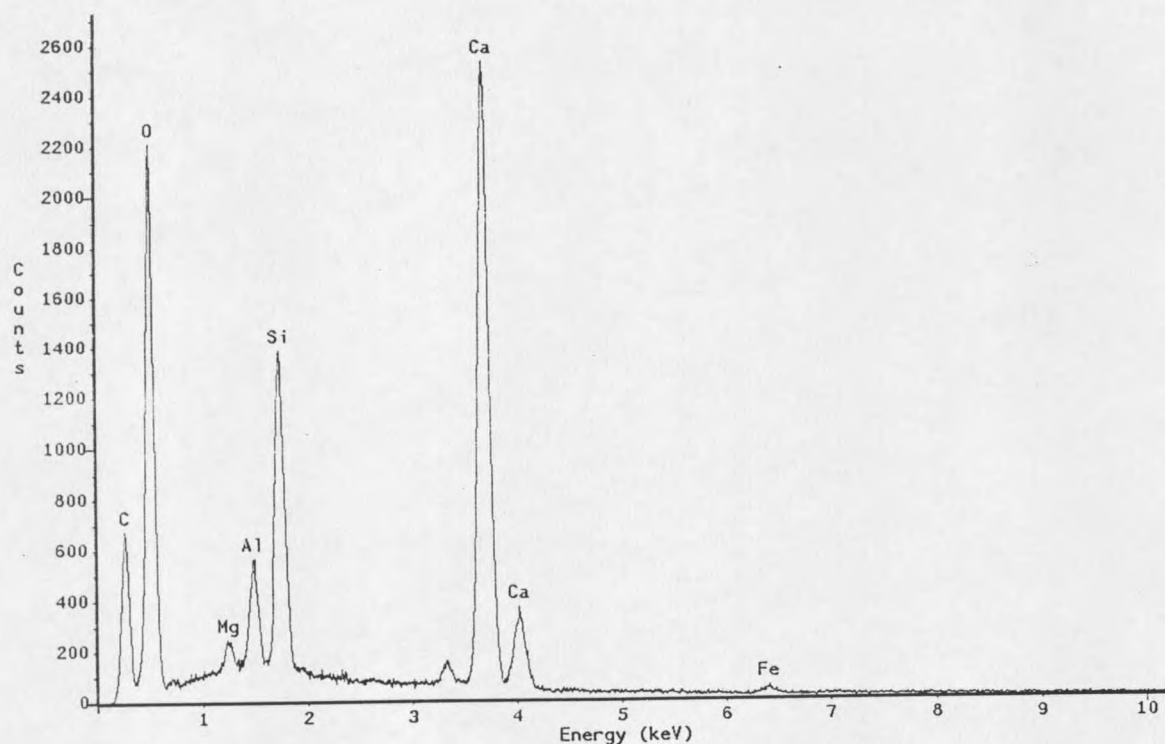
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00311	1.729	0.62	0.54	+/- 0.15	MgO	0.89	0.296
Al-K	0.00080	1.458	0.12	0.12	+/- 0.08	Al ₂ O ₃	0.22	0.057
Si-K	0.00067	1.236	0.08	0.08	+/- 0.07	SiO ₂	0.18	0.040
P-K	0.00131	1.166	0.14	0.15	+/- 0.09	P ₂ O ₅	0.35	0.066
Ca-K	0.66830	1.042	48.49	69.61	+/- 0.72	CaO	97.40	23.203
Fe-K	0.00590	1.212	0.36	0.71	+/- 0.28	FeO	0.92	0.171
K-K	0.00000	0.914	0.00	0.00	+/- 0.00	K ₂ O	0.00	0.000
Na-K	0.00000	2.405	0.00	0.00	+/- 0.00	Na ₂ O	0.00	0.000
S-K	0.00040	1.064	0.04	0.04	+/- 0.10	S	0.04	0.018
O-K	---	7.112	50.16	28.74	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 95. EDS elemental analysis on the microlithons in sample SRR1-1. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00630	1.646	0.96	1.04	+/- 0.06	MgO	1.72	0.380
Al-K	0.05835	1.424	6.97	8.31	+/- 0.17	Al ₂ O ₃	15.70	2.745
Si-K	0.18351	1.325	19.59	24.31	+/- 0.22	SiO ₂	52.02	7.717
P-K	0.00042	1.475	0.05	0.06	+/- 0.06	P ₂ O ₅	0.14	0.018
Ca-K	0.06643	1.123	4.21	7.46	+/- 0.23	CaO	10.44	1.659
Fe-K	0.09745	1.209	4.78	11.79	+/- 0.30	FeO	15.16	1.881
K-K	0.02902	1.151	1.93	3.34	+/- 0.16	K ₂ O	4.02	0.762
Na-K	0.00241	2.218	0.53	0.53	+/- 0.07	Na ₂ O	0.72	0.207
S-K	0.00059	1.294	0.05	0.08	+/- 0.06	S	0.08	0.021
O-K	---	2.731	60.93	43.08	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 96. EDS elemental analysis on the cleavage domain in sample TRR2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.



Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Compound Formula	Compound Wt %	Stoich- iometry
Mg-K	0.00519	1.655	0.89	0.86	+/- 0.06	MgO	1.43	0.389
Al-K	0.02368	1.421	3.15	3.37	+/- 0.15	Al ₂ O ₃	6.36	1.372
Si-K	0.08034	1.257	9.08	10.10	+/- 0.17	SiO ₂	21.61	3.956
P-K	0.00014	1.278	0.01	0.02	+/- 0.07	P ₂ O ₅	0.04	0.006
Ca-K	0.44511	1.076	30.19	47.89	+/- 0.42	CaO	67.01	13.145
Fe-K	0.01339	1.218	0.74	1.63	+/- 0.19	FeO	2.10	0.321
K-K	0.01106	1.021	0.73	1.13	+/- 0.07	K ₂ O	1.36	0.318
Na-K	0.00000	2.280	0.00	0.00	+/- 0.00	Na ₂ O	0.00	0.000
S-K	0.00083	1.152	0.08	0.10	+/- 0.06	S	0.10	0.033
O-K	---	5.719	55.12	34.91	---	---	---	24.000
Total			100.00	100.00			100.00	

Figure 97. EDS elemental analysis on the microlithons in sample TRR2. The upper diagram shows the counts per second for each respective element. The lower table shows each elements relative abundance. The compound weight percent and stoichiometry are based on the simple oxide for each cation.

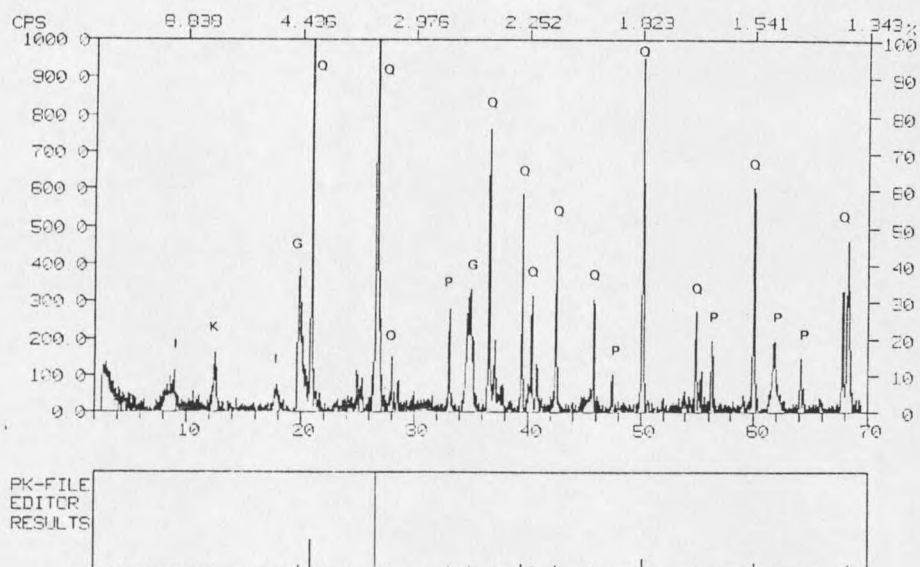


Figure 98. X-ray diffraction pattern of sample DTR1 on the insoluble minerals left over from the whole rock dissolution process. The identified peaks are given below. The following are the minerals identified from the peaks present: I = illite, K = kaolinite, G = glauconite, Q = quartz, O = orthoclase and P = pyrite.

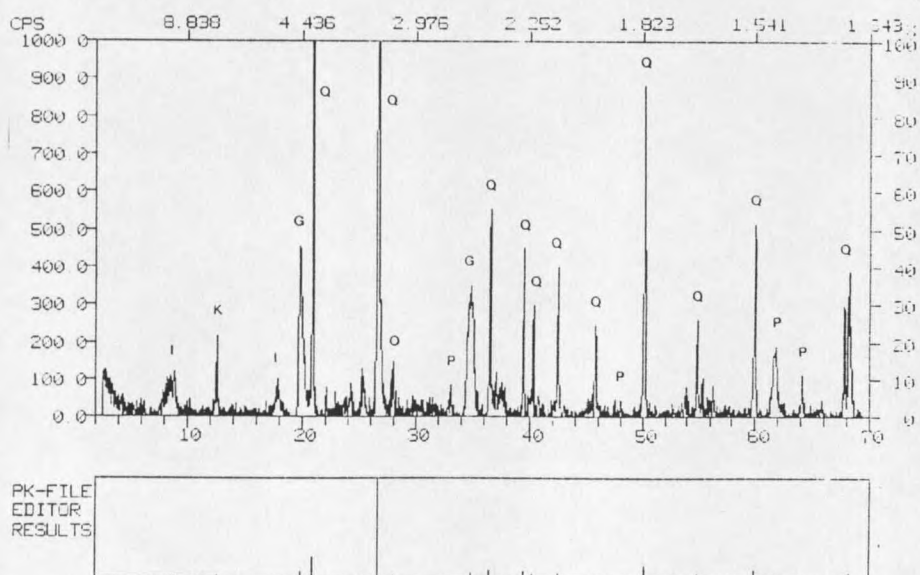


Figure 99. X-ray diffraction pattern of sample DTR4 on the insoluble minerals left over from the whole rock dissolution process. The identified peaks are given below. The following are the minerals identified from the peaks present: I = illite, K = kaolinite, G = glauconite, Q = quartz, O = orthoclase and P = pyrite.

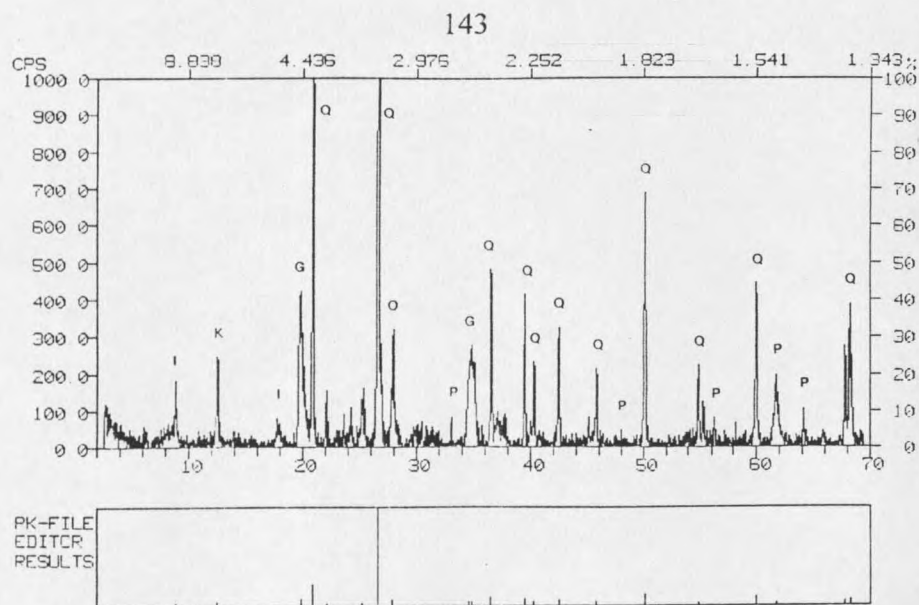


Figure 100. X-ray diffraction pattern of sample PTR1 on the insoluble minerals left over from the whole rock dissolution process. The identified peaks are given below. The following are the minerals identified from the peaks present: I = illite, K = kaolinite, G = glauconite, Q = quartz, O = orthoclase and P = pyrite.

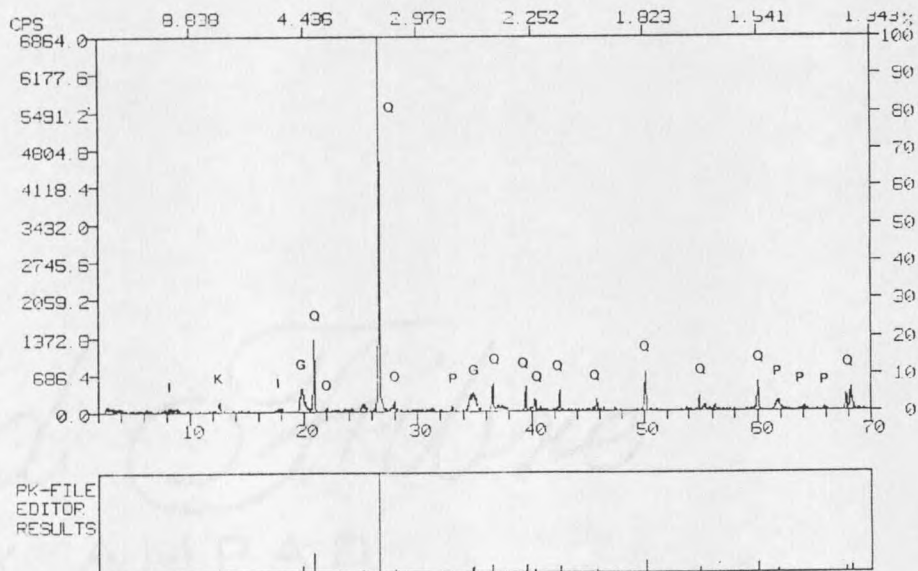


Figure 101. X-ray diffraction pattern of sample SRR1 on the insoluble minerals left over from the whole rock dissolution process. The identified peaks are given below. The following are the minerals identified from the peaks present: I = illite, K = kaolinite, G = glauconite, Q = quartz, O = orthoclase and P = pyrite.

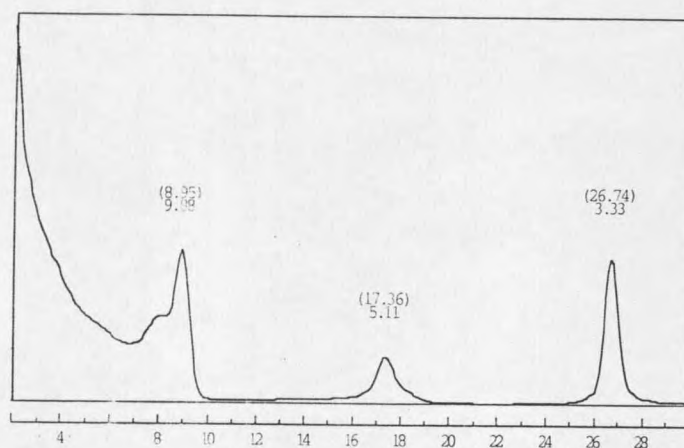


Figure 102. Experimental X-ray diffraction pattern from a sample containing R3 ordered 10% expandable illite/smectite, with the sample treated with glycol.

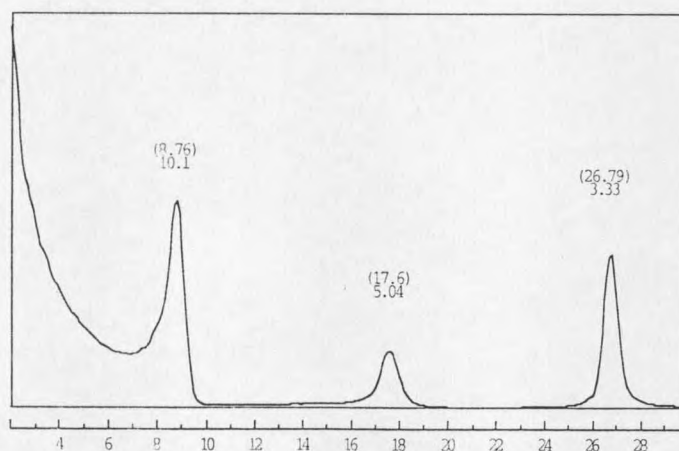


Figure 103. Experimental X-ray diffraction pattern from a sample containing R3 ordered 5% expandable illite/smectite, with the sample treated with glycol.

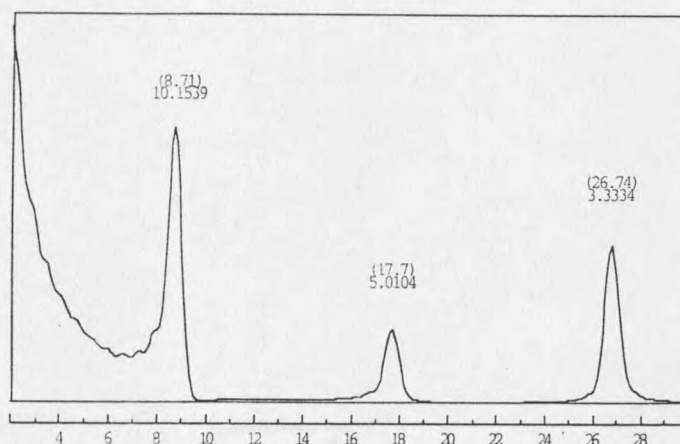


Figure 104. Experimental X-ray diffraction pattern from a sample containing R3 ordered 1% expandable illite/smectite, with the sample treated with glycol.

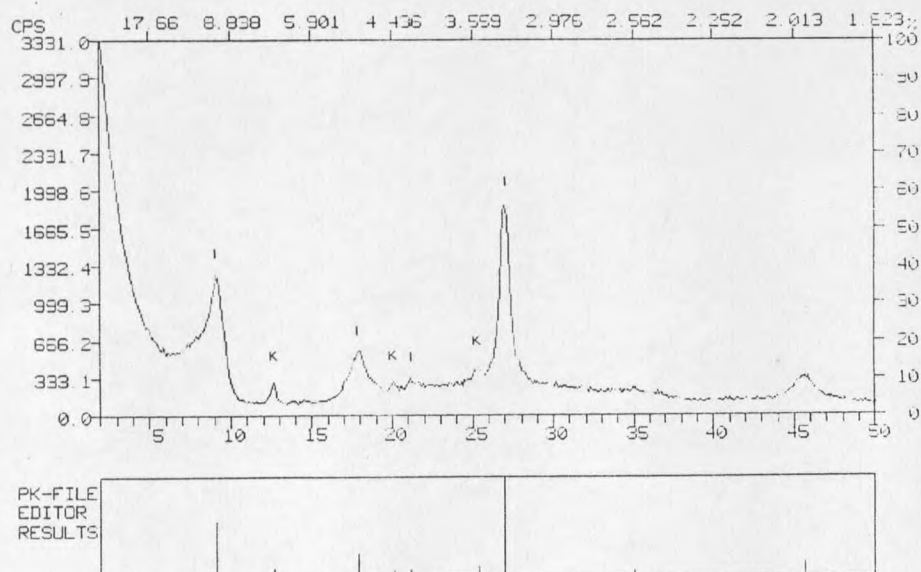


Figure 105. X-ray diffraction pattern of clay minerals directly from the cleavage domains within sample BTR1. The sample contains 5% expandable illite/smectite as determined when comparing the pattern with Figs. 104, 105 and 106. "I" indicates illite/smectite peaks and "K" for kaolinite.

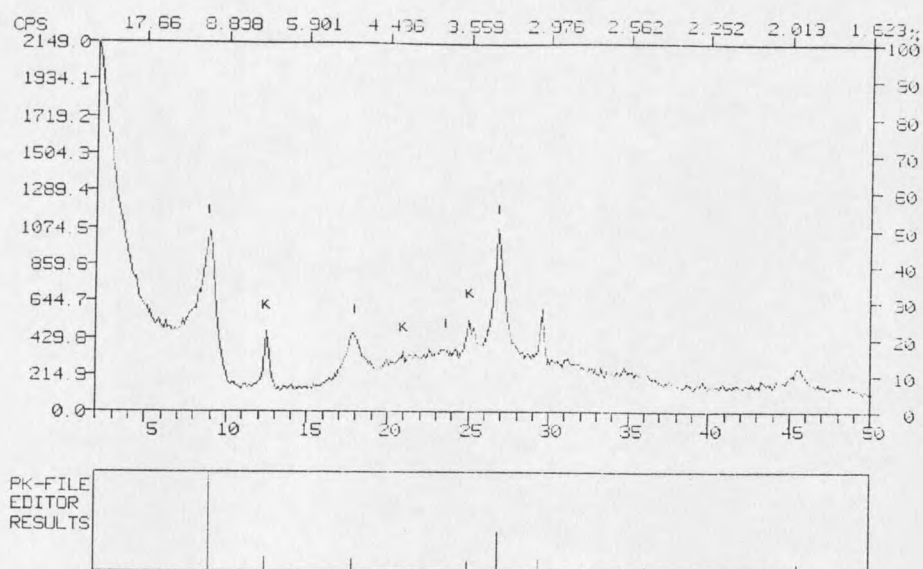


Figure 106. X-ray diffraction pattern of clay minerals directly from the cleavage domains within sample DTR1. The sample contains 5% expandable illite/smectite as determined when comparing the pattern with Figs. 104, 105 and 106. "I" indicates illite/smectite peaks and "K" for kaolinite.

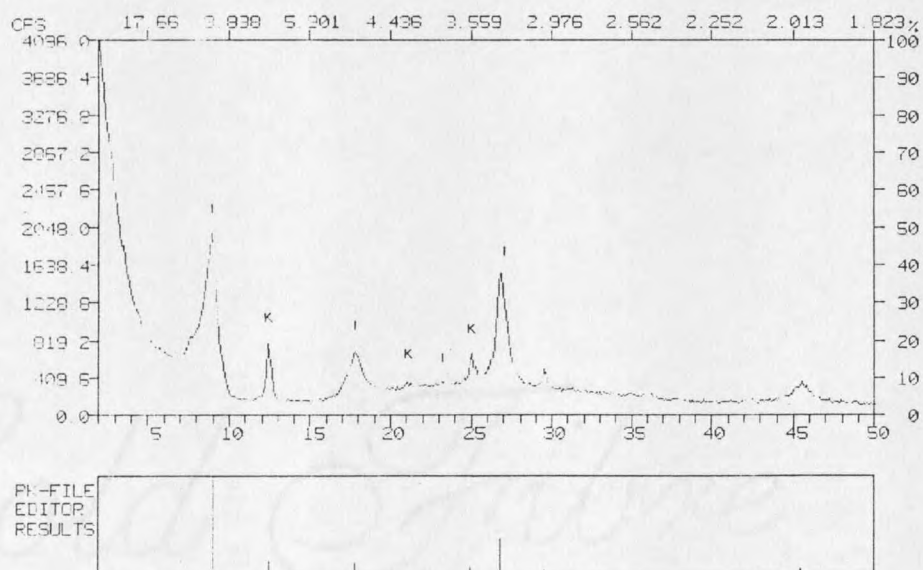


Figure 107. X-ray diffraction pattern of clay minerals directly from the cleavage domains within sample BTR4. The sample contains 5% expandable illite/smectite as determined when comparing the pattern with Figs. 104, 105 and 106. "I" indicates illite/smectite peaks and "K" for kaolinite.

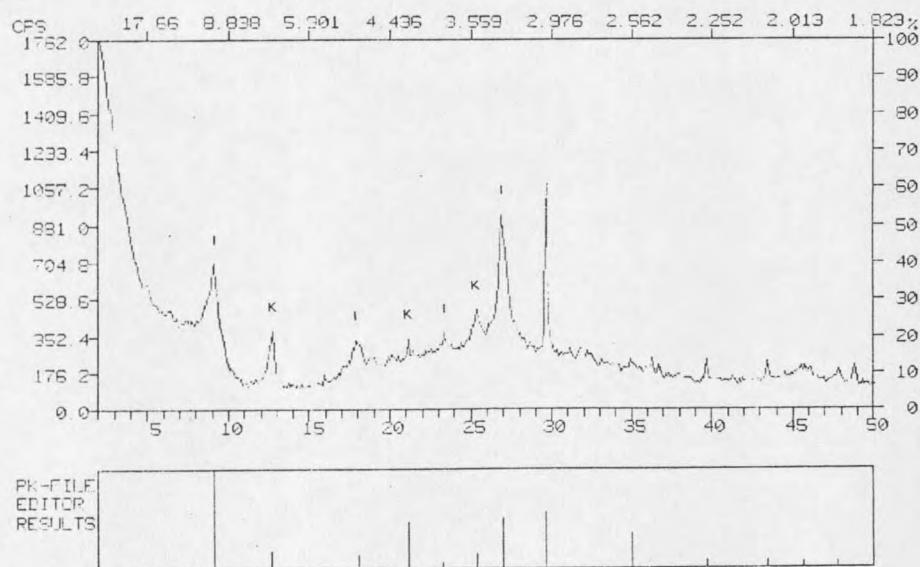


Figure 108. X-ray diffraction pattern of clay minerals directly from the cleavage domains within sample SRR1. The sample contains 5% expandable illite/smectite as determined when comparing the pattern with Figs. 104, 105 and 106. "I" indicates illite/smectite peaks and "K" for kaolinite.

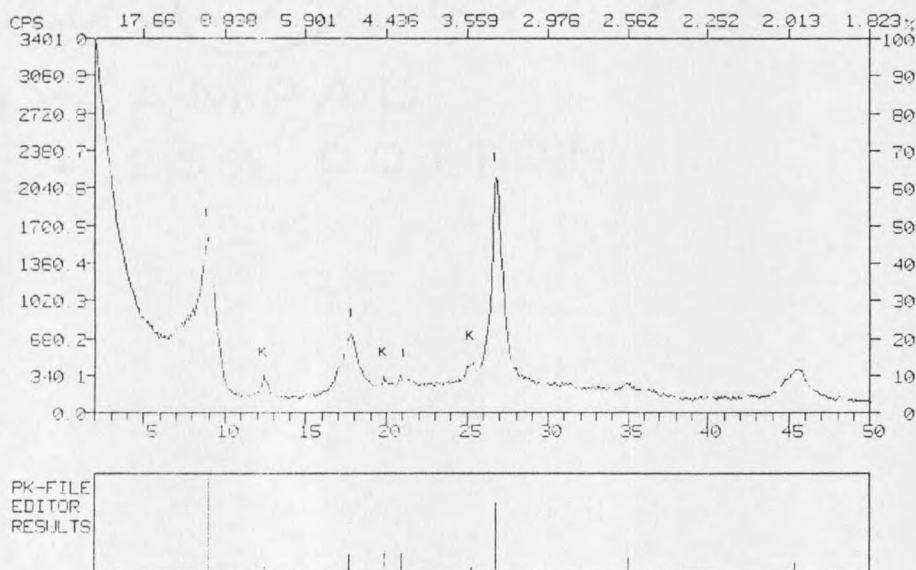


Figure 109. X-ray diffraction pattern of clay minerals from the whole rock dissolution process from sample SRR1. The sample contains 5% expandable illite/smectite as determined when comparing the pattern with Figs. 104, 105 and 106. "I" indicates illite/smectite peaks and "K" for kaolinite. Note that there is little difference from the pattern obtained from the cleavage domains (Fig. 110).

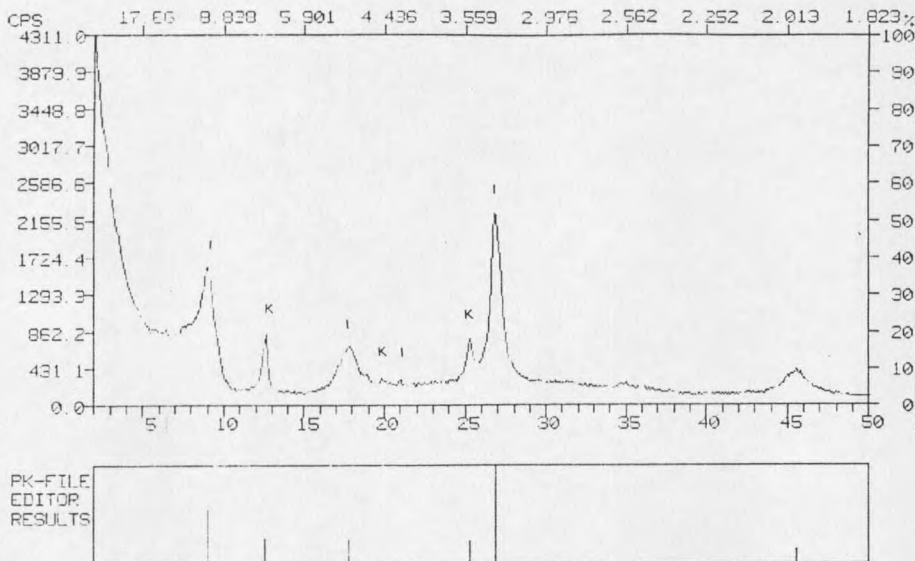


Figure 110. X-ray diffraction pattern of clay minerals from the whole rock dissolution process from sample GRR1. The sample contains 5% expandable illite/smectite as determined when comparing the pattern with Figs. 104, 105 and 106. “I” indicates illite/smectite peaks and “K” for kaolinite.

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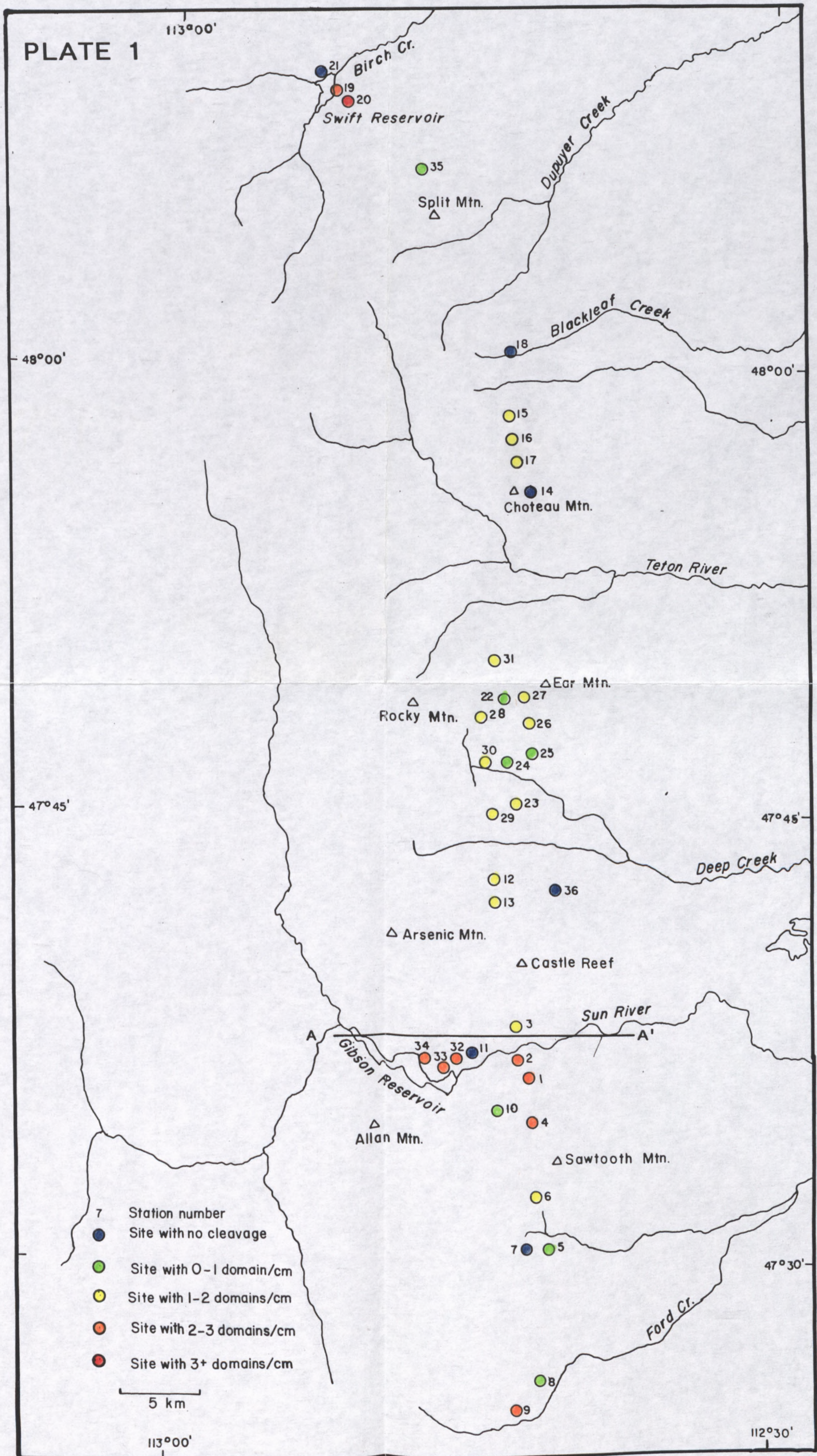
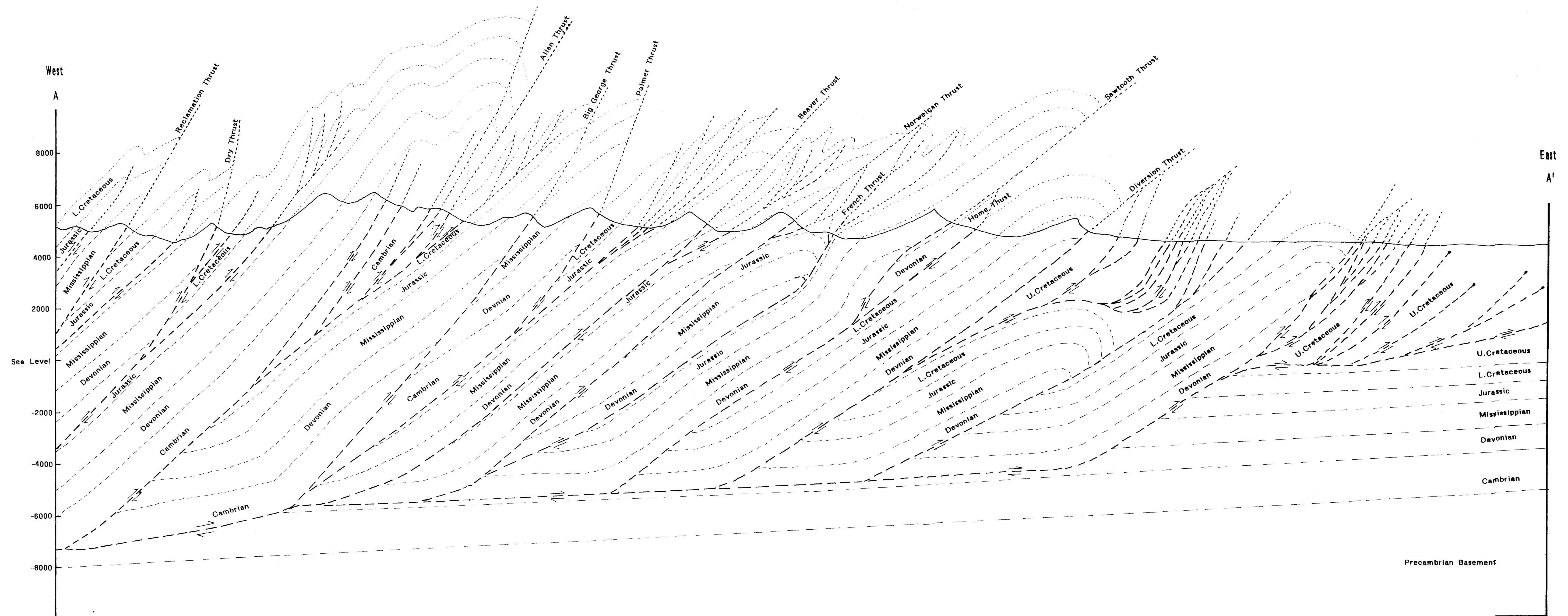
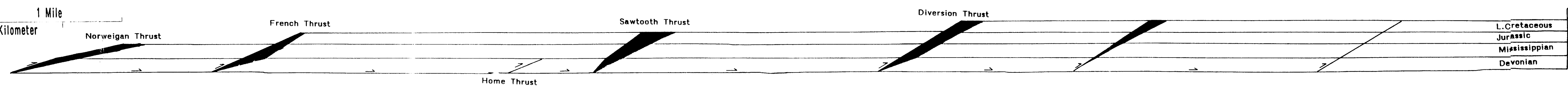


PLATE 2 Cross-section Across the Sawtooth Range in the Sun River Canyon Area



Scale: 1:24000

1 Mile
1 Kilometer



KEY

Thick lines indicate faults, with the direction of offset indicated by arrows.

Thin lines indicate bed contacts.

All contacts are inferred from surface data and previous studies (Mudge 1965, 1966, 1967, 1968, 1982; Cannon, 1979; Mitra, 1986).

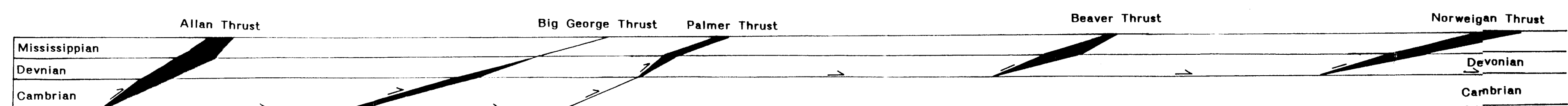


Plate 2

Scale for Restored Beds: 1:48000

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