Internal deformation in the Backbone thrust sheet, Sawtooth Range, Montana
by Bethany A Ihle

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

Abstract:
The distribution and magnitude of internal deformation within thrust sheets is not well documented because internal deformation has generally been considered insignificant compared to shortening by thrust faulting across an entire thrust belt. However, in the Backbone thrust sheet in northwest Montana, internally deformed Middle Cambrian limestones are overlain by apparently undeformed shale and dolomite. The distribution, mechanisms and amount of internal deformation are documented using macroscopic, mesoscopic and microscopic structural elements for the purpose of determining their contribution to the overall shortening, the sequence of deformation and the mechanics of emplacement for the thrust sheet.

Macroscopic internal deformation varies laterally in the thrust sheet. Thrust faults create an imbricate zone at the leading edge whereas folds dominate the intraplate region. Mesoscopic internal deformation varies vertically with distance from thrust faults and lithology of the footwall. Three deformational domains are defined based on distribution of mesoscopic structural elements. Domain I, is proximal to the Backbone thrust and it is dominated by mesoscopic fault arrays and tectonic veins where Cambrian limestone is thrust over competent rocks. Where Cambrian limestone is thrust over shale, these features are less well-developed. Domain II is located in the strata overlying Domain I and in macroscopic intraplate folds. Domain II is cleavage dominated and contains mesoscopic folds, boudins and pencil structures. Domain III is the remaining undeformed strata in the upper part of the thrust sheet.

The important mechanisms of deformation in Domain I are faulting, extension fracturing, recrystallization and pressure solution. These mechanisms are significant at the mesoscopic and microscopic scales. Fault surfaces are' affected by frictional sliding and pressure solution slip. The dominant mechanism of deformation in Domain II is pressure solution as indicated by spaced cleavage and pencil structures. Minor extensional fracturing is responsible for calcite veins and boudins.

Macroscopic folding and thrust imbrication contribute 55% internal shortening. Pressure solution deformation accounts for an additional 15% shortening; thus, total shortening due to internal deformation is approxiamtely 70%. Fault zone deformation contributes simple shear strain and longitudinal shortening to internal deformation in Domain I.

The sequence of deformation in the Backbone thrust sheet is primarily constrained by geometric relationships between cleavage and structural elements. Cleavage formed early in the history of the thrust sheet, contemporaneously with microscopic strain. Macroscopic folding, formed during thrusting, postdates cleavage and passively rotated it into fans. Faulting was the final increment of deformation.

INTERNAL DEFORMATION IN THE BACKBONE THRUST SHEET, SAWTOOTH RANGE, MONTANA

by

Bethany A. Ihle

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

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

June 1988

APPROVAL

of a thesis submitted by

Bethany A. Ihle

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

5/5/88 — Date

David R. [illegible] — Chairperson, Graduate Committee

Approved for the Major Department

5-5-88 — Date

[illegible] — Head, Major Department

Approved for the College of Graduate Studies

June 10, 1988 — Date

Henry L Parsons — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Director of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature *[signature]*

Date 6/10/88

ACKNOWLEDGEMENTS

Many individuals and funding sources were instrumental in getting me through this thesis. First I'd like to thank my funding sources, Chevron U.S.A, Tenneco and the Montana Geological Society who kept me in beer and supplies in the field. My advisor, Dr. David R. Lageson, suggested the project, guided my thinking on thrust sheet deformation and made comments which greatly improved this manuscript. Drs. James G. Schmitt and David W. Mogk served on the reading committee and contributed good ideas. Dr. John Childs provoked my thinking on the project and inspired me to continue. My student comrades were remarkable for their friendship and help during the stressful days. The remaining faculty and the office staff, especially Sara and Ann, are commended for handling the daily crises with a smile.

I'd like to thank Conrad Bressie who helped me overcome my fear of bears. My younger brother, Jack Ihle, made a noble effort to be interested in geology while serving five weeks as a field assistant. Thanks, Jack! Bill and Jimmie Jones of Dupuyer are given special thanks, for without their interest and generosity, this project would have taken much longer. It certainly would not have been as much fun!

Thanks, Craig, for your love and understanding.

Thanks, Monte, for the many things you taught me.

Last of all, I'd like to thank my family, especially my parents, Renee and Luther Ihle, for their support and encouragement, and for believing that I could do this.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

TABLE OF CONTENTS—Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES--Continued

LIST OF FIGURES--Continued

LIST OF FIGURES--Continued

Figure | Page

LIST OF PLATES

ABSTRACT

The distribution and magnitude of internal deformation within thrust sheets is not well documented because internal deformation has generally been considered insignificant compared to shortening by thrust faulting across an entire thrust belt. However, in the Backbone thrust sheet in northwest Montana, internally deformed Middle Cambrian limestones are overlain by apparently undeformed shale and dolomite. The distribution, mechanisms and amount of internal deformation are documented using macroscopic, mesoscopic and microscopic structural elements for the purpose of determining their contribution to the overall shortening, the sequence of deformation and the mechanics of emplacement for the thrust sheet.

Macroscopic internal deformation varies laterally in the thrust sheet. Thrust faults create an imbricate zone at the leading edge whereas folds dominate the intraplate region. Mesoscopic internal deformation varies vertically with distance from thrust faults and lithology of the footwall. Three deformational domains are defined based on distribution of mesoscopic structural elements. Domain I is proximal to the Backbone thrust and it is dominated by mesoscopic fault arrays and tectonic veins where Cambrian limestone is thrust over competent rocks. Where Cambrian limestone is thrust over shale, these features are less well-developed. Domain II is located in the strata overlying Domain I and in macroscopic intraplate folds. Domain II is cleavage dominated and contains mesoscopic folds, boudins and pencil structures. Domain III is the remaining undeformed strata in the upper part of the thrust sheet.

The important mechanisms of deformation in Domain I are faulting, extension fracturing, recrystallization and pressure solution. These mechanisms are significant at the mesoscopic and microscopic scales. Fault surfaces are affected by frictional sliding and pressure solution slip. The dominant mechanism of deformation in Domain II is pressure solution as indicated by spaced cleavage and pencil structures. Minor extensional fracturing is responsible for calcite veins and boudins.

Macroscopic folding and thrust imbrication contribute 55% internal shortening. Pressure solution deformation accounts for an additional 15% shortening; thus, total shortening due to internal deformation is approxiamtely 70%. Fault zone deformation contributes simple shear strain and longitudinal shortening to internal deformation in Domain I.

The sequence of deformation in the Backbone thrust sheet is primarily constrained by geometric relationships between cleavage and structural elements. Cleavage formed early in the history of the thrust sheet, contemporaneously with microscopic strain. Macroscopic folding, formed during thrusting, postdates cleavage and passively rotated it into fans. Faulting was the final increment of deformation.

INTRODUCTION

Purpose of Study

Deformation of rocks in fold and thrust belts includes elements of three fundamental processes: 1) translation along faults; 2) rotation of strata; and 3) internal deformation. Translations and rotations have been measured and integrated in regional scale studies which determine structural geometry, sequence of events and the amount of shortening in thrust belts (e.g. Royse and others, 1975, Dahlstrom, 1970). However, the distribution and degree of internal deformation and its contribution to shortening within thrust sheets is less well documented. Internal deformation has generally been considered insignificant compared to shortening across an entire thrust belt (Allmendinger, 1982, Elliott, 1976b).

In the Swift Reservoir area of northwestern Montana, internally deformed middle Cambrian strata are overlain by apparently undeformed upper Cambrian and Devonian strata in the Backbone thrust sheet (Singdahlsen, 1986). This study was undertaken to address the significance of this internal deformation and the observed strain heterogeneity. More specifically, the goals of this study were: 1) to define the variation in style and intensity of internal deformation; 2) to identify the mechanisms that produced the deformation; 3) to quantify internal deformation and determine its contribution to shortening within the thrust sheet; and 4) to determine the sequence of deformation and identify features which provide insight into mechanics of emplacement of the Backbone thrust sheet using macroscopic, mesoscopic and microscopic structural elements.

Understanding the internal deformation within thrust sheets is important for several reasons. First, internal deformation is not accounted for in constructing balanced cross sections, and yet it may represent a significant amount of the total shortening. Second, variations in the distribution of internal deformation have many implications for exploration geology including subsurface predictions of geometry and depth continuity of structures. Third, studies of internal deformation can provide constraints for determining the sequential development of thrust sheets (e.g.Simon and Gray, 1982) and may contribute to understanding the mechanical processes involved in emplacement of coherent thrust sheets (e.g. Reks and Gray, 1983; Allmendinger, 1982).

Area of Study

The Sawtooth Range of northwestern montana is part of the Cordilleran foreland fold and thrust belt (Figure 1). It lies directly south of Glacier National Park and is characterized by complexly thrusted and folded Paleozoic and lower Mesozoic sedimentary rocks. The Swift reservoir study area is located in the northern part of the Sawtooth Range (Figure 2). The northwest trending Backbone thrust sheet in the Swift Reservoir area is composed of numerous smaller-scale thrust imbricates and intraplate folds; it's surface trace is about 13 km long. The Backbone thrust places Cambrian and Devonian strata over

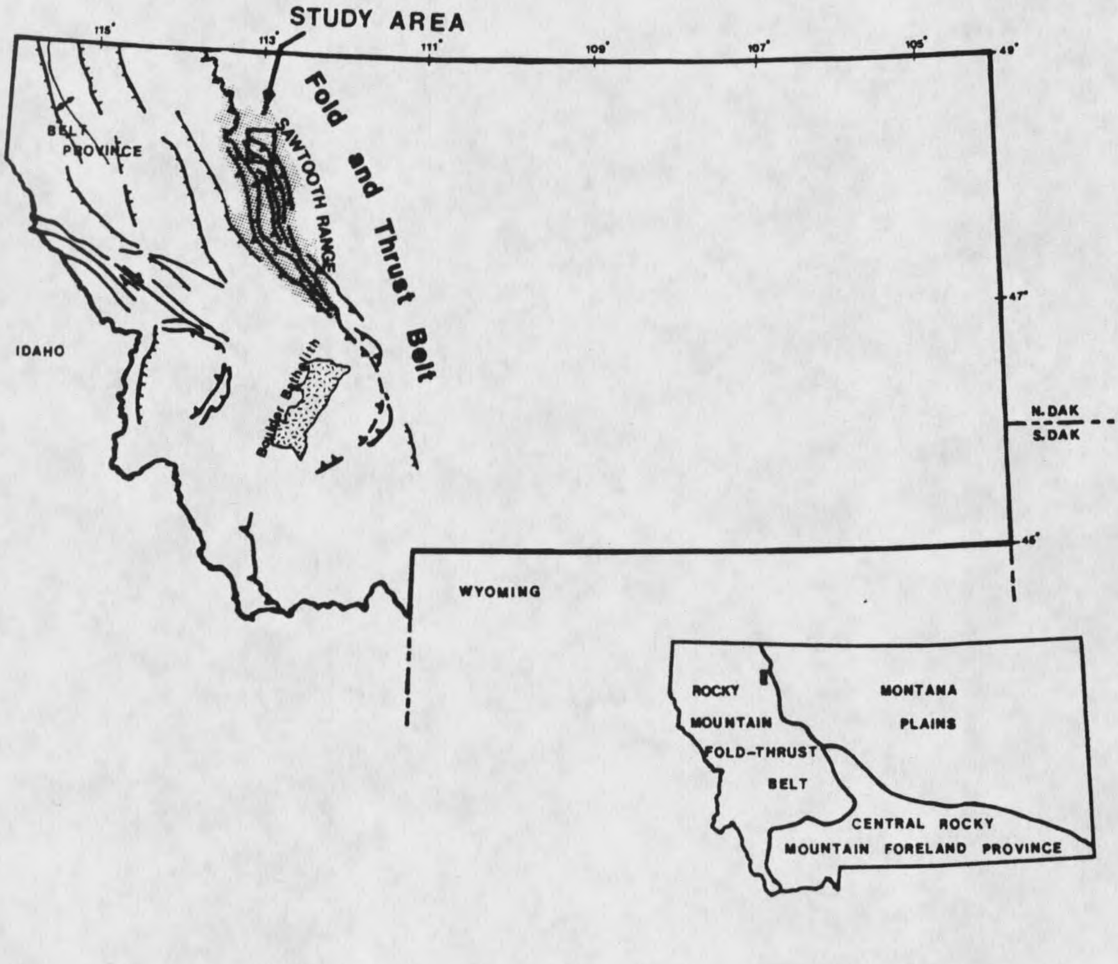

Figure 1. Generalized tectonic map of northwestern Montana (after Taylor and Ashley, 1986).

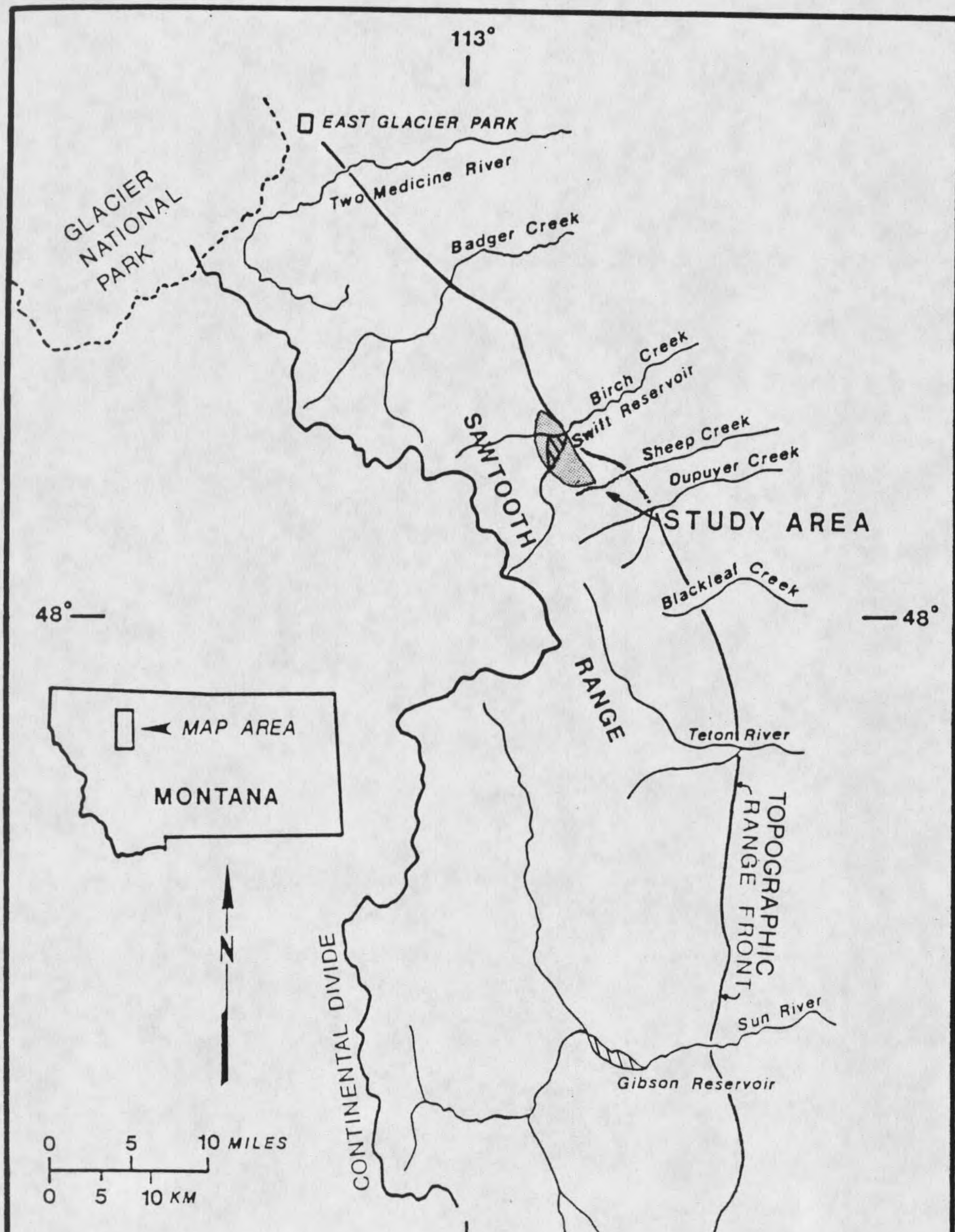

Figure 2. Study area location map, Sawtooth Range (from Singdahlsen, 1986).

Upper Paleozoic and Mesozoic strata. Excellent exposure of the Backbone thrust sheet and its footwall strata occur along the shores of Swift Reservoir and Birch Creek which flows normal to the strike of the thrust.

The study area is approximately 25 km west of the town of Dupuyer, Montana in Pondera and Teton Counties. Access to the area is by a maintained gravel road to the Swift Dam site, then by foot and horse trails. The area is covered by the Fish Lake and Swift Reservoir 7.5 minute United States Geological Survey topographic quadrangles.

Previous Investigations

Previous geologic studies of the Sawtooth Range and surrounding area provided an overall structural and stratigraphic framework for this study. Stratigraphic investigations by Deiss (1939) and Mudge (1972a) defined mappable units and lithologic characteristics of Paleozoic strata in the Sawtooth Range. Deiss (1943b), Mudge (1972b), and Mudge and Earhart (1980), have discussed the regional structural framework. Mudge (1982) also provided an excellent summary of the structural geology of the Sawtooth Range and surrounding area.

Several master's theses of the Swift Reservoir area provided the preliminary geologic mapping, structural analysis and stratigraphic interpretations needed to undertake this study. Most recently, Singdahlsen (1986) conducted geologic mapping and a structural analysis of the Mesozoic and Paleozoic units in the area from Swift Reservoir south to Dupuyer Creek. His work suggested that Swift Reservoir is on a structural culmination formed by polyphase deformation of the

Backbone thrust sheet. A study of the area directly west of Swift Reservoir by Feucht (1971) concentrated primarily on stratigraphy and deformational styles. His work provided the first estimates of principal stress directions for deformation from stereonet plots of bedding and fold axes.

Methods of Investigation

To achieve the defined study goals, field investigation, structural analysis, strain analysis and petrographic examination were performed. Field investigation was initiated in 1986 by conducting detailed geologic mapping of macroscopic structural elements at a scale of 1:8,000. Sites with good exposures of mesoscopic structural elements were then examined and are designated in the text by stations with small letters. At each station, orientations of geometric elements, kinematic indicators and their relationship to other structures were recorded. Sampling for petrographic study included oriented samples of rocks from fault zones, cleavage, vein-fill material and boudins. In addition, 19 oriented samples of oolites were collected for strain analysis; sampling and analytical procedures are discussed in a later section.

Structural analysis consisted of plotting geometric elements of both macroscopic and mesoscopic structures on lower hemisphere equal area stereonets. From these data, the areal kinematic axes were determined and local deviations noted. The pre-thrust orientation of cleavage was determined by rotating bedding back to horizontal.

Variations in internal deformation were determined by detailing the distribution and intensity of development of macroscopic and mesoscopic structural elements. Petrographic inspection of cleavage and rocks from fault zones provided information on internal deformation at the microscopic scale. Deformation mechanisms were determined by comparing outcrop and petrographic observations with similar observations cited in literature covering other fold and thrust belts. The amount and significance of internal deformation was approximated by various techniques using macroscopic and mesoscopic structural elements. Microscopic strain was determined using the Fry Method (Fry, 1979) on the oriented samples containing ooids. These data were then analyzed to determine the sequence of deformation and a reasonable emplacement history for the Backbone thrust sheet.

GEOLOGIC SETTING

The Sawtooth Range is an arcuate salient within the Cordilleran foreland fold and thrust belt. It consists primarily of west-dipping, closely-spaced thrust faults and complex folds in Paleozoic and Mesozoic strata. The Sawtooth Range corresponds to Subbelt II in Mudge's (1982) subdivision of the Northern Disturbed Belt. Mudge (1982) also provides an excellent summary of tectonic and stratigraphic relations of the Sawtooth Range and surrounding region. Deformation in the fold and thrust belt, constrained by radiometric age dates and structural relationships, occurred primarily in the Paleocene (Mudge, 1982).

The overall geometry of the Sawtooth Range is characterized as an imbricate thrust system (Boyer and Elliott, 1982). An imbricate thrust system is defined by thrust sheets whose thrusts repeat the size and shape of the neighboring thrust so that the sheets overlap like roof tiles (Boyer and Elliott, 1982). Imbricate thrust systems are divided into two major types: imbricate fans and duplexes (Figure 3). Boyer and Elliott (1982) and Mitra (1986) suggest that the Sawtooth Range is a large duplex structure whose roof thrust (Lewis thrust) has eroded leaving the underlying thrust sheets exposed. Boyer and Elliott (1982) also suggest that the Sawtooth Range may be a trailing imbricate fan where the thrust with the largest displacement (Lewis thrust) was ramped behind a series of imbricate thrust sheets but never covered them (Figure 3). In both interpretations, the deformation that formed the Sawtooth Range affected Paleozoic and Mesozoic rocks structurally below the Lewis thrust sheet.

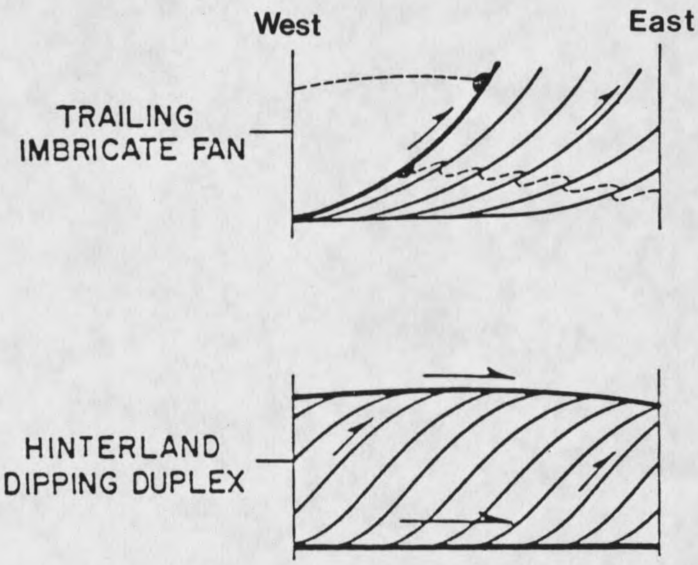

Figure 3. Sawtooth Range geometry generalized by two types of thrust system (from Boyer and Elliott, 1982).

The configuration of the Precambrian crystalline basement probably played an important role in the structural development of the Sawtooth Range (Mudge, 1982). The Sweetgrass Arch, composed of the Kevin-Sunburst Dome and the South Arch, is a basement high located just east of the central part of the Sawtooth Range. It is thought to have acted as a buttress which caused thrusts to ramp steeply during their translation eastward (Mudge, 1982). This high, established prior to Middle Jurassic sedimentation (Mudge, 1982), is reflected by northwest trending structure contours on top of the crystalline basement (Figure 6).