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**ORIGIN AND CLASSIFICATION OF MIDDLE WALLACE
BRECCIAS, MESOPROTEROZOIC BELT SUPERGROUP,
MONTANA AND IDAHO**

A Thesis

Presented for the

Master of Science Degree

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ABSTRACT

A series of enigmatic breccias in the Wallace Formation, Mesoproterozoic Belt Supergroup, have been variously interpreted as originating from: (1) syndepositional downslope slumping; (2) syndepositional evaporite dissolution and collapse; or (3) post-depositional tectonic faulting. Each hypothesis carries its own implications regarding the depositional and diagenetic history of the Belt basin. Examination of several Middle Wallace breccia outcrops suggests that they can be grouped into two distinct categories based on size of breccia bodies, clast size, and relationships with surrounding strata, and matrix composition. Results indicate that rather than a single origin, these two breccia groups originate from distinctly different mechanisms, suggesting a varied syn- and post-depositional history of the Wallace Formation. Group 1 breccias, typified by the Trout Creek locality, are concordant with surrounding strata, occur in conjunction with soft-sediment folding, and contain detrital sand and silt in the matrix. These characteristics suggest a syndepositional downslope slump mechanism of brecciation. Group 2 breccias, typified by the Lostkey locality, are extremely large breccia bodies, contain clasts >10 m, and contain abundant authigenic quartz and feldspar in the matrix. These breccias are the result of a post-depositional tectonic mechanism of brecciation. Both groups show evidence of secondary overprinting by hydrothermal fluids. Group 1 breccias are associated with syndepositional faulting on the western edge of the Belt basin, and Group 2 breccias are related to pluton emplacement in the Late Cretaceous through Early Tertiary.

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1. INTRODUCTION

Understanding the origin of breccias is an important component in deciphering the geologic history of an area (Blount and Moore, 1969; Morrow, 1982). Brecciation of host rock frequently results in increased porosity and permeability, and can therefore act to concentrate syn- and post-depositional fluid flow. As a result, breccia deposits frequently host both hydrocarbon and mineral deposits (Middleton, 1961; Sawkins and Sillitoe, 1985). Depending on the mode of origin of the breccia, these deposits can also provide evidence for interpretation of depositional environments (Spence and Tucker, 1997), development of basin geometries (Haas, 1999), and the effects of subsequent tectonic activity (Laznicka, 1989; and references therein).

Many difficulties exist in constraining the genesis of breccia deposits. The difficulty in interpreting the origin of breccias results first from the similarity of features that exist within breccias of different origins. Clast composition and roundness may be similar in tectonic, slump, or hydrothermal breccia deposits (Blount and Moore, 1969). Additionally, breccias are frequently poorly preserved in outcrop, making it difficult to recognize salient features in the field (Blount and Moore, 1969; Morrow, 1982). Finally, breccias may also result from overprinting of two or more distinct brecciation mechanisms, further confounding interpretation of their genesis. For example, it is not unusual for breccias that result from synsedimentary faulting to be cemented, then rebrecciated at a later point by dissolution resulting from the migration of fluids or by fault reactivation (Middleton, 1961; Lee and Wilkinson, 2002; Nielson, 1999; Swennen *et al.*, 1990).

Despite these difficulties, several workers have attempted to develop criteria for distinguishing different breccia types (Middleton, 1961; Stanton, 1966; Blount and Moore, 1969; Morrow, 1982; Swennen *et al.*, 1990). Laznicka (1989) lists an extensive collection of literature regarding breccia classification. Clast size, sorting, composition, and the relationship of the breccia body with surrounding strata are important features in the classification of breccias. Typically, clast size depends on the scale of the brecciation process; large-scale brecciation mechanisms such as gravity flows and tectonic forces are needed to produce large clasts (Morrow, 1982; Spence and Tucker, 1997; Drzewiecki and Simo, 2002). Sorting of breccia clasts also depends on brecciation mechanism: in syndepositional breccias, clasts may be sorted, whereas sorting rarely occurs in post-depositional brecciation (Stanton, 1966; Morrow, 1982). Clast composition is controlled by timing of brecciation as well as mechanism. In syndepositional breccias, clast lithologies typically mimic those of correlative undisturbed strata (Middleton, 1961; Stanton, 1966; Blount and Moore, 1969). In post-depositional brecciation, clast lithologies may be different from surrounding strata as a result of large-scale reorganization of stratal blocks. Relationship of the breccia body to surrounding strata is controlled primarily by timing of brecciation. If brecciation occurs syndepositionally, the contact between the breccia body and under and overlying strata will be conformable, whereas post-depositional brecciation typically dissects host strata (Stanton, 1966).

Diverse Origins of Breccias

Slump breccias result from subaqueous downslope transport of strata in which beds are deformed and disrupted (Walker, 1992). These breccias may be conformably

bedded with under and overlying strata and frequently reveal minor scour of underlying strata. The matrix of slump breccias commonly contains detrital material resulting from fluidization and redeposition of unlithified strata (Blount and Moore, 1969). Most slump breccias exhibit a high clast/matrix ratio (Lee and Wilkinson, 2002).

Solution, or collapse, breccias result from dissolution of evaporite or carbonate minerals, creating voids which facilitate gravitational collapse of strata (Stanton, 1966). These include karst breccias, cave collapse breccias, or evaporite dissolution breccias. The breccia body is typically discordant with surrounding strata. Also, solution breccias normally have a sharp lower contact with an unconformable upper contact (Stanton, 1966). Clast composition is that of strata surrounding the area of dissolution, commonly carbonate lithologies, and the matrix is commonly composed of chemically precipitated minerals (Stanton, 1966; Morrow, 1982; Pope and Grotzinger, 2003). Clasts within evaporite collapse breccias may have voids resulting from dissolved evaporite minerals (Cooper, 1970). A crude stratification may exist in these breccia types, with clasts composed of units from higher in the stratigraphic section (Ohle, 1985; Wenrich, 1985; Swennen *et al.*, 1990).

Tectonic breccias occur where a rock body is fractured and brecciated by folding and/or faulting (Blount and Moore, 1969). These breccias are recognized by proximity to faults, and clasts are often internally fractured as a result of the faulting. Clasts are subangular to angular, with somewhat matching boundaries as transportation and rotation of clasts is minimal (Blount and Moore, 1969). In small-scale brecciation events, rock flour is commonly present because of particle-on-particle abrasion along the fault trace (Cooper, 1970). Although the terms tectonic and fault breccias are often used

interchangeably, the two breccia types are distinctly different. Fault breccias contain fault gouge and slickensides and are limited to the damage zone near the fault (Billi and Sorti, 2004), whereas in tectonic breccias the breccia bodies may occur over a larger area (Cooper, 1970). Also, fault breccias are generally composed of smaller clasts than tectonic breccias as a result of scale of deformation.

Hydrothermal breccias occur where warm fluids concentrate along fractures and dissolve soluble strata (Wenrich, 1985; Lee and Wilkinson, 2002). These fluids can be magmatically derived or warm basinal brines. Clast size depends on amount of fluids present, and extent of fracture network. Hydrothermal breccias may be linked to fault and tectonic breccias as faults enable pathways for fluid flow (Sibson, 1987). The matrix of hydrothermal breccias commonly contains a variety of minerals that precipitated out of the migrating fluids (Ohle, 1985; Sillitoe, 1985).

Current Study

A series of enigmatic breccias occur in the Mesoproterozoic Wallace Formation, Belt Supergroup, northwestern Montana and Idaho. These breccias crop out along a 150 km transect from western Montana to eastern Idaho (Godlewski, 1981) (Fig. 1).

Proposed mechanisms for the origin of these breccias include: (a) syndepositional downslope slumping (Godlewski, 1981; Thiessen and Wallace, 1996); (b) evaporite-solution collapse (Campbell, 1960); (c) and post-depositional tectonic brecciation (Collins and Winston, 1999).

Each of the different modes of origin proposed for these breccias has important implications for basin geometry, ocean chemistry in the Proterozoic, and tectonic

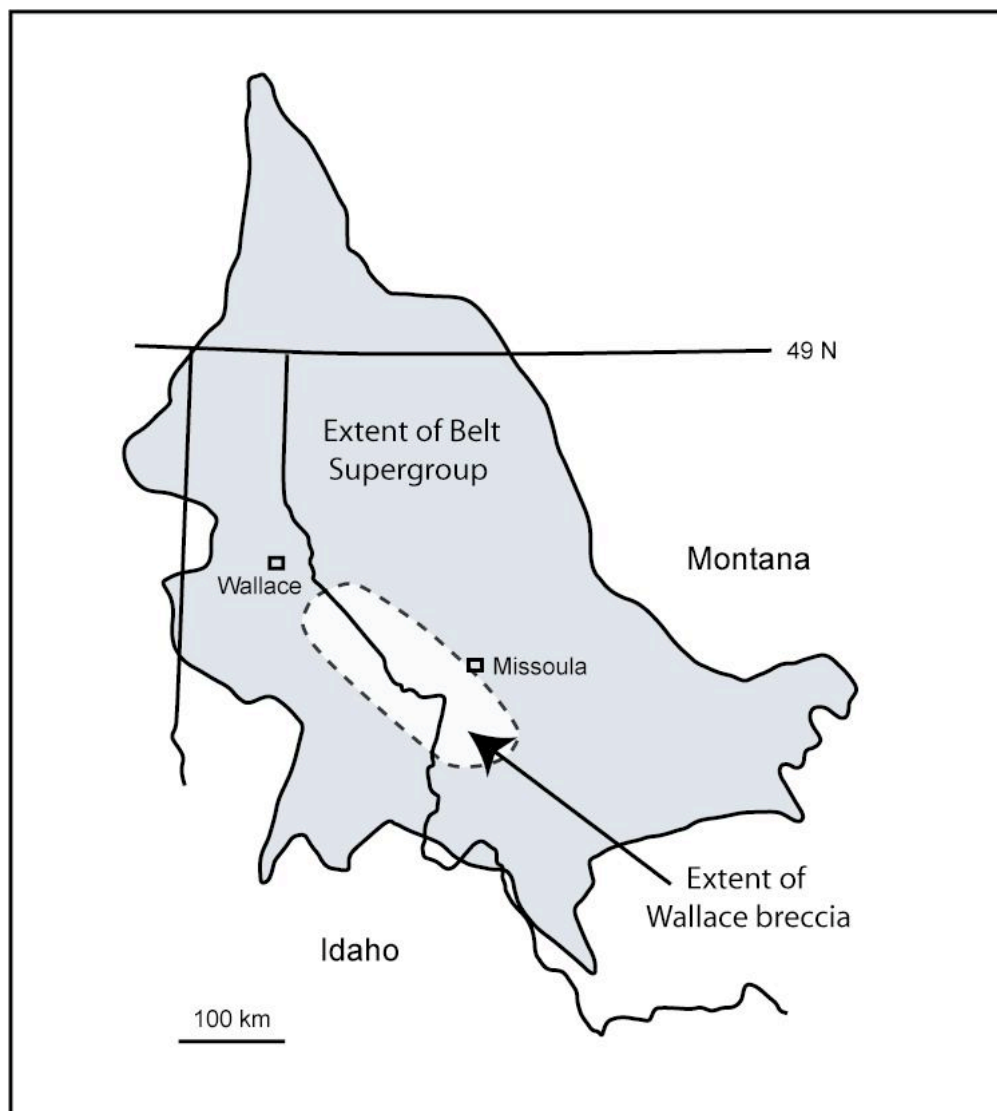


Figure 1: Extent of Middle Wallace breccias and the Belt Supergroup. Shaded region indicates overall trend and occurrences of breccias. Breccias crop out along a 150 km transect. Modified from Godlewski (1981).

processes that have occurred after deposition. Downslope slump breccias imply basin geometries that may help explain facies distributions in the Belt; evaporite collapse implies significant evaporite deposition at 1.45 Ga—prior to the first known massive sulfates in the geologic record—and thus helps to place constraints on Precambrian ocean chemistry; and tectonic breccias can help to clarify possible fluid migration pathways related to regional ore mineralization trends. Possible reasons for the conflicting interpretations of breccia origins are: similarity of clast compositions in all outcrops; an absence of clear sorting of clasts; and limited exposure of the breccia bodies and surrounding strata and the contacts between the two.

2. GEOLOGIC SETTING AND TECTONIC HISTORY

The Mesoproterozoic Belt Supergroup in the northwestern U.S. and the correlative Purcell Supergroup of southwestern Canada consist of up to 20 km of mixed siliciclastic and carbonate strata exposed over an area of >250,000 km² (Harrison, 1972) (Fig. 1). Belt Supergroup strata rest unconformably on 1.7 Ga basement (Harrison *et al.*, 1980). The origin of the Belt basin has been controversial for over a century. Deposition of the Belt Supergroup occurred in an active rift basin (Anderson and Davis, 1995; Luepke and Lyons, 2001); however, the setting of the rift basin is debated. Winston (1986) suggests that the Belt basin represents deposition in an intracratonic lacustrine environment, whereas others have proposed a restricted marginal-marine setting (Grotzinger, 1986). Among the difficulties in determining the depositional setting for the Belt strata are: (1) controversies regarding the geologic character of an unpreserved western landmass; (2) uncertain facies interpretation of non-fossiliferous strata; (3) generally poor geochronological constraints on the age and duration of sedimentation; and (4) overprinting of the Belt strata by several penetrative and nonpenetrative tectonic events.

Recent geochronologic work on the Belt basin has constrained the duration of all but the uppermost Belt Supergroup deposition to ~70 Ma (Evans *et al.*, 2000), with up to two-thirds of deposition occurring in a 20-30 my interval (Luepke and Lyons, 2001). Zircons in the Moyie sills in the Prichard Formation (lower Belt), some 15 – 20 km beneath the top of Belt strata, have a U-Pb age date of 1468 ± 2 Ma (Anderson and Davis, 1995). Episodic mafic volcanism, probably related to extension, occurred in the Belt as indicated by the 1368 ± 2 Ma U-Pb dates from zircons in sills emplaced in upper Belt

strata (Doughty and Chamberlain, 1996; Evans *et al.*, 2000; Ross and Villeneuve, 2003). These time intervals indicate subsidence rates of 0.4 to 0.2 m/1000 yrs (Winston *et al.*, 1999). Together, the thickness of the Belt Supergroup, the inferred rapid subsidence/sediment accumulation rates, and the generally mafic composition of syndepositional magmatism support an interpretation of the Belt basin as an intracratonic, rift-related basin that underwent episodic extension (Anderson and Davis, 1995; Evans *et al.*, 2000; Ross and Villeneuve, 2003). C and S isotopic examination of Belt strata further suggest dominantly marine waters that experienced episodic isolation from the adjacent sea (Frank *et al.*, 1997; Lyons *et al.*, 2000; Luepke and Lyons, 2001; Gellatly and Lyons, 2005).

Syndepositional faulting was active in the basin throughout Belt deposition (Winston, 1986). The Lewis and Clark line, a fault zone 50-100 km wide and 200–250 km long, composed of west-northwest-trending faults, traverses western Montana and northern Idaho (Fig. 2). Movement along these faults most likely began in the Proterozoic and was reactivated later in the late Cretaceous through early Tertiary Laramide orogeny (Winston, 1986; White, 1998; Mauk, 2002).

Three Proterozoic tectonic events affected the Belt basin. The East Kootenay orogeny, which involved extensional deformation, occurred at >1360 Ma (Doughty and Chamberlain, 1996; Luepke and Lyons, 2001). Gentle folding, cleavage development, and mafic and felsic magmatism are linked with this orogenic event. A second tectonic event occurred during 1030–1120 Ma, affecting Belt rocks through low- to medium-grade (greenschist to low amphibolite facies) thermal metamorphism (Doughty and Chamberlain, 1996). The third and final Proterozoic tectonic event was the Goat

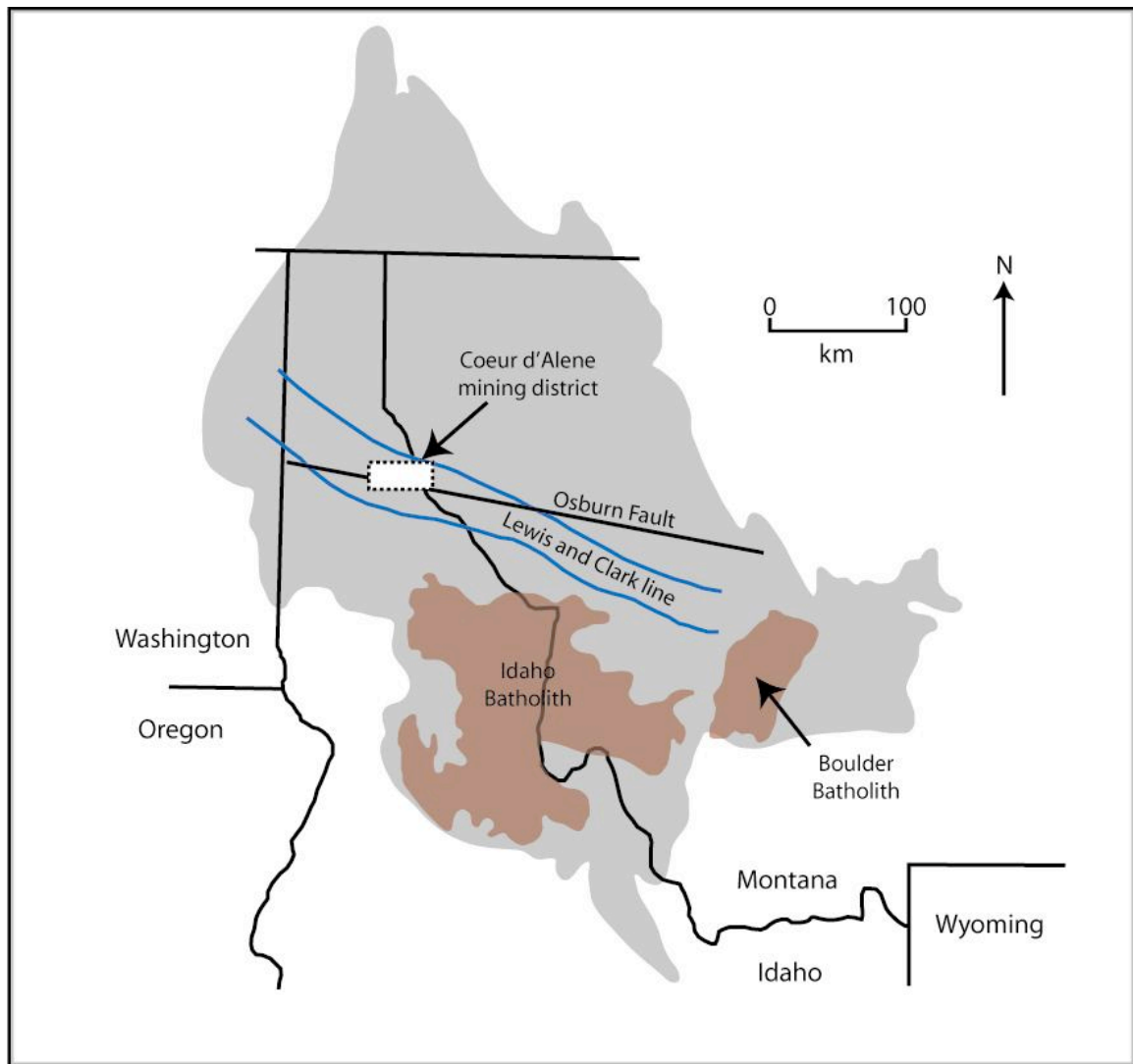


Figure 2: Major tectonic and igneous features in the Belt Supergroup. Gray shaded region is extent of Belt Supergroup outcrop. The Lewis and Clark line is a fault zone composed of west-northwest trending structures (White, 1998) and the Idaho batholith was emplaced in the early Tertiary (Criss and Fleck, 1987). Modified from Mauk (2002).

River orogeny that occurred during 900–800 Ma and was associated with uplift, block-faulting and low grade regional metamorphism (Anderson and Davis, 1995; Doughty and Chamberlain, 1996).

The Late Cretaceous Laramide orogeny shortened the Belt rocks by thrust faulting (Price and Sears, 2001), resulting in Belt Supergroup strata thrust over Paleozoic and Mesozoic strata (Elston *et al.*, 2002). The Belt strata were moved easterly, from several km near the Helena embayment, up to >100 km along the Lewis overthrust in southern Alberta (Elston *et al.*, 2001; Pratt, 2001; Price and Sears, 2001). This faulting was accompanied by gentle folding, high temperature metamorphism, pluton emplacement, and hydrothermal activity between 140 and 45 Ma (Fleck *et al.*, 2002). The Idaho batholith, a large granitic igneous body, was emplaced in the Late Cretaceous (Criss and Fleck, 1987). Metamorphic grade in the Belt strata is generally low, and increases from east to west (Maxwell and Hower, 1967). Eastern Belt rocks are near pristine, while metamorphism up to amphibolite facies is present in the western Belt strata.

In the Wallace 30' x 60' quadrangle, two major tectonic features are present. The Lewis and Clark line and Montana's western thrust belt intersect within the quadrangle. Compression occurred in the Cretaceous, producing asymmetric to overturned northeast-verging folds accompanied by northwest-trending fault systems. Mid-Tertiary extension followed the compressional event, reactivated Late Cretaceous thrusts (Lonn and McFadden, 1999) and the Osburn Fault, a right-lateral strike-slip fault, displaced strata up to 25 km near the Montana-Idaho border in the Wallace quadrangle (Mauk, 2002).

Sedimentation of the Belt Supergroup and the MBC

Sedimentation of the Belt basin reveals regional differences: the southwestern portion of the basin received coarse-grained, siliciclastic sediment; the northeast portion was sediment starved and contains mostly locally precipitated carbonate; and the western part of the basin contains a mixture of carbonate and siliciclastic deposition (Ross and Villeneuve, 2003). The western side of the basin produced much of the siliciclastic sediment that was deposited in the Belt basin (Winston, 2001). Sedimentary environments of the Belt Supergroup range from turbiditic deep-water environments to continental mudflats. The lower Belt (Prichard Formation) (Fig. 3) is composed predominantly of turbiditic and deltaic sedimentary rocks mixed with pyrite-bearing, thinly laminated siltstone and sandstone, representing a major transgressive phase. The overlying Ravalli Group (Burke, Revett and St. Regis Formations) is composed predominantly of fluvial sedimentary rocks that were deposited on sand and mud flats, and marks the end of the transgression. Directly overlying the Ravalli Group is the Middle Belt Carbonate (Helena and Wallace Formations) that was deposited during a transgressive phase that was marked by the retreat of the shoreline and deposition of predominantly shallow-water carbonate rocks (Grotzinger, 1986). The uppermost portion of the Belt is the Missoula Group (Snowslip, Shepard, Mt. Shield Formations, Bonner Quartzite, and Libby Formation) that contains fluvial sedimentary rocks along with sandstone and siltstone from playa and perennial lake deposits and represents a progradational sequence (Link, 1998; Winston, 1986, 1998).

The Middle Belt Carbonate (MBC) interval of the Belt Supergroup is composed of the 1.45 Ga Helena and Wallace Formations (Aleinikoff *et al.*, 1996), which consist of

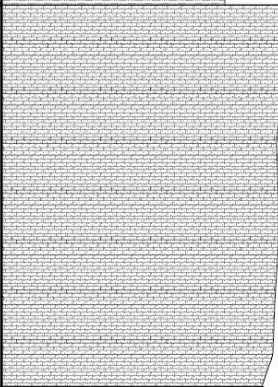
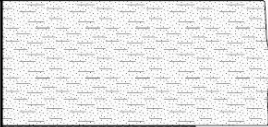
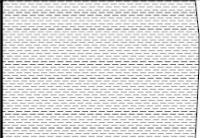
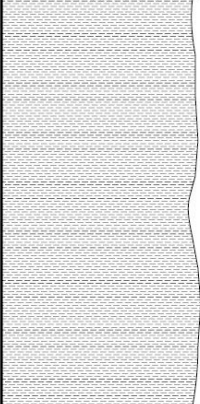
Belt Supergroup	Missoula Group	Libby Formation	
		Bonner Quartzite	
		Mt. Shields Formation	
		Shepard Formation	
		Snowslip Formation	
	Middle Belt Carbonate	Wallace Formation	
		Helena Formation	
	Ravalli Group	St. Regis Formation	
		Revett Formation	
		Burke Formation	
	Lower Belt	Prichard Formation	

Figure 3: Generalized stratigraphy, Belt Supergroup, western Montana and Idaho. After Anderson and Davis (1995).

500–3000 m of mixed carbonate and siliciclastic strata (Winston, 1998). Although the Belt basin is multiply deformed (Anderson and Davis, 1995; Campbell, 1960; Evans *et al.*, 2000; Pratt, 2001), most of the east-central Helena/Wallace Formations remain largely undeformed. Regional metamorphic grade increases westward to greenschist facies in the western Wallace Formation (Luepke and Lyons, 2001).

In the eastern basin, the Helena Formation consists of cyclic interbeds of fine sand and silt capped by microsparitic carbonate deposited in intertidal to shallow subtidal environments. To the west, the Wallace Formation contains a greater proportion of sand interbedded with clayey-carbonate, marking deposition in shallow subtidal conditions proximal to a southwestern sediment source (Grotzinger, 1986). During Wallace deposition, the western portion of the Belt basin was situated on a subaqueous slope with growth faulting occurring as a result of uplift in the west (Grotzinger, 1986). Sediment source for the Belt basin during deposition of the MBC was from a southwestern landmass that produced alluvial fans shedding sediment from the margin. At the time of Wallace Formation deposition, the Belt basin was most likely undergoing westward tectonic expansion as a result of continued rifting (Winston, 2004).

The Wallace Formation has been divided into three subunits by Harrison (1972). The lowermost unit is composed of thick, laminated argillite, and dolomitic argillite in alternating sequences 1–10 m thick. Sediments are graded and contain load casts, convoluted bedding, and desiccation cracks (Grotzinger, 1986). Near the top of the lower member, sand beds are present and are cross- or planar-laminated (Grotzinger, 1986). These sediments were deposited on shallow, gently sloping flats everywhere above wave-base, and intermittently the sediments were subaerially exposed. The middle member of

the Wallace Formation is composed of cycles of intraclast packstones, dolomitic siltstones, sheet sands and bedded dolomites (Grotzinger, 1986). Load casts and hummocky cross-stratification are abundant, as well as scours in the sandstone and argillite beds (Godlewski, 1981; Grotzinger, 1986). The middle member was deposited in alternating deep and shallow water, everywhere near or above wave-base. Higher in the section, water depth increases as a result of a transgression (Grotzinger, 1986). In western Montana, thickness estimates for the Middle Member of the Wallace Formation vary from 700 to nearly 2000 m (Lewis, 1998; Lonn and McFadden, 1999; Lonn *et al.*, 2003). Breccias occur in this unit. The upper unit of the Wallace Formation is comprised of sandstone, siltstone and dolomite (Grotzinger, 1986). Cross-lamination and grading of the sandstone is present in the upper unit (Grotzinger, 1986). Deposition of the upper unit occurred below fair-weather wave base. Episodic influx of sediment from a western source area was occurring during this time (Grotzinger, 1986).

3. FIELD LOCALITIES

Breccia deposits examined here occur in western Montana and Idaho in the Bitterroot and Sapphire Mountains (Fig. 4). Most outcrops are in a transect approximately 10 miles east of the geographical border of Montana and Idaho. The Trout, Dry, Cedar, and Lost Creek localities are accessible by forest roads immediately southwest of the town of Superior, Montana. Lolo #1 and 2 localities are located on State Highway 12, approximately 3 and 5 miles, respectively, from the town of Lolo Hot Springs, Montana. Finally, the Lostkey breccia locality is accessible from Skalkaho Highway, approximately 15 miles east of Hamilton, Montana, and is the outcrop over which Skalkaho Falls flows. Coordinates and road locations are listed in Table 1.

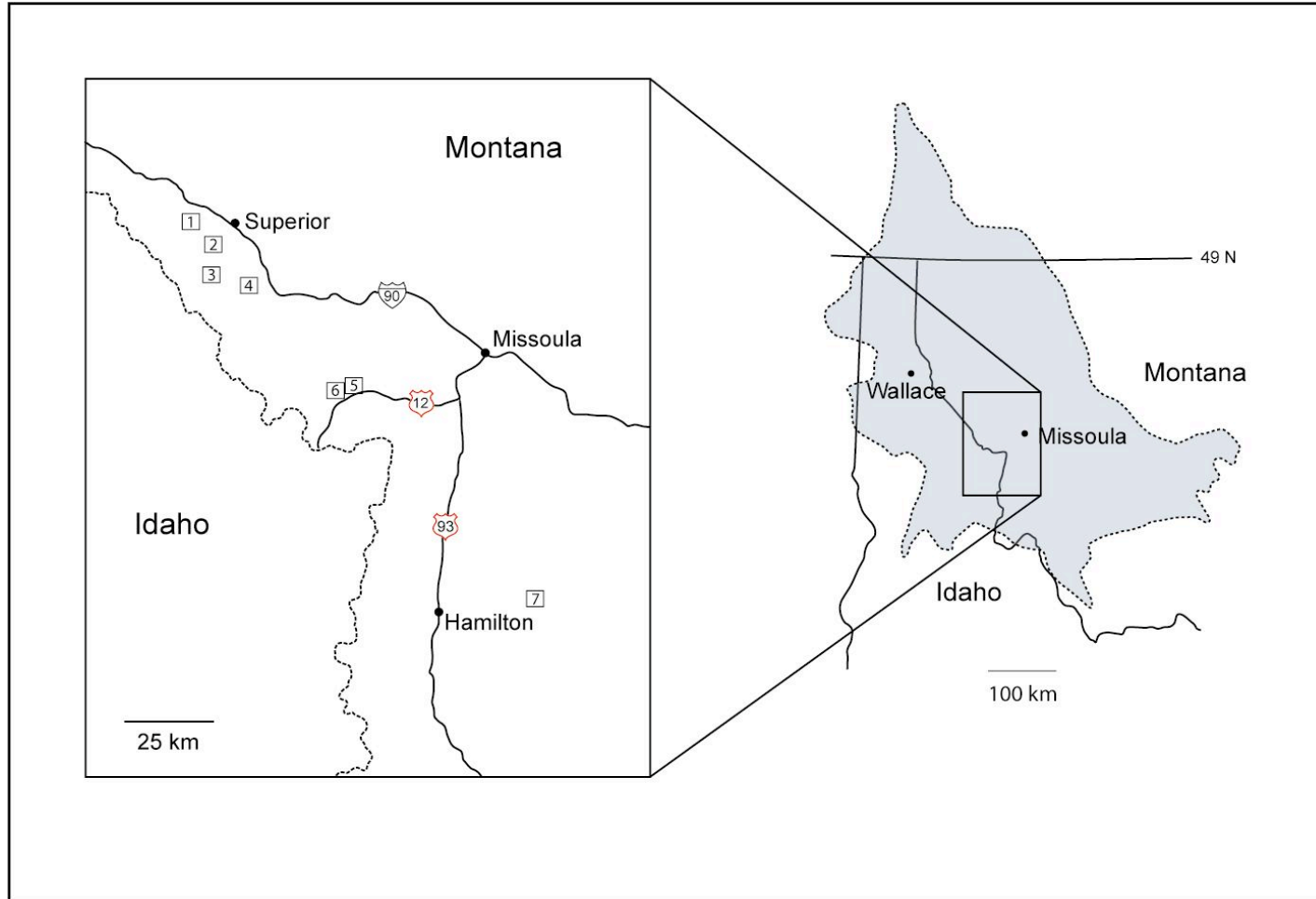


Figure 4: Map of breccias examined in this study. Breccia localities studied: (1) Dry Creek, (2) Lost Creek, (3) Cedar Creek, (4) Trout Creek, (5) Lolo #2, (6) Lolo #1, (7) Lostkey.

Table 1: Coordinates of breccias localities.

Localities	lat/long	Access
Trout Creek	N 47°02.309' W 114°57.559'	Just southwest of mile marker 15 on Trout Creek Rd (FR 250).
Dry Creek	N 47°11.589' W 115°05.393'	On north side of Dry Creek Rd (FR 342).
Cedar Creek	N 47°05.432' W 115°02.045'	On Cedar Creek Rd (FR 320)
Lost Creek	N 47°07.970' W 115°03.140'	On FR 7865, off of Cedar Creek Rd.
Lolo #1	N 46°45.175' W 114°29.988'	On north side of Highway 12, approximately 3 miles northwest of Lolo Hot Springs.
Lolo #2	N 46°46.040' W 114°27.997'	On north side of Highway 12, approximately 5 miles northwest of Lolo Hot Springs.
Lostkey	N 46°15.450' W 113°49.581'	On Highway 38, west of Hamilton, immediately east of Skalkaho Falls

4. DESCRIPTION AND INTERPRETATION OF WALLACE BRECCIAS

Breccia localities are divided into groups based on four main criteria. The first of these is the size of the main breccia body. The dimensions of the breccia bodies differ in size from approximately 10x15 m to 200x200 m. The second criterion for division is clast size. All localities contain small clasts (~2 cm), but two localities also contain much larger clasts (>10 m). The third criterion is the breccia's relationship with the surrounding strata. At four of the seven localities, a sufficient amount of contact with surrounding strata can be observed to determine the relationships of breccia with surrounding strata. At the other three, no contact with surrounding strata was observed. Finally, the composition of the matrix is used to differentiate breccia bodies.

Upon field, hand sample, and petrographic examination of breccia localities, two distinct groups emerged (Table 2). These have been labeled Groups 1 and 2. Group 1 consists of the Trout Creek, Dry Creek, Lost Creek and Cedar Creek localities; Group 2 consists of the Lostkey and Lolo #1 localities (Fig. 4). A final outcrop, Lolo #2, did not fit into either group and is described separately.

Although the breccias have been divided into groups, similarities exist across all localities (Table 2). Clast composition of all breccias is that of the Middle Wallace Formation. Lithologies are sandstone (quartzite)¹, siltstone (argillite), and some localities contain clasts of dolomitic sandstone. Also, all localities contain clasts that are both bedded and oligomictic. None of the breccias exhibit clear grading, sorting, or

¹ Note: In many map descriptions on the Wallace Formation, the terms sandstone and quartzite are used interchangeably (Campbell, 1960; Wallace et al., 1976; Harrison et al., 1986; Wallace *et al.*, 1989; Lewis, 1998; Lonn and McFadden, 1999; Lonn *et al.*, 2003). In many areas the sandstone has been metamorphosed sufficiently to be termed quartzite; other localities did not experience a sufficient degree of metamorphism to be termed quartzite. In this thesis, the term sandstone is used for all lithologies that were deposited as sand-sized grains, regardless of later metamorphic history. The term sandstone implies depositional history which is more useful for the context of this study.

Table 2: Characteristics of Wallace Formation breccias.

	Breccia body size (m)	Clast size	Clast composition	Grading	Matrix composition	Other features
Group 1						
Trout Creek	10x20	2 - 250 cm	Dolomitic sandstone and siltstone	No	Detrital sand and silt, coarse-grained carbonate	Soft-sediment folding, concordant with surrounding strata
Cedar Creek	6x15	2 - 300 cm	Dolomitic sandstone and siltstone	No	Detrital sand and silt, coarse-grained carbonate	Soft-sediment folding, concordant with surrounding strata
Lost Creek	6x20	2 - 250	Dolomitic sandstone and siltstone	No	Detrital sand and silt, coarse-grained carbonate	High clast/matrix ratio
Dry Creek	11x17	2 - 150 cm	Dolomitic sandstone and siltstone	No	Detrital sand and silt, coarse-grained carbonate	No contact with surrounding strata
Group 2						
Lostkey	200x200	2 cm - >10 m	Bedded dolomitic sandstone and siltstone	No	Authigenic quartz and feldspar, minor coarse-grained carbonate	Immense size of breccia body and clasts, no contact with surrounding strata
Lolo #1	30x70	2 cm - >10 m	Bedded dolomitic sandstone and siltstone	No	Authigenic quartz and feldspar, minor coarse-grained carbonate	Immense size of breccia body and clasts, no contact with surrounding strata
Undetermined						
Lolo #2	2x3	2 - 10 cm	Dolomitic sandstone and siltstone	No	Authigenic quartz and feldspar, coarse-grained carbonate	Breccia confined to core of faulted fold

imbrication of clasts anywhere within the breccia bodies. Clast orientation is essentially random.

Group 1 – Trout Creek, Dry Creek, Lost Creek and Cedar Creek

Group 1 breccias are typified by Trout Creek. The outcrop at Trout Creek (Fig. 4) is 148 m long with the thickness varying from less than 5 m up to 20 m (Fig. 5). The beds surrounding the breccia body are composed of cycles of thin-bedded sandstone, siltstone, and dolomitic sandstone. Bed thicknesses range from 3–15 cm. The main breccia body is approximately 10 m thick by 45 m in length. The contact between the breccia body and the underlying strata is everywhere conformable (Fig. 6). The upper contact between the breccia and the overlying strata is obscured throughout most of the outcrop area, but where present, is observed to be conformable.

Breccia is clast supported (Fig. 7), and clast size is bimodal. The larger clasts are 5–15 cm, and the smaller clasts are 1–2 cm (Fig. 8). Several larger clasts also exist: one large clast is ~250x150 cm. Clasts are subangular to angular (Fig. 8). Whereas most clasts are dolomitic sandstone, clasts of bedded siltstone and sandstone with minor dolomite are also present. There is no preferred orientation, imbrication, or grading of clasts. Some clasts have been fractured, but no internal deformation was observed. Within the breccia interval are ~5 m soft-sediment folds in several of the larger slump blocks (Fig. 9).

The matrix of Group 1 breccias is composed of detrital quartz sand and silt, authigenic quartz and feldspar, and coarse-grained carbonate (Fig. 10). Coarse-grained carbonate is the primary matrix component, comprising ~75% of the matrix. The detrital

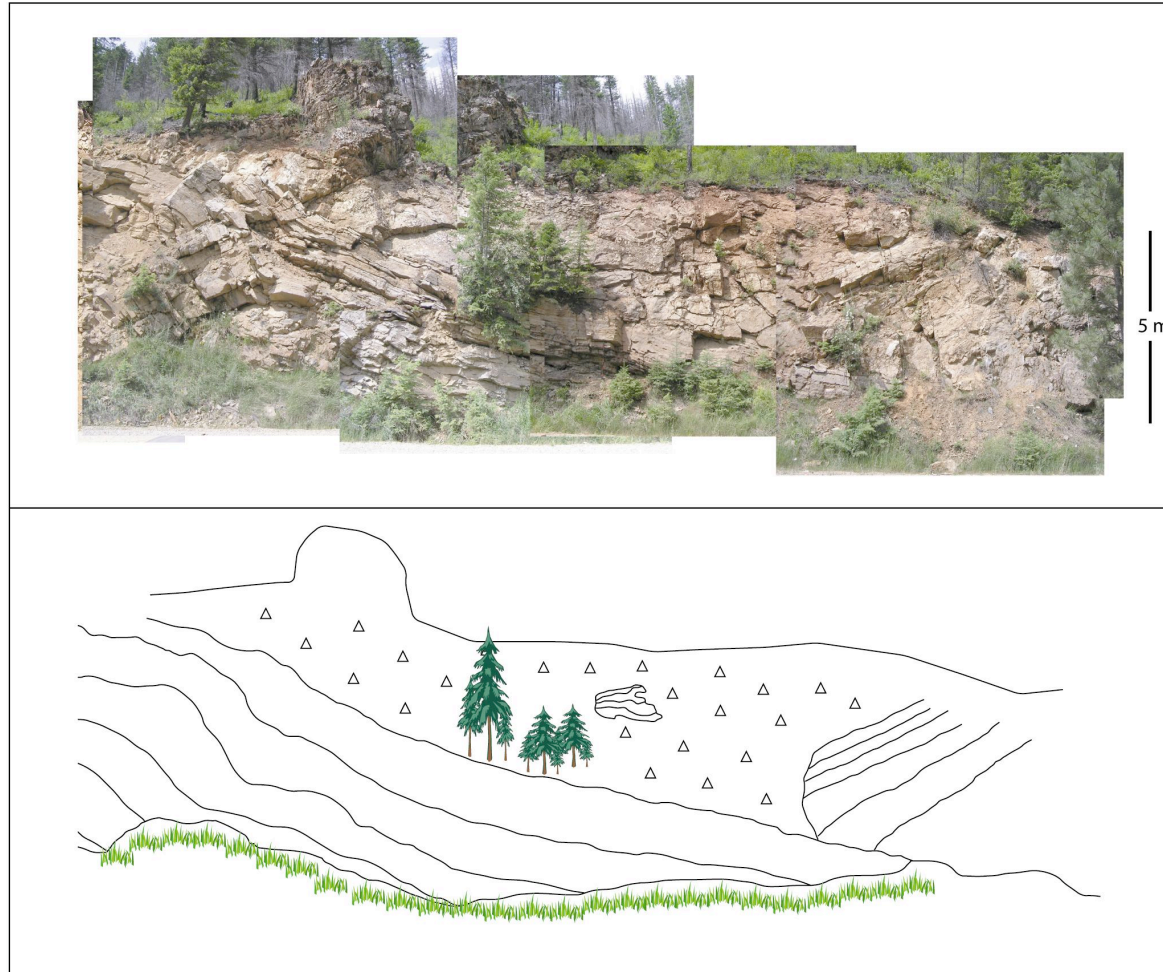


Figure 5: Outcrop photo from Trout Creek locality and outline of bedding and breccia body. Beds of the Middle Wallace Formation are traced, and breccia is represented by triangles. One large clast is outlined within the breccia body.



Figure 6: Conformable contact between breccia body and underlying strata at Trout Creek locality.



Figure 7: Detailed photo of Trout Creek breccia. Clasts are dolomitic sandstone and siltstone, and matrix is detrital sand and silt and coarse-grained carbonate. Bimodal clast size is evident is shown. 13 cm pencil for scale.

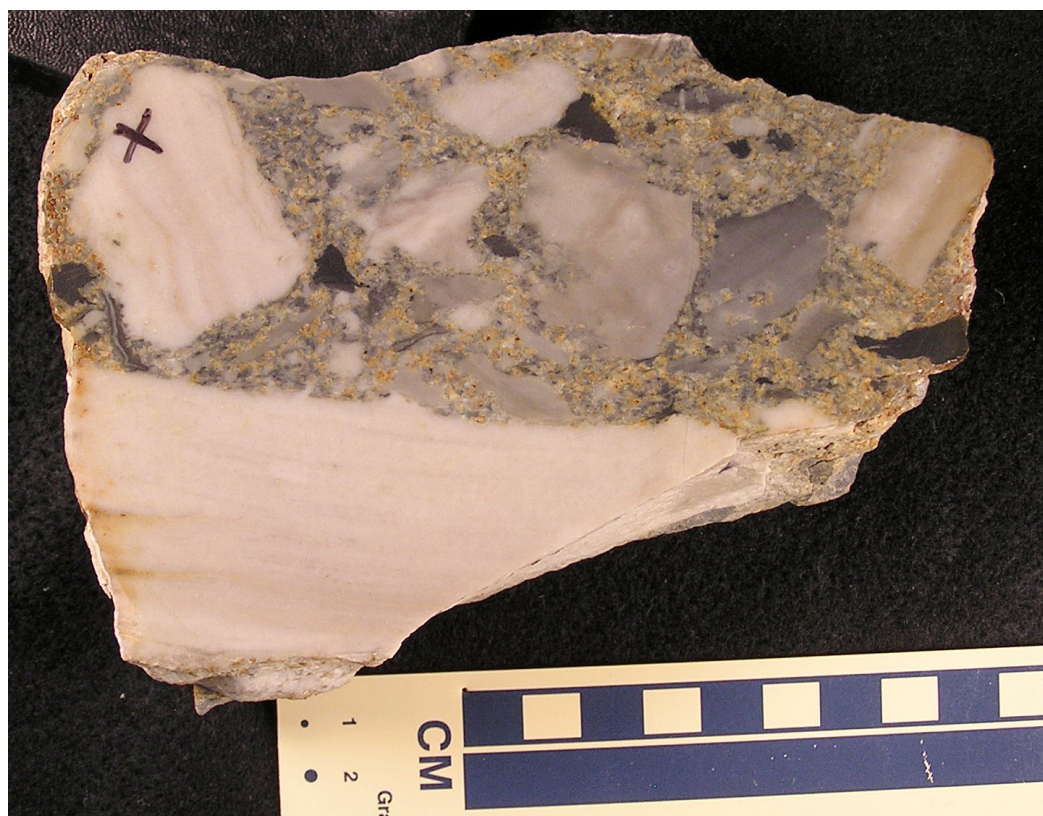


Figure 8: Sawed slab of Trout Creek breccia. Clasts are subangular to angular dolomitic sandstone (light-colored) and siltstone (dark-colored), and matrix is detrital sand and silt, and coarse-grained carbonate.

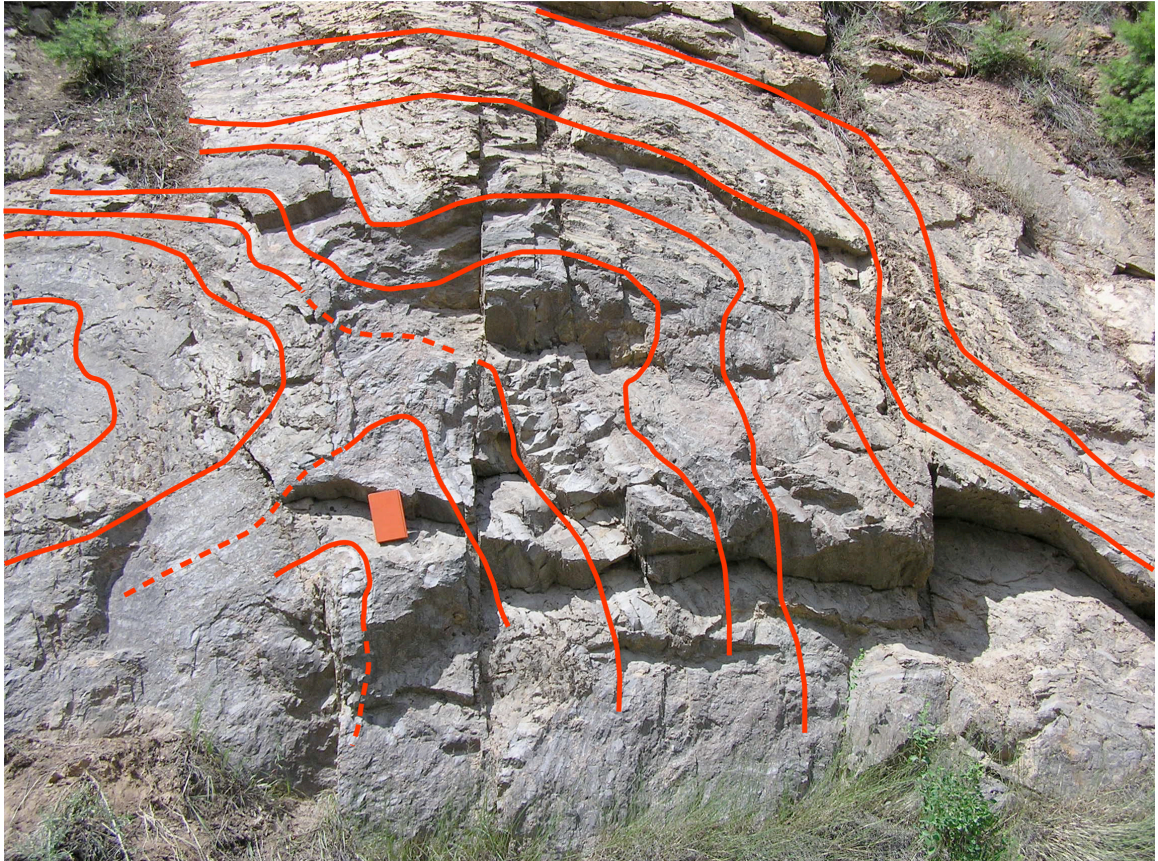


Figure 9: Soft-sediment folding in Trout Creek breccia. Slumped and folded beds are northeast of breccia interval. Field book for scale.

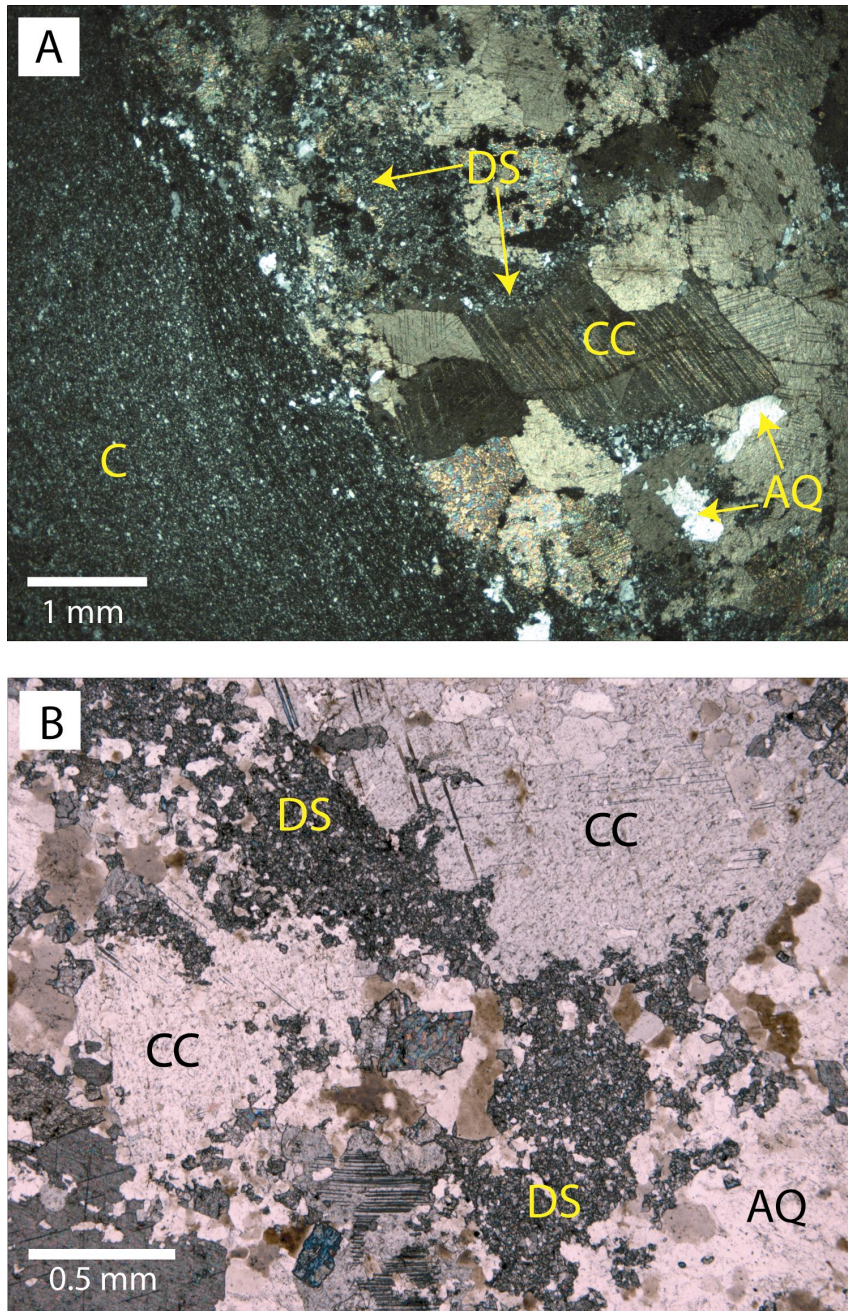


Figure 10: Thin section photo of breccia from Group 1 localities. A is Dry Creek, B is Cedar Creek. Clast (C) relationship with matrix is a sharp contact. Group 1 breccias matrix composed of detrital sand and silt (DS), coarse-grained carbonate (CC), and authigenic quartz (AQ).

sand and silt component is ~20%, and authigenic quartz and feldspar comprise ~5% (percentages are approximations). The boundaries between clasts and matrix are commonly sharp. The carbonate within the matrix formed much later than the detrital sand; several of the crystals are saddle dolomite, indicating post-depositional formation.

Dry Creek, Cedar Creek, and Lost Creek are also included in Group 1 breccias (Fig. 4). These localities are similar to Trout Creek with regards to bedding. Size of the breccia bodies at these localities is similar to Trout Creek: Cedar Creek is 6x15 m; Dry Creek is 11x17 m; and Lost Creek is 6x20 m. All breccias are clast supported, and subangular to angular. Clast lithologies are sandstone, siltstone, and dolomitic sandstone. Most clasts are oligomictic, but bedded clasts are also present. There is no preferred orientation of clasts, nor is any imbrication or grading present. The matrix at all Group 1 breccias contains detrital sand and silt, as well as authigenic quartz and feldspar and coarse carbonate. Detrital sand comprises ~20% of the matrix; coarse-grained carbonate comprises 75%, and authigenic quartz and feldspar make up the remaining 5% (percentages are approximations).

Strata surrounding the main breccia body at Dry Creek has been eroded and covered by float, resulting in no observed contact between the breccia body and the surrounding strata. Numerous structures are present in the Cedar Creek outcrop including folding, faulting, and an outcrop exposure of a mafic igneous intrusion to the southwest of the main breccia body. These structures crosscut the main breccia body, indicating later deformation. The breccia body at Lost Creek (Fig. 6) is the most complex breccia studied in this research, because of obscured contacts and poor outcrop preservation.

Interpretation

These localities are united by several features. All four localities contain detrital sand and silt in the matrix, as well as coarse-grained carbonate and minor authigenic quartz and feldspar. Clast sizes and composition are similar at these outcrops, and regional distribution also connects these localities. These breccias form a line that trends northwest, following the geographic border of Montana and Idaho (Fig. 4).

The Trout Creek outcrop provides the clearest evidence for mode of origin of Group 1 breccias. The breccia body rests conformably on top of the underlying strata (Fig. 6), and upsection from the main breccia body, beds of the Middle Wallace rest conformably on top of soft-sediment folded strata. The concordance of the breccia body with the beds suggests deposition of the breccia followed by continued deposition of Middle Wallace strata.

The subangular to angular clasts at these localities are evidence for at least partial lithification of the strata prior to slumping. Had the beds not been lithified, bedded clasts would have been broken apart (Walker, 1992). However, soft-sediment folds suggest that beds of the Middle Wallace were not fully lithified at time of slumping (Fig. 9). This apparent discrepancy between unconsolidated sediment and lithified beds can be explained by the rheology of different materials. Partially lithified beds could act in both a brittle and ductile manner, depending on strength of individual beds. Several siltstone clasts within the main breccia body are also folded, although the vast majority of sandstone clasts behaved brittly (Theriault, 1989). The plastic deformation of siltstone and brittle deformation of sandstone clasts led Godlewski (1981) to state that these lithologies had differing degrees of lithification at the time of deformation.

The matrix at all Group 1 localities contains detrital quartz sand and silt, along with coarse-grained carbonate and minor authigenic quartz and feldspar (Fig. 10). The presence of the detrital sand and silt suggests that brecciation occurred syndepositionally. The provenance of the detrital sand and silt is the unlithified strata of the Middle Wallace. Minerals observed in the matrix and fractures throughout the entire outcrop include authigenic quartz and feldspar, siderite (and other coarse-grained carbonate), and minor apatite and hematite. These minerals were precipitated during later hydrothermal activity. Elemental analysis of vein material on two Trout Creek samples showed extremely high Fe^{2+} concentrations (from 32,970 to 54,077 ppm), indicating fluids from an anoxic environment. O isotope values of vein material at Trout Creek ($^{18}\text{O}/^{16}\text{O}$ of -17.06, -16.92, and -17.38 relative to PDB) suggest hydrothermal fluids 44° above those of normal marine fluids (Marshall, 1992). Saddle dolomite, also associated with hydrothermal activity, is present in vein and matrix material.

Group 2 – Lostkey and Lolo #1

Group 2 breccias are typified by the Lostkey locality. The Lostkey breccia body is located immediately east of Skalkaho Falls (Fig. 4). No observable contact between the breccia body and non-brecciated Wallace Formation was observed. The surrounding strata can be found approximately 100 m in either direction from the breccia body. The Middle Wallace in this area is dolomitic sandstone and siltstone. The breccia bodies are immense, much larger than at any other locality. The observed portion is over 150 m thick and 150 m long (Fig. 11). While no contact was observed, the extreme thickness demands cross-cutting of surrounding strata. Breccia is clast supported, and clasts exhibit



Figure 11: Outcrop photo of lower one-third of Lostkey breccia. Breccia body is extremely large, and entire breccia body could not be photographed due to topography. Note person for scale.

bimodality, with the smaller clasts ranging from 5–10 cm in diameter, and larger clasts up to 10x10 m (Fig. 12). Clast composition is both oligomictic dolomitic sandstone and siltstone, and bedded cycles of dolomitic sandstone and siltstone. Clasts are subangular to angular, and no preferred orientation, imbrication, or grading of clasts exists (Fig. 13).

The matrix is authigenic quartz and feldspar, and coarse-grained carbonate, with no detrital sand or silt (Fig. 14). Authigenic quartz and feldspar (albite and oligoclase) comprise ~50% of the matrix, with coarse-grained carbonate comprising the other 50% (percentages are estimations). Boundary between clasts and matrix is normally sharp, but in some cases the clast edges are etched, and sand and silt particles are included in coarse carbonate crystals.

The breccia body at Lolo #1 (Fig. 4) exhibits the same characteristics as the Lostkey breccia. The main breccia body is approximately 30x70 m (Fig. 15), with several smaller satellite outcrops of breccia. As with Lostkey, the size of this breccia body suggests cross-cutting of surrounding strata.

Interpretation

Group 2 breccias have a very different character than the other two groups, in both the size of individual clasts as well as the size of the breccia bodies (Fig. 12). The matrix consists of authigenic quartz and feldspar, and coarse-grained carbonate. Tectonic breccias commonly have a matrix composed of authigenic minerals (Blount and Moore, 1969). The lack of detrital sand in the matrix and the abundance of bedded clasts suggest post-depositional brecciation of well-lithified strata. The scale of Group 2 breccias suggests an origin of much greater spatial scale than Group 1 breccias. The immense size

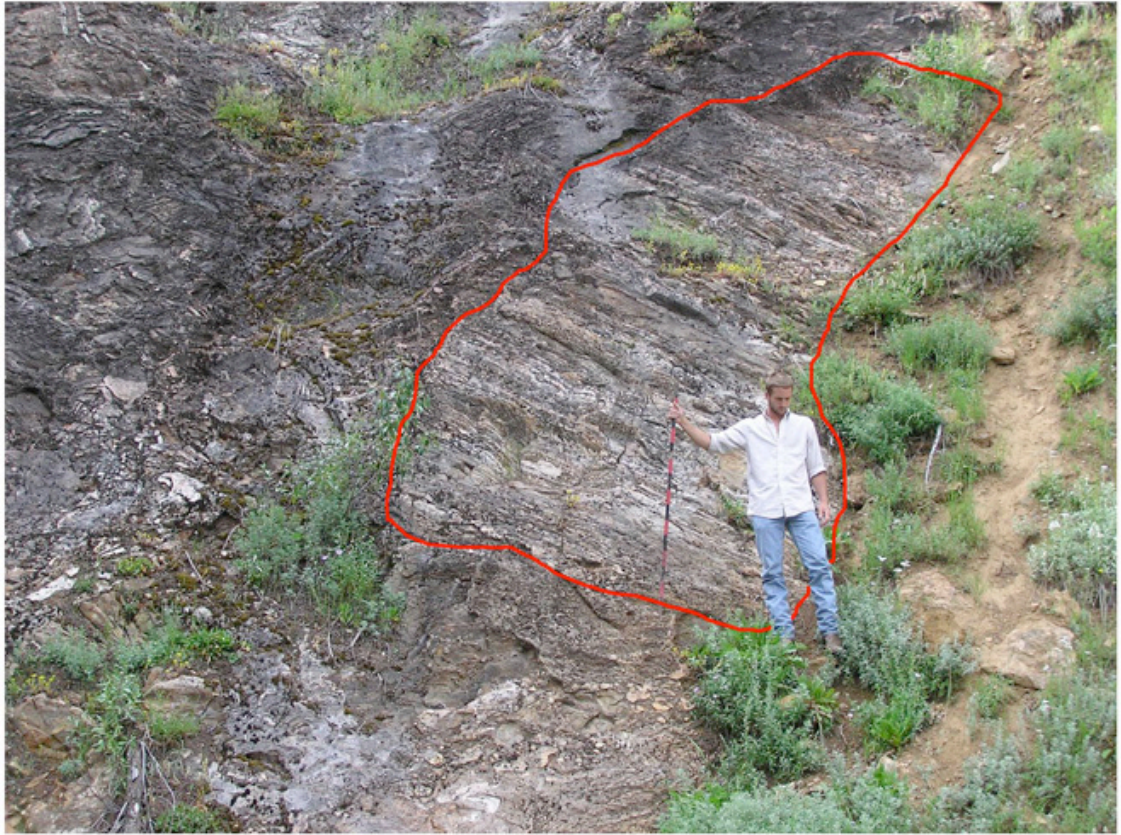


Figure 12: Large clast in Lostkey breccia. Clast is bedded dolomitic sandstone and argillite. Matrix is authigenic quartz and feldspar and coarse-grained carbonate.



Figure 13: Cut surface of sample from Lostkey breccia. Clast composition is dolomitic sandstone and siltstone. Matrix is authigenic quartz and feldspar and coarse-grained carbonate.

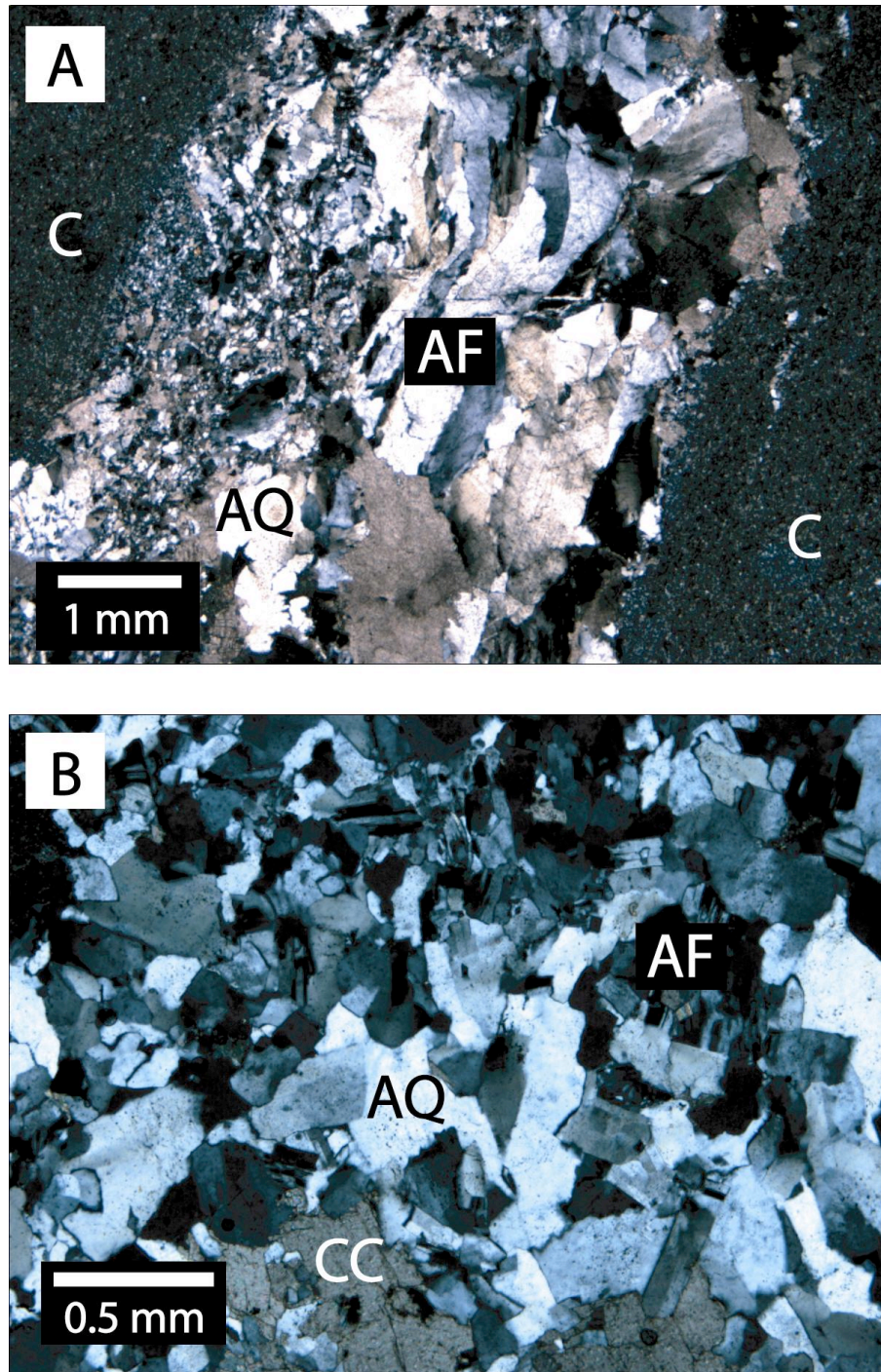


Figure 14: Thin section photos of Lostkey breccia. In A, two siltstone clasts (C) are shown, with matrix of authigenic feldspar (AF) and quartz (AQ). B shows closer view of matrix containing authigenic feldspar (AF), quartz (AQ), and coarse-grained carbonate (CC).



Figure 15: Outcrop photo of Lolo #1 breccia. No contact with surrounding strata was observed. Note person for scale.

of Group 2 breccias also suggests a tectonic mechanism. The most likely brecciation mechanism is post-depositional pluton emplacement in the Middle Wallace and accompanying hydraulic fracturing (Murphy, 1984). Intrusions were emplaced into Belt strata at 1370 Ma (Evans *et al.*, 2000; Ross and Villeneuve, 2003). This age coincides or postdates suggested ages for end of Belt deposition (Doughty and Chamberlain, 1996; Ross and Villeneuve, 2003). Another episode of plutonism occurred from 140 – 45 Ma, with the Idaho Batholith intruding in the Late Cretaceous (Mora and Valley, 1991; Fleck *et al.*, 2002).

A possible scenario is stress placed on beds of the Wallace Formation from pluton migration lower in the Belt strata. Upwarping of the Wallace Formation strata began, and fluid migration from the pluton accumulated below a layer of impermeable fine-grained siltstone. Excess fluid pressure caused a rapid transition from ductile to brittle deformation (Murphy, 1984). Fluids migrated through the fractures into the Wallace, facilitating further brecciation (Ohle, 1985) (Fig. 16). Once fractures are opened, tectonic forces acting on the strata can cause deformation with much less pressure (Ohle, 1985; Clark and James, 2003). The abundance of authigenic quartz and feldspar within the matrix implies hydrothermal fluid flow into fractures within the Middle Wallace. Fractures act as fluid flow pathways in areas of brittle fracture and faulting with associated brecciation (Sibson, 1987). While the pluton is not observable on the surface, sufficient evidence in the form of the matrix composition suggests a granitic magma body present below the Wallace Formation.

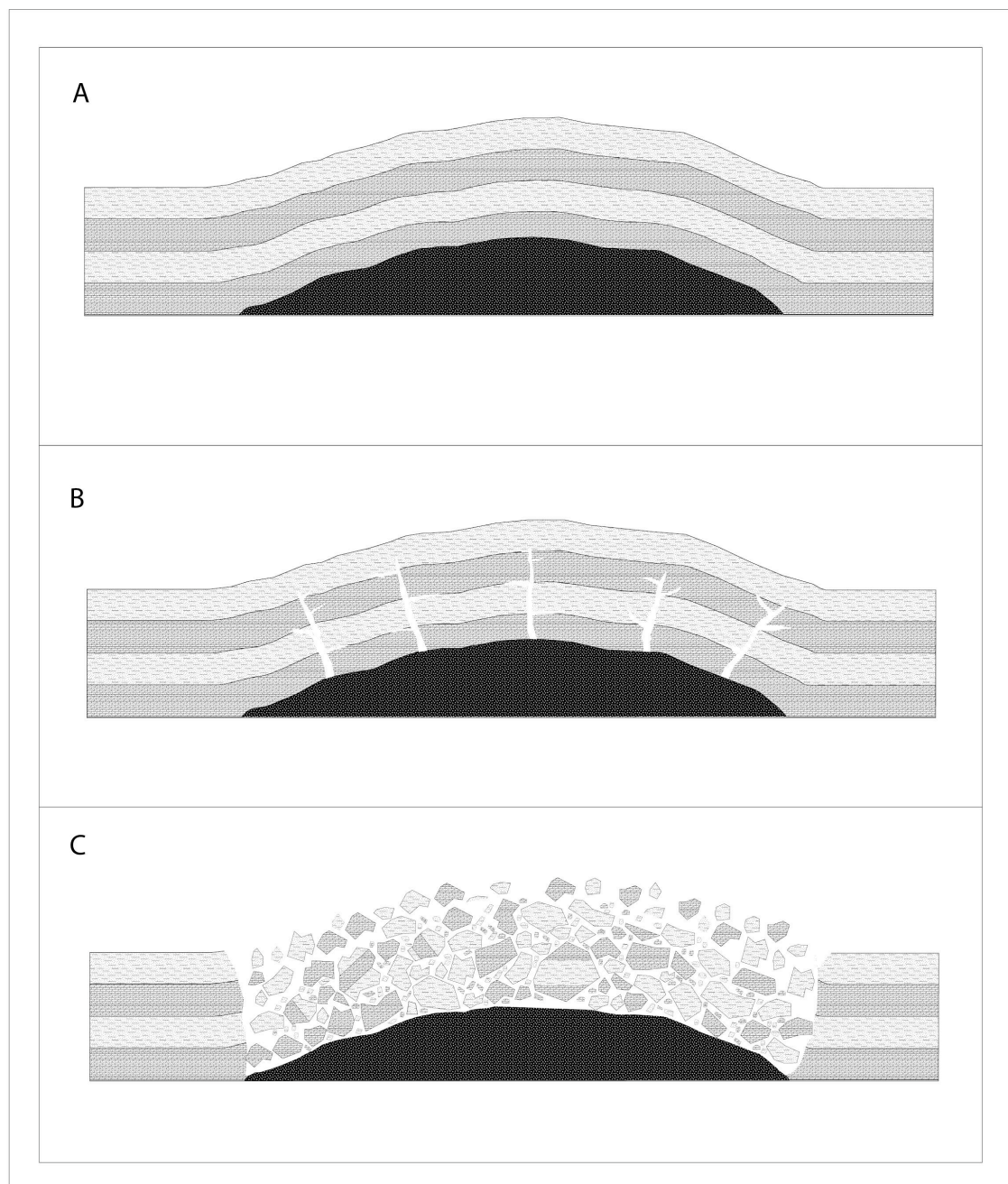


Figure 16: Possible brecciation mechanism for Group 2 breccias. Pluton emplacement creates upwarping of the Wallace Formation (A). Hydraulic fracturing of the strata begins (B). Massive brecciation occurs, with hydrothermal fluids filling matrix (C).

Lolo #2

The Lolo #2 breccia does not fit into the above groups. The dimensions of the entire outcrop are 40 m thickness and 75 m long (Fig. 17). The outcrop at Lolo #2 is dominated by a small-scale thrust fault that is present in the center of the outcrop. Beds from the northwest were thrust onto beds from the southeast. Other structures exist in the outcrop: to the west of the thrust is a set of small high-angle thrust faults that cut folded strata (Fig. 17).

The breccia body is 2x3m (Fig. 18) and occurs within the core of the thrust. Breccia is clast supported. Clasts are 5–10 cm and angular to subangular (Fig. 19). No larger clasts are present. Clasts are dolomitic sandstone and siltstone, and no preferred orientation of clasts, nor is any imbrication or grading present (Fig. 20).

Matrix is composed of authigenic quartz and feldspar and coarse carbonate (Fig. 21). Areas of abundant authigenic feldspar are present in the matrix. Feldspar compositions are albite and oligoclase. Authigenic feldspar comprises ~30% of matrix, authigenic quartz is ~30%, and coarse-grained carbonate comprises the remaining 40% (percentages are estimated). No detrital sand or silt is present in the matrix. Clast boundaries commonly exhibit coarse-grained carbonate growths.

Interpretation

Features in the Lolo #2 breccia body suggest that the mechanism of brecciation is localized folding and faulting. Post-depositional deformational structures are abundant at Lolo #2. A thrust is the main structure (Fig. 17), and to the west of that is a set of steeply-dipping thrust faults. The breccia body is confined to the footwall of the thrust

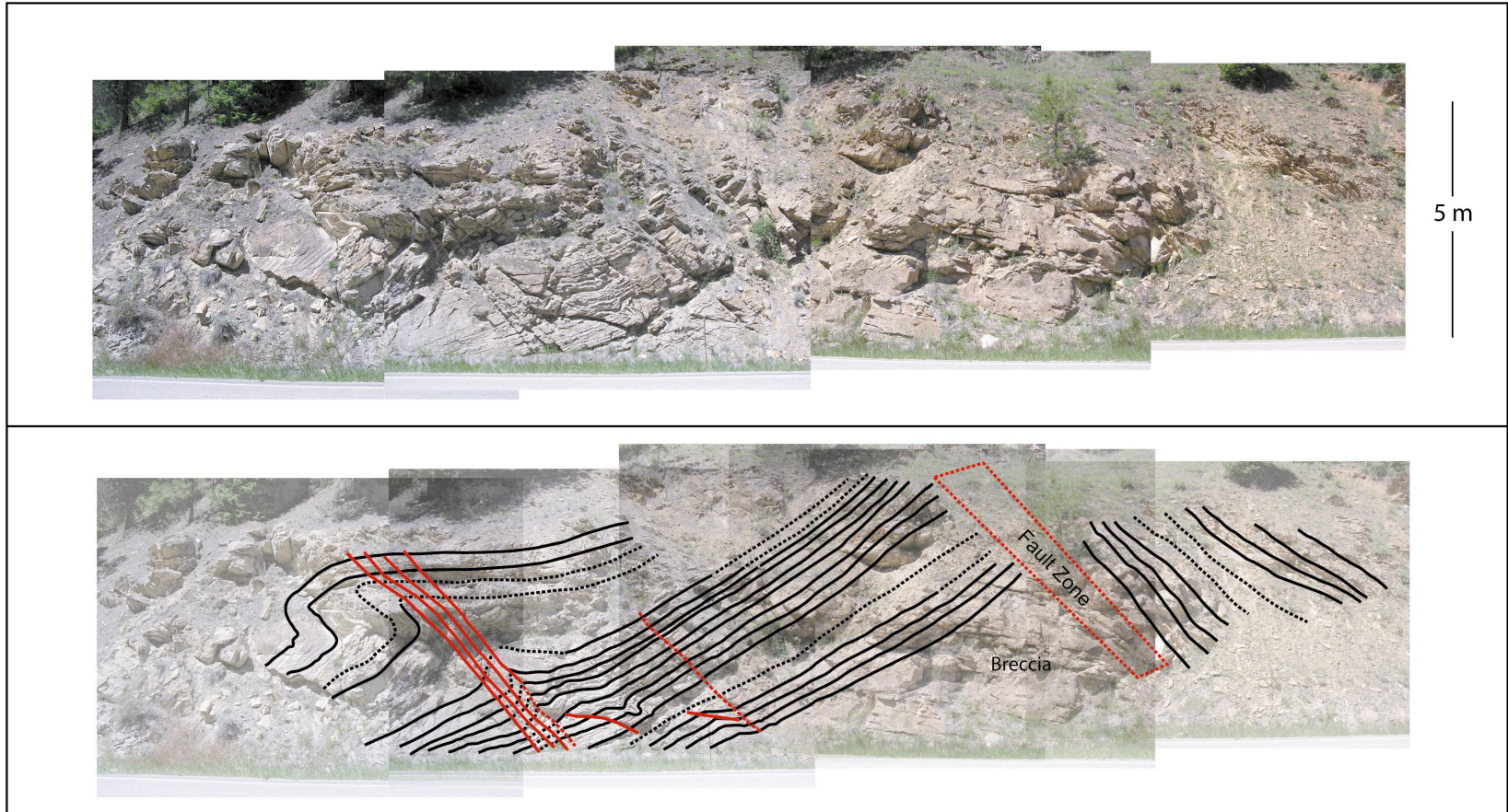


Figure 17: Outcrop photo and outline of bedding from Lolo #2 locality. Break thrust fault in the center of the photo and outline is the dominant structure in the outcrop. Breccia is confined to the core of the fault. Other small-scale folding and faulting is present to the left of the main fault.

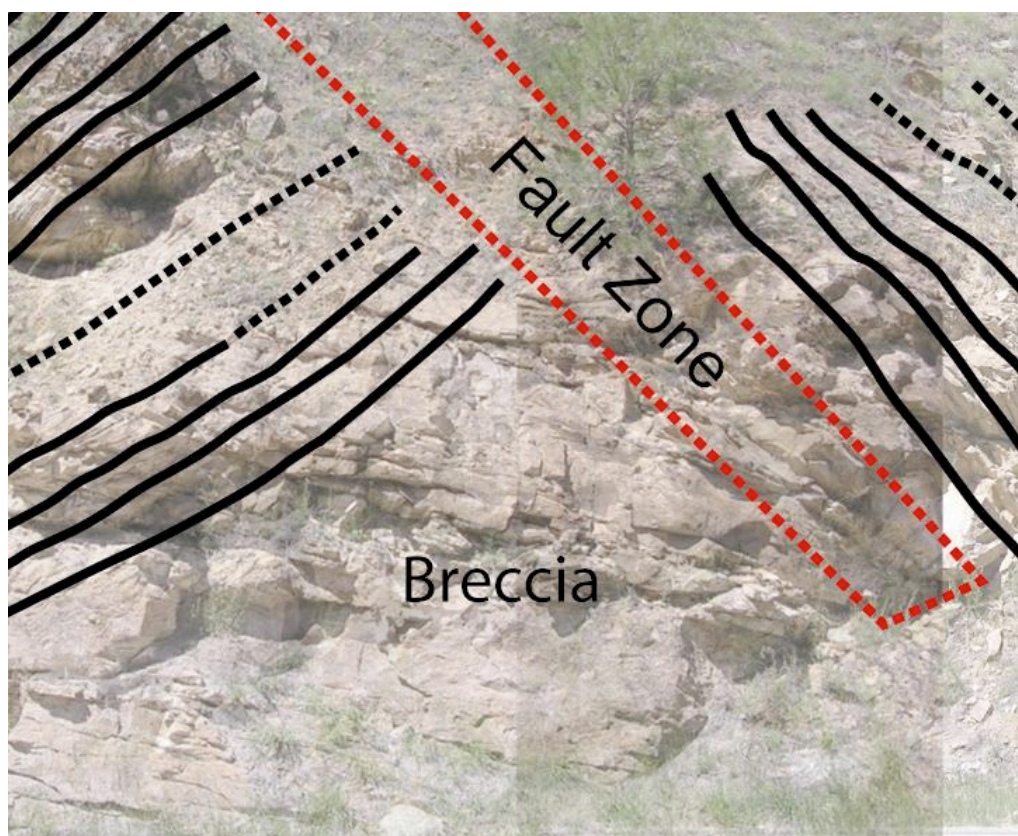


Figure 18: Detailed photo of breccia body and surrounding strata at Lolo #2 locality. Surrounding strata is outlined in red, and breccia body is shown by blue triangles.



Figure 19: Detailed photo of Lolo #2 breccia. Clasts are subangular to angular, and breccia is matrix supported. Note 8 cm knife for scale.

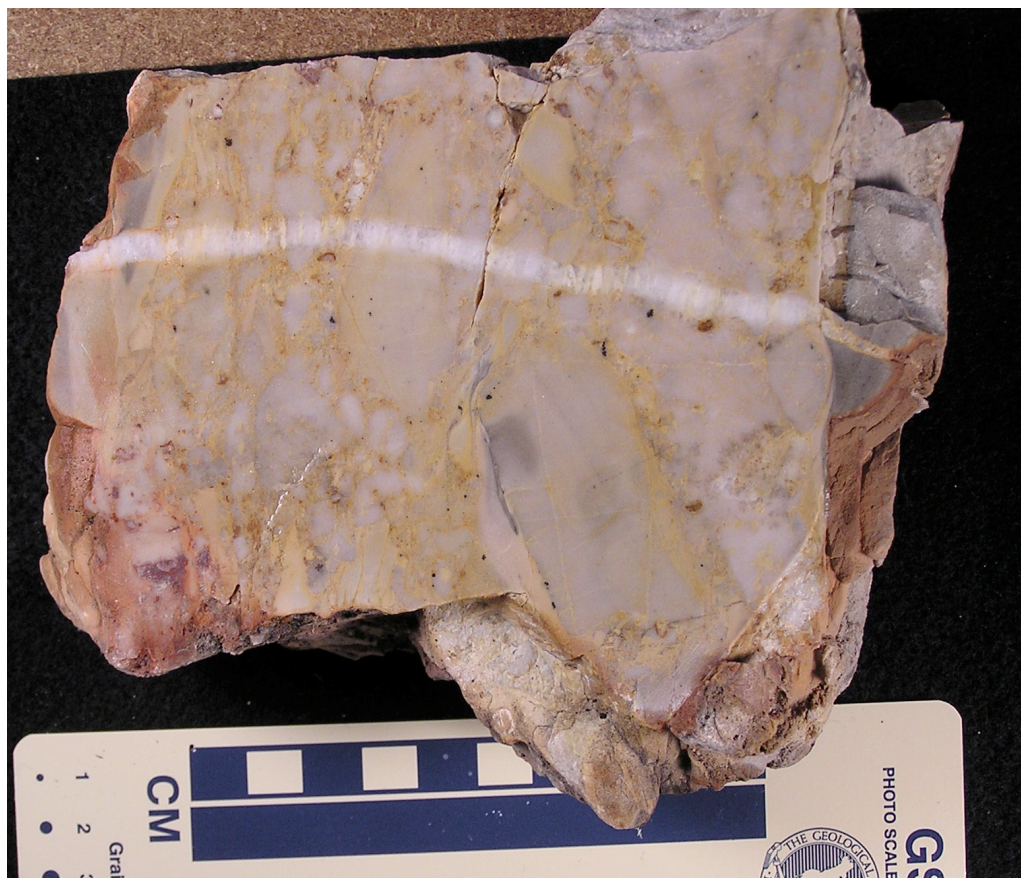


Figure 20: Sawed surface of sample from Lolo #2 outcrop. Clasts are dolomitic sandstone and siltstone, and matrix is authigenic quartz and feldspar and coarse carbonate. Quartz vein (white) cuts breccia. No preferred orientation of clasts is present, and later quartz vein cuts clasts and matrix.

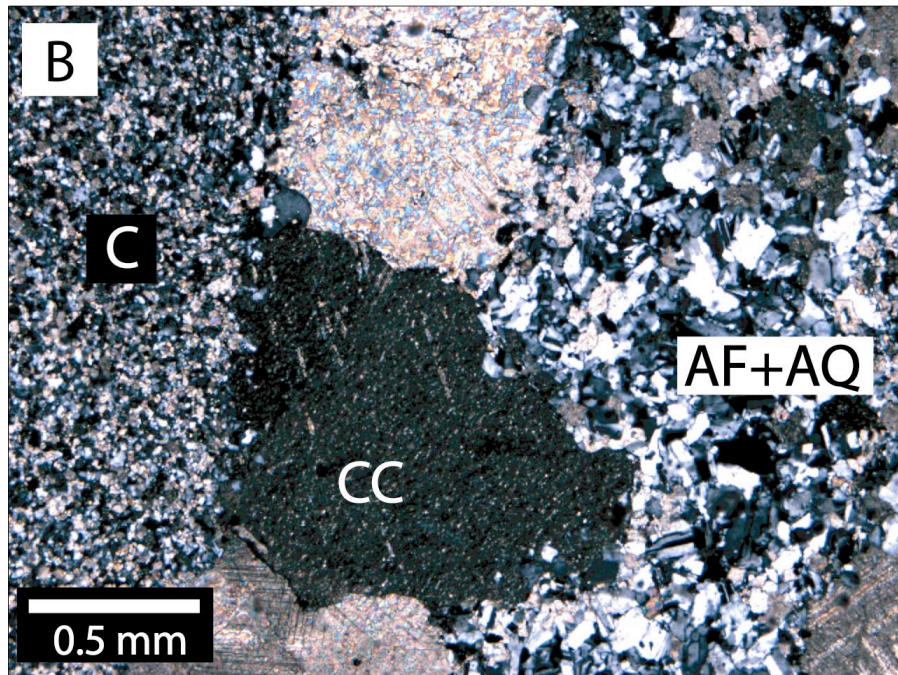
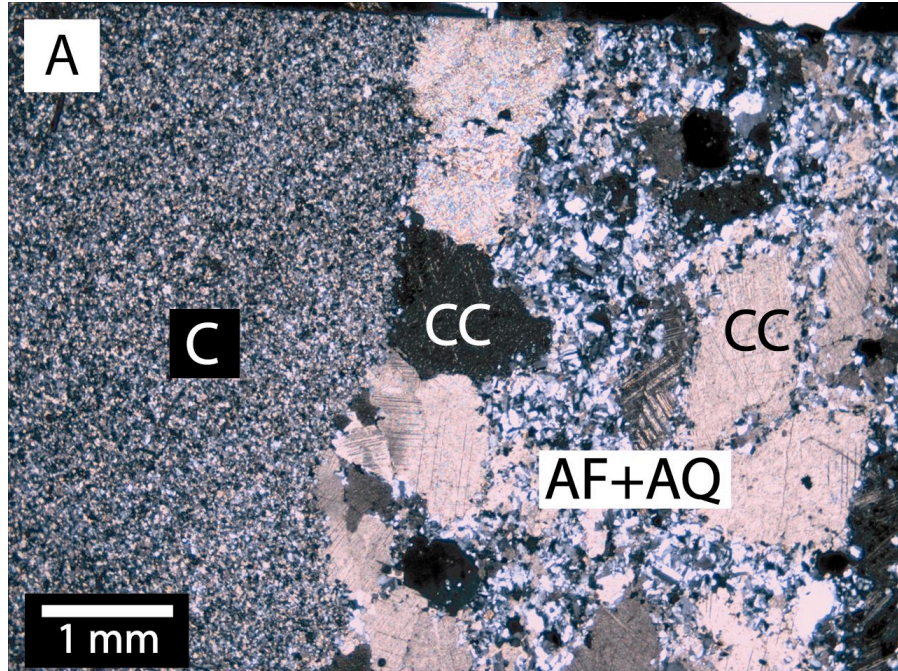


Figure 21: Thin section photos of breccia at Lolo #2 locality. Clast (C) boundary is sharp, with coarse carbonate (CC) precipitated on clast. Authigenic feldspar and quartz (AF+AQ) is abundant in the matrix.

fault, with clasts composed of wall rock: dolomitic sandstone and siltstone, and bedded sandstone and siltstone. Folding most likely began as a result of compressional stress creating the breccia within the core. Thrusting followed, breaking the hinge of the fold (Ohle, 1985; Clark and James, 2003). A feldspar and iron-rich carbonate fluid may have facilitated brecciation at the time of faulting, or the breccia may have acted as a pathway for the fluid after brecciation.

The matrix at Lolo #2 locality contains no detrital sand or silt, differentiating this from Group 1, and suggesting that strata were fully lithified at the time of brecciation. The matrix is predominantly authigenic feldspar and quartz, and coarse-grained carbonate. Tectonic breccias in carbonate rocks commonly may have a matrix composed of authigenic minerals, indicating fluids present during brecciation, or secondary overprinting by hydrothermal fluids (Blount and Moore, 1969).

5. DISCUSSION

The Middle Wallace breccias can be divided into two distinct groups using the characteristics above, each with a different brecciation mechanism. Different mechanisms each have significant implications for the geologic history of the Belt basin and the Belt Supergroup.

Slump model

Group 1 breccias (Trout, Lost, Dry, and Cedar creeks) are the product of syndepositional slumping. Their spatial distribution and coincident mode of origin suggest a possible relationship between the respective localities (Fig. 4). Godlewski (1981) proposed localized faulting and creation of a shelf-slope-basin environment as a mechanism for slump initiation. Sediments were transported to the slope base by episodic earthquakes, and future breccia clasts were contributed to these sediments by debris flows. Additional earthquakes created sheet flows that covered the sediments, and the unit was eventually lithified.

The above model would create slump breccias like those of Group 1, although this model implies a range of depositional environments that have not been observed in the Middle Wallace Formation in this area. The under- and overlying strata in Group 1 outcrops are similar to those of the rest of the Middle Wallace Formation in the field area, suggesting a similar offshore shallow subtidal environment. Also, the Belt basin at the time of Wallace Formation deposition was a shallow-water basin (Frank *et al.*, 1997). Sedimentary structures within the Middle Wallace Formation, such as ripple marks, hummocky cross-stratification, and desiccation cracks (Winston, 1998) also suggest a

shallow water environment. The shelf-slope-basin environment of Godlewski (1981) is not believed to have been present during deposition of the Wallace Formation.

Although the shelf-slope-basin environment was not present, slumping can occur in a shallow slope environment with little transportation (Walker, 1992). The presence of bedded clasts suggests that the clasts were not transported a long distance from the initial point of movement (Walker, 1992). Syndepositional faulting occurring at time of deposition would provide the triggering mechanism to initiate the slumping (Grotzinger, 1986; Winston, 1986).

Hydrothermal Activity

Wallace Formation sediments have been affected by both prograde and retrograde metamorphism and fluid-rock interaction (Mora and Valley, 1991). Two major episodes of deformation and metamorphism have occurred in Belt Supergroup rocks. The first deformational event was the East Kootenay extensional event that occurred at approximately 1360 Ma and involved folding, development of a primary penetrative fabric, and felsic magmatism (Mora and Valley, 1991; Doughty and Chamberlain, 1996; Luepke and Lyons, 2001). The second episode occurred in the late Mesozoic–early Cenozoic (140–45 Ma) and included folding, faulting, high temperature metamorphism, magmatism, and regional hydrothermal activity (White, 1998). The Idaho batholith was emplaced in central Idaho during this time (Fleck et al., 2002). Emplacement of the Idaho and Boulder batholiths in the Late Cretaceous provided the necessary components to create Group 2 breccias, and the spatial relationship of these breccias to both the Idaho and Boulder batholiths suggest correlative timing in the late Cretaceous–Early Tertiary

(Fig. 22). The minerals in the matrix at Group 2 breccias (authigenic quartz and feldspar, coarse carbonate) are similar to those of the mineral deposits in the Coeur d'Alene mining district (White, 1998).

Timing of brecciation at Group 1 is syndepositional, but clearly hydrothermal fluids were present post-brecciation, as alteration of the matrix overprints primary features. Late Cretaceous through Early Tertiary metamorphism introduced hydrothermal fluids at these localities, and Group 1 breccias acted as conduits for fluid flow. The Group 2 breccias are clearly post-depositional and are the result of upwarping and hydraulic fracturing. An argument can be made that post-depositional brecciation should be observed in the overlying Missoula Group. However, significant dissection of the Belt strata has occurred, resulting in the Wallace Formation forming the uppermost Belt strata (Lewis, 1998).

Mineralization in the Wallace Formation

The Coeur d'Alene mining district (Fig. 22) is an important deposit of Ag, Pb, and Zn, with over 34,300 metric tons of silver, 7,288,300 metric tons of lead, and 2,870,000 metric tons of zinc produced as of 1998 (Fleck *et al.*, 2002). All mineral deposits are hosted within Belt rocks, and much of the district is in the Wallace Formation (Fleck *et al.*, 2002). Coeur d'Alene mineralization is typically vein type, with some mineralization occurring in matrix of breccias (Theriault, 1989). Mineralization of the Coeur d'Alene district occurred in the late Cretaceous/early Tertiary (Eaton *et al.*, 1995; Criss and Eaton, 1998; White, 1998; Fleck *et al.*, 2002). The gangue minerals associated with Coeur d'Alene mineralization are similar to those found in veins and

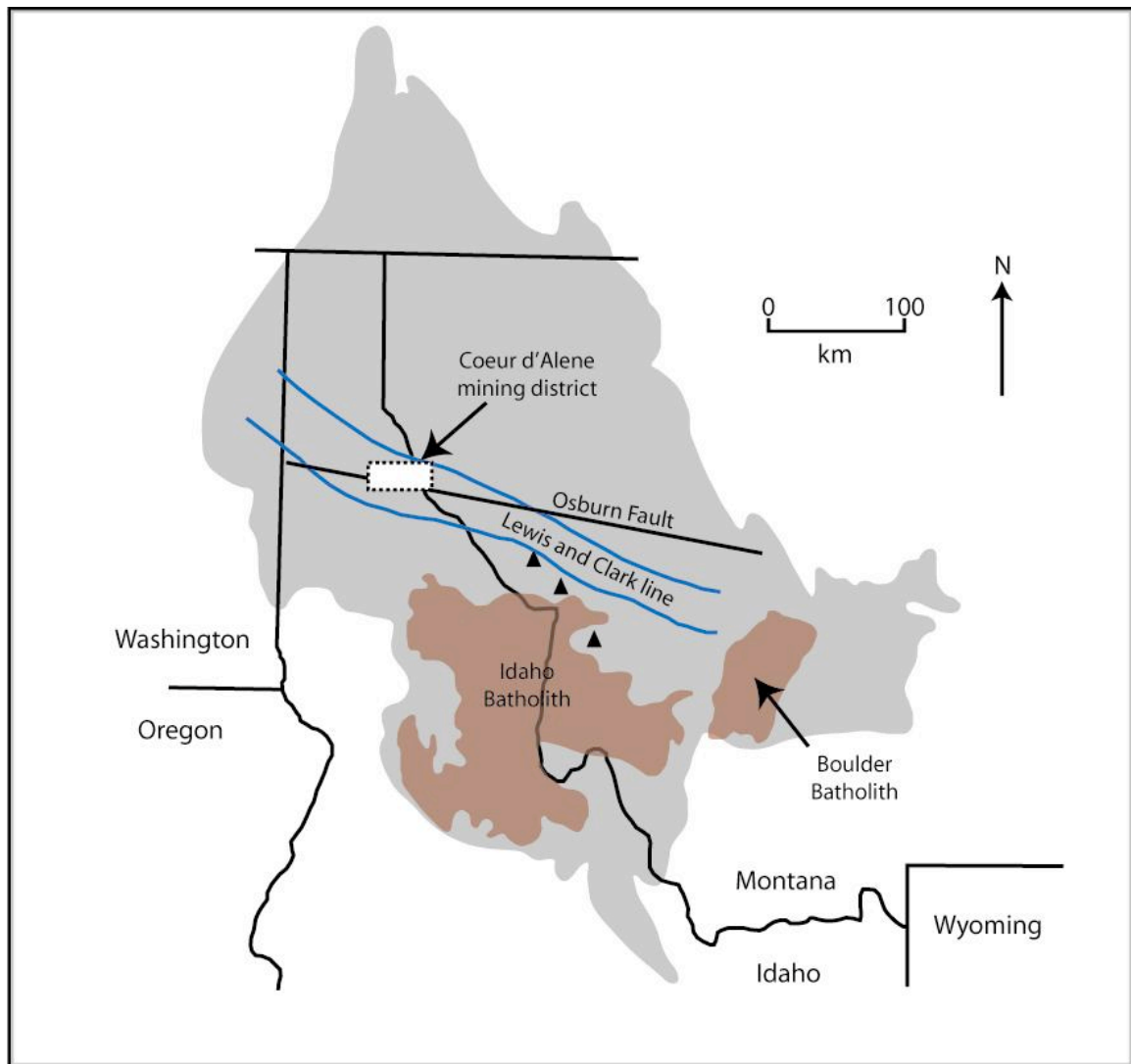


Figure 22: Position of breccia localities in relation to major tectonic and igneous features in the Belt Supergroup, and the Coeur d'Alene mining district. Modified from Mauk (2002).

matrix at localities studied herein – siderite, ankerite and quartz (Fleck et al., 2002).

Major mineral deposits also occur in breccias near the Osburn fault zone: Pb, Zn, and minor Ag has been produced from this area (Campbell, 1960). The matrix of breccias in this study contain similar mineral assemblages to the Coeur d’Alene mining district (Campbell, 1960) and mineralization occurred coevally with the Coeur d’Alene (Mauk, 2002).

The Wallace Formation in the Superior area has been mined for fluorite, lead and zinc, as well as minor amounts gold, silver and copper ore (Campbell, 1960). However, the absence of significant mineral deposits in the Wallace Formation in the field area may be indicative of different underlying strata. In areas of mineral deposits, such as the Coeur d’Alene district, the fluids were clearly rich in Pb, Zn, and Ag. This enrichment is the result of fluid formation in shales of the Prichard Formation, a pyritic shale sequence in the lower Belt (Schieber, 1991). The Wallace Formation in the field area may not overlie a thick sequence of the Prichard Formation, and the hydrothermal fluids were not as heavily enriched as a result.

The lack of significant mineral deposits in the Wallace Formation in this area may also result from the presence of the Lewis and Clark line, a fault zone 50-100 km wide and 200–250 km long composed of west-northwest trending faults, traverses western Montana and northern Idaho (White, 1998). Mineralization is concentrated along the fault zone, and the Coeur d’Alene district is located within this zone (Fleck *et al.*, 2002). These faults may have been the preferential pathways for flow of the enriched fluids. The breccia localities studied herein lie outside of the Lewis and Clark line.

Although the Middle Wallace breccias in the field area have not been found to contain significant mineral deposits, detailed study of more outcrops may provide answers as to the regional fluid flow regime. As stated above, the matrix of these breccias act as hydrothermal fluid flow pathways. The spatial distribution of the Group 1 breccias suggests that more localities may be found along a N-NW trending line in that area. The immense size of the Group 2 breccias is significant in that a breccia body of this size may host considerable mineral deposits.

6. CONCLUSIONS

The Middle Wallace breccias have in the past been attributed to a single brecciation mechanism. This investigation suggests that, although certain characteristics are constant throughout all breccia localities, individual breccias can be divided into two groups, each with a distinct brecciation mechanism:

- Group 1 breccias (Trout Creek, Dry Creek, Cedar Creek, Lost Creek) are the result of synsedimentary downslope slumping. The evidence for this is the detrital quartz sand in the matrix, intra-stratal position of the breccia bodies, and the association with soft-sediment folding.
- Group 2 breccias (Lostkey and Lolo #1), which are much larger and contain much larger clasts compared to Group 1, are the result of hydraulic fracturing associated with pluton emplacement in the Late Cretaceous–Early Tertiary . The evidence for hydraulic fracturing is the size of breccia bodies, lack of detrital sand in the matrix, and abundant authigenic quartz and feldspar in the matrix.

The different breccia groups each have a distinct mechanism of origin and the respective origins can aid in deciphering depositional environments and post-depositional tectonic and metamorphic history of the Belt Supergroup.

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He intends to die along the highway like some old high-line pole.