

STRUCTURAL ANALYSIS OF CLEAVAGE AT SANDY HOLLOW, MCCARTNEY
MOUNTAIN FOLD-AND-THRUST SALIENT, SOUTHWEST MONTANA

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

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DEDICATION

This document is dedicated to all who have encouraged my research throughout my geologic education. My advisor, Dr. David Lageson, has nurtured my understanding of the difficult subject of structural geology and has demonstrated patience throughout my degree at Montana State University. My committee members, Dr. James Schmitt and Dr. Colin Shaw, have been extremely influential with my thesis research giving me support academically whenever needed. My undergraduate advisor, Dr. Stephan Harlan, has been particularly influential in my geological career, encouraging me to go to graduate school and giving me advice about a variety of subjects. I thank the Geological Society of America for a graduate research grant, and the MSU Earth Science department for the excellent experience of working as a teaching assistant.

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ABSTRACT

The McCartney Mountain salient is a distinct convex-east segment of the Sevier fold-and-thrust belt in southwest Montana, lying east of the Pioneer batholith and west of basement-cored Laramide uplifts. Prominent features of the central part of the salient include the in-sequence Sandy Hollow thrust fault (displacing Permian over Lower Cretaceous strata), and hanging wall and footwall syncline-anticline pairs that display complex intra-formational duplexes and parasitic detachment folds at all scales.

Cleavage occurs in the argillaceous carbonate members of the Cretaceous Kootenai and Triassic Dinwoody formations throughout the area. Cleavage has been systematically mapped and characterized according to morphology, domainal spacing and orientation for all exposed outcrops of a distinctive yellowish dolomitic unit in the lower limestone member of the Kootenai. Cleavage within this unit exhibits planar morphology with domainal spacing at the mm-cm scale, classified as moderate to very strong spaced cleavage.

Structural orientation data divides the cleavage into two populations. S1 is defined by cleavage that trends N-S, dips east, and is inferred to be reoriented axial planar cleavage that may have been modified during late-stage shortening as the frontal fold-and-thrust system impinged against basement uplifts in the foreland. S2 is recognized by E-W striking cleavage that dips within 10° of vertical, cross cutting hanging wall, and footwall folds in the area. S2 is inferred to have formed during the final stages of deformation in the Sandy Hollow fold-and-thrust system. S2 may reflect N-S shortening caused by lateral forces along the salient boundary as the fold-and-thrust system propagated eastward into the salient nose.

INTRODUCTION

The McCartney Mountain salient is a small-scale, convex-east segment of the Sevier fold-and-thrust belt in southwest Montana (Figure 1). The chord of the salient strikes roughly north with a length of 48 km and a width of 16 km (Brumbaugh and Dresser, 1976). The Sandy Hollow field area is located in the apex of the salient at the eastern extent of the frontal fold-and-thrust belt. The field area contains several well exposed thrust sheets with associated folds, as well as sedimentary units that display intense cleavage. Previous cleavage studies in fold-and-thrust belts indicate that cleavage intensity typically decreases towards the foreland, eventually becoming absent in frontal thrust sheets (Mitra and Yonkee, 1985; Yonkee, 2005). Therefore, the Sandy Hollow field area provided an opportunity to investigate atypical cleavage development.

Tectonic cleavage is an expression of internal strain accommodated by sedimentary units within a deformed terrain. Cleavage domains have been shown by previous studies to form perpendicular to the local finite shortening direction (e.g. Wanless, 1979; Onasch, 1983). Structural analysis of cleavage domain orientation can be utilized to yield information regarding the direction of maximum shortening. Cleavage-structure relationships can also be analyzed to determine the relative timing of cleavage development. Therefore, sedimentary units that contain several populations of cleavage record the complex evolution of fold-and-thrust belt deformation.

Physical attributes of cleavage domains, such as morphology and intensity, vary as a function of rock composition and strain magnitude (e.g. Engelder and Marshak,

1985). Spatial variability of cleavage attributes can be used to deduce strain gradients in relation to local structural geometry, and the effects of lithologic variation.

Cleavage has been identified in a well exposed distinctive yellow dolomitic limestone unit (Kk2a) in the informal lower limestone member of the Lower Cretaceous Kootenai Formation within the Sandy Hollow field area. This unit was chosen for the focus of this study after preliminary field observations indicated that this unit contained several cleavage populations distinguished by domain orientation. Cleavage within this unit was characterized according to domain morphology, intensity, and orientation to address the foremost research problem: Why is tectonic cleavage so well developed in frontal fold-and-thrust sheets of the McCartney Mountain salient? This research question can be broken down into several more specific questions, from a mesoscopic to macroscopic scale:

- 1) Does proximity to local structures influence cleavage domain morphology, and/or intensity?
- 2) Does lithologic variability control cleavage development, and/or cleavage attributes?
- 3) What are the structural relationships between cleavage, and local fold-and-thrust belt structures?
- 4) What is the relative timing of cleavage formation with respect to local fold-and-thrust belt structures?
- 5) What are the viable tectonic mechanisms responsible for cleavage development?

Field mapping, laboratory analyses, and stereographic techniques were combined to investigate each of the defined research questions. The results of this research led to the recognition of several cleavage-structure relationships that were utilized to propose models for the kinematic evolution of cleavage development. These models were in-turn used to explore several hypotheses that describe the possible tectonic mechanisms responsible for the development of the various cleavage populations within Kk2a.

BACKGROUND INFORMATION

Regional Tectonic Framework

The McCartney Mountain salient delineates the eastern front of the fold-and-thrust belt in southwest Montana, and lies within the temporal and spatial overlap zone of contractile and extensional structures north of the Eastern Snake River Plain (e.g. Kulik and Schmidt, 1988; Schmidt et al., 1988; Perry et al., 1989) (Figure 1). The overlap zone includes structures associated with the Cretaceous to Eocene Sevier orogenic belt, the late Cretaceous to Eocene Laramide foreland province, the late Cretaceous to early Paleogene Montana-Idaho batholith province, and several phases of Cenozoic extension (Figure 2) (Appendix A).

Sevier Fold-and-Thrust Belt

The Sevier fold-and-thrust belt is part of the Cordilleran orogenic belt that extends the length of the North American continent from Alaska to southern Mexico. Subduction of the Farallon and Kula plates along the western margin of North America from Late Jurassic to early Paleogene led to the deformation of Proterozoic and Phanerozoic miogeoclinal strata, and formation of a retroarc foreland basin (Dickinson, 2004; DeCelles, 2004). The Sevier fold-and-thrust belt is characterized by west dipping stacked imbricated thrust sheets that translated as a deforming sedimentary wedge eastward

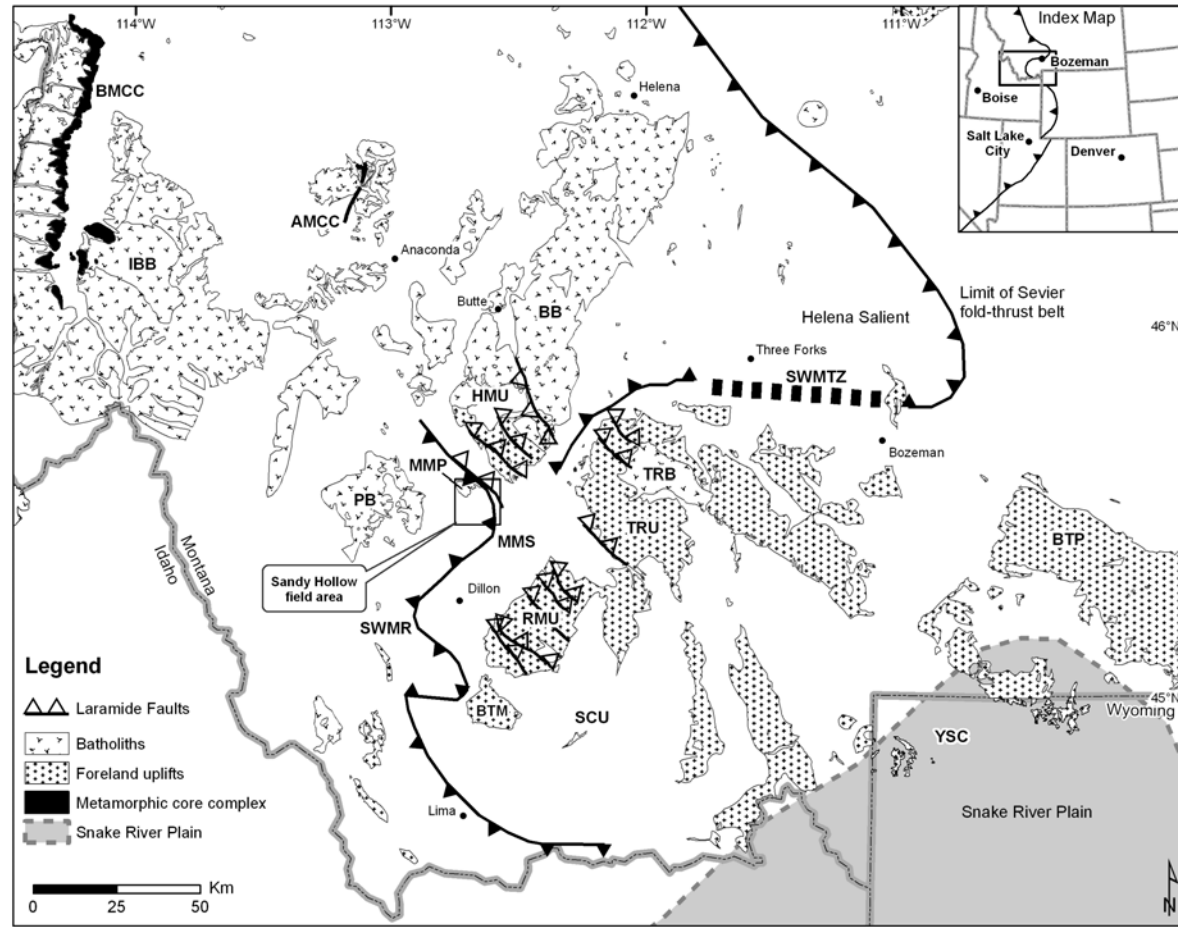


Figure 1. Tectonic framework map illustrating the interaction between several styles of deformation including the Idaho-Montana Batholith province, Laramide foreland uplift province, Sevier fold-thrust belt, metamorphic core complexes, and the limit of the Snake River Plain & Yellowstone caldera. AMCC = Anaconda metamorphic core complex, BB = Boulder Batholith, BMCC = Bitterroot metamorphic core complex, BTP = Beartooth Plateau, BTM = Blacktail Mountains, HMU = Highland Mountain Uplift, IBB = Idaho-Bitterroot Batholith, MMP = McCartney Mountain Pluton, MMS = McCartney Mountain Salient, PB = Pioneer Batholith, RMU = Ruby Mountain Uplift, SCU = Snowcrest Uplift, SWMTZ = Southwest Montana Transverse Zone, SWMR = Southwestern Montana Recess, TRB = Tobacco Root Batholith, TRU = Tobacco Root Uplift and YSC = Yellowstone caldera. The inset map shows the regional Sevier fold-and-thrust belt limit illustrating large scale recesses and salients. This figure was constructed from multiple figures from the following sources: Kulik and Schmidt, 1988, Schmidt et al., 1988, O'Neill et al., 1990, O'Neill et al., 2004, DeCelles, 2004, Dickinson, 2004. GIS data source: Stoesser et al., 2005.

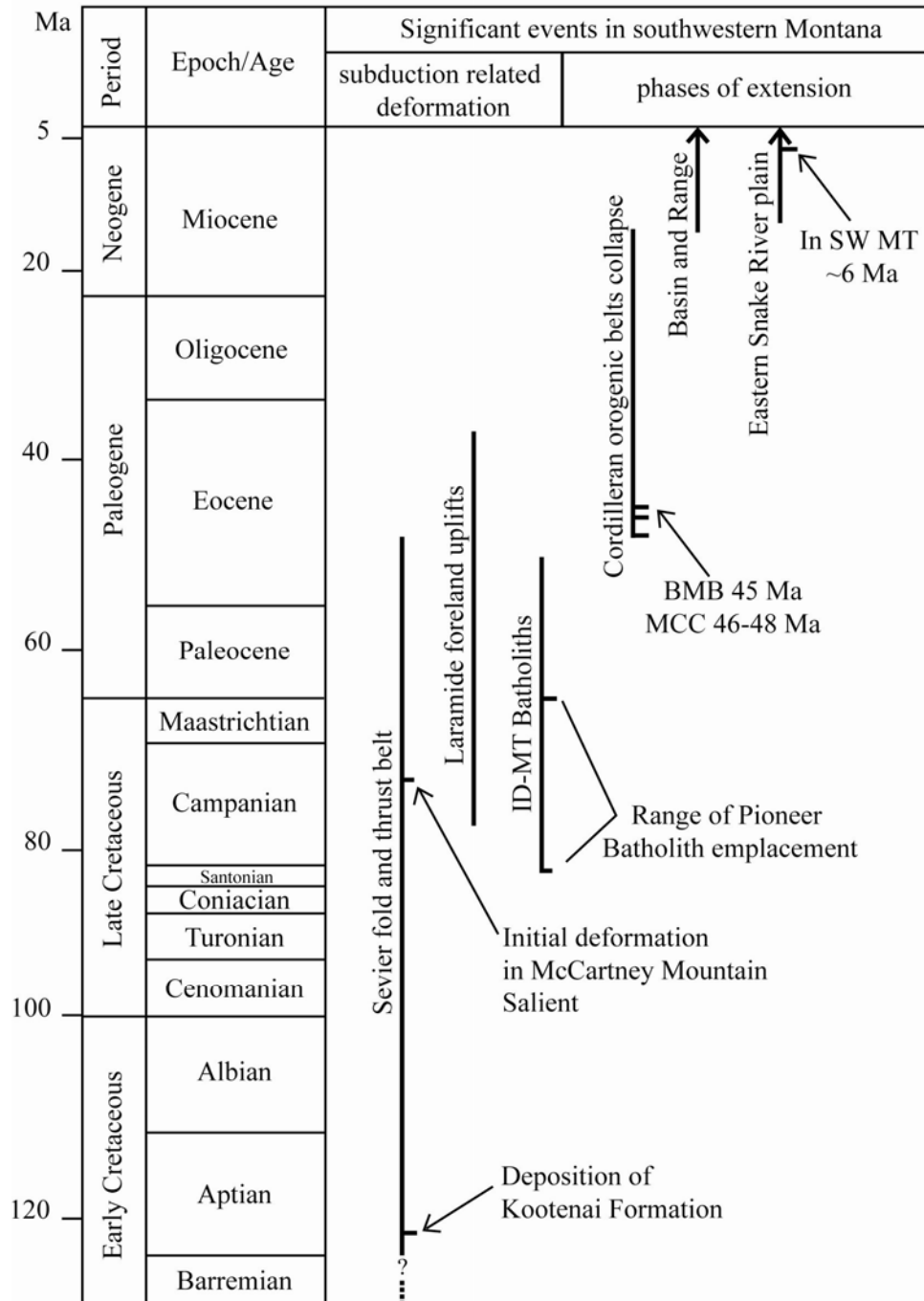


Figure 2. Summary diagram of overlapping tectonic events that have affected southwest Montana including Sevier fold-and-thrust belt, Laramide foreland uplifts, Idaho-Montana Batholith province and several phases of extension. Abbreviations BMB and MCC stand for Block Mountain Basalt and metamorphic core complex, respectively. Literature sources for approximate dates are outlined in Appendix A.

towards the North American craton or foreland (Armstrong, 1968). Propagation of the fold-and-thrust belt did not occur in southwest Montana until Late Cretaceous time, (Campanian) and is constrained by growth strata, radiometric dating of igneous deposits, and cross-cutting field relationships (Kalakay, 2001). Total shortening estimates for the southwest Montana region are at least 75 - 50 km (Skipp, 1988).

Sevier and Laramide Overlap Zone

Southwest Montana is characterized by the interaction of classic Sevier thin-skinned structures, and basement-cored Laramide uplifts, within a spatial overlap of 100-150 km, and temporal overlap from the Late Cretaceous to early Eocene (Kulik and Schmidt, 1988) (Figure 2). Frontal fold-and-thrust systems in southwest Montana have been noted by previous workers to impinge against basement-cored structures of the foreland (e.g. Ruppel and Lopez, 1984; Kulik and Schmidt, 1988; Schmidt et al., 1988). Uplifted basement blocks act as structural ramps, and can be termed frontal, lateral, or oblique according to the relative orientation of the ramp to the tectonic transport (Kulik and Schmidt, 1988) (Figure 3). Thin-skinned thrust faults are forced to ramp up-section as their basal décollement encounters high-angle faults within crystalline basement rocks (Kulik and Schmidt, 1988). Consequently, thin-skinned thrust sheets share common geometries with the basement structure in the footwall (Schmidt et al., 1988). Additionally, Archean metamorphic rocks have been observed in the hanging wall of several leading edge thrusts in the Tobacco Root and Highland Mountains (Schmidt et al., 1988). The occurrence of Archean rocks in the hanging wall of frontal thrusts has

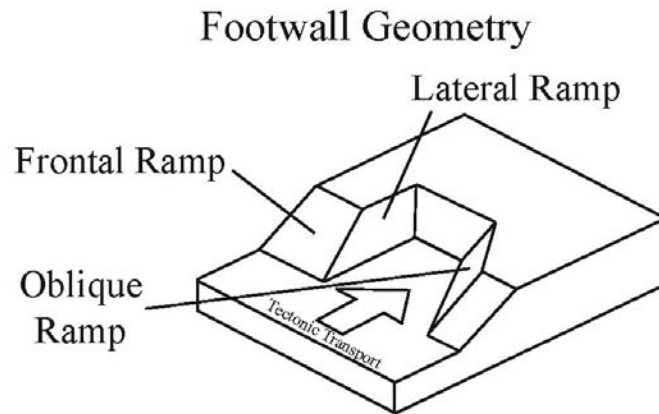


Figure 3. Diagram illustrating footwall ramp geometries.

been explained as tectonic slices of basement-cored structures incorporated into the hanging wall as thrusts ramped up along pre-existing Laramide structures (Schmidt et al., 1988; Skipp, 1988).

Folds, fracture sets, and cleavage may also form as a result of basement impingement. The orientation of these features may also be controlled by the orientation of the associated basement ramp, as further discussed in later sections.

The McCartney Mountain salient is surrounded by several Laramide uplifts including the Highland, Tobacco Root, and Ruby Mountains (Figure 1). Major basement structures, including the Rochester and Biltmore anticlines in the Highland Mountains as well as the Pole Canyon and Brooks Creek anticlines in the Tobacco Root Mountains, may have controlled salient geometry by spatially limiting frontal thrust propagation (Kulik and Schmidt, 1988; Schmidt et al., 1988).

Montana-Idaho Batholith Province

Many Late Cretaceous (80-70 Ma) plutonic bodies occupy eastern Idaho and western Montana including the Boulder, Idaho, Tobacco Root, and Pioneer batholiths as part of the Montana-Idaho Batholith Province (Figure 1). The Pioneer Batholith is located west of the Sandy Hollow field area, and occupies a central position within the McCartney Mountain salient. The Pioneer Batholith was emplaced from 83-65 Ma as determined by K-Ar dating techniques (Snee, 1982) (Figure 2).

Southwest Montana Cenozoic Tectonism

Several phases of over-printing extension have been documented throughout the region, and have been linked to several processes, including: 1) gravitational collapse of the Sevier and Laramide orogenic belts; 2) upper crustal extension related to Basin and Range processes; and 3) extension related to Eastern Snake River plain magmatism (e.g. Thomas et al., 1995; Janecke et al., 2001).

Gravitational collapse of the Sevier and Laramide orogenic belts started in middle Eocene, and continued into the early middle Miocene (Constenius, 1996; Janecke et al., 2001). Convergence along the western margin of the North American continent was greatly reduced around 50 Ma thus diminishing the west to east compressional stress in the Cordilleran orogenic belts (Constenius, 1996). The development of metamorphic core complexes has also been shown to correspond with the collapse of structural and magmatic culminations within the fold-and-thrust belt (Constenius, 1996; Janecke et al., 2001; O'Neill et al., 2004). The Anaconda and Bitterroot core complexes of Montana and

Idaho are thought to have developed coevally in middle Eocene time (O'Neill et al., 2004) (Figure 1).

Eocene crustal extension was accompanied by the emplacement of regional magmatic belts such as the Challis-Lowland Creek and Absaroka volcanic provinces of northwestern United States (Chadwick, 1981; Feeley, 2003). These provinces are characterized by compositionally diverse suites of plutonic and volcanic rocks (Chadwick, 1981; Feeley, 2003).

Basin and Range processes (17 Ma to present) have affected southwest Montana by producing northeast trending grabens that preserved syn-extensional deposits, including arkosic sandstones, fluvial sandstones and gravels, debris flow deposits, tephras, and volcanic flows (Thomas et al., 1995; Janecke et al., 2001). Crustal adjustments caused by the Eastern Snake River plain have also been shown to have produced extensional faults in southwest Montana starting sometime after 6 Ma (Fritz and Sears, 1993; Thomas, et al., 1995).

Local Stratigraphy of the Kootenai Formation

In southwest Montana the Aptian Kootenai Formation overlies the Kimmeridgian Morrison Formation, representing a regional unconformity that is locally angular (DeCelles, 1986; Schwartz and DeCelles, 1988). The Kootenai is overlain by the Albian Blackleaf Formation with a gradational contact (DeCelles, 1986). The Kootenai

Formation is correlative with the Gannet Group of the Wyoming-Idaho-Utah thrust belt (Zaleha, 2006). The Kootenai Formation is characterized by diverse non-marine strata that can be subdivided into distinct lithologic informal members and units (Figure 4). This study divides the Kootenai into four informal members: Kk1, from the distinctive, basal chert pebble conglomerate to the top of a red to green, claystone and mudstone unit; Kk2, from the base of a recessive, silty, orange, lacustrine dolomite to the top of a dark gray, massive, lacustrine, fossiliferous limestone; Kk3, a thick section of red to green, claystone and mudstone with isolated sandstone lens; Kk4, from the top of the fine-grained member to the top of a distinctive gray, lacustrine gastropod limestone (DeCelles, 1986; Schwartz and DeCelles, 1988). This study investigated tectonic cleavage in a yellowish micritic dolomitic lacustrine limestone unit within the second informal member of the Kootenai, referred to here as Kk2a (Figure 4).

Previous Cleavage Studies

Deformed sedimentary units in the Appalachian fold-and-thrust belt have been the subject of many early cleavage development studies. These studies focused on cleavage-structure relationships, factors that control cleavage development, and deformational processes responsible for cleavage formation (Wanless, 1979; Gray, 1981; Onasch, 1983; Engelder and Marshak, 1985; Marshak and Engelder, 1985; Mitra, 1988).

Cleavage development has also been recognized in many sedimentary units throughout the Cordilleran orogenic belt. Well studied examples include cleavages that

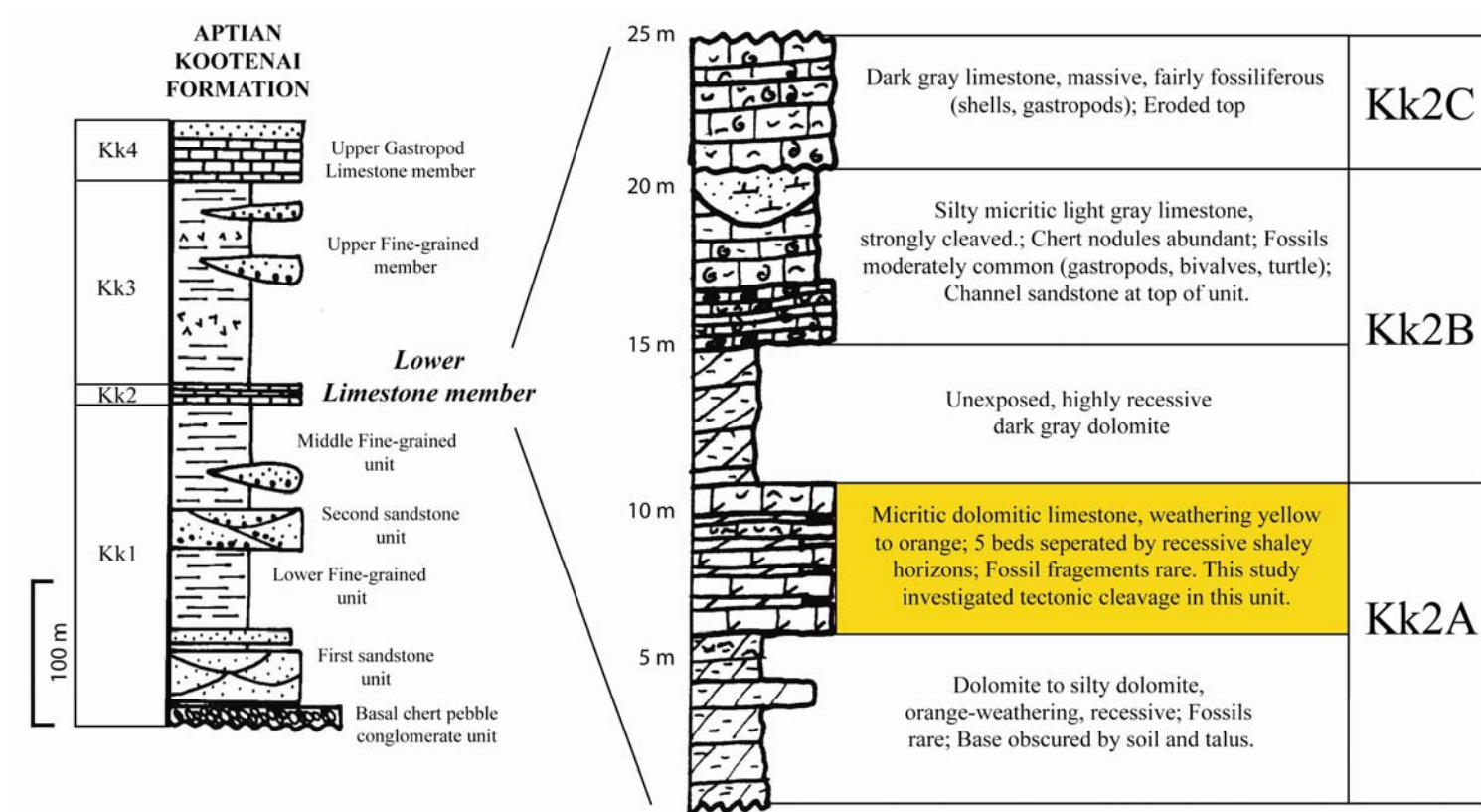


Figure 4. Stratigraphy and nomenclature of the Lower Cretaceous Kootenai Formation. This study divides the Kootenai into four informal members and further divides the Lower Limestone member into three informal units. The focus of this study was to investigate cleavage in Kk2a, a dolomitic limestone unit. Stratigraphic columns were modified from: Schwartz and DeCelles, (1988); Kiorpes, (1990).

developed in Mississippian limestone units such as the Banff Formation in the Front Ranges of the Canadian Rocky Mountains, and the Madison Group in the U.S. Sevier orogen (e.g. Spang et al., 1979; Geiger, 1980). Additionally, the Jurassic Twin Creek Limestone, exposed in the Wyoming-Idaho-Utah thrust belt, contains several populations of cleavage that record the complex evolution of thrust sheet emplacement (Yonkee, 1983; Mitra and Yonkee, 1985; Coogan and Royse, 1990). Valuable information regarding the physical conditions of cleavage development, process of cleavage refraction, and cleavage-structure relationships have been gained by these studies.

In southwest Montana, Geiger (1980) documented several generations of cleavage development that demonstrate strain partitioning across the McCartney Mountain salient. Her conclusions indicate that strain increased to the north due to impingement of the thrust belt against a basement-cored foreland structure, the Rochester anticline. Elevated temperatures, due to the emplacement of the Pioneer batholith, facilitated ductile deformation and allowed late-stage cleavage development in several units, including the Mississippian Madison limestone (Geiger, 1980).

Kiorpes (1990) investigated the process of cleavage development as a strain mechanism that can cause significant volume loss, and lead to unbalanced cross-sections. He analyzed a well exposed outcrop of the lower limestone member of the Kootenai Formation (Kk2) in the Sandy Hollow field area. Analysis of the intensely cleaved upper argillaceous limestone units indicated that total volume loss by pressure solution process was up to 15%. Cleavage was not recognized in the lower dolomitic unit at this location.

However, his findings indicated that the restore bed length of the dolomitic unit was shortened by about 13%, similar to other analyzed units, possibly by stress induced dolomitization. He states that future work would be necessary to properly address strain accommodation in the lower dolomitic unit of the lower limestone member of the Kootenai.

GEOLOGY OF THE SANDY HOLLOW FIELD AREA

The Sandy Hollow field area contains well exposed examples of thin-skinned, in-sequence thrust faults with associated syncline-anticline pairs that display complex intra-formational duplexes and parasitic folds. The prominent thrust faults in the field area are the Sandy Hollow and Hogback thrusts (Figure 5).

Sandy Hollow Thrust Fault

The restored Sandy Hollow thrust sheet contains about 1,150 meters of Mississippian through Cretaceous strata (Figure 6). The Sandy Hollow thrust has a stair-step geometry with the regional décollement in the shaley Mississippian-Pennsylvanian Amsden Formation (Figures 7 and 8). Ramps are located in the Pennsylvanian Quadrant Sandstone, the upper Dinwoody Formation, and the lower Cretaceous Kootenai Formation (Figure 7). Flats tend to be located in the thinly bedded limestones of the Permian Phosphoria, and lower shaley unit of the Dinwoody Formations. The Sandy Hollow thrust sheet is dissected by several imbricate thrusts that initiate along a flat within the Dinwoody shale. Duplex horse structures displace the basal chert pebble conglomerate of the Kootenai along upper ramps.

The Sandy Hollow thrust strikes roughly north-to-northeast. The trace of the thrust abruptly changes for about 800 meters to strike east-to-southeast with a steep

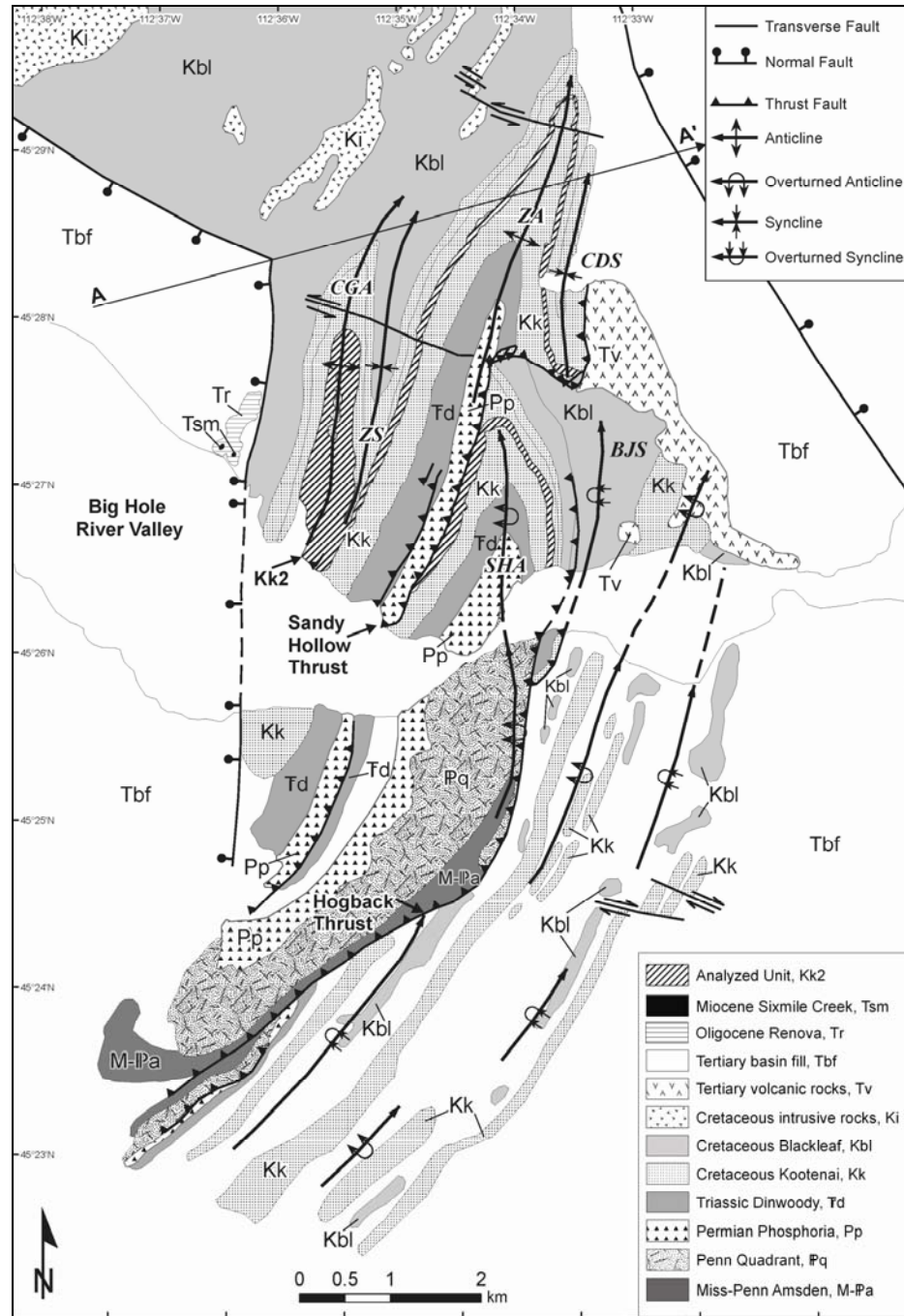


Figure 5. Detailed geologic map of the Sandy Hollow field area showing the major structures: Sandy Hollow thrust, Hogback thrust and associated hanging wall and footwall folds. BJS = Buffalo Jump syncline, CDS = Coal Draw syncline, CGA = Creasey Gulch anticline, SHA = Sandy Hollow anticline, ZA = Ziegler anticline and ZS = Ziegler syncline. Tertiary basin fill (Tbf) represents undifferentiated Cenozoic deposits. Tertiary volcanic deposits (Tv) represent Eocene Block Mountain basalt. Diagonal pattern represents the informal middle limestone member of the Cretaceous Kootenai Formation, including the analyzed unit, Kk2a. Dashed fault traces and fold axes indicate inferred data. Arrows on transverse faults indicate relative movement. A-A' cross-section line is presented in Figure 7. Note the cross-section line continues to the north east for about 0.5 km. This map is the result of GIS compilation of maps from Brandon (1984) and unpublished field maps by the author.

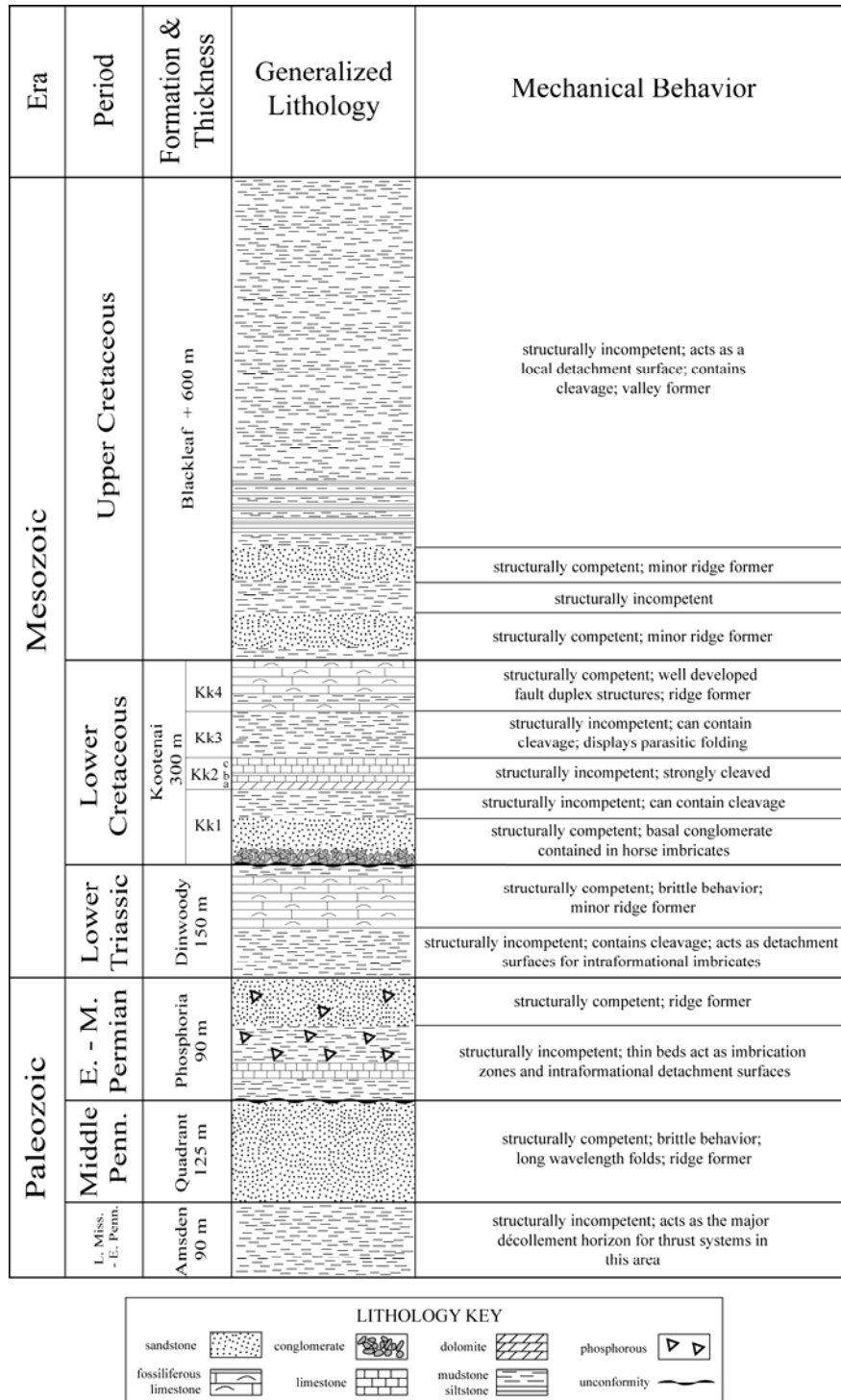


Figure 6. Mechanical stratigraphy diagram summarizing deformation style for lithographic units involved in thrusting at the Sandy Hollow field area. The Jurassic Morrison Formation is shown as a thin shaley unit as part of the upper Dinwoody. Note that this study investigated cleavage in the lower dolomitic unit in Kk2a. Stratigraphic column was modified from Brandon (1984).

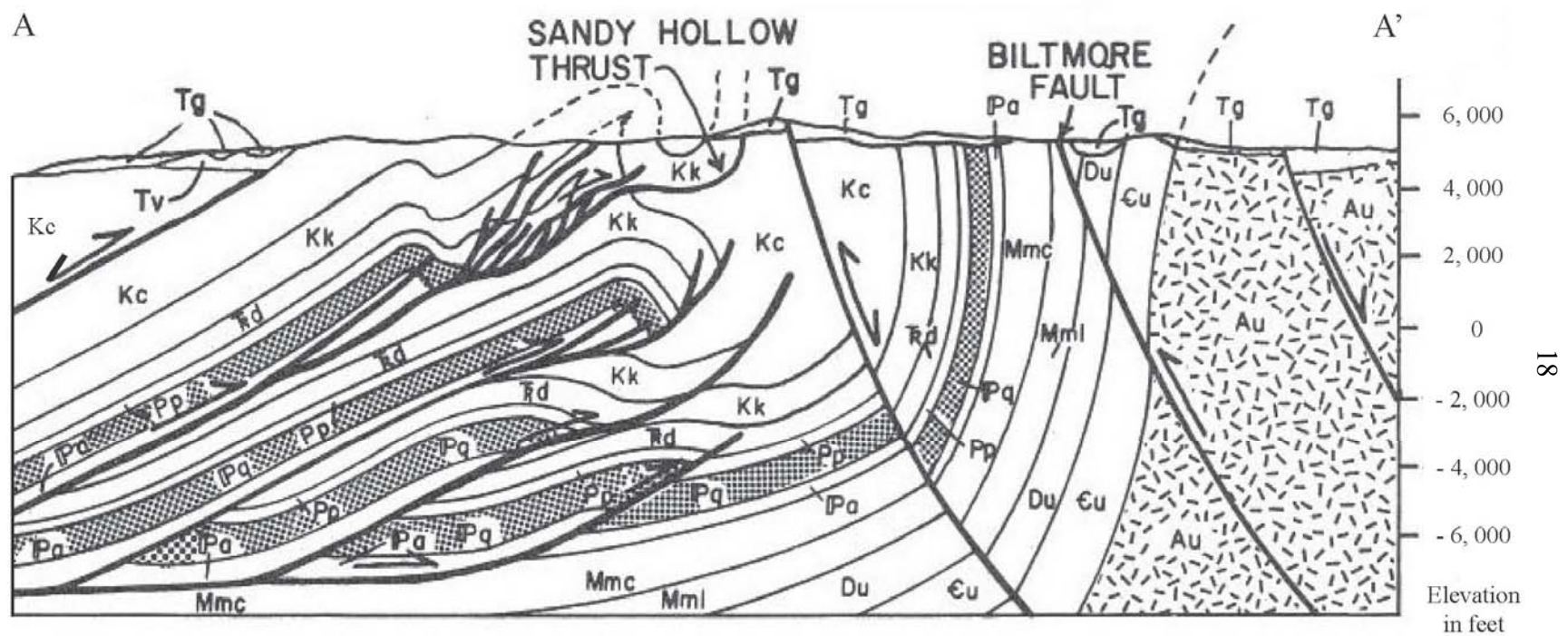


Figure 7. Structural cross-section line A-A'; location shown on Figure 5. Modified from Schmidt et al. (1988) by changing the symbol in the upper left hand corner from a thrust symbol to a reactivated thrust symbol. This reflects a normal fault that can be clearly seen in the field and is shown on the geologic map of the Sandy Hollow area, Figure 5.

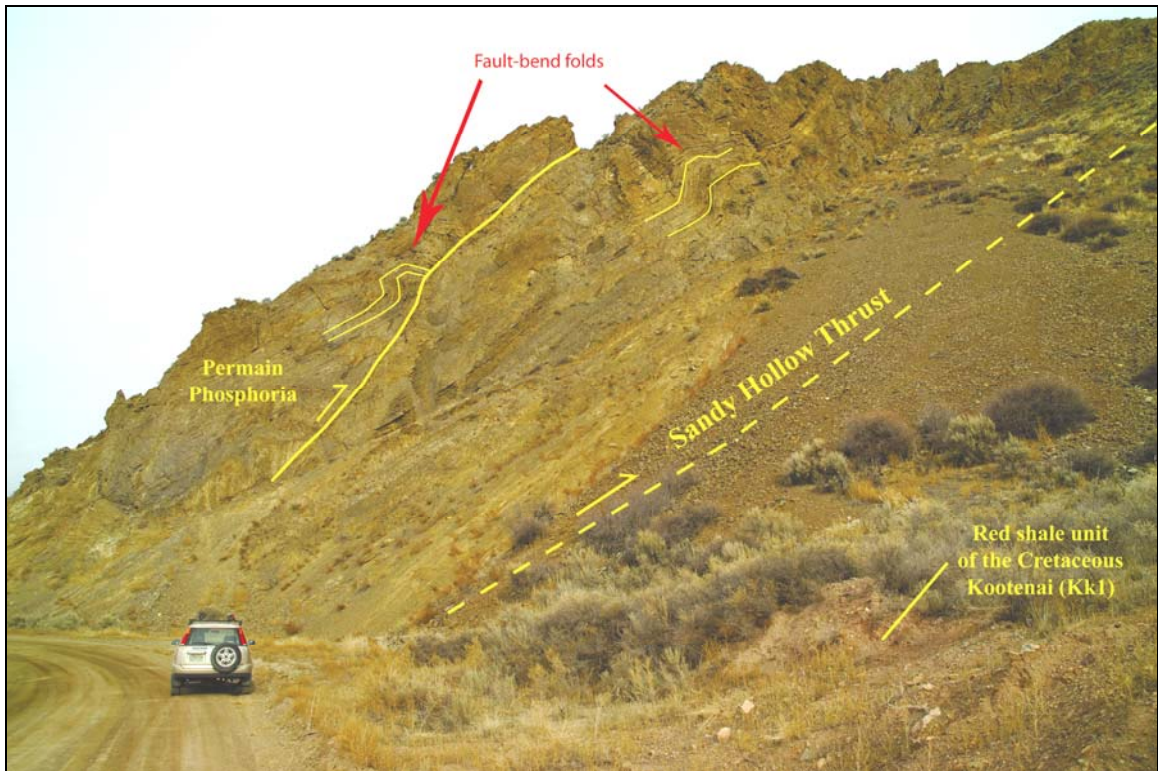


Figure 8. Photograph of the Sandy Hollow thrust displacing the Permian Phosphoria Formation over the Lower Cretaceous Kootenai Formation. Photograph is looking roughly north along Burma Road. Photograph illustrates several thrust geometries including: steep west dip of the Sandy Hollow thrust, fault-bend folds, and the stair-step geometry of the thrust surface. Note: all photographs have been taken by the author unless otherwise noted.

north- to-northeast dip (Figure 5). The trace of the thrust again turns to continue roughly northward, but is obscured by Eocene Block Mountain basalt, and younger surficial deposits (Figure 5). Previous workers interpreted this along-strike variation as a result of impingement of the Sandy Hollow thrust against a pre-existing footwall anticline (Sandy Hollow anticline), causing a “collision structure” (Brumbaugh and Dresser, 1976; Hendrix and Porter, 1980). More recent detailed mapping and structural analysis of the Sandy Hollow thrust indicate that: 1) the change in strike is characteristic of a folded thrust associated with the in-sequence development of the Hogback thrust, 2) the Sandy Hollow anticline is a hanging wall feature of the Hogback thrust, and 3) the “collision structure” is a footwall duplex structure that developed in a ramp area to facilitate the transfer of slip towards the foreland (Brandon, 1984; Schmidt et al., 1988).

Description of Folds

The Sandy Hollow thrust sheet displays several first-order folds including, from west to east, Creasey Gulch anticline, Ziegler syncline, and Ziegler anticline (Figure 5). Folds located in the hanging wall of the Sandy Hollow thrust have experienced co-axial refolding by in-sequence development of the Hogback thrust and, consequently, are all slightly asymmetric (Appendix B) (Fleuty, 1964; William and Chapman, 1983).

The Creasey Gulch anticline is a disharmonic, upright, asymmetric, tight cylindrical fold that plunges slightly to the south and trends 194° (Figure 9). The shape of the anticline exhibits an equant, sub-rounded form (Appendix B) (Fleuty, 1964; William

and Chapman, 1983). The Creasey Gulch anticline displays parallel folds in competent limestone units, and more similar behavior in less competent shaley units along the hinge zone (Ramsay, 1962) (Figure 10) (Appendix B). This fold is interpreted to be a fault-bend anticline related to a ramp of the Sandy Hollow thrust within the Quadrant Formation (Figure 7).

The Ziegler syncline is a disharmonic, steeply inclined, asymmetric, tight, cylindrical fold that plunges 03° to the north and trends 020° (Figure 11). The shape of the anticline is described as an elongate, sub-angular to parabolic fold (Appendix B) (Fleuty, 1964; William and Chapman, 1983). The fold ranges from class 1C to class 3 to class 2 within the incompetent upper shaley unit of Kootenai Formation in the hinge zone of the structure, while approaching parallel style along the limbs (Ramsay, 1962) (Figure 10) (Appendix B). This fold is also interpreted to be a fault-bend fold that developed as a result of down-flexing of the thrust package as the thrust propagated through a flat located within the Phosphoria Formation (Figure 7).

The Ziegler anticline is a disharmonic, steeply inclined, asymmetric, tight, cylindrical fold that plunges 09° north and trends 014° (Figure 12). The fold has an equant, sub-rounded form that approaches a chevron fold (Appendix B) (Fleuty, 1964; William and Chapman, 1983). The anticline displays similar behavior in the thickened hinge zone within incompetent units, and a parallel style along the limbs of all deformed units (Ramsay, 1962) (Figure 10) (Appendix B). The Ziegler anticline developed as a fault-bend fold as the Sandy Hollow thrust ramped up-section through the competent limestone unit of the Dinwoody Formation (Figure 6) (Schmidt et al., 1988).

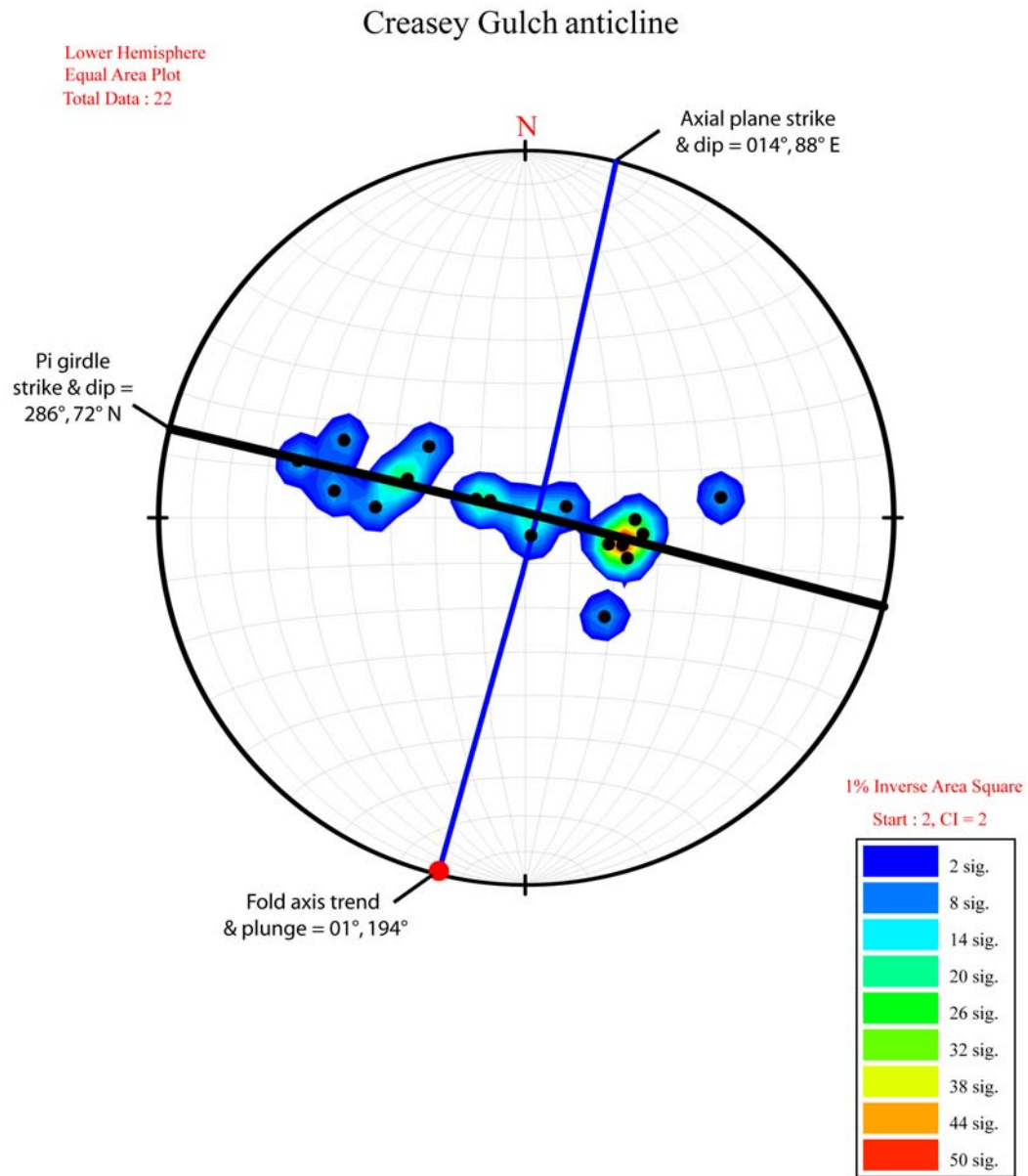


Figure 9. Equal-area, lower-hemisphere projection of the poles to folded bedding along the Creasey Gulch anticline. Fold is considered cylindrical because 90% of the folded bedding poles are within 10° of the π girdle. Diffuse pole clusters indicate rounded, parabolic shape. Red circle: fold axis, Blue great circle: fold axial plane, Black great circle: π girdle, Contour unit: sigma.

Figure 10. Fold train diagram illustrating fold style based on the Ramsay classification (1962). Hinge zones are commonly classified as class 2 similar style while most limbs approach class 1B parallel style. Note that the middle limestone member of the Kootenai Formation (Kk2) is consistently classified as 1B indicating that this bed behaved competently and maintained constant bed thickness.

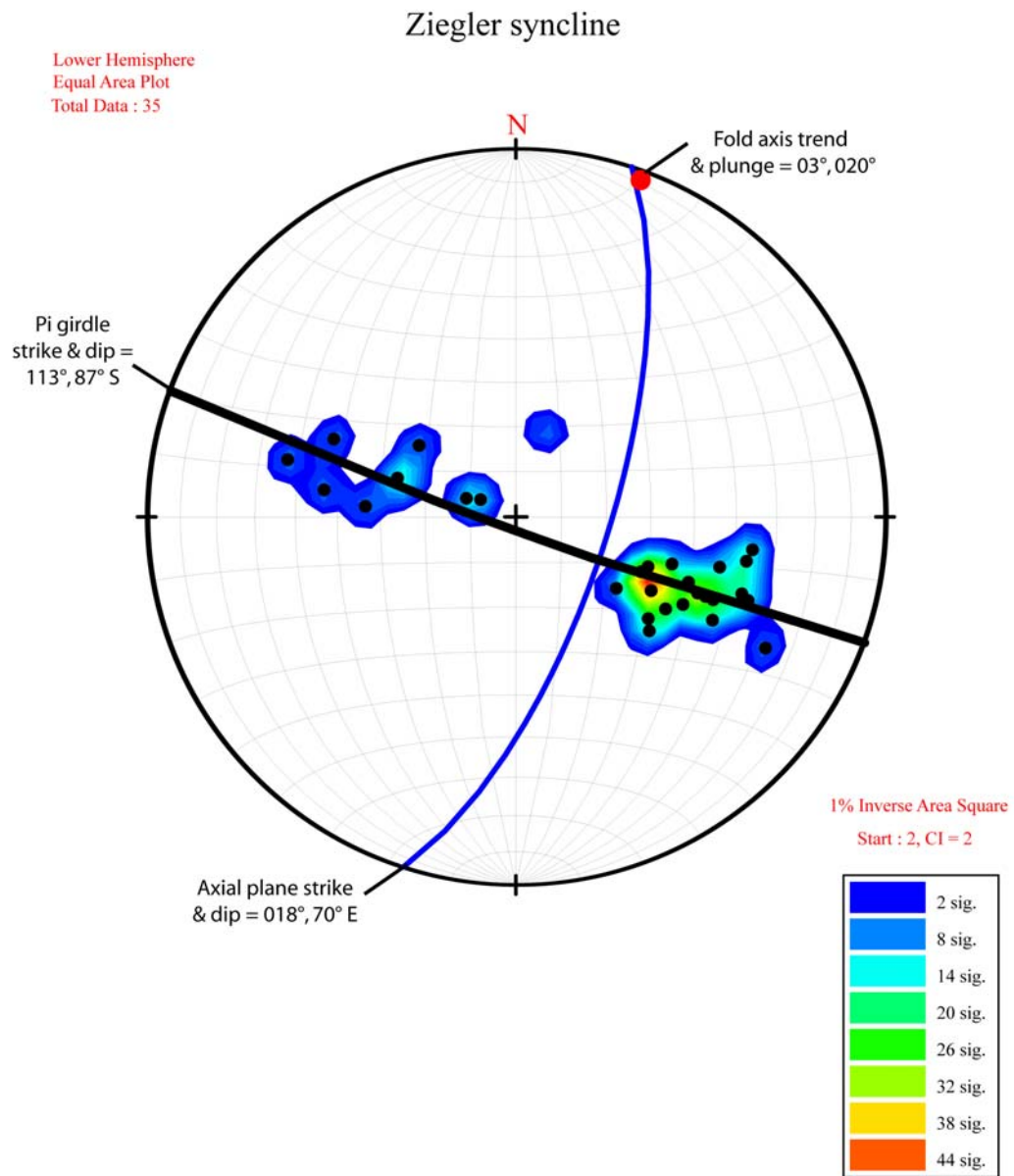


Figure 11. Equal-area, lower-hemisphere projection of the poles to folded bedding along the Ziegler syncline. Fold is considered cylindrical because 90% of the folded bedding poles are within 10° of the π girdle. Pole clusters indicate sub-rounded shape. Red circle: fold axis, Blue great circle: fold axial plane, Black great circle: π girdle, Contours unit: sigma.

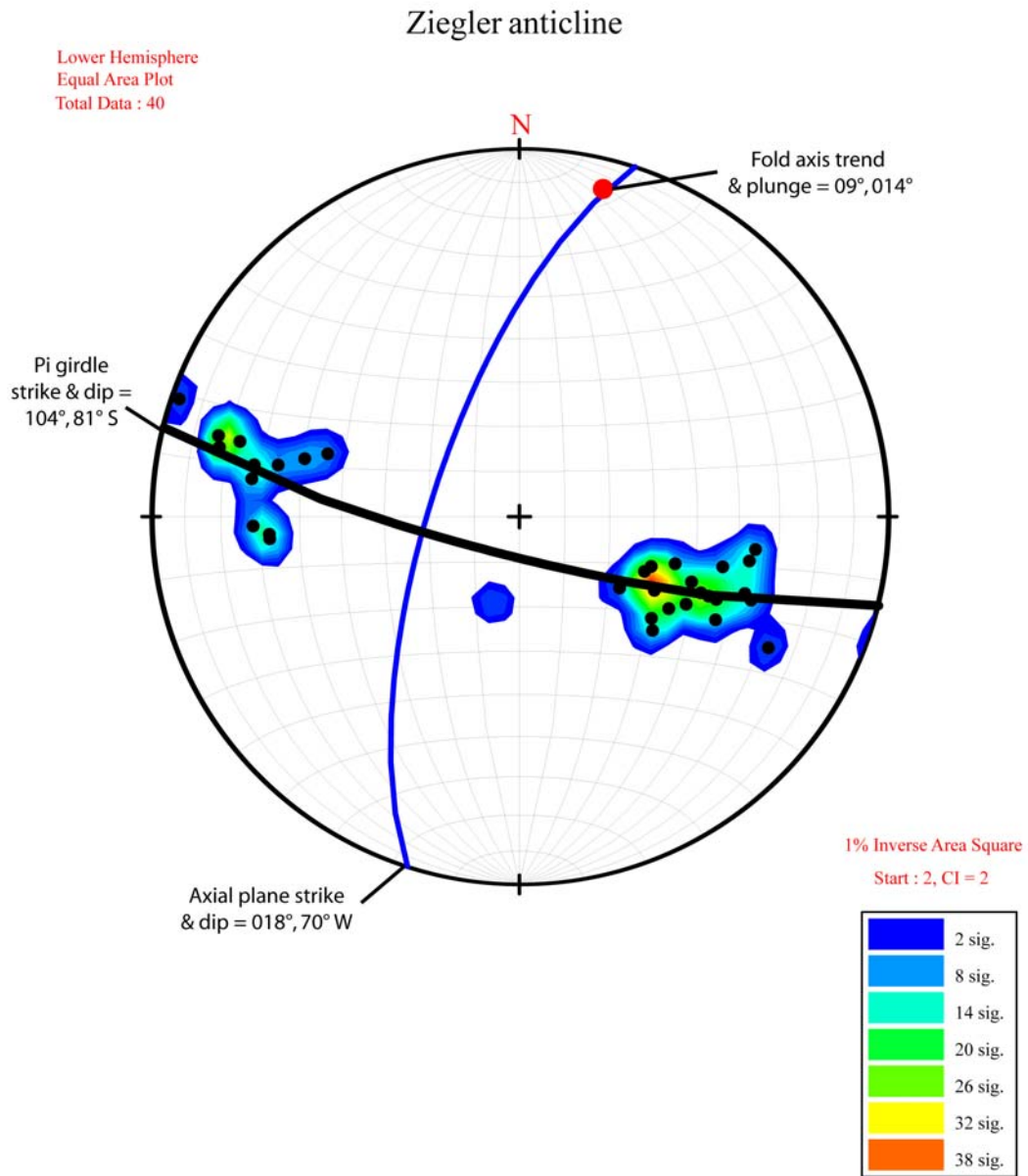


Figure 12. Equal-area, lower-hemisphere projection of the poles to folded bedding along the Ziegler anticline. Fold is considered cylindrical because 90% of the folded bedding poles are within 10° of the π girdle. Concentrated pole clusters indicate straight limbs, approaching chevron fold. Red circle: fold axis, Blue great circle: fold axial plane, Black great circle: π girdle, Contours unit: sigma.

This fold is dissected by many intraformational imbricate thrust faults that initiated along a flat within the Phosphoria Formation, some of which may exist as blind thrusts.

Small-scale parasitic detachment folds are also present in the Sandy Hollow thrust sheet that detach within the shale units above and below limestone units of the Dinwoody and Kootenai formations (Figure 13). The hinge zone of the Ziegler anticline contains a well developed shear-couple fold-pair within the Dinwoody limestone indicating flexural slip along the limbs of the anticline (Figure 14).

The footwall of the Sandy Hollow thrust or, alternatively, the hanging wall of the in-sequence Hogback thrust, is dominated by the Sandy Hollow anticline (Figure 5). The anticline is a disharmonic, steeply inclined, east-verging, closed, cylindrical fold that plunges 17° to the north and trends 350° (Figure 15). The shape is characterized as equant, sub-angular to parabolic (Appendix B) (Fleuty, 1964; William and Chapman, 1983). The Sandy Hollow anticline exhibits similar folding within the Dinwoody and lower unit of the Kootenai formations along the hinge zone. Parallel folding dominates the limbs as well as the entire folded middle limestone unit of the Kootenai (Ramsay, 1963) (Figure 10) (Appendix B). This structure is a fault-bend fold that developed as the Hogback thrust ramped through the Quadrant Formation, and has probably also experienced minor refolding as the next in-sequence thrust propagated into the foreland (Figure 7) (Schmidt et al., 1988).

A footwall duplex structure, in close proximity to the along-strike variation of the Sandy Hollow thrust, strongly deforms the upper gastropod limestone unit of the Kootenai (Figure 16). Various disharmonic parasitic detachment folds, and small-scale



Figure13. Second-order folds in the Sandy Hollow thrust sheet. A. Parasitic, disharmonic folding in Kk2b; B. Detachment folding in Kk4; C. Large-scale detachment folding in Kk4; D. Parasitic, plunging fold in the upper Dinwoody Formation. Photos B and C taken by D.R. Lageson

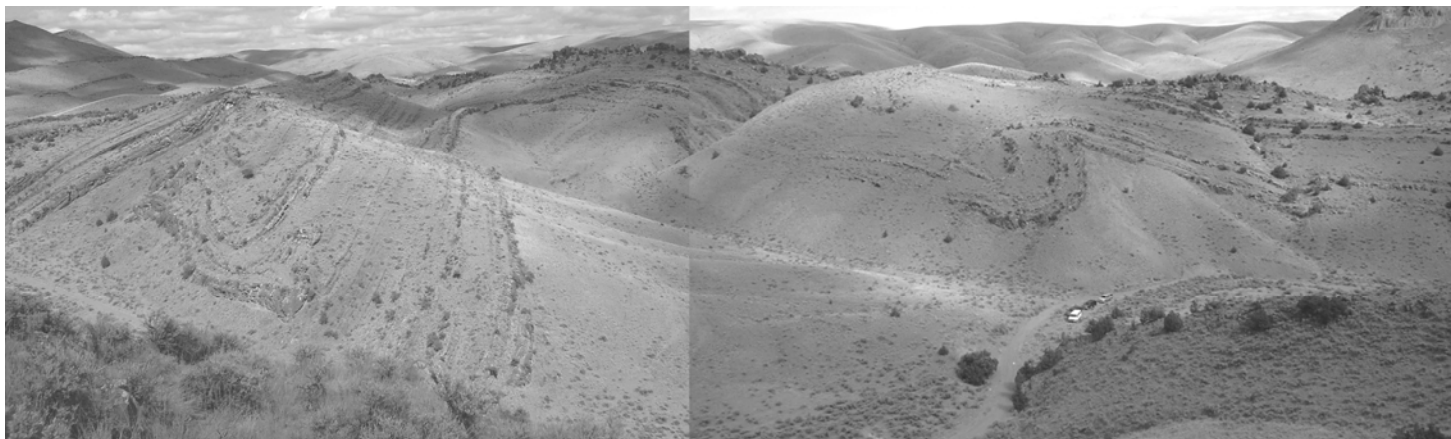


Figure 14. Shear-couple fold-pair in the upper Dinwoody Formation along the limbs of the Ziegler anticline. Photograph is looking north, northeast. Note field vehicle for scale.

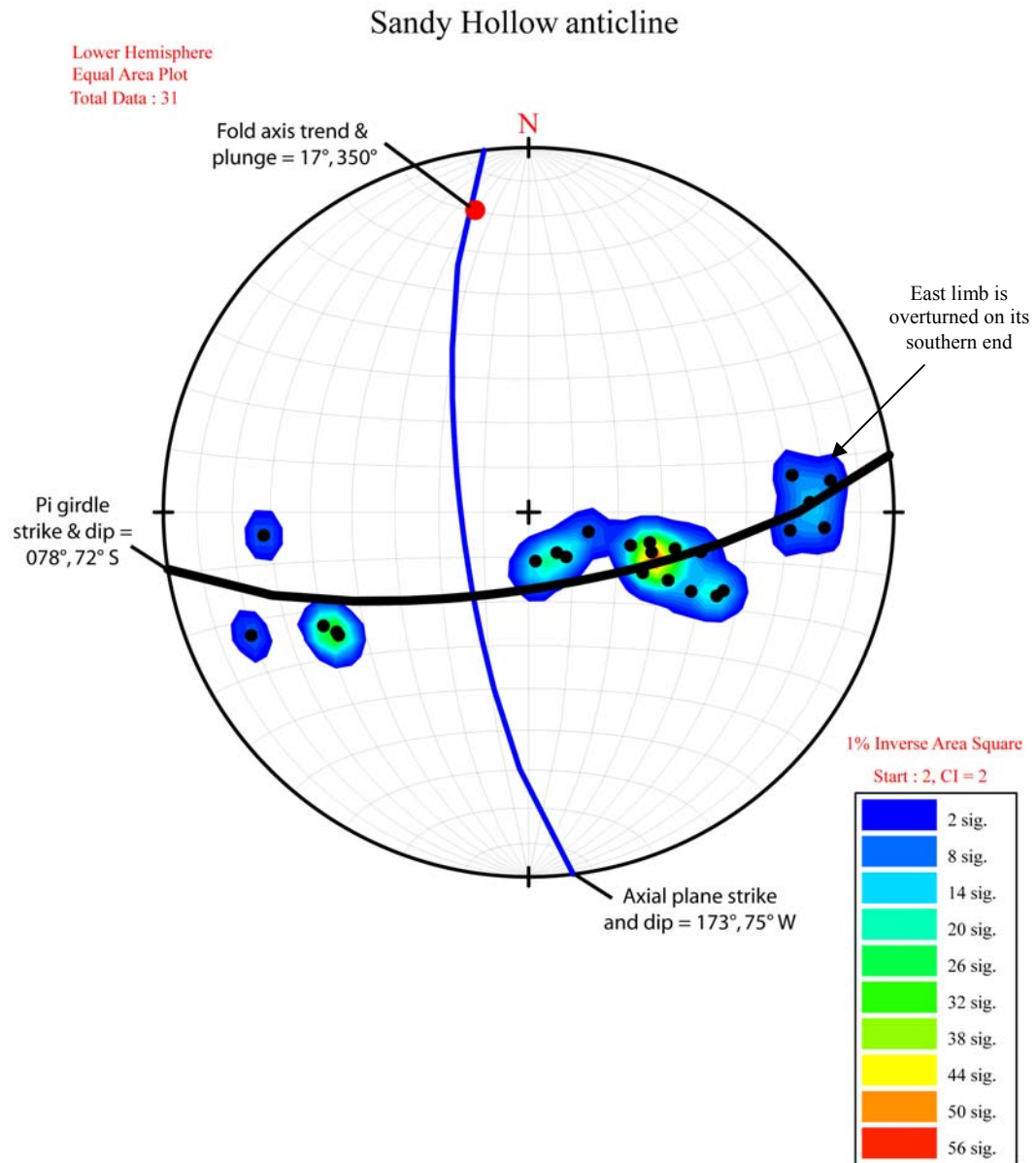


Figure 15. Equal-area, lower-hemisphere projection of the poles to folded bedding along the Sandy Hollow anticline. Fold is considered cylindrical because 90% of the folded bedding poles are within 10° of the π girdle. Note overturned east limb. Red circle: fold axis, Blue great circle: fold axial plane, Black great circle: π girdle, Contours unit: sigma.

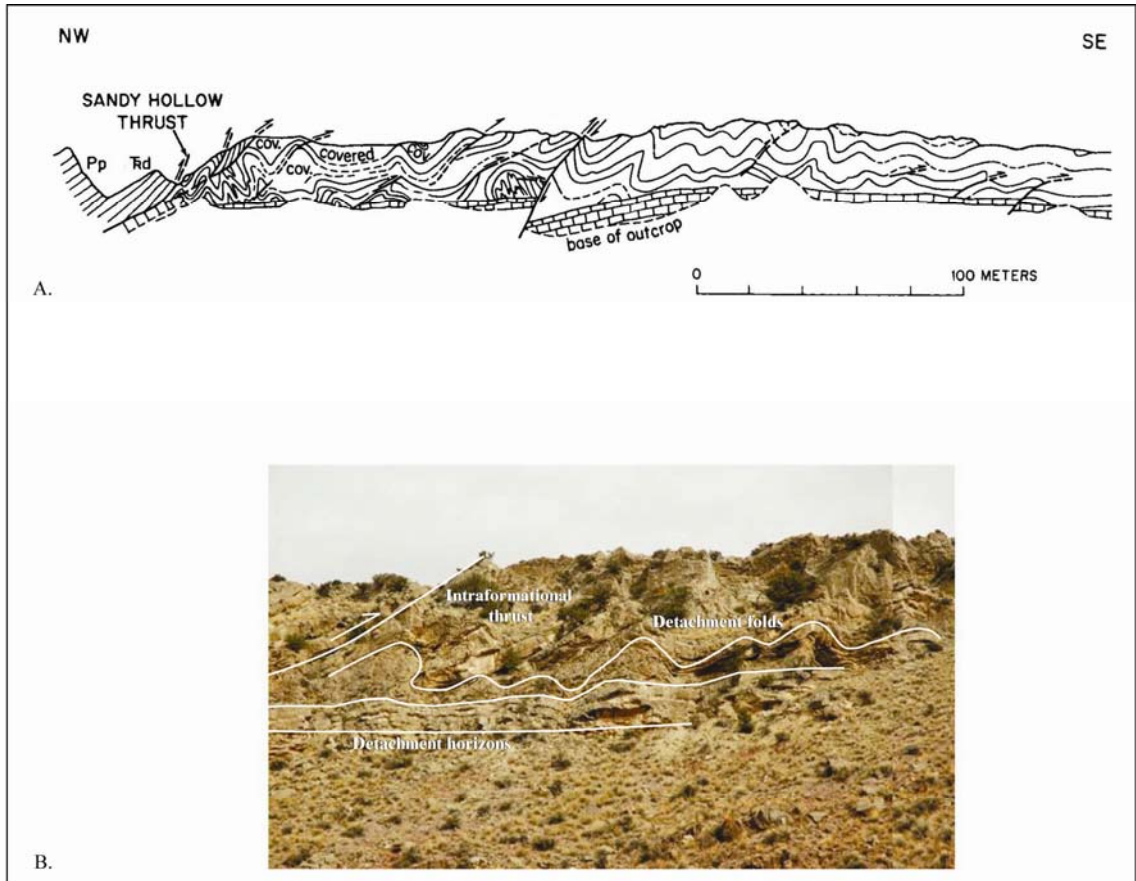


Figure 16. Duplex structure in the Sandy Hollow footwall localized within Kk4. A. Interpreted cross-section showing intraformational thrusts, small scale detachment folds and the over riding Sandy Hollow thrust (Hendrix and Porter, 1980). B. Annotated photograph of roughly the middle portion of the outcrop; taken by Scott McLeod.

intraformational thrusts formed to accommodate foreland directed slip along the ramped surface of the overlying Sandy Hollow thrust. The interbedded fine-grained layers of Kk4 act as local detachment surfaces, allowing the fold to increase in amplitude and transfer slip eastward.

Miscellaneous Features

The McCartney Mountain intrusive body is located within the Sandy Hollow field area, and contains granodiorite and quartz monzodiorite plutons (Figure 1). It is interpreted to be a series of tongue-shaped sills genetically linked to the Pioneer Batholith that were emplaced along a footwall ramp-hanging wall flat between the Anglers thrust to the west, and Sandy Hollow thrust to the east (Gunckel, 1990; Kalakay, 2001). Cooling indicators for the McCartney pluton indicate a K/Ar biotite date of 74 ± 1 Ma (Brumbaugh and Hendrix, 1981). Also, many smaller sills have intruded fine-grained units throughout the field area including the Vaughn and middle Flood members of the Blackleaf, lower and upper mudstones of the Kootenai, and lower Dinwoody Formation (Figure 5).

Several strike-slip faults offset intrusive bodies as well as folded sedimentary units in the Sandy Hollow field area (Figure 5). In the northern part of the field area, movement is sinistral, whereas to the south movement is dextral. These faults could have accommodated shear along the boundaries of the salient as the fold-and-thrust belt propagated into the salient 'nose' becoming progressively laterally limited.

Two normal faults are located in the Sandy Hollow field area, both of which are interpreted to be reactivated reverse/thrust faults. The eastern normal fault is most likely a fault splay related to the reactivated Biltmore reverse fault (Figure 7). Archean crystalline rocks, and lower Paleozoic sedimentary units, exposed 4 km east of the study area, are interpreted to have been uplifted by the Biltmore fault system. Reactivation of this fault splay probably occurred during the gravitational collapse of many northwest trending reverse faults in the early to middle Miocene (Schmidt et al., 1988).

Along the southern flank of the McCartney Mountain intrusion, a normal fault displaced Oligocene Renova and Miocene Sixmile Creek Formations against the lower clastic unit of the Flood member of the Cretaceous Blackleaf Formation. This fault is interpreted to be a reactivated west-dipping thrust fault with down to the south-southwest movement (Figures 5 and 7).

Block Mountain, located in the eastern part of the field area, displays well developed columnar basalt, dated to an age of 44.8 Ma (Chadwick, 1981). The emplacement of this volcanic body is interpreted to be related to the Challis magmatic belt, active during a period of major Eocene extension (Christiansen and Yeats, 1992). The basaltic body was probably emplaced along a fissure, and now represents an excellent example of topographic inversion (Chadwick, 1981). The basalt covers the northern portion of the Sandy Hollow thrust as well as much of the Hogback thrust footwall.

Much of the topography surrounding the Sandy Hollow field area is covered by thick gravel deposits interpreted to be fluvial in origin (Hanneman, 1989). Provenance data indicate clasts were sourced from the Highland and Pioneer Mountains (Hanneman, 1989). The age of the deposit is poorly constrained by a few late Miocene fossils, and a 3.7 Ma air-fall tuff (Hanneman, 1989).

CLEAVAGE FUNDAMENTALS

Terminology

The term cleavage generally refers to the tendency of a rock to break along a secondary plane of weakness. Different types of cleavage are classified according to: 1) spacing of weakness planes, and 2) relationship to pre-existing rock layering (Powell, 1979). Cleavage spacing refers to the pervasiveness of weakness planes. Penetrative or continuous cleavage describes cleavage that is observable at all scales (Figure 17). Spaced or non-continuous cleavage is recognized by observable portions of uncleaved rock, called microlithons, separated by cleavage domains (Figure 17). Cleavage that cross-cuts original rock layering is termed disjunctive, while crenulation cleavage deforms preexisting layering (Figure 17). The term cleavage in this paper will be used to describe a secondary, spaced fabric composed of clay-rich domains in sedimentary rocks that are at high-angles to bedding.

Process of Cleavage Formation

Spaced cleavage forms in sedimentary rocks during low-grade metamorphism ($T < 200^{\circ}\text{C}$, $P < 5\text{ kb}$) at shallow crustal depths ($< 8\text{ km}$) (Spang et al., 1979; Mitra and Yonkee, 1985; Engelder and Marshak, 1985). Pressure solution is considered to be the major process responsible for spaced cleavage development (e.g. Alvarez et al., 1978;

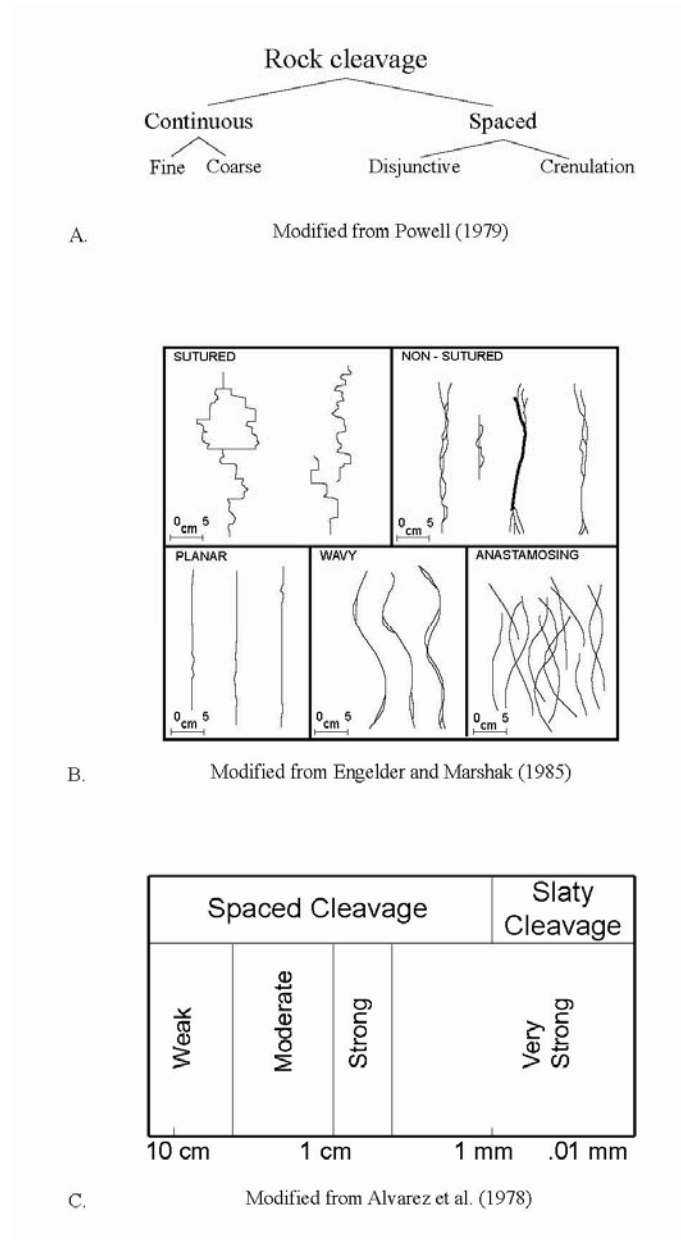


Figure 17. Summary of Cleavage Terminology. A. Types of cleavage based on scale of observation and relationship to bedding; B. Weathered cleavage domain morphology classification; C. Cleavage domain spacing or intensity classification.

Onasch, 1983). Pressure solution is a multi-part process: 1) strain concentrated at grain-to-grain contacts acts to dissolve grain material, 2) dissolved material located in grain-boundary fluid films diffuses to areas of lower strain, and 3) dissolved material precipitates in areas of lower strain along grain contacts (Marshak and Engelder, 1985).

The rate of dissolution is controlled by the magnitude of normal stress across a grain-to-grain contact (Engelder and Marshak, 1985). Pressure solution is dependent on rock-water interaction and, as a consequence, is largely controlled by: 1) amount of pore fluid, 2) amount of fluid circulation, and 3) the percentage of clay-quartz matrix (Engelder and Marshak, 1985; Marshak and Engelder, 1985). Insoluble grains increase the efficiency of the pressure solution process by attracting fluid films to their boundaries, thereby establishing paths for the diffusion of dissolved solute (Engelder and Marshak, 1985). A minimum of 10% clay-quartz matrix is a requirement for the development of pressure solution induced cleavage (Wanless, 1979).

The term grain in this paper, when referring to grain-boundary dissolution, is a coherent structural particle. In this study, cleavage is investigated in a micritic dolomitic limestone. The pressure solution process is therefore dissolving the boundaries of micritic dolomite crystals.

Cleavage Classification and Controls on Development

Classification of Cleavage

Cleavage classification is based on domainal spacing, and the shape of cleavage domains. These attributes vary with rock composition and strain magnitude associated

with structural geometry. Domainal spacing is the perpendicular distance between individual cleavage domains. Alvarez et al. (1978) classified cleavage according to domainal spacing distinguishing between weak (> 5 cm), moderate (1-5 cm), strong (0.5-1 cm), and very strong (< 0.5 cm) (Figure 16). Wanless (1979) classified domain morphology by describing the outcrop pattern of weathered cleavage domains. Following the Wanless classification, Engelder and Marshak (1985) described cleavage domain morphology as sutured, non-sutured, planar, wavy, or anastomosing (Figure 17). This classification does not imply information regarding the process of cleavage formation, and is therefore favored over genetic morphology classifications.

Lithologic Controls

The stratigraphic distribution of cleavage within a deformed terrane is controlled by lithology. Rock units that contain higher amounts of clay have been observed to develop cleavage, while pure limestones or sandstones deform by intracrystalline mechanisms resulting in undulose extinction, deformational bands, and/or twin lamellae (Engelder and Marshak, 1985). Changes in rock composition within the same lithologic unit may control the distribution of cleavage if the clay-quartz content varies considerably. Cleavage is most commonly observed in argillaceous limestones, and to a lesser degree, impure dolomites and sandstones (e.g. Wanless, 1979).

Calcite, the dominant mineral in limestones, has a higher solubility rate than dolomite (Figure 18). Since the strain rate for pressure solution is proportional to the solubility of calcite/dolomite (and to diffusivity), a higher strain rate is needed to develop

cleavage in dolomitic rocks than is necessary for cleavage development in limestone lithologies (Schweitzer and Simpson, 1986; Mitra and Yonkee, 1985).

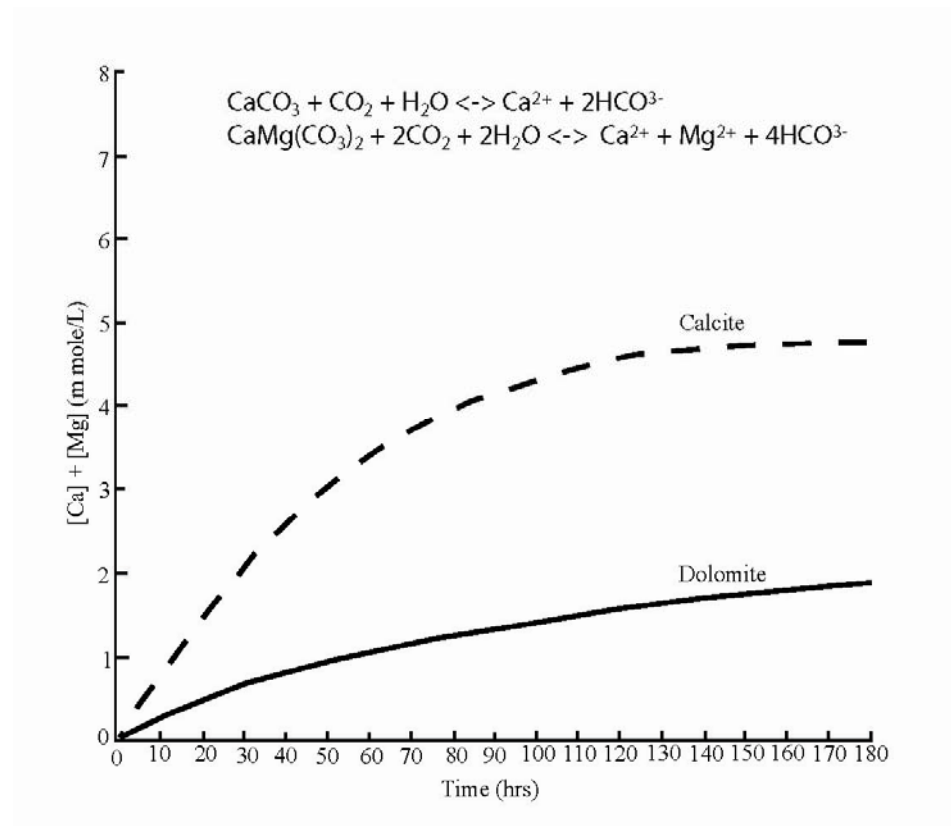


Figure 18. Calcite and dolomite solubility curves illustrating a lower solubility rate for dolomite as compared to limestone. Modified from Herman (1982).

Cleavage intensity is directly related to the amount of clay in a given lithologic unit. Units with high clay content (>15%) are more susceptible to cleavage development and therefore can display closely spaced cleavage domains (Wanless, 1979; Engelder and Marshak, 1985; Marshak and Engelder, 1985). Domain morphology is also strongly controlled by rock composition (Wanless, 1979; Engelder and Marshak, 1985). In general, rock units that contain more than 20% clay material will display planar or non-sutured domains while units with at least 10% clay content will have sutured or pitted

cleavage domains (Wanless, 1979; Engelder and Marshak, 1985). Also, rock units that contain fossils or chert may display sutured cleavage morphology as the cleavage domains are deflected by these inhomogeneities.

Structural Controls

Cleavage may vary in intensity and domain morphology within the same rock unit as a function of strain distribution related to structural position (Alvarez et al., 1978). Cleavage intensity greatly increases in areas of high strain such as overturned limbs and along fault zones (the higher the strain, the closer spacing of cleavage domains). Field observations indicate that cleavages that develop in zones of low strain will exhibit wavy morphology whereas in areas of high strain they tend to be dominantly planar (Gray, 1981; Marshak, 1983).

Cleavage domains have been shown to form perpendicular to maximum finite shortening direction (e.g. Wanless, 1979; Onasch, 1983). Structural analysis of cleavage domain orientation reveals cleavage-structure geometric relationships that are utilized to deduce the evolution of a deformed terrane. Relative timing of cleavage development is inferred by cross-cutting relationships between cleavage and structural features.

Three common geometric relationships exist and include: 1) fanning cleavage, 2) axial planar cleavage, and 3) transect cleavage (Figure 19).

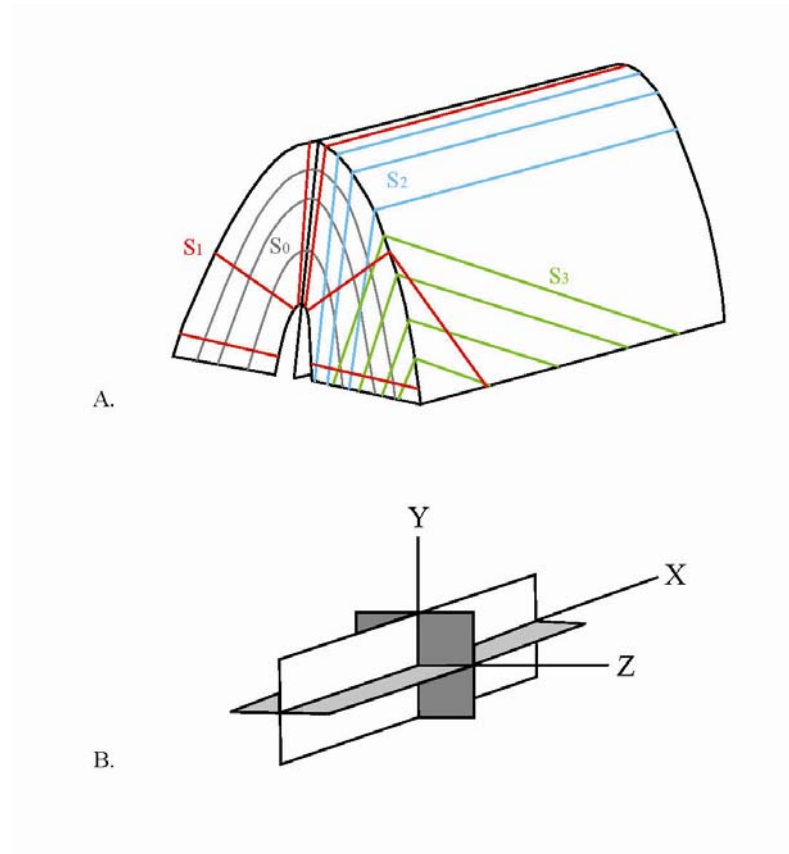


Figure 19. Summary diagram of cleavage orientation A. Cleavage-fold relationships; S_0 indicates bedding; S_1 shows fanning cleavage; S_2 shows axial planar cleavage; S_3 shows transect cleavage. B. Strain axes; Axial plane of fold in A lies in the XY plane.

Cleavage can form perpendicular to bedding during early layer-parallel shortening as a precursor to faulting and folding as a result of shear movement between two beds with contrasting ductility (Ramsay, 1963; Gray, 1981; Marshak and Engelder, 1985). Cleavage domains are then subsequently rotated during folding, producing a fanning geometry about the fold axis (e.g. Gray, 1981).

Frequently, cleavage domain orientation is parallel to sub-parallel to local fold axial surfaces. This geometric relationship implies that previously formed cleavage has

been reoriented in response to fold formation to lie within the plane of the fold axis, or that the initial timing of cleavage development overlapped with the formation of the fold (Engelder and Marshak, 1985; Marshak and Engelder, 1985). Further evidence of the latter relationship is the intensification of cleavage in overturned fold limbs or in hinge zones of tight folds (Mitra and Yonkee, 1985).

Transect cleavage is neither fanning nor axial planar. Transect cleavage can be developed by various mechanisms. Cleavage may develop during initial flexural-slip folding followed by progressive fold flattening that passively rotates selective cleavage planes. This mechanism produces partial cleavage fans. Cleavage may also be reoriented during backthrusting and/or as younger thrust sheets ramp up-section. Adjustment of the deforming thrust sheet related to along-strike variations in the regional fold-and-thrust belt can also cause late-stage cleavage development (Yonkee, 1983; Mitra and Yonkee, 1985; Marshak and Engelder, 1985). Local late-stage folds develop as thrust sheets climb up-section over foreland footwall ramps (Mitra and Yonkee, 1985; Coogan and Royse, 1990). Cleavage that forms in association with foreland footwall structures often has an axial planar relationship to second-order late-stage folds, consequently cross-cutting first-order pre-existing structures (Mitra and Yonkee, 1985; Coogan and Royse, 1990). Lastly, cleavage that strikes at high angles to fold-and-thrust structures may have formed in response to a younger, unrelated tectonic event.

METHODS OF ANALYSIS

Outcrop Methods

Classification of Morphology

Outcrop observations of cleavage domain morphology in Kk2a were collected during detailed field mapping of the Sandy Hollow field area. Morphology descriptions were guided using the morphology classification scheme of Engelder and Marshak (1985) to determine lithologic and local structural controls that may have affected cleavage development (Figure 17).

Classification of Cleavage Intensity

Cleavage intensity outcrop measurements were recorded as the perpendicular distance between individual cleavage domains in centimeters with an accuracy of ± 2 mm. Ten to fifteen measurements were taken and averaged at each outcrop site. The domainal spacing classification scheme of Alvarez et al. (1978) was used in this study to characterize cleavage as weak (> 5 cm), moderate (1-5 cm), strong (0.5 – 1 cm), or very strong (< 0.5 cm) (Figure 17). Intensity measurements were tied to a GIS/GPS database as a spatial attribute. Maps of intensity variability throughout the field area were produced from these data. Bedding dip angle and cleavage intensity values from the same field station were extracted from the GIS database. Bar graphs were produced to compare these values, and to analyze possible relationships between fold and cleavage development.

Collection of Oriented Samples

Oriented samples were collected using the procedure outlined by Compton (1984, p. 46). The extraction of oriented samples was not possible at all locations due to poor exposure and/or because the sample would fall apart before the extraction was complete. Thirty-three oriented samples were collected from field locations throughout the Sandy Hollow area to aid in the production of oriented thin sections. Only twelve samples remained intact from the field to the rock preparation laboratory due to the brittle nature of Kk2a.

Collection of Structural Orientation Measurements

Orientation of cleavage and bedding planes were measured using a Brunton compass and recorded in the right-hand rule form. Most outcrops contained more than one cleavage population, distinguished by average orientation. Several cleavage planes of similar orientation were measured within the same outcrop, and the mean orientation was recorded to ensure accuracy was not affected by domain morphology variation.

Laboratory Methods

Thin Section Investigation

Six out of twelve oriented samples survived billet preparation. Therefore, only a limited microscopic investigation was completed. Thin sections were cut perpendicular to cleavage domains. Microscopic investigations were conducted on six oriented thin sections using a petrographic microscope (Nikon Eclipse Lv 100 POL) with a mounted digital camera. Photomicrographs were taken at magnifications ranging from 20x to

200x in plane polarized light with a few taken in cross-polarized light to illustrate the presence of calcite. Photomicrographs reflect the true orientation of cleavage domains with the top of the picture representing the top of the slide producing an oriented photomicrograph.

Microscopic morphologic characteristics of individual domains were documented by recording the overall cleavage domain shape and perpendicular domain thickness. Microscopic intensity measurements were recorded by measuring domain spacing in micrometers (μm) and converted to millimeters (mm).

Chemical Dissolution

Chemical dissolution analysis was performed to determine the percent- by-weight of insoluble material within samples of Kk2a. Hand samples with representative cleavage were taken from the Ziegler anticline nose, the west limb of the Creasey Gulch anticline, and the east limb of the Sandy Hollow anticline (see Appendix C for the rock sample location map). Unweathered rock samples were crushed using a disk mill. Crushed samples were sorted to a size of 1.5Φ using a mechanical sieve. Fifteen grams of each sample were carefully selected to ensure metal contamination from the mill was not introduced to the sample. The sample particles were then reduced to powder form using a porcelain mortar and pestle to increase the surface area to effectively accelerate chemical dissolution. Three powdered samples for each field location were then weighed using an electronic balance to an accuracy of one ten-thousandth of a gram.

The samples were then transferred to a glass microfibre filter (90 mm ø) and placed inside a porcelain funnel. The funnel was fitted with a rubber stopper to an Erlenmeyer flask with air suction. Approximately 14 mL of 6 M HCL was used to dissolve each sample. The reaction was considered complete when the powdered sample stopped effervescing. The sample was then rinsed with distilled water to drive off any remaining acid. The sample and filter were then removed, covered, and allowed to dry for 48 hours to ensure all water had evaporated. Finally, the sample was weighed and calculations were made to determine the percent-by-weight of insoluble materials within the sample.

X-Ray Diffraction (XRD)

XRD analysis was conducted on a Scintag XGEN 4000 diffractometer, using CuK α radiation. Four powdered samples (three insoluble residue samples and one undissolved sample) were put onto side-load random powder mounts and analyzed from 4° to 65° 2θ with step size of 0.02° and a step scan rate of 0.04° per minute. Mineral identification was determined using Scintag Inc. DMSNT software by comparing experimental d-spacing values, and d-spacing values published in the International Centre for Diffraction Data (ICDD) database.

Stereographic Analysis

Cleavage domain and bedding orientation data were tied to a GIS/GPS database to preserve the coordinates of each measurement. This also allowed for the production of

detailed outcrop maps that illustrate cleavage-bedding relationships. Equal-area, lower-hemisphere stereonet projections were produced and analyzed using RockWare StereoStat v. 1.7.4. Manual stereonet methods were also employed to ensure the accuracy of numeric results produced from the StereoStat software.

Cleavage Data

Several geometric cleavage populations were recognized and grouped according to average strike and dip. It was therefore assumed that cleavage populations that exhibit similar geometries formed cogenetically. Analysis was as follows: 1) cleavage poles were plotted and contoured using a 1% area contouring method with a contour interval of 2 sigma, and a smoothing technique of inverse area square (method of Vollmer, 1995); 2) cleavage poles were analyzed using the Fisher method (1953) to compute the geometric mean cleavage pole; and 3) bedding π – girdle and π – point were plotted to represent the average fold orientation for the Sandy Hollow field area to reveal geometric cleavage-structure relationships.

OBSERVATIONS

Variable cleavage was documented throughout the Sandy Hollow field area within Kk2a. Three groups of cleavage were recognized based on average planar domain orientation. However, groups 2 and 3 are collectively analyzed within the intensity section of this chapter given that the average orientation of these groups only varied slightly. Groups 2 and 3 will be further joined as one population of cleavage within the Discussion chapter.

Cleavage Domain Morphology

Mesosopic Observations

Cleavage that developed within Kk2a exhibited dominantly planar morphology consistent throughout the Sandy Hollow field area (Figure 20). In some areas, the cleavage domains seemed to terminate into a wavy or non-sutured pattern towards the top or bottom of individual beds (Figure 21).

Microscopic Observations

Domain shape in thin section varied from roughly planar to sutured (Figures 22 & 23). In all documented cases, domains that are dominantly planar are also thicker (Figure 22). For example, Figure 22A shows a planar domain with a thickness of 62.5 μm ; Figure 22B shows a sutured domain with a domain thickness of only 37.5 μm . Two types of domain suturing were observed, straight sutures and rounded sutures. Figure 22B illustrates a straight sutured domain with pitted sections linked by perpendicular domains.

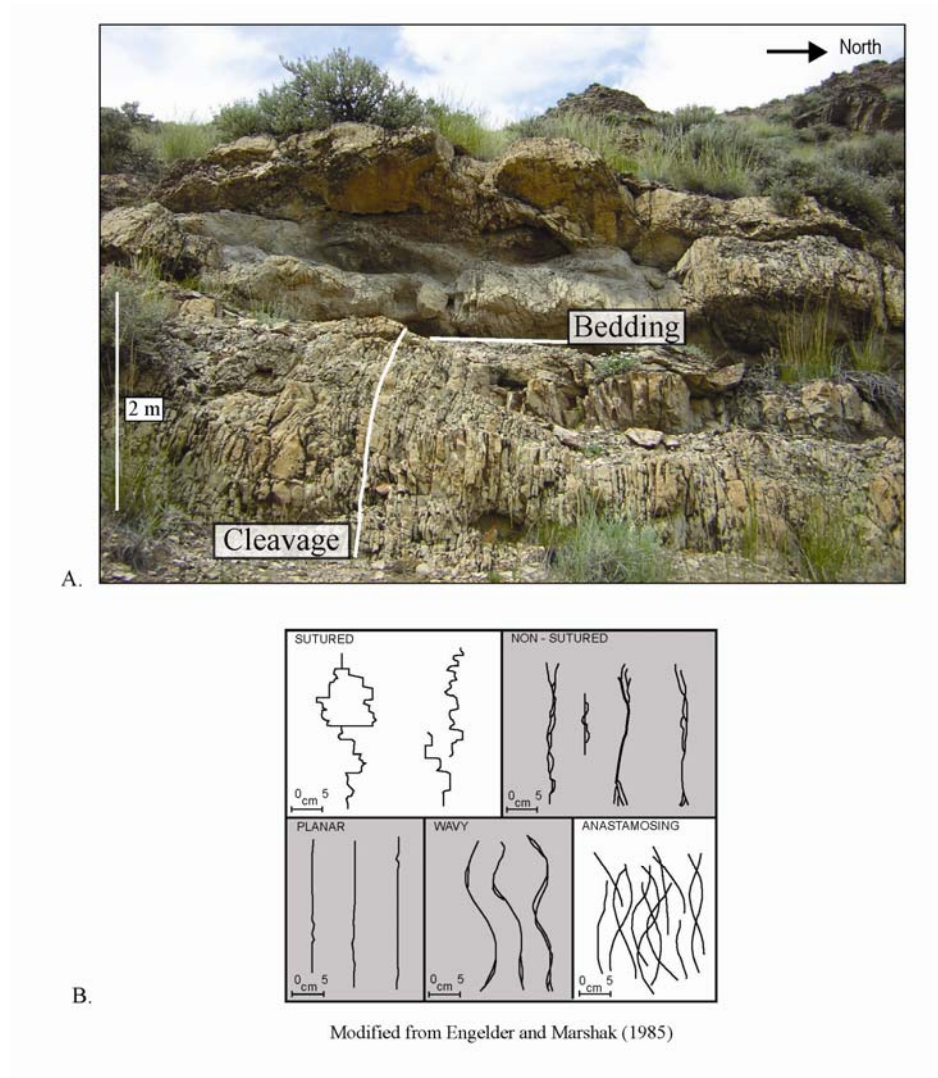
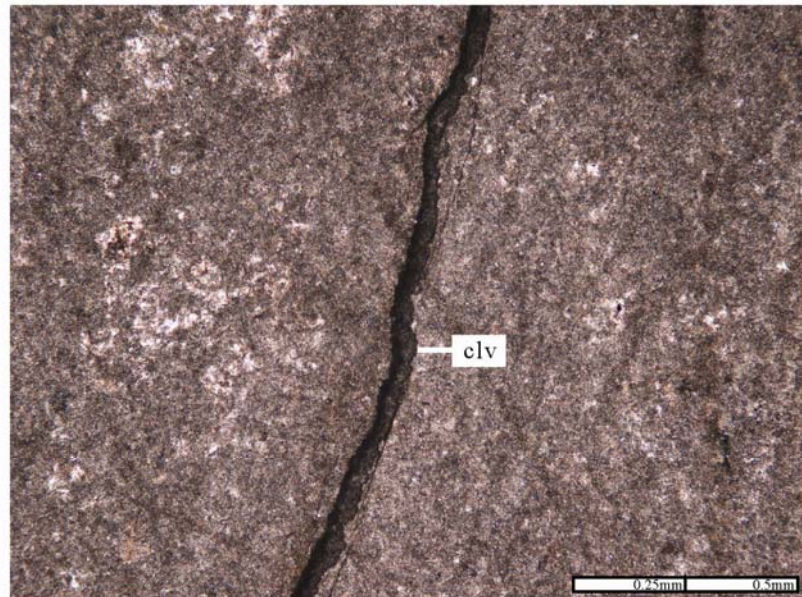


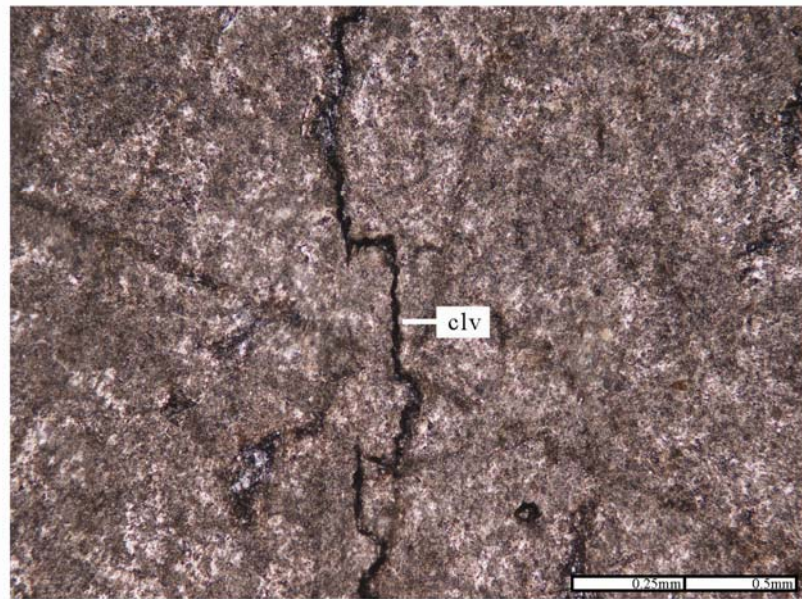
Figure 20. Outcrop observation of cleavage domain morphology. A. Kk2a outcrop along the west limb of the Sandy Hollow anticline illustrating planar cleavage morphology and relationship to bedding. B. Gray area indicates range of cleavage morphology classification in the Sandy Hollow field area.



Figure 21. Outcrop observation of wavy cleavage morphology. Note the bottom of the picture is the bottom of the bed. The scale north arrow reflects true geographic direction.

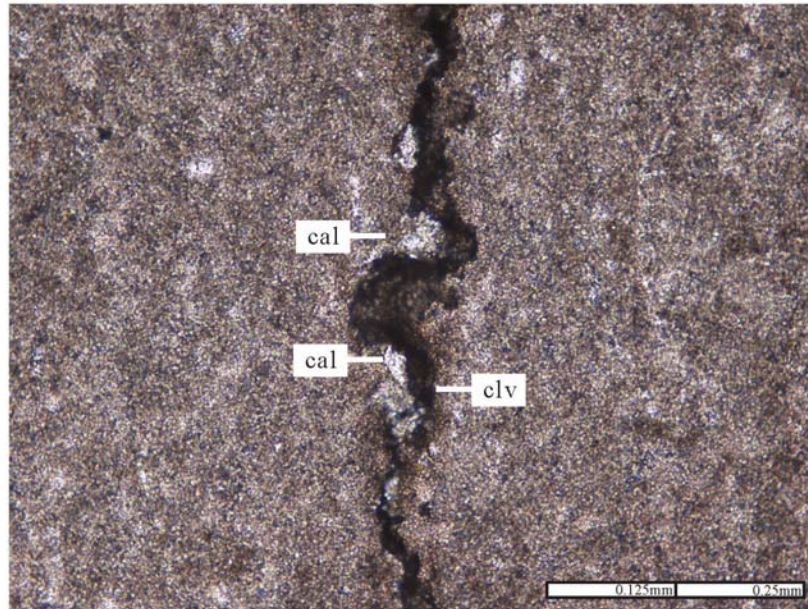


A. Planar morphology; seam thickness = $62.5\ \mu\text{m}$

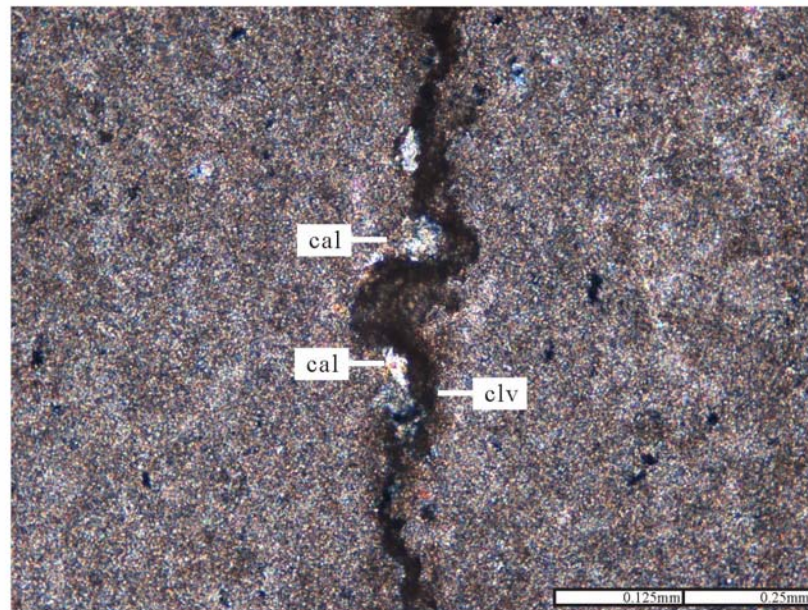


B. Highly sutured morphology; seam thickness = $37.5\ \mu\text{m}$

Figure 22. Microscopic observation of cleavage domain morphology. Both microphotographs were taken in plane polarized light. A. Cleavage morphology is dominantly planar. B. Cleavage morphology is highly sutured and thin. Note that lighter linear features shown in the background of the microphotographs are artifacts from the thin section production process.



A. Sutured morphology around calcite minerals;
seam thickness = 35 μm ; PPL



B. Sutured morphology around calcite minerals;
seam thickness = 35 μm ; XPL

Figure 23. Microscopic observation of cleavage domain morphology. Cleavage is sutured around calcite grains. A. Microphotograph taken in plane polarized light. B. Microphotograph taken in cross-polarized light.

Enveloping surfaces of the domain remain parallel to each other, reflecting development perpendicular to principal shortening direction. Rounded sutured domains appear to have been influenced by the presence of large sparry regions within the micritic matrix of the rock unit. In Figure 23, the cleavage domain is seen to curve around the sparry region until continuing on a planar path.

Cleavage Domain Intensity

Mesosopic Observations

Cleavage intensity in Kk2a ranged from > 50 cm to < 1 cm throughout the field area (Figure 24). Cleavage intensity values varied greatly even within the same outcrop probably due to the presence of a weathered “film” on outcrop surfaces that inhibited observations. The majority of intensity measurements, however, taken at the mesoscopic scale would classify cleavage in Kk2a as strong to moderate spaced cleavage (Alvarez et al., 1978).

Spatial variability maps were produced for recognized cleavage groups to illustrate cleavage-structure relationships (Figure 25 and 26). Intensity distribution in relation to fold hinge zones and proximity to thrust faults did not demonstrate a clear pattern. If cleavage is related to folding, it would be expected that cleavage intensity would increase as bedding dip increased. Bedding dip angles as compared to cleavage intensity also did not yield any clear results (Figures 27 and 28).



Spaced Cleavage			Slaty Cleavage
Weak	Moderate	Strong	Very Strong
10 cm	1 cm	1 mm	.01 mm

B.

Modified from Alvarez et al. (1978)

Figure 24. A. Photograph of mesoscopic observation of domain spacing. B. Gray area indicates dominant cleavage intensity through the Sandy Hollow field area classifying cleavage intensity as moderate to very strong.

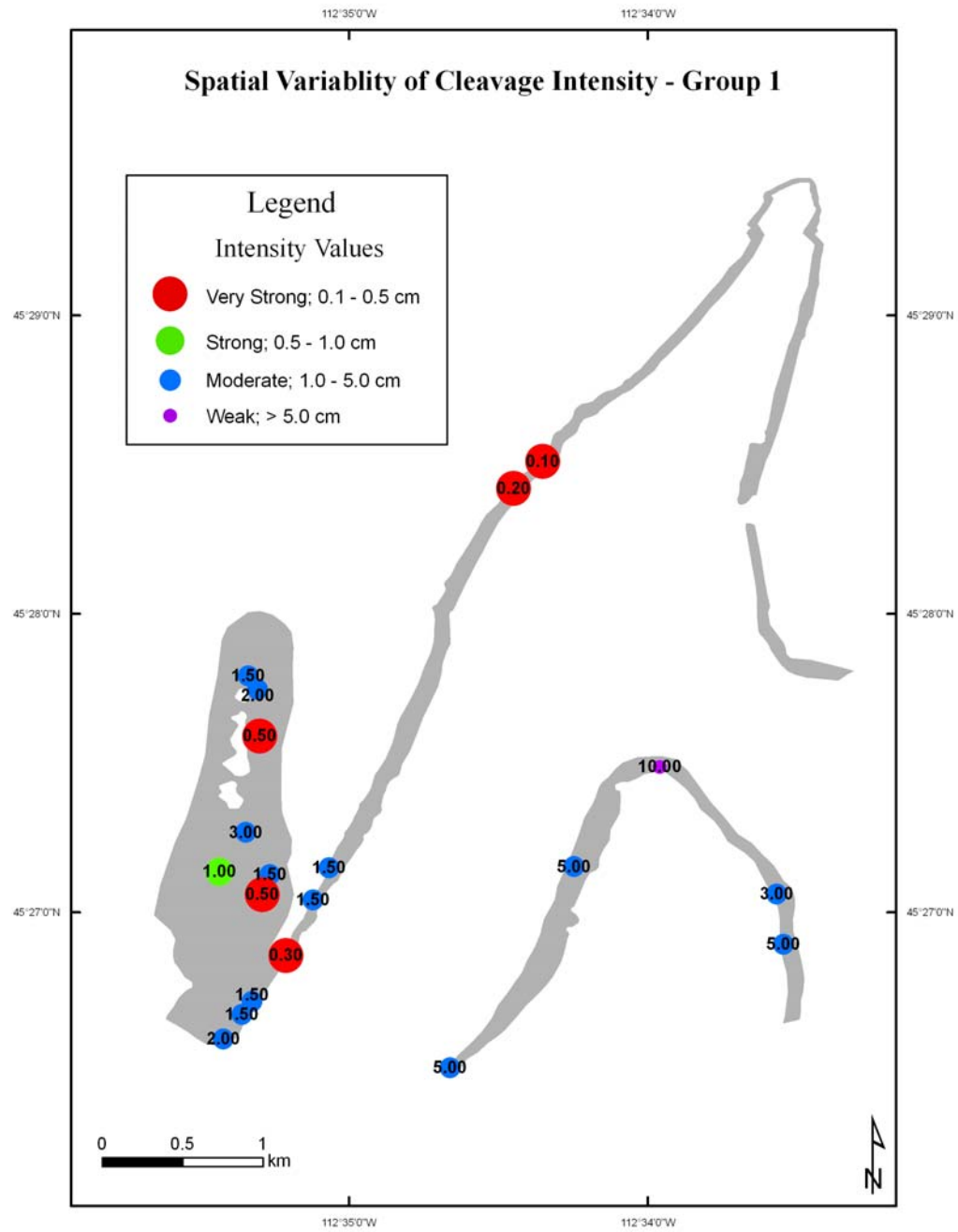


Figure 25. Spatial variability of cleavage intensity for group 1. Lower values indicate increased distance between individual cleavage domains termed strong cleavage.

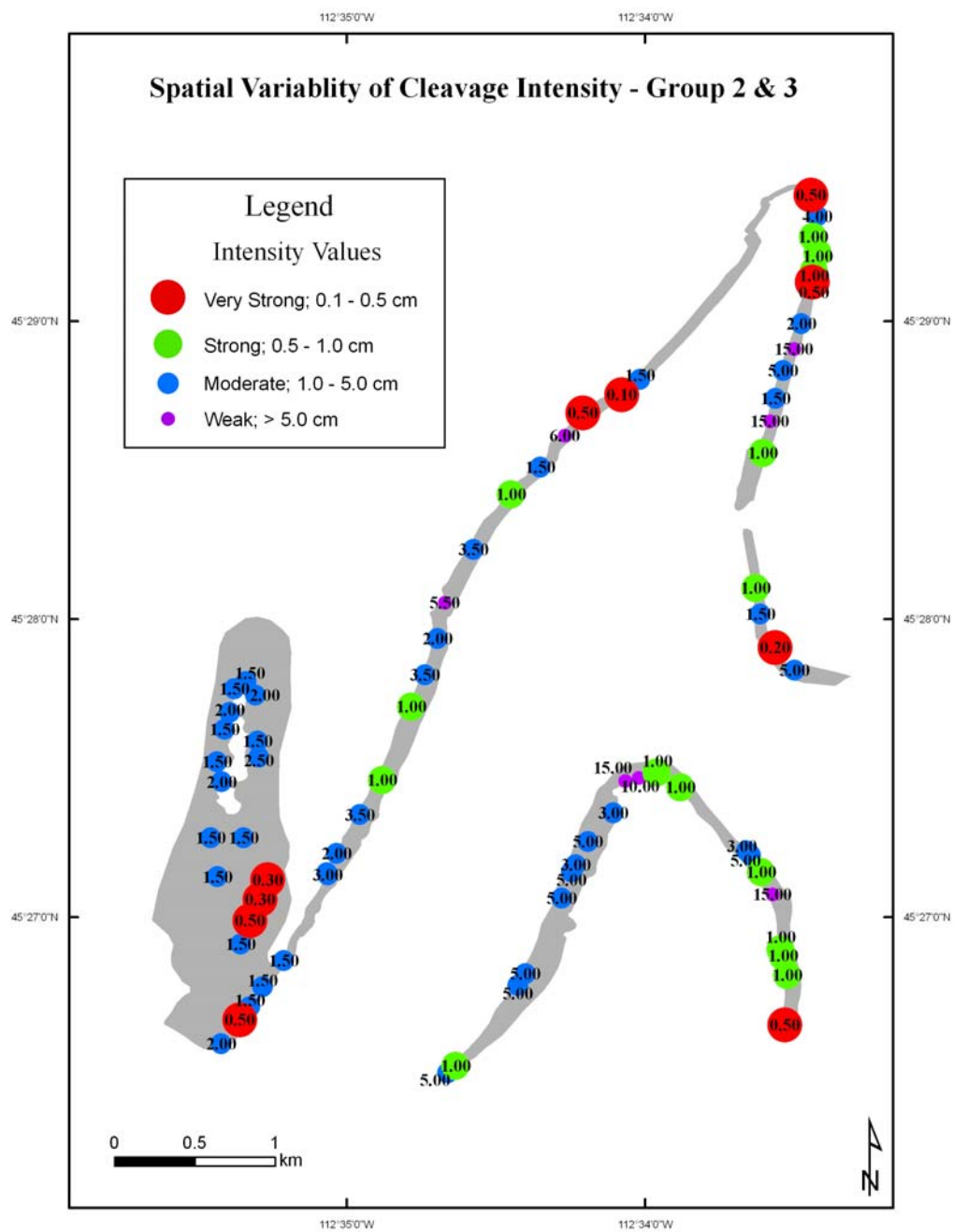


Figure 26. Spatial variability of cleavage intensity for groups 2 and 3. Lower values indicate increased distance between individual cleavage domains termed strong cleavage.

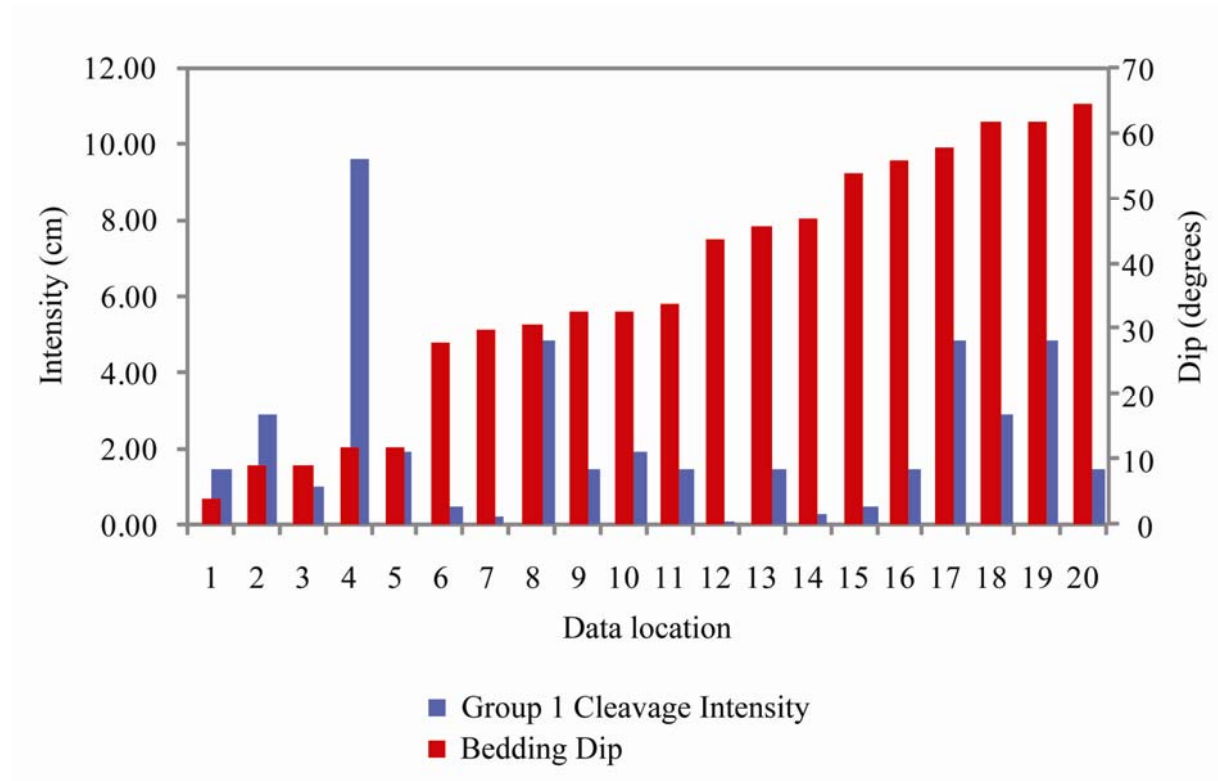


Figure 27. Cleavage intensity for group 1 plotted against bedding dip for the same field location. Statistical analysis (parameters: Bedding dip $\geq 50^\circ$ and Cleavage intensity ≤ 1.0 cm) indicates 6% correlation between intense cleavage and high bedding dip. Bedding has been sorted from low dip to high dip in order to more clearly illustrate the relationship between high bedding dip values and low cleavage spacing values.

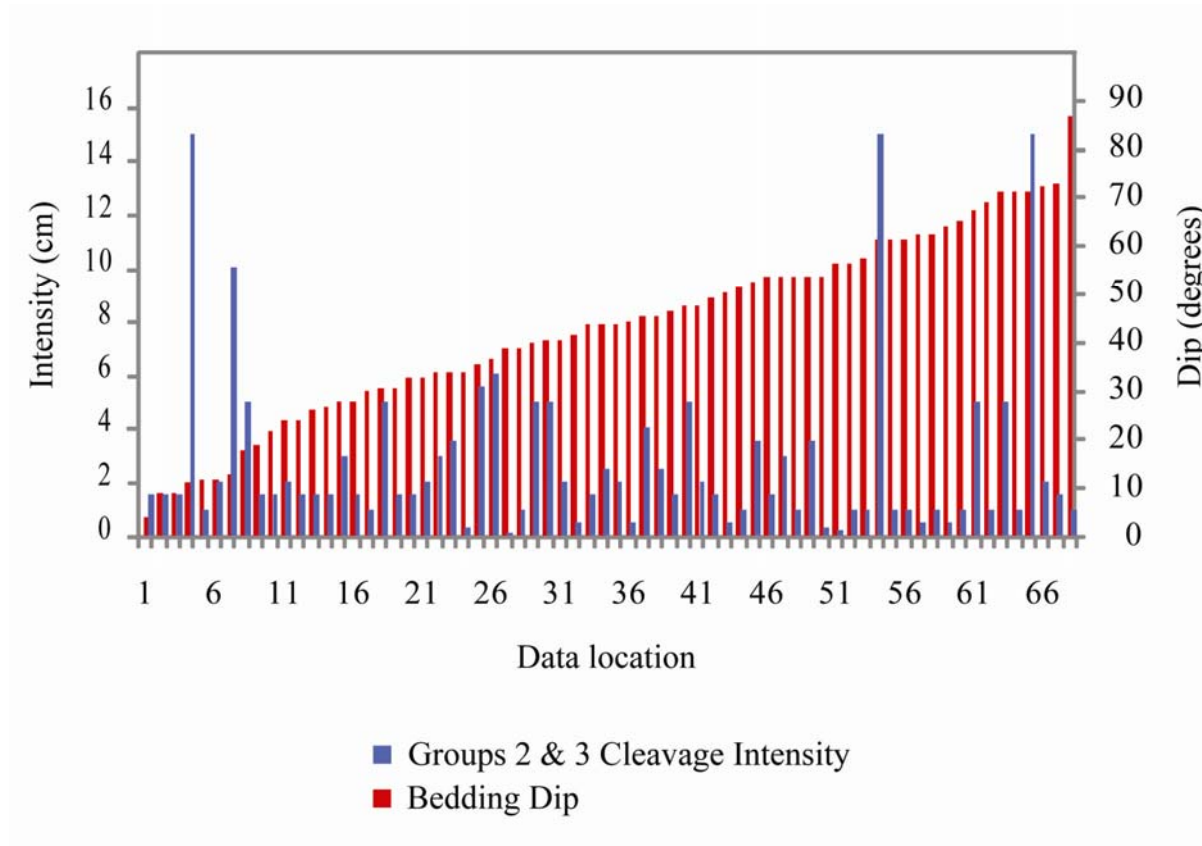


Figure 28. Cleavage intensity for groups 2 and 3 plotted against bedding dip for the same field location. Statistical analysis (parameters: Bedding dip $\geq 50^\circ$ and Cleavage intensity ≤ 1.0 cm) indicates 24% correlation between intense cleavage and high bedding dip. This correlation percentage is probably artificially high due to the relatively large number of cleavage intensity values that are classified as strong. Bedding has been sorted from low dip to high dip in order to more clearly illustrate the relationship between high bedding dip values and low cleavage spacing values.

Microscopic Observations

The maximum domain spacing cannot be distinguished in thin sections due to the limited field of view. However, at the microscopic scale, minimum intensity values are more accurately measured than at the mesoscopic scale. Intensity values measured in thin section fell between 5 – 2 mm, classified as strong spaced to very strong spaced cleavage. In Figure 29, domains A and B are spaced 4.35 mm apart while B and C are only spaced 1.90 mm apart.

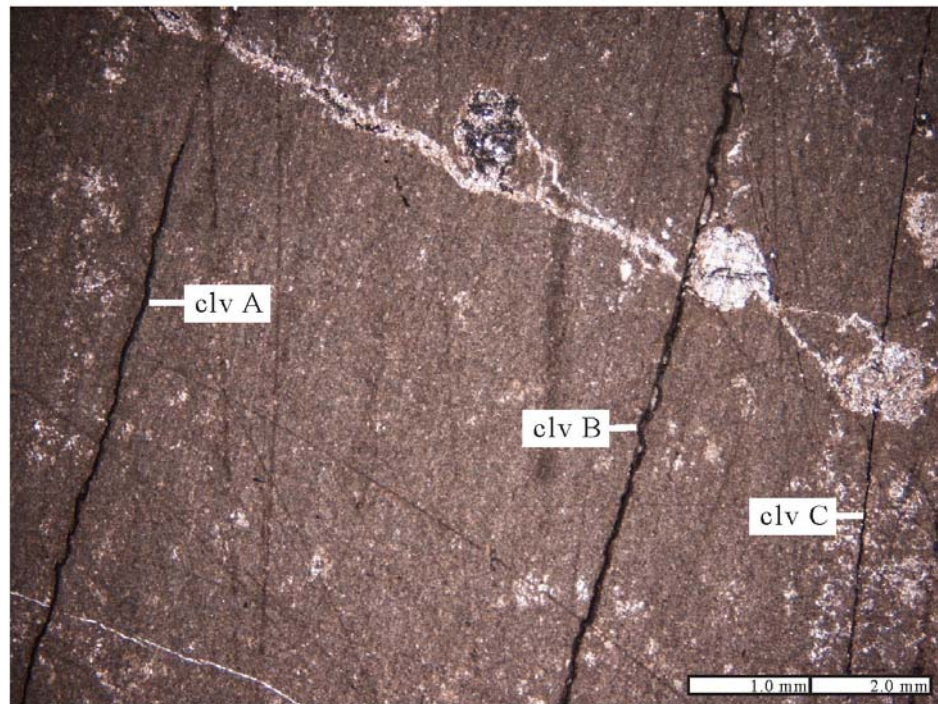
Laboratory Analysis

Chemical Dissolution

Percent of insoluble residue by weight ranged from 28.90% to 32.50% with an overall mean of 31.02% (Appendix C). The percent by weight calculations did not yield significant insoluble lithologic variability within Kk2a and, therefore, can be ruled out as a possible control for intensity variations throughout the field site. However, the results of this analysis did support the minimum insoluble material content of 10% that Wanless (1979) outlined as a requirement for cleavage development.

X-Ray Diffraction

The analysis of XRD data for an undissolved, bulk rock (sample ID 001) showed that the dominate minerals present in Kk2a are dolomite and quartz with small amounts of calcite and clay (Figure 30). The small amount of calcite probably represents sparry regions along cleavage domain boundaries, and secondary replacement of fossils as seen in thin section (Figures 23 and 31). The diffractogram illustrates the efficiency of the



Domain Intensity, A- B = 4.35 mm; B-C = 1.9 mm, PPL

Figure 29. Microphotograph documenting cleavage domain spacing. Microphotograph was taken in plane polarized light. Note that lighter linear features shown in the background of the microphotographs are artifacts from the thin section production process.

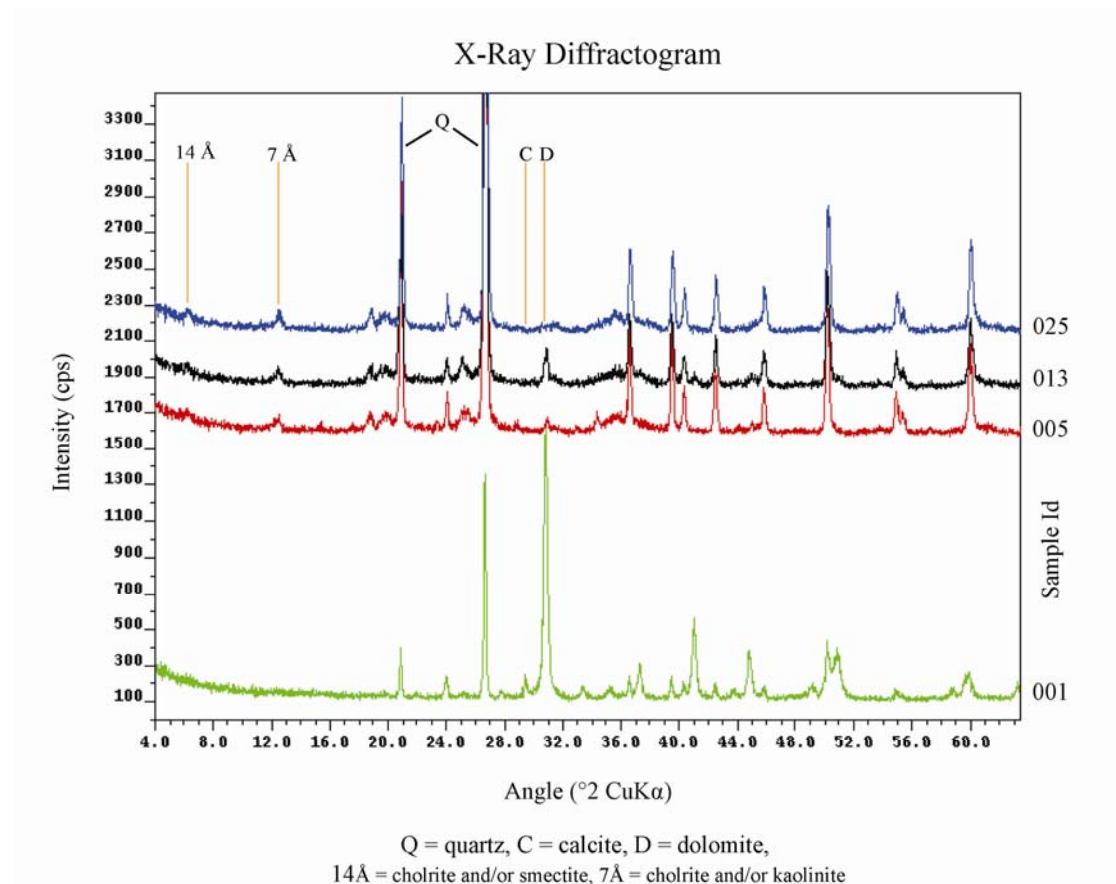


Figure 30. X-Ray diffractogram for an undissolved Kk2a sample (001) and three residue samples (005, 013, 025). Bulk sample results show that Kk2a is mainly composed of dolomite and quartz. Residue samples show the efficiency of the chemical dissolution process with minor amounts of dolomite and a strong signal of quartz and clays. See Appendix C for a location map of rock samples used in this analysis.

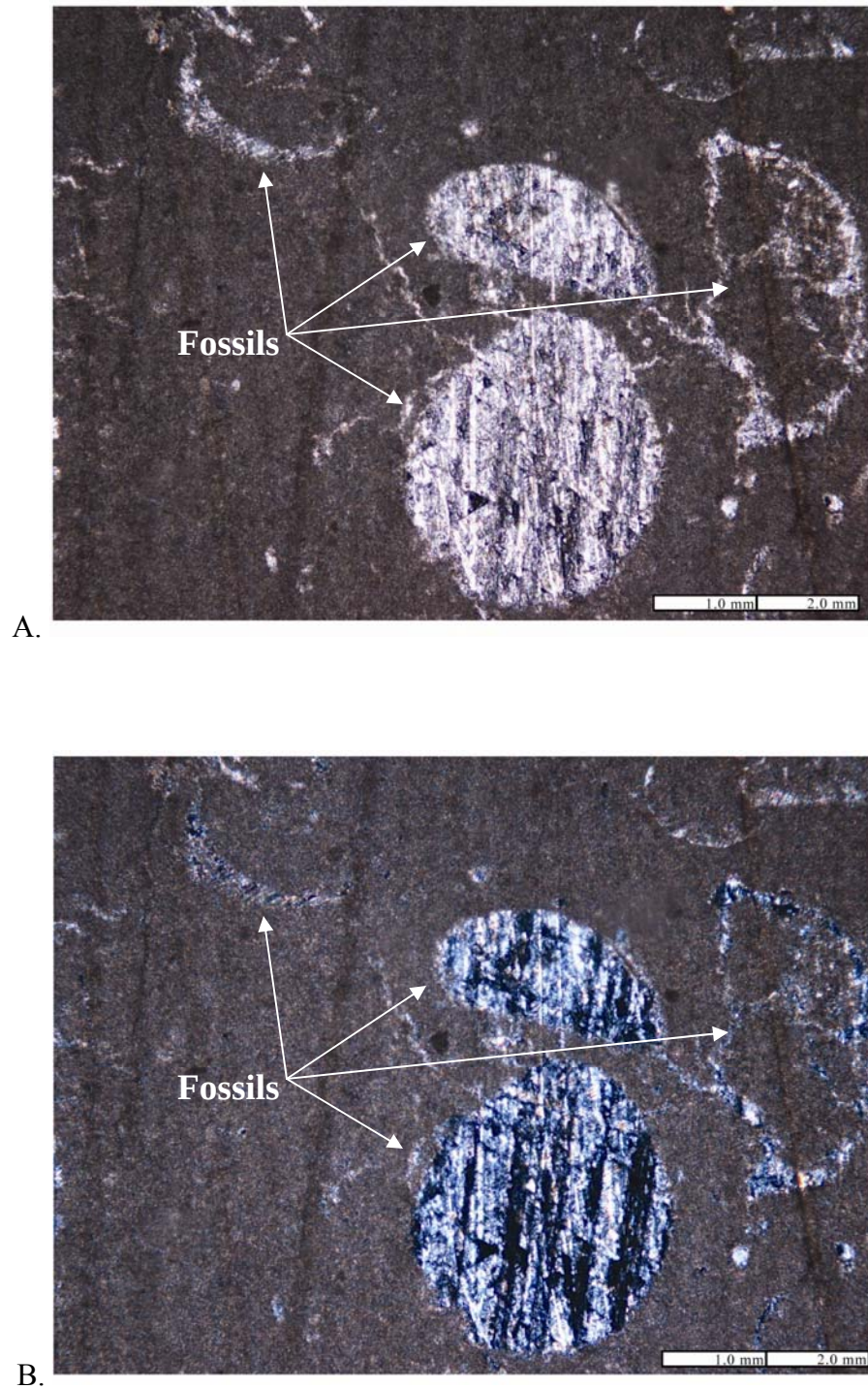


Figure 31. Examples of fossils contained in Kk2a. A. Microphotograph taken in plane polarized light. B. Microphotograph taken in cross-polarized light. Fossils probably represent the majority of calcite found in Kk2a from XRD analysis. Note that lighter linear features shown in the background of the microphotographs are artifacts from the thin section production process.

dissolution process showing a low concentration of dolomite and calcite in the dissolved samples. The diffractogram also shows 7 Å and 14 Å peaks in the clay region that represent chlorite (7 Å and 14 Å peaks), smectite (14 Å peaks) and/or kaolinite (7 Å peaks). These data only identify some combination of chlorite, kaolinite and/or smectite. Other chemical analyses would have to be performed in order to further identify the clays in Kk2a.

Structural Analysis

The π -method was used to obtain an average fold axis trend and plunge for all folded bedding data which produced a value of $08^\circ, 007^\circ$. Therefore, fold axis orientation indicates that folds within the Sandy Hollow field area developed as a result of a maximum shortening direction of west-east. This information will be used to deduce cleavage-structure relationships in future sections.

Cleavage

Group 1: Cleavage domains with predominately northeast strike and moderate southeast dip are recognized as group 1 ($n = 18$). Group 1 occurred throughout the field area but was concentrated along limbs of the Creasey Gulch anticline (Figure 32). Contouring results show a concentration of poles to cleavage planes in the northwest quadrant with a Fisher axis value of $54^\circ, 300^\circ$. Similarly, the Fisher analysis gave an average cleavage strike and dip of $030^\circ, 36^\circ$ E.

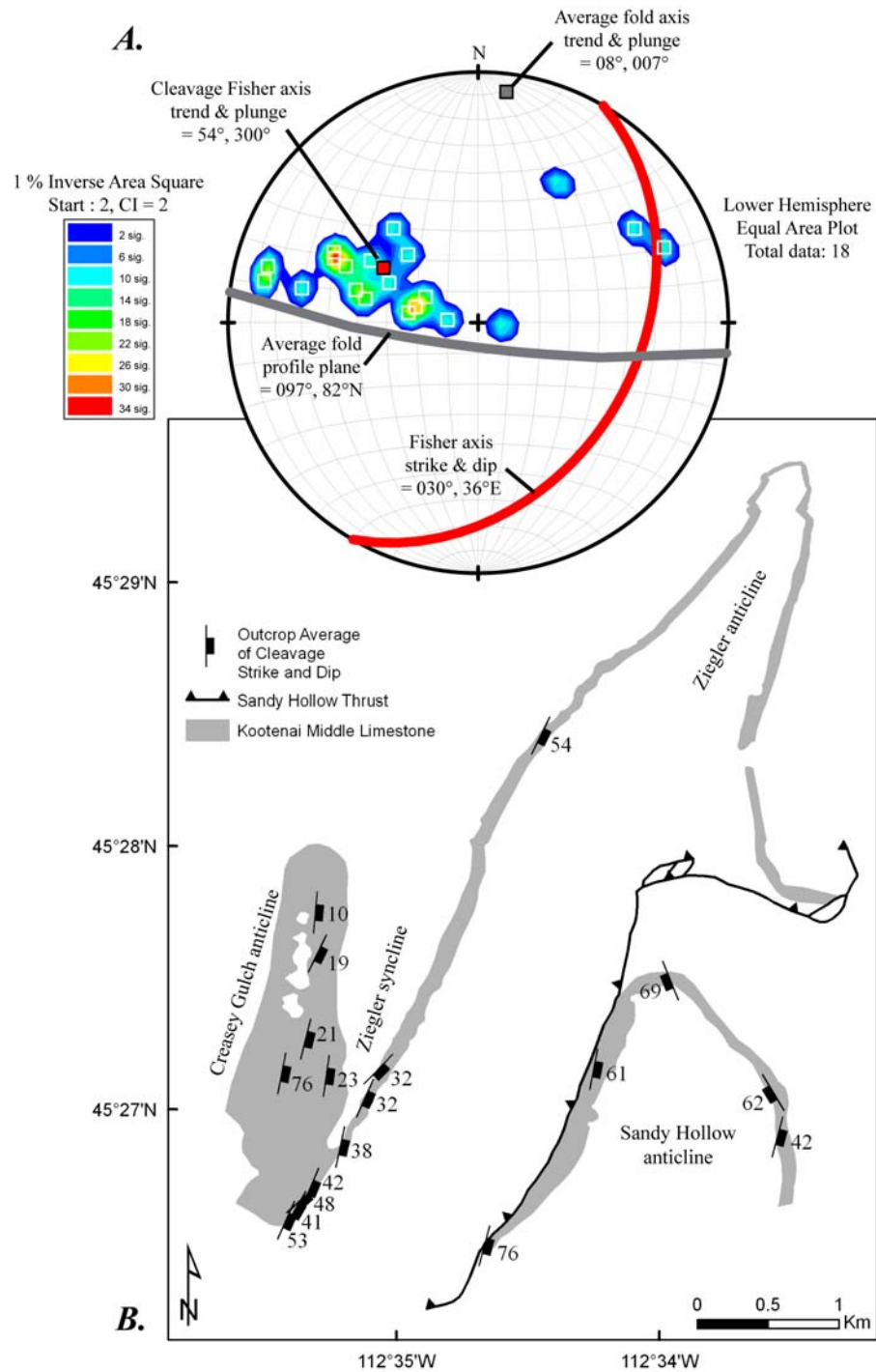


Figure 32. Geometric data for group 1 cleavage. A. Equal-area, lower-hemisphere projection showing contoured poles to cleavage planes with associated Fisher axis indicated by red box. Note contour range is in units of sigma. Best-fit great circle and fold axis shown by gray line and gray box, respectively. B. Outcrop map of Kk2a showing location for plotted orientation data. See Appendix D for complete dataset.

Group 2: Group 2 cleavage is recognized by east-west strike and steep north dip ($n = 25$). Group 2 occurs only in the hanging wall of the Sandy Hollow thrust (Figure 33). Cleavage pole contouring illustrates a concentration in the central southern portion of the stereonet projection with a Fisher axis trend and plunge of 23° , 185° . The average orientation of cleavage in group 2 expressed as a plane is 275° , 67° N (Figure 33).

Group 3: Cleavage with mainly east-west strike and steep south dip are recognized as group 3 ($n = 71$). Group 3 cleavage exist in abundance at every measured outcrop throughout the Sandy Hollow field area (Figure 34). Contouring results showed excellent concentration of cleavage poles in the north central section of the stereoplot. Average orientation of group 3 cleavage planes was calculated to be 090° , 70° S with a Fisher axis trend and plunge of 20° , 360° (Figure 34).

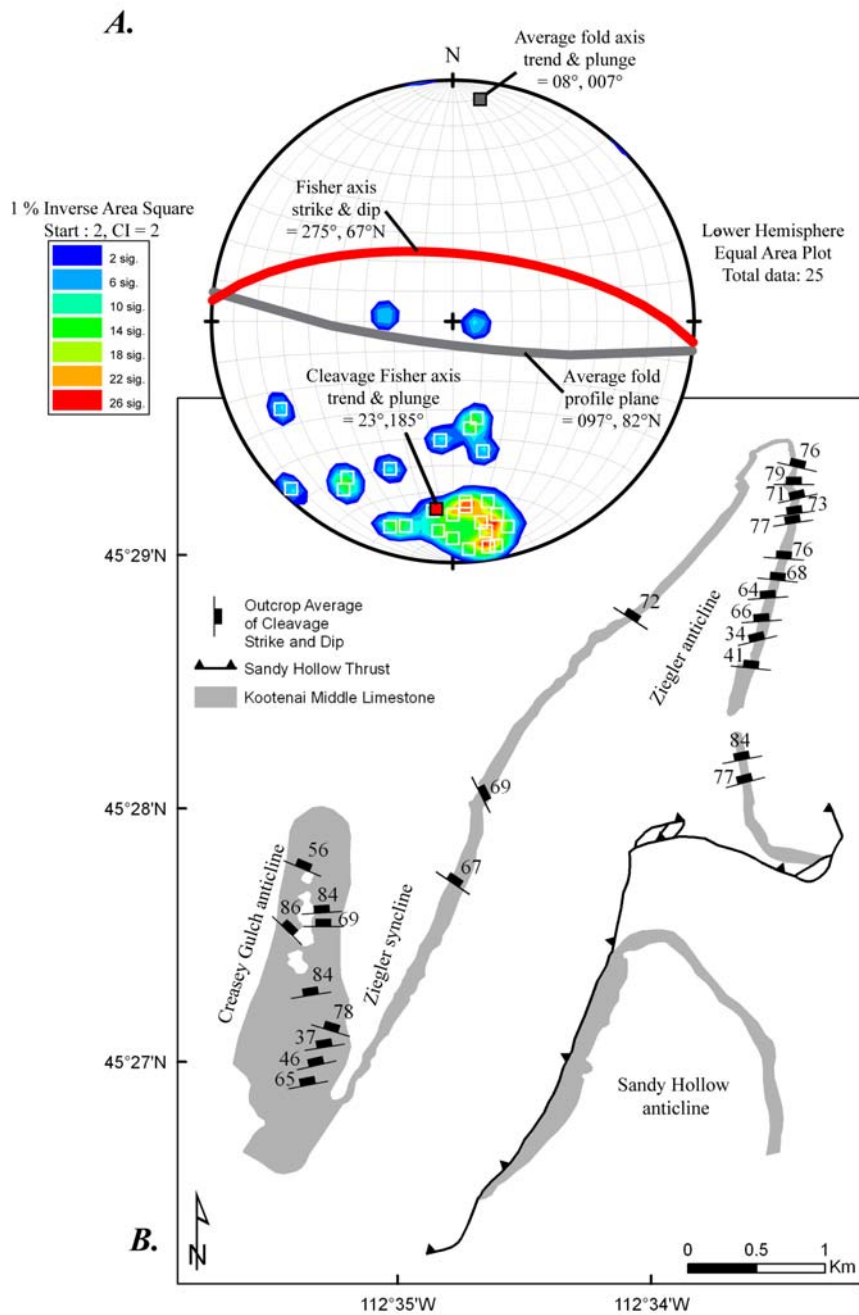


Figure 33. Geometric data for group 2 cleavage. A. Equal-area, lower-hemisphere projection showing contoured poles to cleavage planes with associated Fisher axis indicated by red box. Note contour range is in units of sigma. Best-fit great circle and fold axis shown by gray line and gray box, respectively. B. Outcrop map of Kk2a showing location for plotted orientation data. See Appendix D for complete dataset.

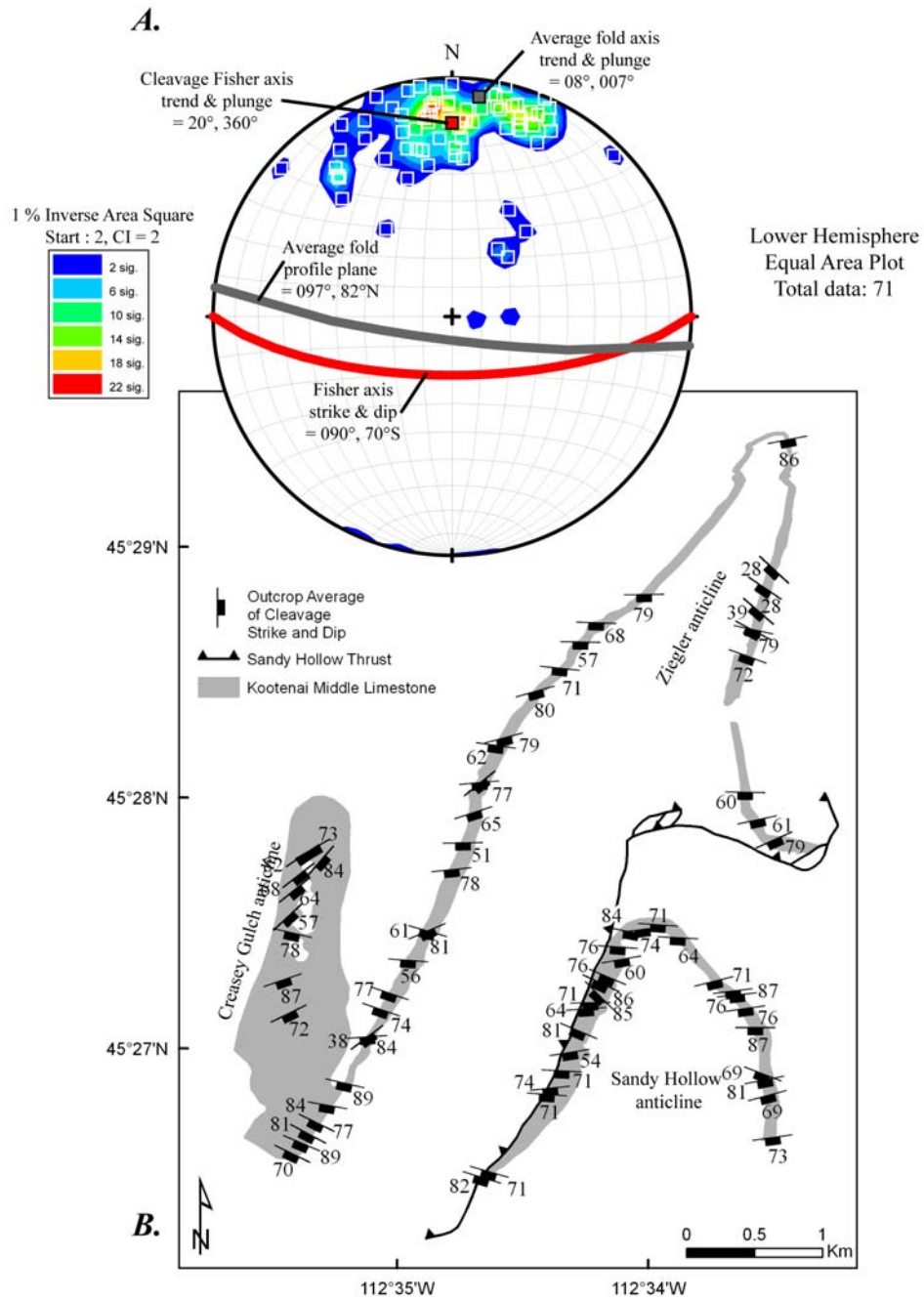


Figure 34. Geometric data for group 3 cleavage. A. Equal-area, lower-hemisphere projection showing contoured poles to cleavage planes with associated Fisher axis indicated by red box. Note contour range is in units of sigma. Best-fit great circle and fold axis shown by gray line and gray box, respectively. B. Outcrop map of Kk2a showing location for plotted orientation data. See Appendix D for complete dataset.

DISCUSSION

Cleavage Domain Characteristics

Cleavage Domain Morphology

Outcrop observations of cleavage in Kk2a classified domain morphology as dominantly planar throughout the field area. Planar morphology in Kk2a is interpreted here to be a result of a generally lithologic homogenous stratigraphic unit accommodating high magnitude strain caused by tectonic shortening. Outcrop observations of wavy to non-sutured morphology towards bedding boundaries may reflect termination geometries of cleavage domains. Wavy to non-sutured geometries are similar to “horse-tailing”, a term usually used to describe terminating geometries of fractures. “Horse-tailing” describes a single surface that branches off as several thinner surfaces. “Horse-tailing” geometries have been cited as evidence for the anti-crack model for cleavage initiation and development (Fletcher and Pollard, 1981). The anti-crack model proposes a mechanism in which the tip of each branch is the site of stress concentration that acts to propagate and displace strain through the rock body (Fletcher and Pollard, 1981).

Microscopic observations of cleavage further indicate sutured domain morphologies. Regions of sparry calcite apparently acted as a barrier to cleavage development, and caused domains to curve around the area creating a rounded sutured domain shape. Straight sutures were also observed, although not as commonly. Lithologic variation was not observed in regions that exhibited straight sutures. However, given the

fine grained nature of Kk2a, the presence of fine grained quartz concentrations acting as barriers should be considered.

Cleavage Domain Intensity

Previous studies have indicated that cleavage domain intensity is controlled by lithologic variations and strain magnitude (e.g. Engelder and Marshak, 1985). Kk2a was found to be relatively compositionally homogenous by the results of sample dissolution and XRD analysis. Thus, major lithologic variation has been discounted as a possible control on cleavage intensity within Kk2a.

Cleavage domain intensity varied greatly throughout the field area. Group 1 cleavage is less abundant with moderate to weak intensity. Spatial patterns for this population illustrate increased intensity along fold limbs and decreased intensity within hinge zones (Figure 25). Comparison of folded bedding dip values to cleavage intensity measurements collected at the same location show a weak association (6%) of higher bedding dips, and more intense cleavage (Figure 27). Groups 2 and 3 are abundant at nearly every outcrop with 94 % of intensity values classified as moderate to strong. Proximity to local structures did not seem to influence cleavage intensity for these groups (Figure 26). Bedding dip compared to intensity measurements for groups 2 and 3 also indicated a weak to moderate positive relationship (24%) (Figure 28). These spatial and structural patterns do not indicate a strong connection between fold geometries and cleavage development.

Lithologic Controls on Stratigraphic Distribution

The stratigraphic distribution of cleavage is a function of mechanical stratigraphy. Dolomite has a lower solubility rate than calcite. A limestone like Kk2a, that has experienced dolomitization, will not develop cleavage as easy as a silty limestone (Figure 18). The second and third units of the informal limestone member of the Kootenai Formation are micritic limestones (Kk2b and c) (Figure 4 and 6). Kk2b and Kk2c exhibit typical cleavage-structure relationships such as fanning and axial planar cleavage in the hinge zone of the Zeigler syncline (Figure 35). Kk2a exhibits atypical cleavage-structure relationships with cleavage striking almost perpendicular to large-scale fold axes. The solubility rate disparity between dolomite and calcite can be used to explain the variability of cleavage development within the three units of the middle limestone member. The upper limestone units probably responded to early layer-parallel shortening with continued cleavage development during fold formation while Kk2a did not form cleavage until fold formation ceased, or during very late-stage fold flattening. Kk2b and Kk2c could have been mechanically exhausted if cleavage evolved over an extended period leading to reduction of pore-fluids and diffusion pathways necessary for the progressive development of cleavage. This hypothesis may explain why Kk2a exhibits different cleavage populations than units directly above it. The amount of shortening, however, experienced by the three limestone units remains unresolved.

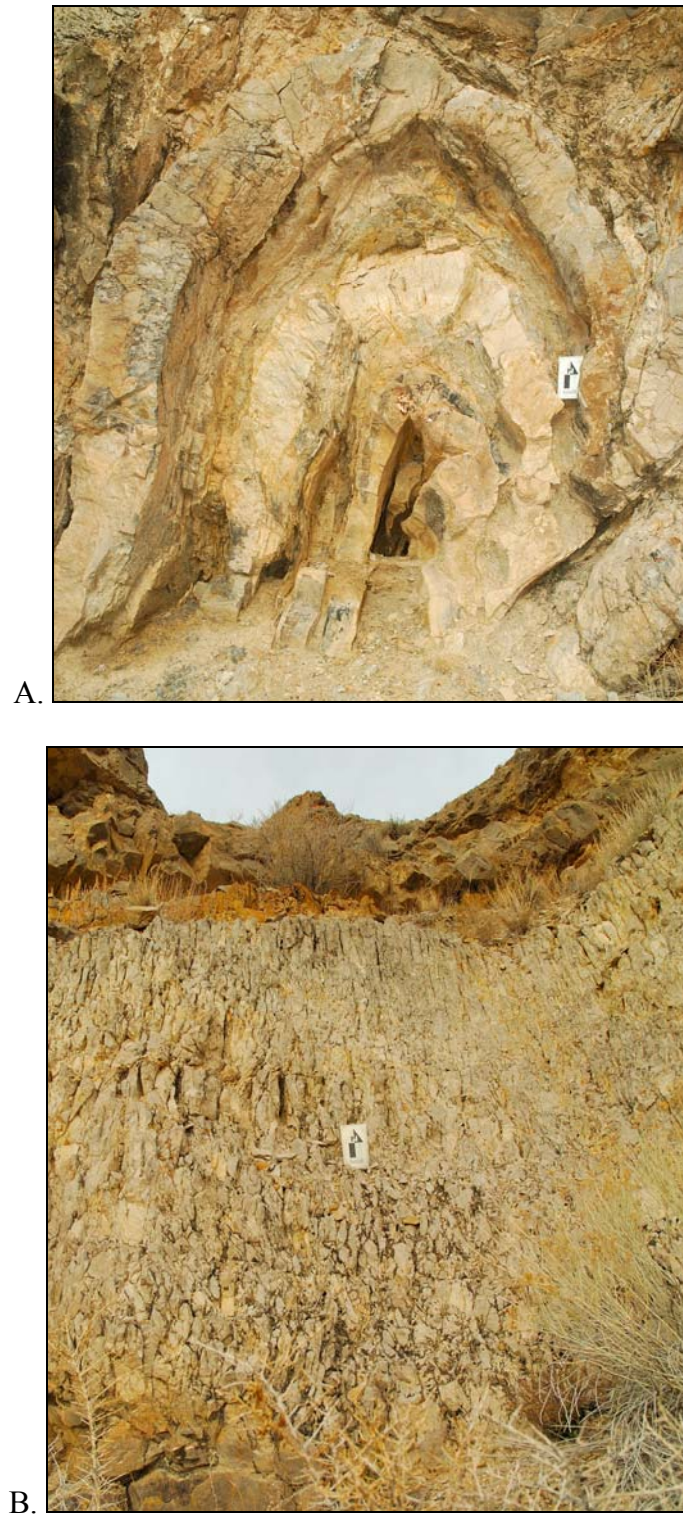


Figure 35. Outcrop observations of Kk2b in the Ziegler syncline hinge zone. A. Cleavage fans around parasitic fold axis. B. Cleavage is parallel to first-order fold axial planes. Photographs are looking to the north. Both photographs taken by Scott McLeod.

Kinematic and Dynamic Interpretations of Cleavage Formation

Relative timing of cleavage development can be inferred from cross-cutting relationships with other structures within the field area. Cleavage planes form perpendicular to the maximum direction of shortening and therefore record finite strain processes operating within the fold-and-thrust system. As previously mentioned three geometric cleavage-structure relationships commonly are observed in fold-and-thrust systems. These relationships can be summarized as follows: 1) cleavage domains that fan about fold axes form during early layer-parallel shortening, and pre-date fold-thrust development; 2) cleavage domains that strike parallel or sub-parallel to axial planes of folds are genetically related to fold formation; and 3) cleavage planes that cross cut first-order local structures form during the final phases of fold-thrust evolution, or form in response to an overprinting younger deformational event. Thus, in the next sections, the average orientation of cleavage populations is utilized to deduce kinematic and dynamic interpretations.

Cleavage group 1 is considered population 1 and further S1 to distinguish this group as the oldest observed cleavage in KK2a throughout the Sandy Hollow field area. Cleavage groups 2 and 3 will be collectively referred to as population 2 and were grouped as such due to the similarity of domain orientations. Population 2 will also be termed S2 to reflect the youngest observed generation of cleavage.

Cleavage Population 1

Cleavage domains recognized in population 1 have an average orientation of 030° , 36° E and are located in the footwall and hanging wall of the Sandy Hollow thrust. The strike of cleavage within this population is sub-parallel to the average trend of local first-order fold axes. However, S1 cleavage planes dip to the southeast at high angles to fold axial planes (Figure 36). Therefore, S1 cleavage can not be considered to be axial planar.

The presence of S1 cleavage in both the hanging wall and footwall implies a late-stage formation during final deformation of the fold-thrust system. This relationship implies that cleavage developed during a similar finite shortening direction as the fold-and-thrust belt but may record late-stage adjustments of the system, perhaps related to continued regional shortening of the fold-and-thrust system against Laramide basement-cored uplifts to the east.

A viable mechanism to facilitate late-stage adjustment of the fold-thrust system includes interaction with basement-cored structures of the foreland (effects of basement buttressing). The Biltmore anticline is the most likely candidate due to the proximity to the field area and orientation of the structure. The Biltmore anticline is considered to have formed on the hanging wall of the Biltmore fault, a high-angle reverse fault that strikes northwest and dips northeast (Figure 6) (Schmidt et al., 1988). If footwall imbrication of the Sandy Hollow-Hogback thrust system progressed further to the east, as suggested by several workers, (Geiger, 1980; Brandon, 1984; Schmidt et al., 1988) interaction of the fold-thrust system with basement-cored structures would be recorded

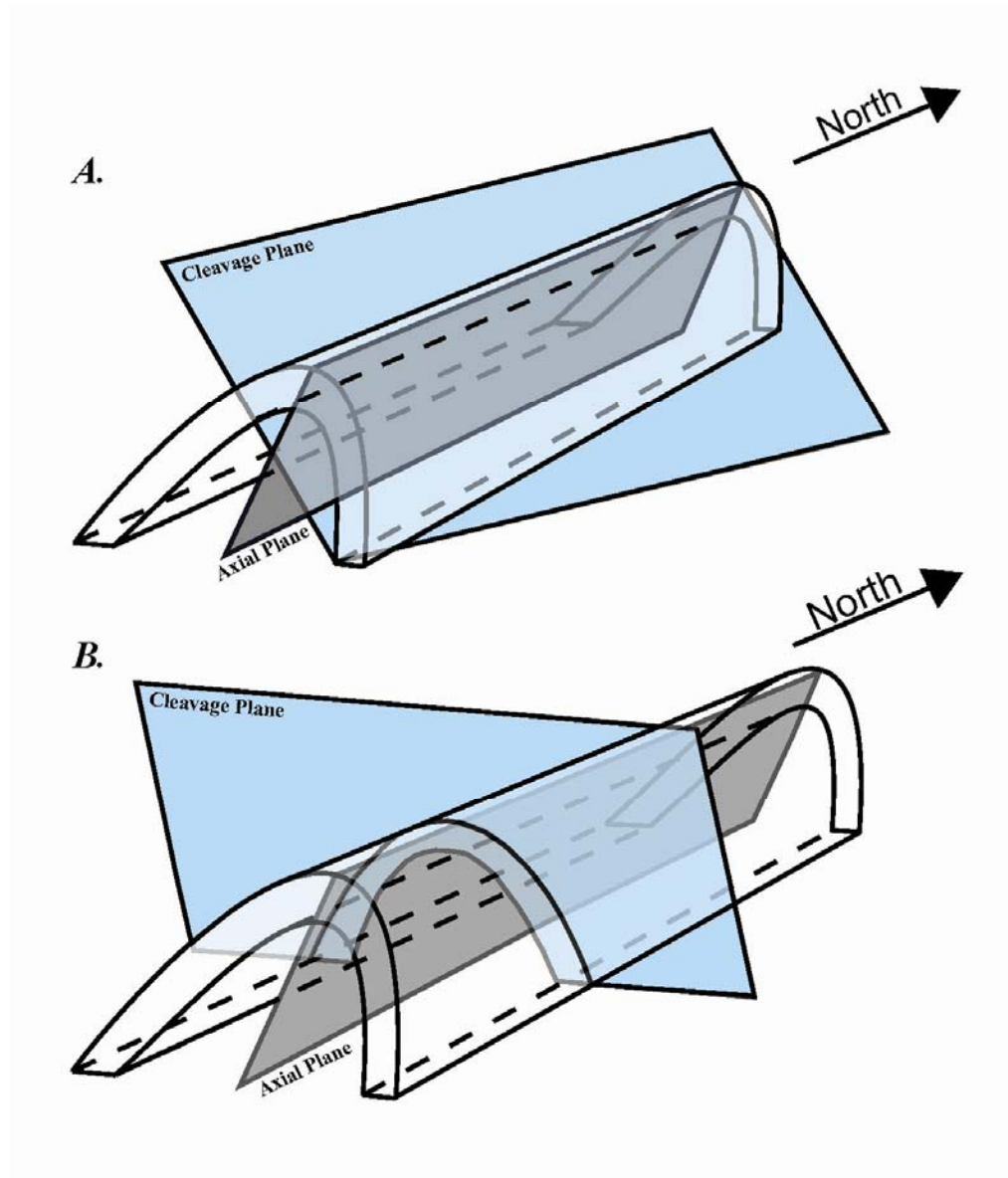


Figure 36. Cleavage-structure relationship diagrams. Best-fit fold axis trend and plunge = 08° , 007° . Axial surface indicated by gray plane. A. Cleavage population 1 strikes on average 030° , 54° E. B. Cleavage population 2 is shown cross-cutting the fold axial plane. Group 2 strikes on average 275° , 67° N. Group 3 strikes on average 090° , 70° S.

by late-stage deformation.

Strain related to late-stage deformation could have been partially accommodated by cleavage development. Orientation of cleavages that formed in response to impingement with the Biltmore system would be expected to form parallel to sub-parallel to the orientation of the foreland structure, an orientation of northwest strike and steep northeast dip. Since S1 strikes northeast and dips gently to the southeast, this mechanism may not be viable. It is possible that strain related to basement buttressing was deflected as the fold-and-thrust system impinged against foreland structures causing variations in maximum shortening directions throughout the region. Basement buttressing has been predicted to cause “stress trajectories that curve to reflect newly-imposed boundary conditions” (Beutner, 1977) (Figure 37). Geometric and kinematic information regarding the earliest location of basement impingement is necessary to further investigate how stress trajectories were affected by basement impingement, requiring 3D seismic reflection data of the subsurface. When the Beutner model is applied to the impingement zone east of the front of the McCartney Mountain salient using an interpreted geologic map, stress trajectories are seen to vary greatly within the nose of the salient (Figures 38 and 39). This model is only one of many possible conditions that may have occurred during the progressive and overlapping strain related to both the propagation of the fold-and-thrust belt into the foreland as well as basement-cored structure movement. However, the model does illustrate that the stress trajectories should be expected to be highly variable within the nose of the salient.

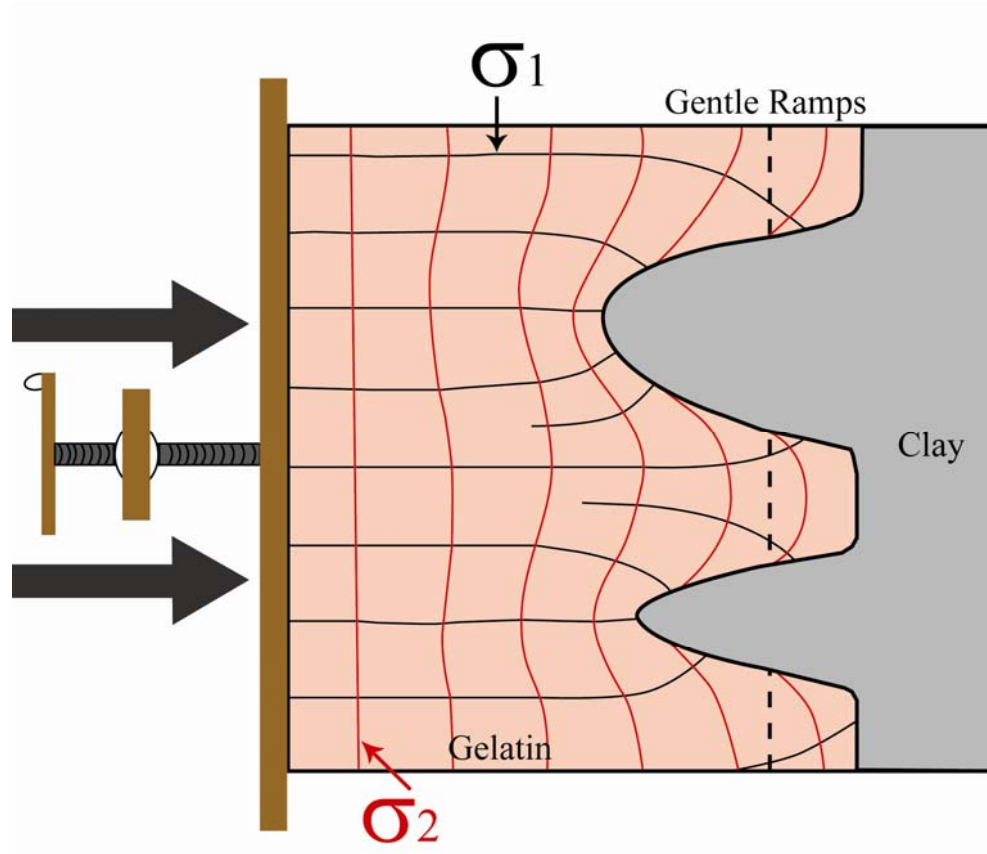


Figure 37. Beutner (1977) model of curved stress trajectories as a result of buttressing. Two materials of highly contrasting mechanical strength are compressed against each other with uniform compression. The gentle ramps allow the gelatin to be translated up onto the clay within salient areas. Lines of principle stress (σ_1) are shown to curve around the newly imposed boundary features of the clay (foreland).

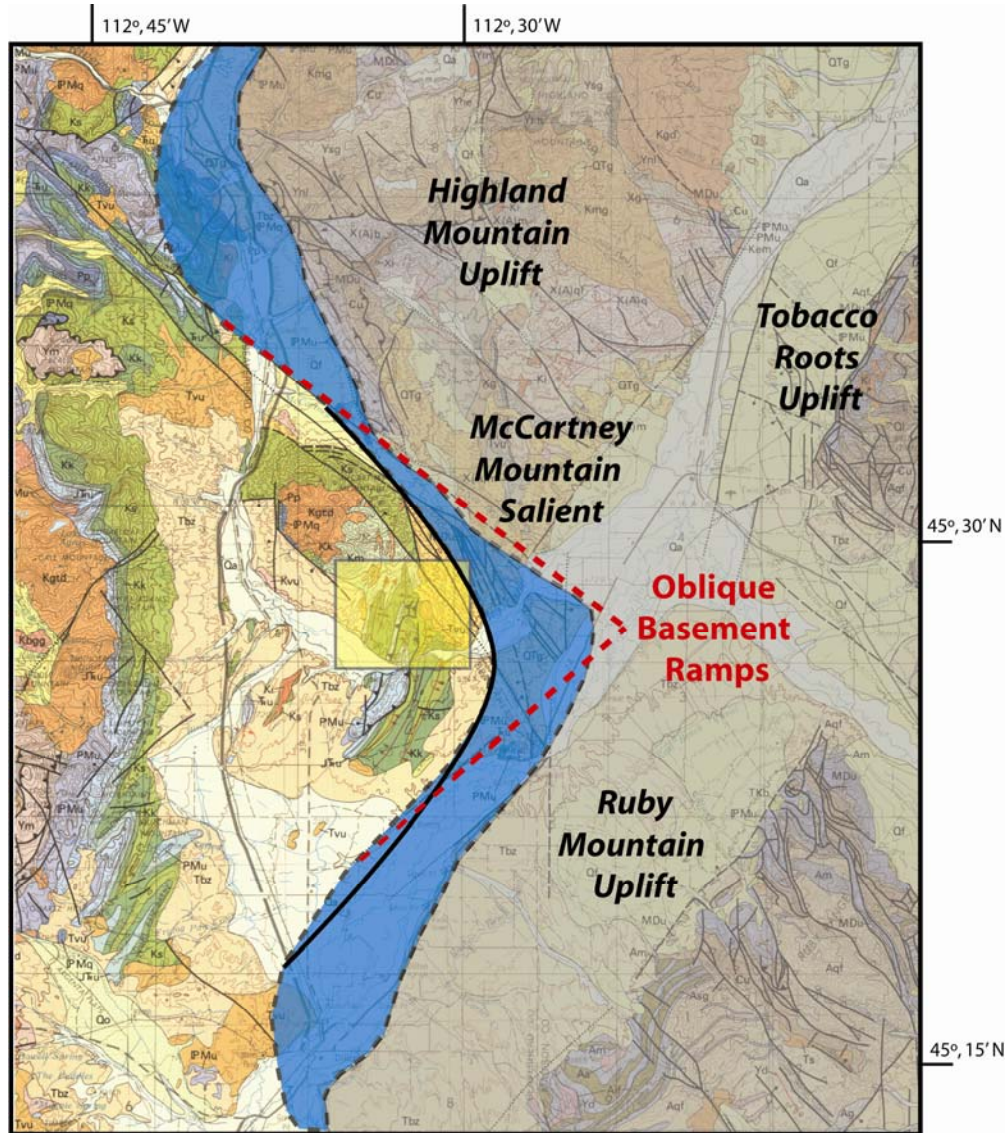


Figure 38. Idealized structural domains of the McCartney Mountain impingement zone. The McCartney Mountain salient geometry is shown to have been largely a consequence of pre-existing foreland basement structures that may have acted as foreland oblique ramps (shown as dashed red lines). The field area is shown as a yellow box. The blue polygon represents the frontal impingement zone. The gray area is interpreted to be dominantly Laramide basement uplifts. The outer boundary of the McCartney Mountain salient is shown as a solid black line. Geologic map from Ruppel et al., (1993).

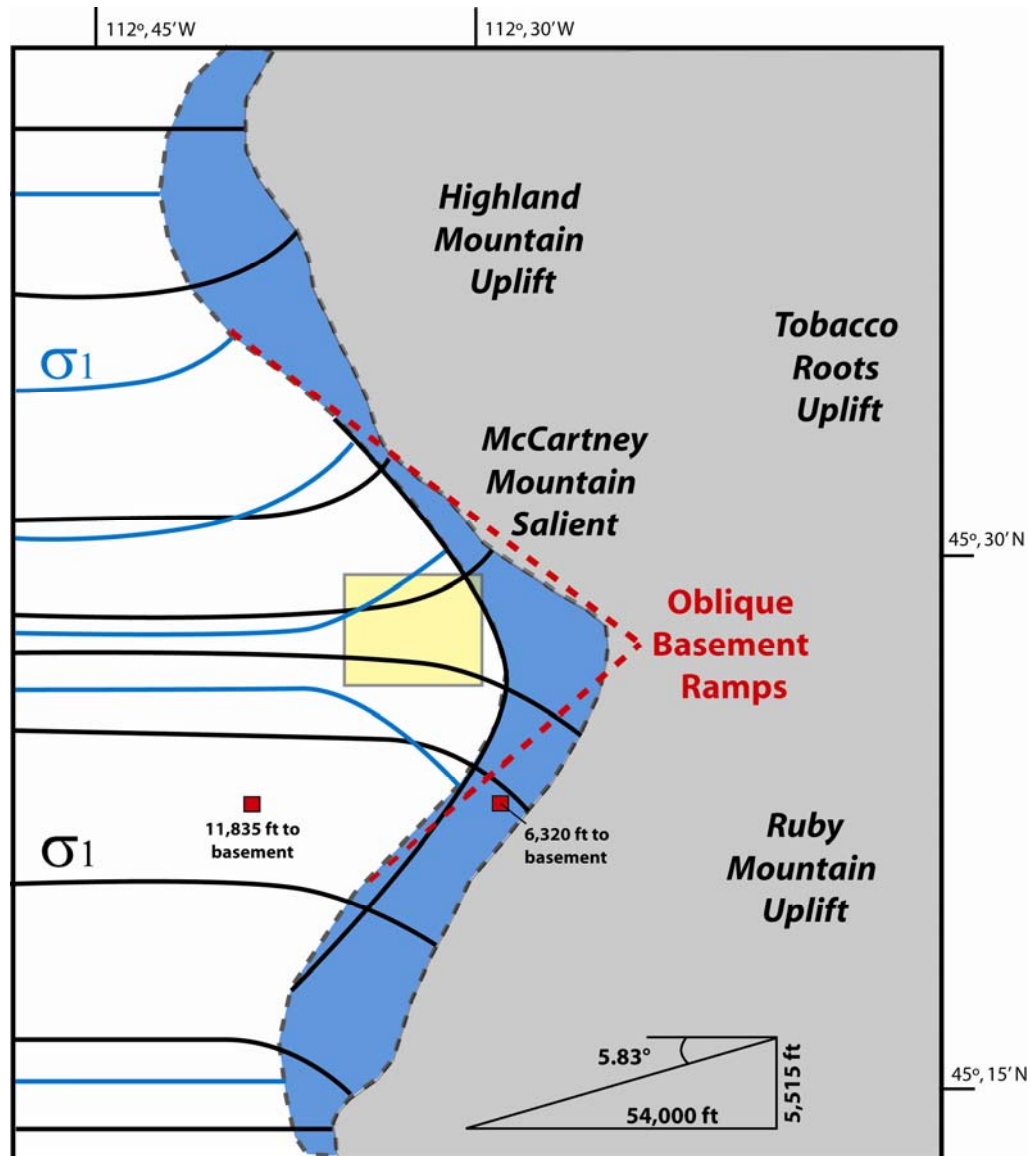


Figure 39. Hypothetical stress trajectories of the McCartney Mountain impingement zone. Maximum stress trajectories are shown to be highly variable within the nose of the McCartney Mountain salient. Black stress trajectories represent one case of impingement in which the fold-and-thrust belt was compressed against the eastern boundary of the interpreted Laramide province. The blue trajectories represent stress paths if the impingement occurred at the western boundary of the interpreted Laramide province. A minimum basement ramp angle of 5.83° was calculated from depth to basement values collected from exploratory oil and gas wells. This is a minimum value since the wells are not located perpendicular to the interpreted basement ramp.

Another factor to consider is whether physical conditions during late-stage deformation were suitable for cleavage development. As previously mentioned, cleavage forms as a result of ductile deformation by fluid assisted grain-boundary diffusion during low-grade metamorphism conditions ($T < 200\text{ }^{\circ}\text{C}$, $P < 5\text{ kb}$) at burial depths $< 8\text{ km}$ (e.g. Engelder and Marshak, 1985). Frontal fold-and-thrust systems are not subjected to deep burial depths due to lack of overriding thrust plates. If frontal imbrications of the Sandy Hollow-Hogback thrust system did interact with the Biltmore system, basal décollements would have ramped up in section, further decreasing burial depth. However, thermal requirements for cleavage development could have been facilitated by heat generated by contemporaneous emplacement of local plutons (e.g. Pioneer and Boulder Batholiths) (Geiger, 1980). Therefore it is reasonable to suggest that S1 could have formed during late-stage deformation related to the impingement of the Sandy Hollow-Hogback thrust system against the Biltmore fault system, assisted by high regional heat flow from shallow plutons in the area.

Cleavage Population 2

Cleavage population 2 is comprised of groups 2 and 3. Cleavage group 2 is characterized by east-west strike with steep north dip with an average orientation of 275° , 67° N . Cleavage group 3 is similarly recognized by east-west strike with steep south dip with an average orientation of 090° , 70° S . S2 was recorded at almost every measured outcrop throughout the Sandy Hollow field area. S2 consistently strikes almost

perpendicular to first-order fold axes (Figure 36). Given that S2 cleavages cross-cut all structural features of the fold-and-thrust system with remarkable geometric regularity, it is confidently interpreted here that S2 developed after fold-thrust deformation in response to a north-south maximum shortening direction.

Salient geometries are largely controlled by pre-existing structural features and are defined by a frontal portion of the deforming sedimentary wedge that has been allowed to propagate further into the foreland (e.g. Yonkee 2005) (Figure 38). The McCartney Mountain salient is bounded to the north, north-east and south-east by foreland basement uplifts that either pre-date or are synchronous with fold-and-thrust deformation in south-west Montana (Figure 38). Data that support pre-existing foreland basement uplifts includes variable isopach patterns of the Jurassic Ellis Group typical of a structurally partitioned and differentially subsiding foreland as well as the incorporation of basement rocks in the hanging wall of thin-skinned thrust faults (e.g. Kulik and Schmidt, 1988; Schwartz and DeCelles, 1988). Progressive propagation into the salient ‘nose’ requires the wedge to interact with inherited foreland structures that may serve as lateral and/or oblique transfer zones (footwall ramps) (Figure 40). Footwall ramps accommodate ‘out-of-the-salient’ movement as the wedge is continually laterally limited. The evolution of the deforming wedge is characterized by structural domains that are divided according to several different directions of maximum shortening in response to lateral adjustment (Figure 38 and 39). Late-stage cleavage forms parallel-to-oblique to lateral transfer zones and axial planar to second-order super imposed folds. S2 cleavage

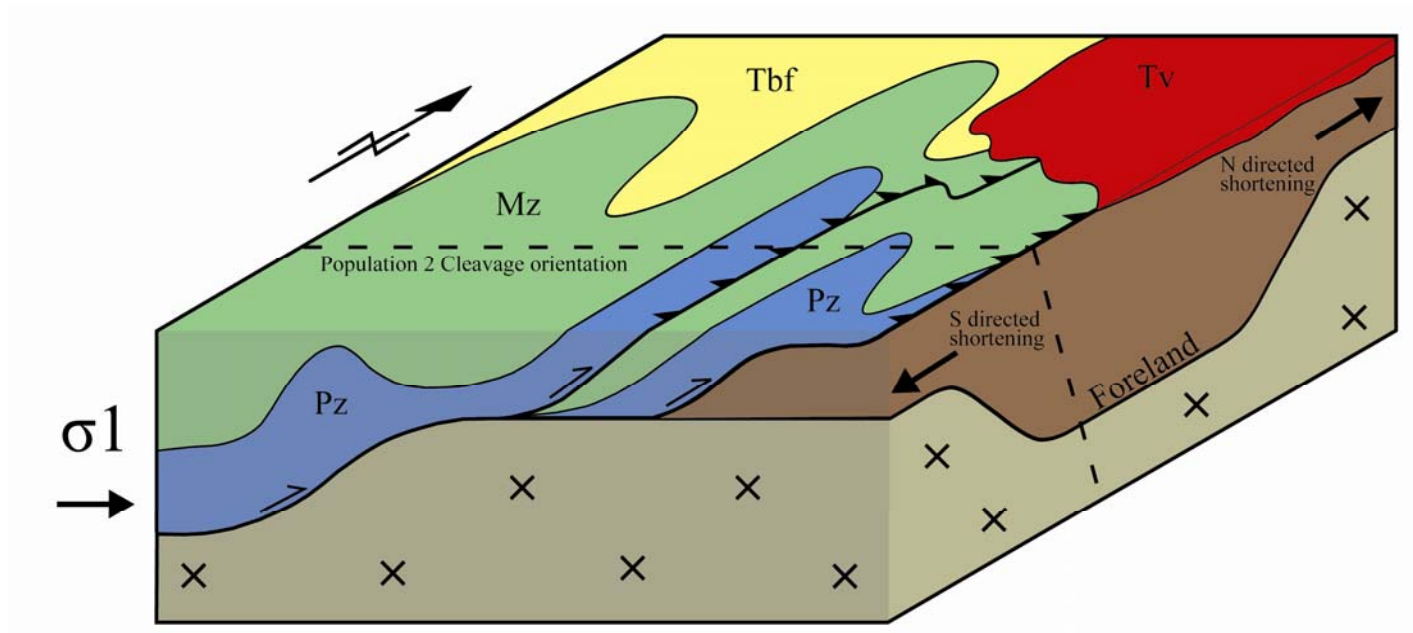


Figure 40. Block diagram of salient movement. As the frontal fold-and-thrust salient propagated into the foreland, it became laterally limited, likely caused by inherited lateral footwall ramps in foreland basement-cored uplifts. This hypothesis is proposed here to provide a tectonic mechanism for north-south shortening event to account for west-east cleavage strikes in population 2 cleavage.

may have formed in response to north-south compression related to late-stage lateral impingement of the salient nose (Figure 40). Although the Sandy Hollow-Hogback thrust system lacks second-order superimposed folds that would reflect strain related to lateral impingement, there are several strike-slip faults that cut first-order folds and igneous intrusive deposits that may have also formed in response to late-stage adjustment of the salient (Figure 4). Strike-slip faults to the north are sinistral while to the south the faults are dextral. These faults could have been acting to effectively shear the outer boundaries of the salient system as the fold-and-thrust belt propagated further into the salient nose.

Hydrocarbon System Importance

Cleavage distribution and intensity variations in fold-and-thrust belts introduce considerable heterogeneities in potential hydrocarbon systems. The pressure solution process, largely responsible for cleavage development, is considered a porosity and permeability reduction mechanism (Mitra, 1988). Local precipitation of dissolved material in the pore network, the suturing of grain boundaries, and the development of clay-rich cleavage domains collectively act to reduce pore volume and inhibit fluid migration (Mitra, 1988). Reduced porosity and permeability degrades reservoir potential by decreasing the space in which hydrocarbons could be stored, and by creating insufficient migration pathways for hydrocarbon recovery. Therefore, structural analysis of cleavage formation aids in predicting hydrocarbon reservoir quality as well as migration pathways in fold-and-thrust belts.

Evidence presented in this study indicates that, at odds to many previous cleavage studies, intense cleavage can form in frontal fold-and-thrust sheets with orientations related to the impingement of thin-skinned features against pre-existing foreland structures. Careful consideration of carbonate reservoirs is necessary to predict cleavage orientation and intensity. Intense cleavage approximating population 2 cleavage in this study would be highly unpredictable without detailed field mapping.

Carbon Dioxide Sequestration Importance

The emerging field of carbon dioxide capture and storage in geological reservoirs also requires detailed reservoir characterization. Many CO₂ sequestration reservoirs are currently proposed within deep saline aquifer systems (i.e. Riley Ridge field on the Moxa Arch, Wyoming) as well as in mature hydrocarbon reservoirs that are located within the Sevier fold-and-thrust belt. Structural fabrics associated with the fold-and-thrust belt, such as cleavage, must be considered as major factors that could control CO₂ plume migration away from the injection site. Cleavage, for example, could cause the injected CO₂ to migrate along clay-rich domains greatly affecting the long term pathway of the plume. Detailed core analysis should be conducted to determine structural fabric characteristics that can be used in pre-injection plume modeling.

Suggestions for Future Work

Collection of additional strain data, such as orientation of fracture, conjugate sets, and cleavage in multiple stratigraphic units is necessary in order to fully investigate strain in the Sandy Hollow field area. Strain accommodation within the middle limestone member of the Kootenai Formation remains enigmatic. A detailed microscopic to macroscopic study of all units within this member is needed to address the disparities of cleavage development. Fluid inclusion analysis of calcite-filled fractures and/or a paleomagnetization investigation is needed obtain timing information for the development of folds. A comprehensive geophysical study (collection of gravity and seismic data) of the outer boundaries of the McCartney Mountain salient is required to gain more information about the interaction of the fold-and-thrust belt against foreland basement structures. Regional geologic mapping, focused on north-south compression, would further reveal viable tectonic models for the development of S2.

CONCLUSIONS

Structural analysis of cleavage within a dolomitic unit of the Kootenai formation in the Sandy Hollow field area elucidates the following conclusions.

- 1) The analyzed unit (Kk2a) is lithologically homogenous as indicated by chemical dissolution, and XRD analysis. Therefore, lithologic variations within the unit can be discounted as a possible control on cleavage intensity or morphology variability.
- 2) Cleavage morphology was observed to be dominantly planar reflecting a tectonic mechanism for cleavage development.
- 3) Cleavage intensity did not yield a recognizable relationship to folded bedding dip or proximity to fold-and-thrust structures. Cleavage intensity within Kk2a is shown to be classified as moderate – very strong.
- 4) Two generations of cleavage were recognized in Kk2a within a frontal fold-and-thrust system. At odds to common cleavage-structure relationships, neither cleavage generation was recognized as fanning cleavage, or as axial planar cleavage.
- 5) Final S1 cleavage development occurred after first-order fold geometries were established in response to a northwest-southeast directed maximum shortening direction. S1 cleavage may have initially formed as axial planar but experienced reorientation by the late-stage adjustment of the Sandy Hollow-Hogback thrust system as a result of basement impingement against the Biltmore fault system.

- 6) S2 cleavage formation post-dates fold-and-thrust deformation, and developed in response to a north-south maximum shortening direction. Lateral limitation of the fold-and-thrust system into the nose of the salient may have created local north-south maximum compression structural domains responsible for S2 development.

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APPENDICES

APPENDIX A

TECTONIC TIMING INFORMATION

Deformational Event	Feature	Age	Dating Technique or Field Evidence	Citations
Sevier fold-thrust belt		Late Cretaceous to earliest Eocene	paleomagnetic dating	Harlan et al., 1988
		Mid-early Cretaceous to mid Eocene (50Ma)	collective dating techniques	Dickinson, 2004
		Late Jurassic to Eocene	collective dating techniques	DeCelles, 2004
Laramide basement cored foreland uplifts	North west trending basement involved reverse faults	70-75 Ma	Deformed strata associated with thin-skinned thrusting ramping up over basement uplifts	Schmidt and O'Neill, 1981; Ruppel et al., 1983; Schmidt and Garihan, 1983; Brandon, 1984
	Blacktail-Snowcrest Uplift	completed by 78 Ma	Palynological dating of syntectonic sediments	Kulik and Perry, 1988
	Ruby Uplift	Latest Cretaceous to late Eocene	strucutral relationships and vertebrate fossils from Beaverhead conglomerate	Tysdal, 1981
	Tobacco Root Uplift	Latest Cretaceous to late Eocene	cross cutting field relationships	Schmidt and Hendrix, 1981
	Highland Mountain Uplift	Latest Cretaceous	cross cutting field relationships	Schmidt et al., 1988
Idaho-Montana Batholith Province	Main phase of emplacement	80-65 Ma	collective dating techniques	Snee, 1982
	Pioneer Batholith	83-65 Ma; Main phase 77-72 Ma	K-Ar dating	Snee, 1982
	Boulder Batholith	80.4 +/- 1.2 to 74.5 +/- 0.9 Ma	U-Pb TIMS and SHRIMP	Lund et al., 2002
	Phillipsberg Batholith	77.2 +/- 1.9 Ma, 73.3 +/- 1.8 Ma	Biotite K-Ar method	Marvin et al., 1989
	Idaho-Bitterroot Batholith	80 - 53 Ma	Ar-Ar SHRIMP	Foster et al., 2001
	Tobacco Root Batholith	75 Ma	K-Ar dating	Schmidt and Hendrix, 1981
	McCartney Mountain pluton	74 +/- 1 Ma	K-Ar biotite date	Brumbaugh and Hendrix, 1981
Extensional phases	Sevier Orogenic collapse	50 - 20 Ma	collective dating techniques	Constenius, 1996; Janecke et al., 2001
	Bitterroot metamorphic core complex	46.4 +/- 0.8 Ma 46 - 48 Ma	40Ar/39Ar cooling dates	Hodges and Applegate, 1993
	Anaconda metamorphic core complex	47.2 +/- 0.14 Ma	40Ar/39Ar age spectrum	O'Neill et al., 2004
	Laramide collapse	49 - 20 Ma	collective dating techniques	Constenius, 1996
	Block Mountain Basalt	44.8 Ma	K-Ar whole rock dating	Chadwick, 1981
	Snake River Plain	starts 17.5 Ma; affected SW MT ~6 Ma	dating of volcanic deposits and tectonic reconstruction models	Fritz and Sears, 1993
	Basin and Range	starts in 17 Ma	collective dating techniques	Thomas et al., 1995

Tectonic timing table showing sources used in the Regional Tectonic section and to produce Figure 2, Deformational events timeline for southwest Montana.

APPENDIX B

FOLD ATTRIBUTES AND BEDDING DATA

S t r u c t u r e N a m e	F o l d e d B e d d i n g O r i e n t a t i o n D a t a		
Sandy Hollow Anticline	S t r i k e	D i p	D i p D i r e c t i o n
	183	70	W
	184	61	W
	193	40	W
	194	34	W
	194	28	W
	198	24	W
	198	14	W
	198	29	W
	201	31	W
	201	31	W
	202	48	W
	204	47	W
	206	35	W
	206	41	W
	208	29	W
	230	13	NW
	235	11	NW
	262	11	N
	327	52	E
	328	52	E
	331	54	E
	336	72	E
	172	62	W
	174	72	W
	355	62	NE
	178	66	W

S t r u c t u r e N a m e	F o l d e d B e d d i n g O r i e n t a t i o n D a t a		
Creasey Gulch Anticline	S t r i k e	D i p	D i p D i r e c t i o n
	232	28	NW
	36	27	S E
	23	45	E
	14	54	E
	4	34	E
	25	9	E
	8	44	E
	18	28	E
	20	12	E
	258	4	NW
	198	19	W
	174	44	W
	196	22	W
	188	26	W
	202	24	W
	181	24	W
	164	9	S W

Tabular orientation data for KK2a folded bedding. Presented in right hand rule form.

Structure Name	Folded Bedding Orientation Data		
Ziegler Anticline	Strike	Dip	Dip Direction
	11	63	E
	12	57	E
	358	62	E
	8	63	E
	18	46	E
	15	51	E
	19	88	E
	15	72	E
	15	74	E
	15	68	E
	13	73	E
	260	18	N
	320	57	E
	338	54	E
	355	58	E
	356	58	E
	201	31	W
	221	39	W
	208	42	W
	218	37	W
	203	44	W
	204	30	W
	209	34	W
	197	36	W
	175	41	W
	191	53	W
	199	54	W
	212	39	W
	188	54	W
	203	48	W
	203	46	W
	200	56	W
	194	47	W
	208	50	W
	207	33	W
	208	65	W
	216	27	W
	207	33	W
	201	41	W

Tabular orientation data for KK2a folded bedding, continued. Presented in right hand rule form. Note that the measurements for the Ziegler syncline are preserved within the east limb of the Creasey Gulch anticline, and the west limb of the Ziegler anticline data.

Creasey Gulch Anticline

Dimensions		
Order of Fold	First	
Amplitude	920 m	
Half-Wavelength	627 m	
Attitude		
Trend of Fold Axis	194°	
Plunge of Fold Axis	01°	Horizontal
Strike of Axial Plane	014°	
Dip of Axial Plane	88° E	Upright
Geometry of Axial Plane	Curved	
Shape		
Aspect Ratio	1.468	Equant
Harmony	1.459	Disharmonic
Symmetry	1° diff	Asymmetric
Bluntness	0.63	Sub-rounded
Tightness	14°	Tight
Cylindricity	Cylindrical	
Curvature Distribution	Diffuse pattern	Rounded form

Ziegler Syncline

Dimensions		
Order of Fold	First	
Amplitude	1667 m	
Half-Wavelength	387 m	
Attitude		
Trend of Fold Axis	020°	
Plunge of Fold Axis	03°	Sub-horizontal
Strike of Axial Plane	018°	
Dip of Axial Plane	70° W	Steeply Inclined
Geometry of Axial Plane	Curved	
Shape		
Aspect Ratio	4.3103	Elongate
Harmony	2.365	Disharmonic
Symmetry	3.5° diff	
Bluntness	0.40	Sub-rounded
Tightness	15°	Tight
Cylindricity	Cylindrical	
Curvature Distribution	Cluster pattern	Parabolic

Fold attributes for the Creasey Gulch anticline and Ziegler syncline.

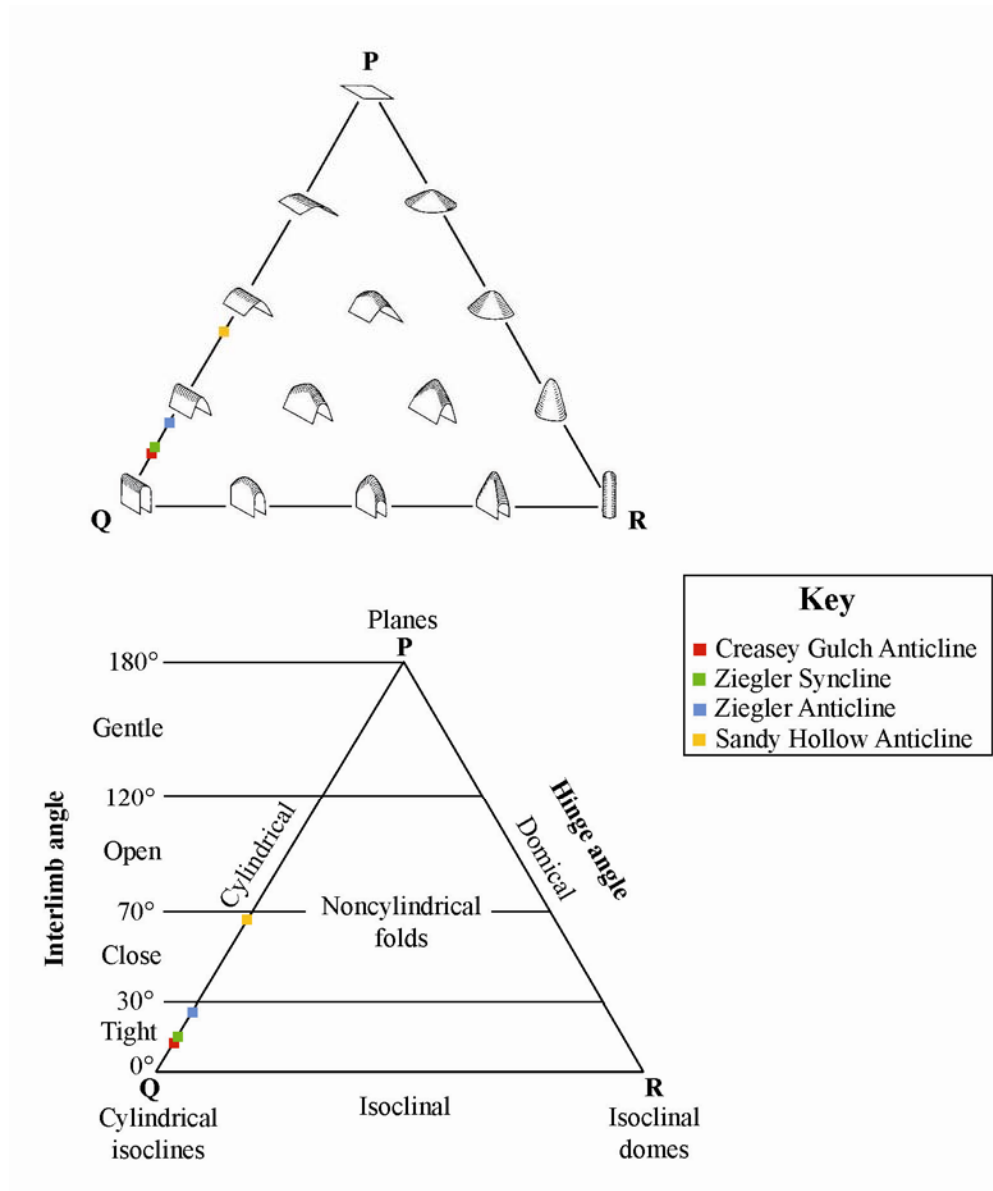
Ziegler Anticline

Dimensions		
Order of Fold	First	
Amplitude	2053 m	
Half-Wavelength	1560 m	
Attitude		
Trend of Fold Axis	014°	
Plunge of Fold Axis	09°	Sub-horizontal
Strike of Axial Plane	018°	
Dip of Axial Plane	70° W	Steeply Inclined
Geometry of Axial Plane	Curved	
Shape		
Aspect Ratio	1.316	Equant
Harmony	0.7424	Disharmonic
Symmetry	5° diff	Asymmetric
Bluntness	0.37	Sub-angular
Tightness	26°	Tight
Cylindricity	Cylindrical	
Curvature Distribution	Cluster pattern	Chevron like

Sandy Hollow Anticline

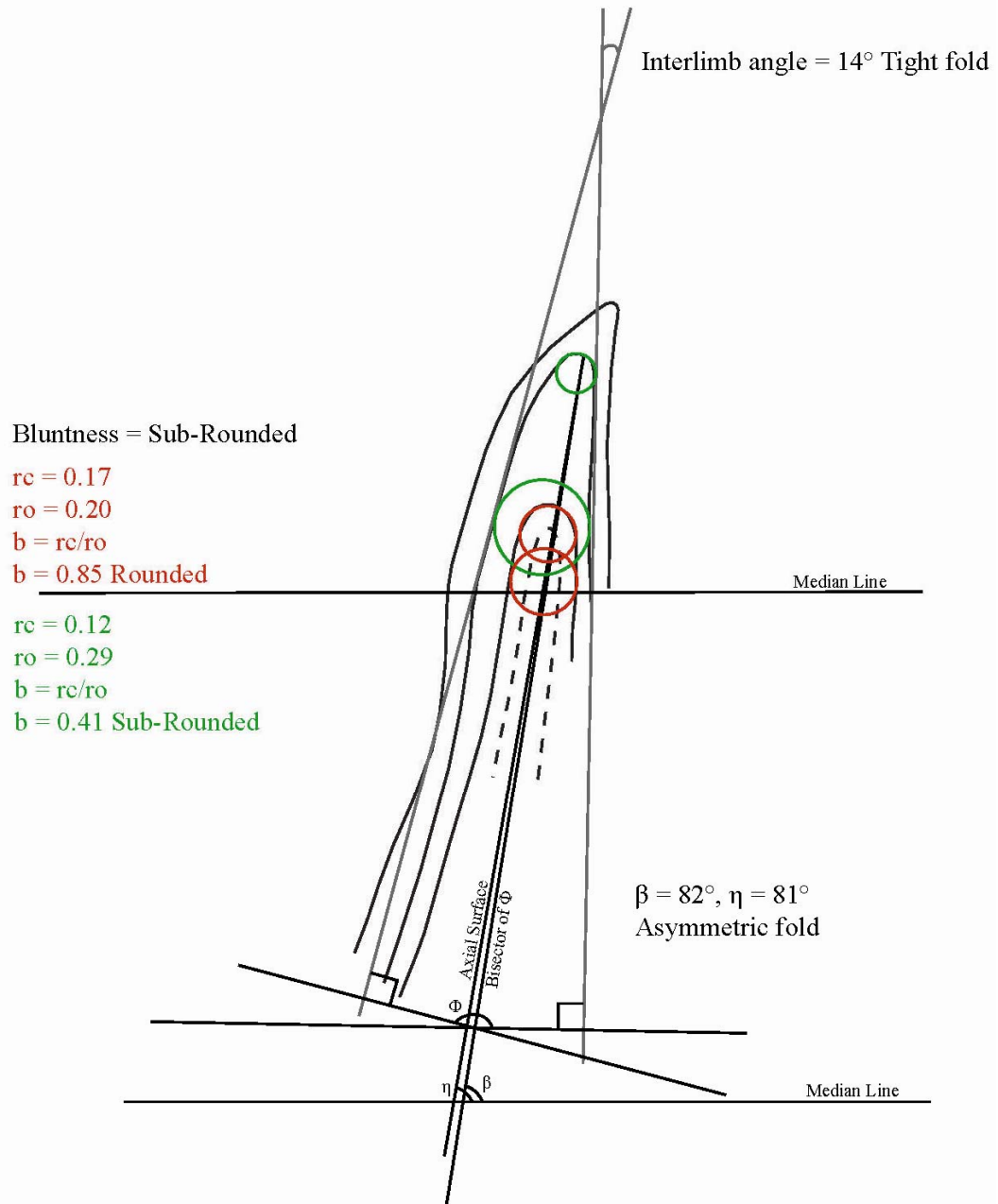
Dimensions		
Order of Fold	First	
Amplitude	1547 m	
Half-Wavelength	1387 m	
Attitude		
Trend of Fold Axis	350°	
Plunge of Fold Axis	17°	Gently plunging
Strike of Axial Plane	173°	
Dip of Axial Plane	75° W	Steeply Inclined
Geometry of Axial Plane	Overtured and curved	East verging
Shape		
Aspect Ratio	1.1153	Equant
Harmony	0.9232	Disharmonic
Symmetry	2° diff	Asymmetric
Bluntness	0.27	Sub-angular
Tightness	64°	Close
Cylindricity	Cylindrical	
Curvature Distribution	Moderately diffuse pattern	Parabolic

Fold attributes for the Ziegler and Sandy Hollow anticlines.

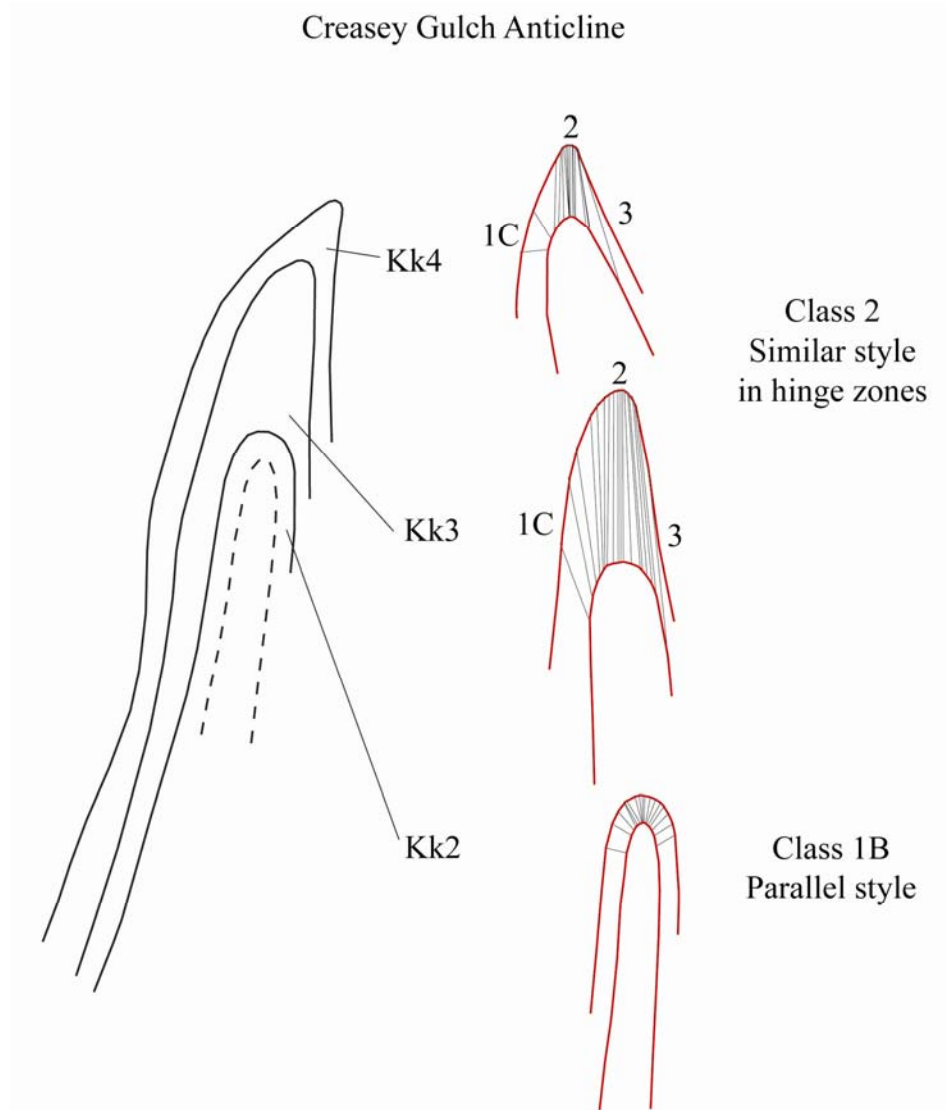


Williams and Chapman (1983) fold classification for synclines and anticlines of the Sandy Hollow field area. Plotted data shows the Sandy Hollow folds classified as cylindrical, tight to closed folds with chevron to parabolic shapes.

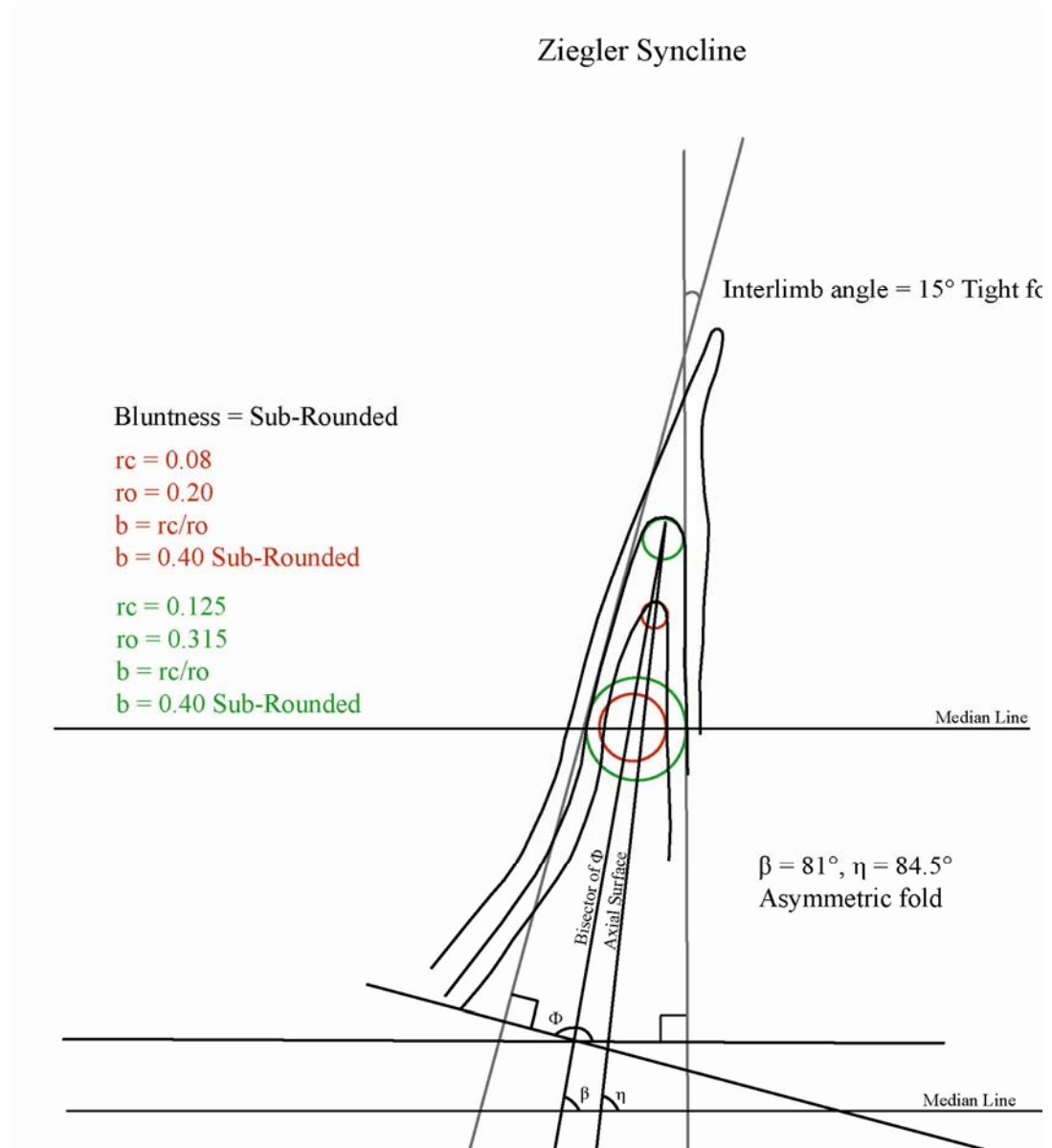
Creasey Gulch Anticline



Draft diagram for Creasey Gulch anticline showing calculation of bluntness, interlimb angle, and degree of symmetry.

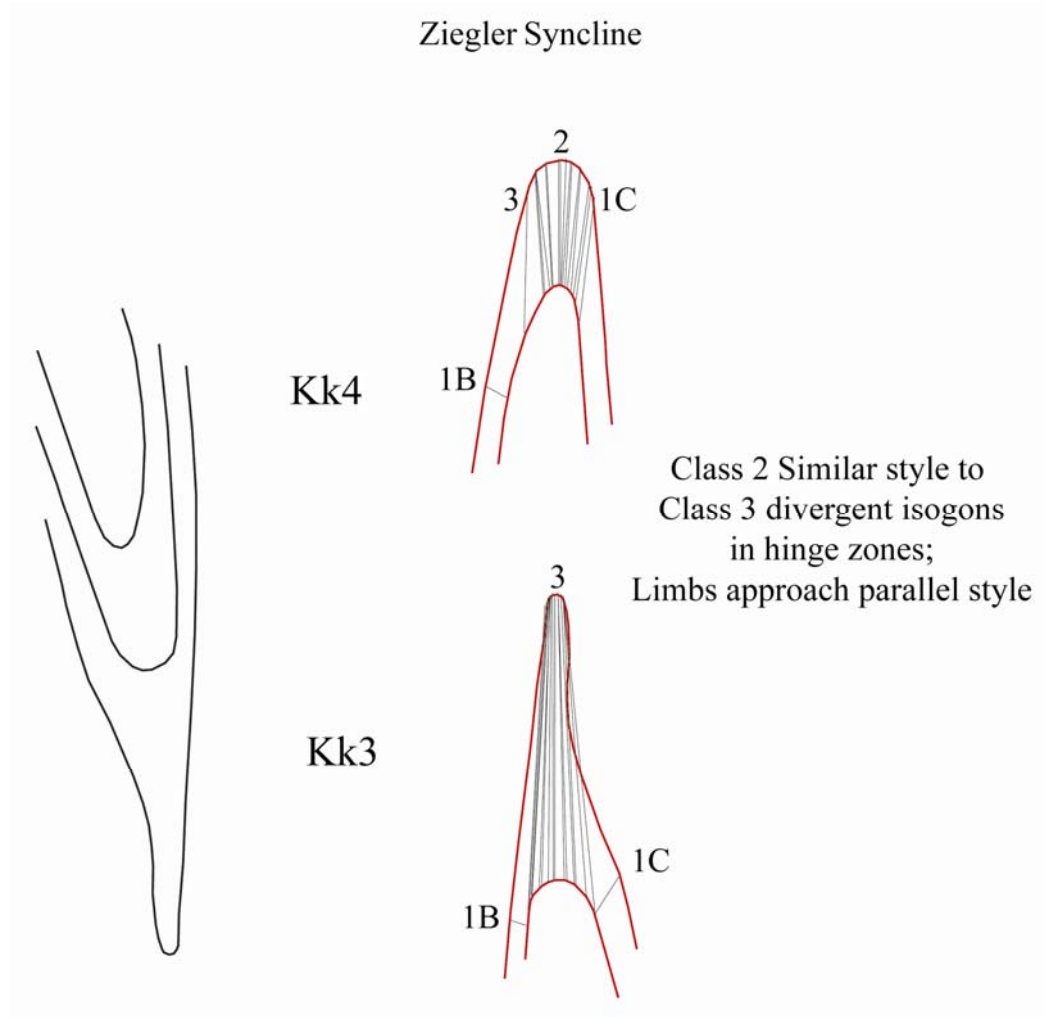


Ramsay classification of the Creasey Gulch anticline showing drafted dip isogons.

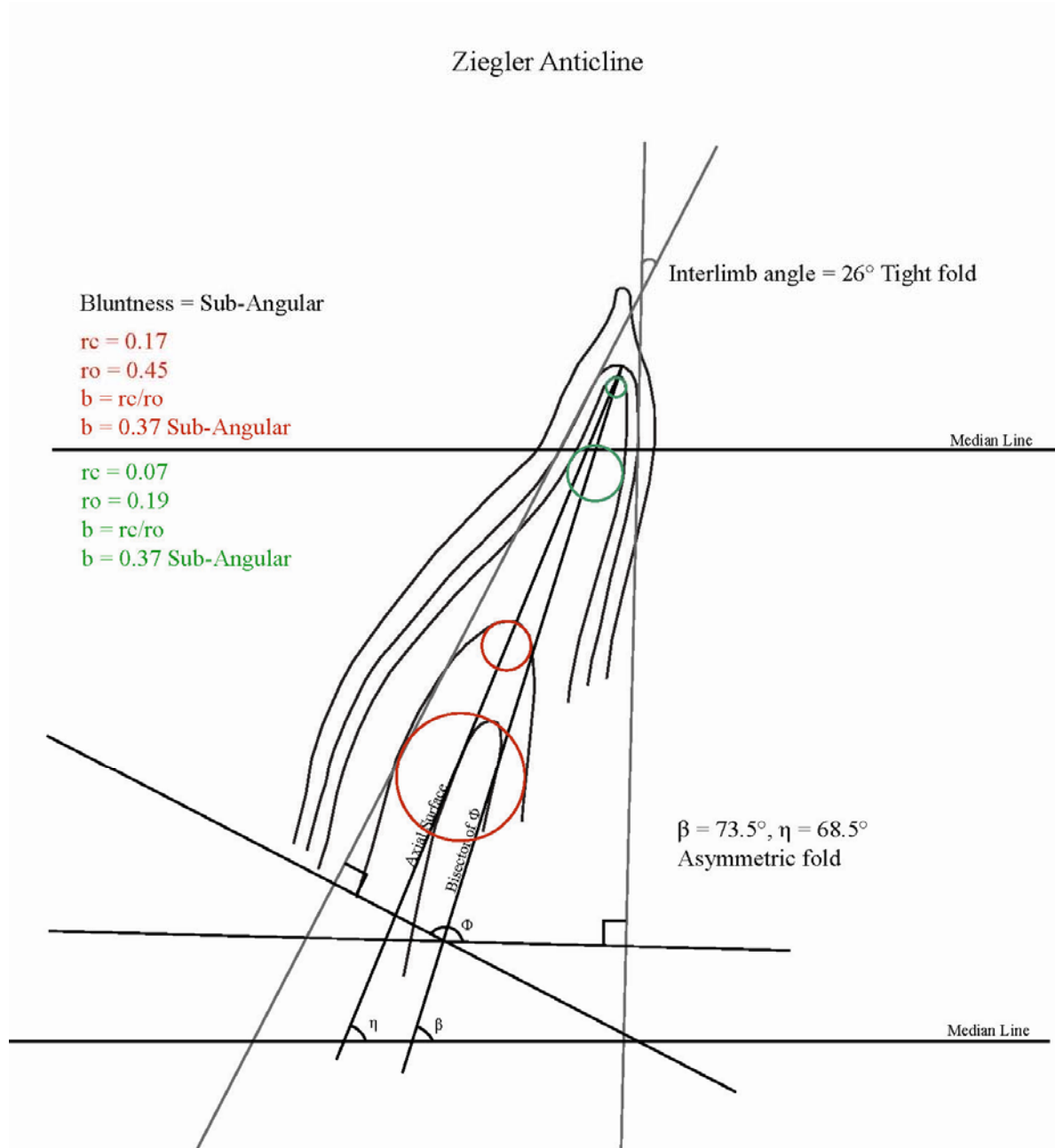


Draft diagram for Ziegler syncline showing calculation of bluntness, interlimb angle, and degree of symmetry.

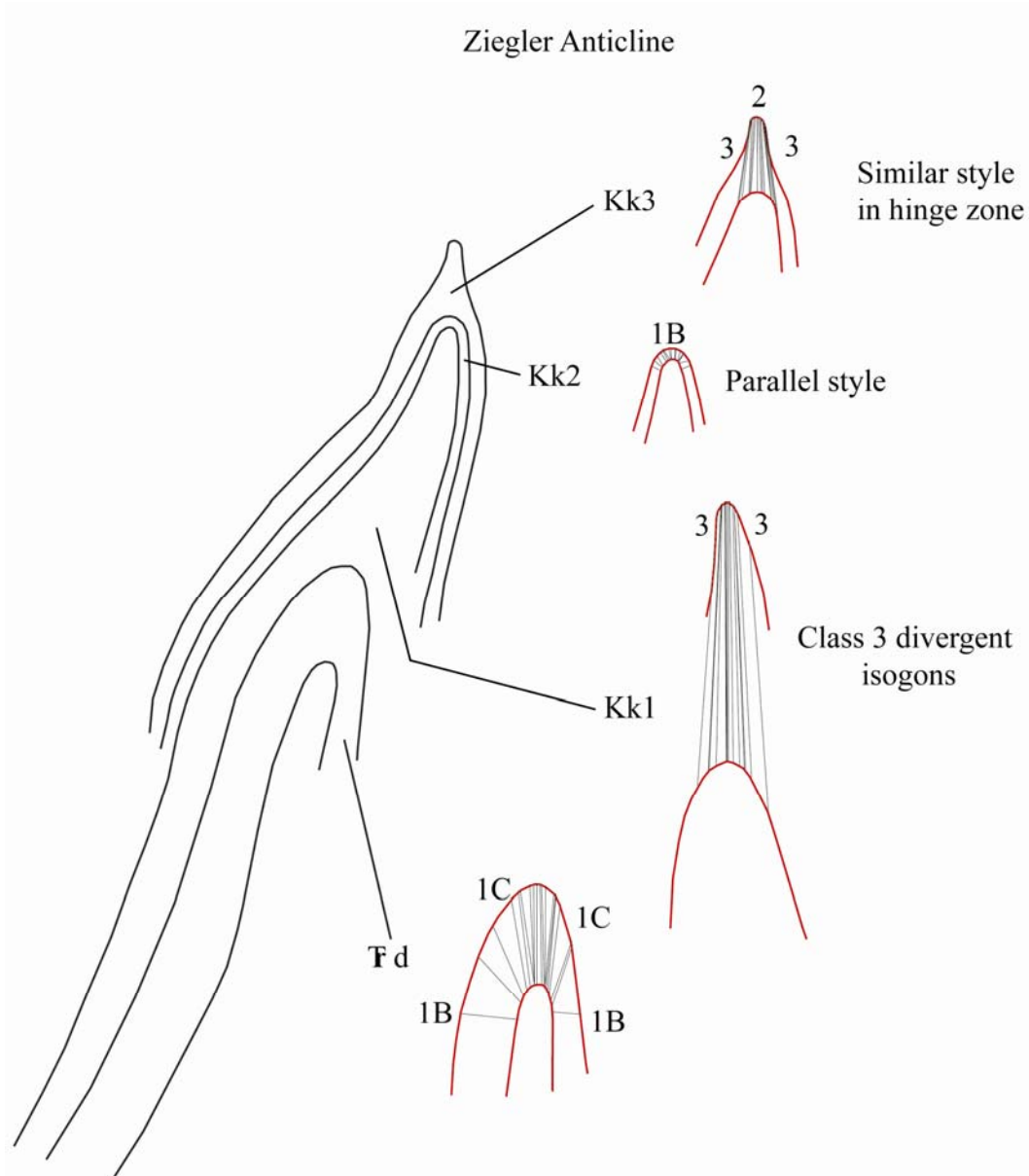
Ziegler Syncline



Ramsay classification of the Ziegler syncline showing drafted dip isogons.

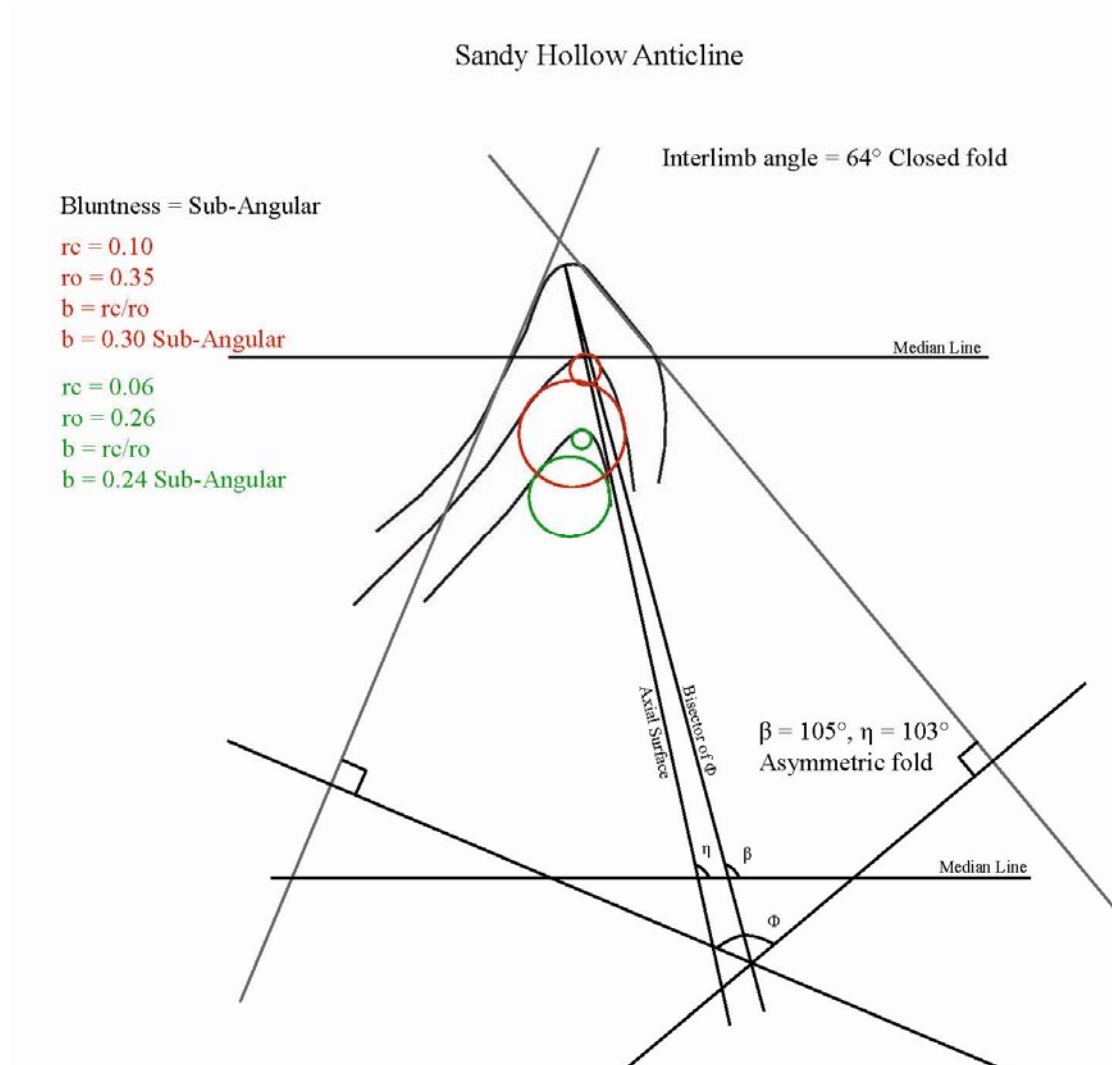


Draft diagram for Ziegler anticline showing calculation of bluntness, interlimb angle, and degree of symmetry.

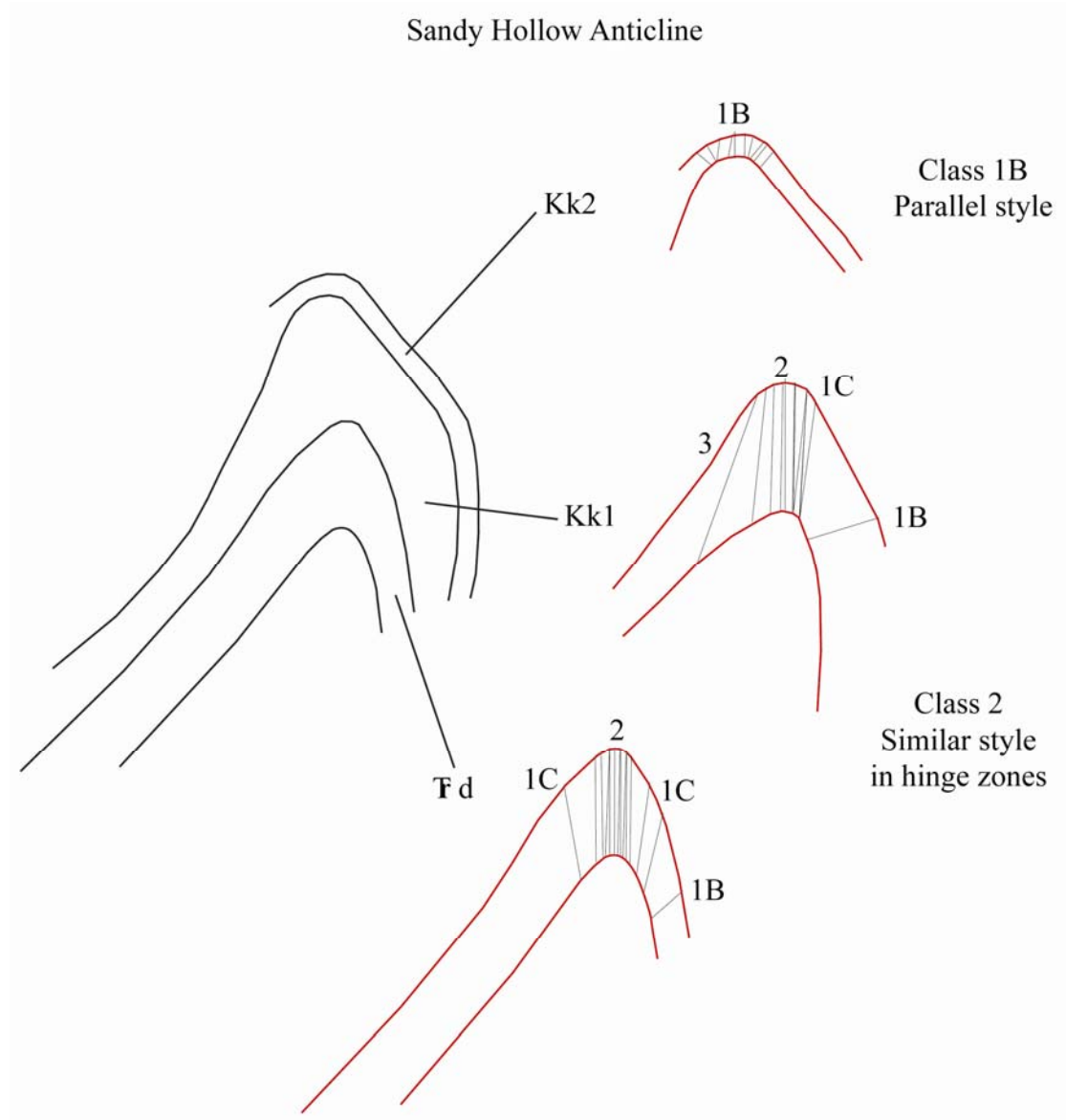


Ramsay classification of the Ziegler anticline showing drafted dip isogons.

Sandy Hollow Anticline



Draft diagram for Sandy Hollow anticline showing calculation of bluntness, interlimb angle, and degree of symmetry.



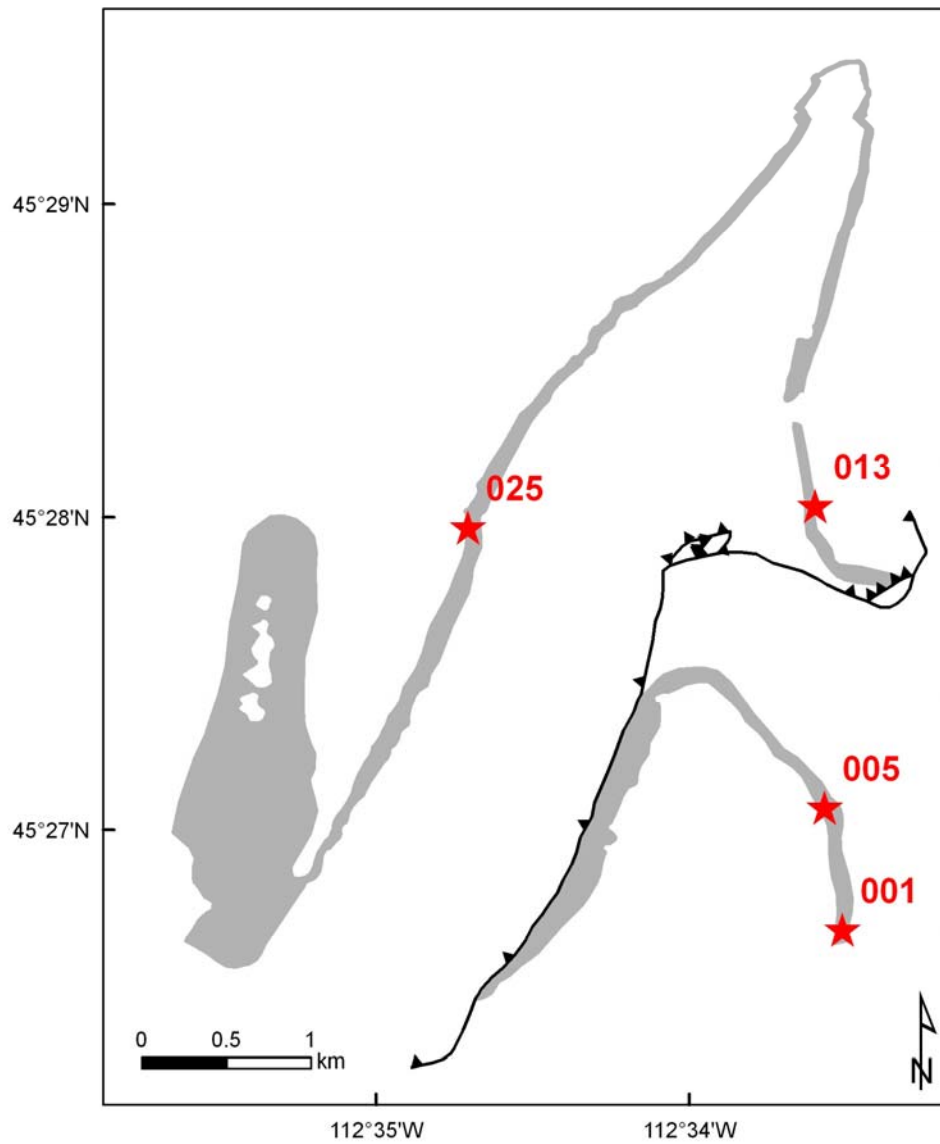
Ramsay classification of the Sandy Hollow anticline showing drafted dip isogons.

APPENDIX C

DISSOLUTION ANALYSIS RESULTS

Sample Name	Filter (g)	Sample & Filter (g)	Initial Sample (g)	Filter top (g)	Total Filter (g)	Final Sample & Filters (g)	Final Sample (g)	% wt	Average %
005-A	0.3491	1.3497	1.0006	0.3492	0.6983	1.0146	0.3163	31.61%	
005-B	0.3472	1.3481	1.0009	0.3463	0.6935	1.0032	0.3097	30.94%	
005-C	0.3465	1.3552	1.0087	0.3458	0.6923	1.0201	0.3278	32.50%	31.68%
013-A	0.3451	1.3503	1.0052	0.3485	0.6936	1.0041	0.3105	30.89%	
013-B	0.3454	1.3467	1.0013	0.3467	0.6921	1.0057	0.3136	31.32%	
013-C	0.3472	1.3520	1.0048	0.3488	0.6960	1.0112	0.3152	31.37%	31.19%
025-A	0.3466	1.3429	1.0063	0.3459	0.6925	0.9833	0.2908	28.90%	
025-B	0.3481	1.3486	1.0005	0.3461	0.6942	1.0023	0.3081	30.79%	
025-C	0.3476	1.3488	1.0012	0.3474	0.6950	1.0039	0.3089	30.85%	30.18%

Tabular results from sample dissolution analysis.



Map showing the locations of rock samples used in the chemical dissolution, and XRD analysis. Sample 001 was used to determine the bulk rock chemistry of Kk2a during XRD analysis. Samples 005, 013, and 025 were dissolved to determine the relative amount of insoluble material within Kk2a. XRD analysis was then performed on the resulting insoluble residues.

APPENDIX D

CLEAVAGE ORIENTATION DATA

Cleavage Group 1

STRIKE	DIP	DIP DXN
8	23	E
14	21	E
26	19	E
5	10	E
26	54	E
44	32	E
24	32	E
12	38	E
23	48	E
48	42	E
30	41	E
24	53	E
11	76	E
15	42	E
149	62	S W
158	69	S W
11	61	E
15	76	E

Tabular orientation data for group 1 cleavage domains. Note theses values represent the mean of several measurements taken at each outcrop.

Cleavage Group 2

S T R I K E	D I P	D I P D X N
333	69	NE
304	67	NE
276	41	N
256	34	N
266	66	N
266	64	N
276	68	N
274	76	N
259	65	N
257	46	N
261	37	N
287	78	N
261	84	N
270	69	N
266	84	N
293	56	N
314	86	N
261	77	N
262	73	N
257	71	N
270	79	N
283	76	N
303	72	N
255	77	N
259	84	N

Tabular orientation data for group 2 cleavage domains. Note theses values represent the mean of several measurements taken at each outcrop.

Cleavage Group 3

S TRIKE	DIP	DIP DXN
79	86	S
89	79	S
92	68	S
91	57	S
96	71	S
74	80	S
75	62	S
85	79	S
72	51	S
89	78	S
84	78	S
106	81	S
94	56	S
109	77	S
109	74	S
86	84	S
103	89	S
100	84	S
116	81	S
118	77	S
113	89	S
116	70	S
110	72	S
102	79	S
83	71	S
90	87	S
66	79	S
78	61	S
91	60	S
98	77	S
82	73	S
75	69	S
79	69	S
111	81	S
82	87	S
84	76	S
76	76	S
93	64	S
94	71	S

Tabular orientation data for group 3 cleavage domains, continued. Note theses values represent the mean of several measurements taken at each outcrop.

Cleavage Group 3 continued

S TRIKE	DIP	DIP DX N
83	74	S
101	84	S
94	76	S
80	60	S
113	76	S
115	86	S
135	85	S
89	71	S
86	64	S
113	81	S
81	54	S
93	71	S
84	74	S
94	71	S
106	71	S
107	82	S
56	73	S E
52	68	S E
51	64	S E
47	57	S E
103	78	S
71	87	S
64	72	S
51	65	S E
67	61	S E
53	38	S E
118	42	S
131	39	S
124	28	S
133	28	S
41	84	S
60	82	S

Tabular orientation data for group 3 cleavage domains, continued. Note theses values represent the mean of several measurements taken at each outcrop.

