Timing of deformation along the leading edge of the Montana Disturbed Belt, northern Crazy Mountains Basin, Montana

by Stephen Scott Harland

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

Abstract:
The timing of Sevier- or detachment-style fold and thrust belt deformation along the leading edge of the Helena salient of the Montana Disturbed Belt has not been well-defined due to a lack of overlying syn- or post-orogenic strata. The easternmost folds of the salient however, are cored with a series of intrusions which appear, on the basis of map pattern, to be pre-, syn-, and post-tectonic with respect to fold and thrust belt deformation. Paleomagnetic fold test and radiometric age data are used in combination with previous structural and stratigraphic studies to more accurately constrain the timing of fold and thrust belt deformation in the northern Crazy Mountains Basin. In addition, a geochronological synthesis of the major tectonic events in the evolution of the Crazy Mountains Basin and surrounding uplifts is presented.

Paleomagnetic fold test data from mafic alkaline sills of the Robinson anticline intrusive complex indicate that in situ site mean direction are well-grouped (D = 327°, I = 58°, k = 46.5, a95 = 7°, N = 8) and that a fold test is negative and significant at the 95% confidence level. This indicates that the intrusions were emplaced subsequent to folding. Radiometric (K-Ar) dates from the Robinson anticline intrusive complex and Comb Creek stock range from 52 to 48 Ma and are therefore early Eocene in age. Robinson anticline sills intrude folded Late Cretaceous to middle Paleocene sedimentary rocks of the Fort Union Formation. Sevier-style fold and thrust belt deformation along the leading edge of the Helena salient of the Disturbed Belt is therefore bracketed as latest Paleocene to earliest Eocene. This age is in reasonably good agreement with that of similar structures along the eastern margins of the northern Montana Disturbed Belt and the Utah-Idaho-Wyoming salient. Elsewhere in the Crazy Mountains Basin and surrounding uplifts, the broad timing of Sevier- and Laramide-style deformation is demonstrated to span the period from Late Cretaceous to earliest Eocene.

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Master of Science

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MONTANA STATE UNIVERSITY
Bozeman, Montana

January 1986

APPROVAL

of a thesis submitted by

Stephen Scott Harlan

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

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ACKNOWLEDGEMENTS

The author would like to thank Dr. David R. Lageson for introducing the thesis problem to me and for his guidance throughout the project. I am also grateful for his constructive criticism during the final stages of the project.

Financial assistance for this project was provided by an American Association of Petroleum Geologists Grant-In-Aid and by grants from Marathon Oil Company, Arco Oil Company, General Hydrocarbons, Inc., and the Montana Bureau of Mines and Geology. This assistance is greatly appreciated.

The author would like to thank the following people for assistance in various stages of fieldwork and sample preparation: Patricia Corry, Jon Harstedt, Mike McKinley, Doug Richmond, Paul Rubright, Hugh Safford, and Cindy Waldo.

The author is grateful to Dr. Steve Sheriff of the University of Montana for aid in the early stages of paleomagnetic sampling and analysis. Dr. John W. Geissman of the University of New Mexico kindly allowed me use of his paleomagnetic lab and assisted me in the analysis and interpretation of data. His help is greatly appreciated. Dr. James G. Schmitt and Dr. David Mogk served on the reading committee and contributed greatly to the final draft of this thesis. Finally, the writer would like to thank his mother and father for their encouragement throughout this project.

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ABSTRACT

The timing of Sevier- or detachment-style fold and thrust belt deformation along the leading edge of the Helena salient of the Montana Disturbed Belt has not been well-defined due to a lack of overlying syn- or post-orogenic strata. The easternmost folds of the salient however, are cored with a series of intrusions which appear, on the basis of map pattern, to be pre-, syn-, and post-tectonic with respect to fold and thrust belt deformation. Paleomagnetic fold test and radiometric age data are used in combination with previous structural and stratigraphic studies to more accurately constrain the timing of fold and thrust belt deformation in the northern Crazy Mountains Basin. In addition, a geochronological synthesis of the major tectonic events in the evolution of the Crazy Mountains Basin and surrounding uplifts is presented.

Paleomagnetic fold test data from mafic alkaline sills of the Robinson anticline intrusive complex indicate that in situ site mean direction are well-grouped ($D = 327^{\circ}$, $I = 58^{\circ}$, $k = 46.5$, $a95 = 7^{\circ}$, $N = 8$) and that a fold test is negative and significant at the 95% confidence level. This indicates that the intrusions were emplaced subsequent to folding. Radiometric (K-Ar) dates from the Robinson anticline intrusive complex and Comb Creek stock range from 52 to 48 Ma and are therefore early Eocene in age. Robinson anticline sills intrude folded Late Cretaceous to middle Paleocene sedimentary rocks of the Fort Union Formation. Sevier-style fold and thrust belt deformation along the leading edge of the Helena salient of the Disturbed Belt is therefore bracketed as latest Paleocene to earliest Eocene. This age is in reasonably good agreement with that of similar structures along the eastern margins of the northern Montana Disturbed Belt and the Utah-Idaho-Wyoming salient. Elsewhere in the Crazy Mountains Basin and surrounding uplifts, the broad timing of Sevier- and Laramide-style deformation is demonstrated to span the period from Late Cretaceous to earliest Eocene.

INTRODUCTION

Purpose of Investigation

The Disturbed Belt is a term used in Montana to describe moderate to intense Sevier-style or decollement-style fold and thrust belt deformation that occurs along the eastern edge of the Cordilleran "Overthrust Belt" (Robinson, 1959; Mudge, 1972; and Woodward, 1981). The Disturbed Belt extends southeastward from near Alberta, Canada, to the Crazy Mountains Basin (Figure 1). East of the Boulder batholith the Disturbed Belt is deflected to form a broad convex-east bulge or salient, termed the Helena salient (Woodward, 1981).

The timing of decollement-style, fold-and-thrust belt deformation within the Helena salient of the Disturbed Belt has not been well constrained. Precise dates for thrust movement are lacking due to a lack of overlying syn-tectonic or post-orogenic strata and suitable fossil assemblages.

The easternmost folds of the Helena salient, however, are cored with a series of igneous intrusions which appear, on the basis of map pattern, to be pre-, syn-, or post-tectonic with respect to fold and thrust belt deformation. Harlan and Lageson (1983) have suggested that radiometric dating, combined with paleomagnetic fold test analysis of appropriate intrusions in the Robinson anticline area (Figure 1), may allow bracketing ages to be placed on fold and thrust belt deformation along the easternmost margin of the Disturbed Belt.

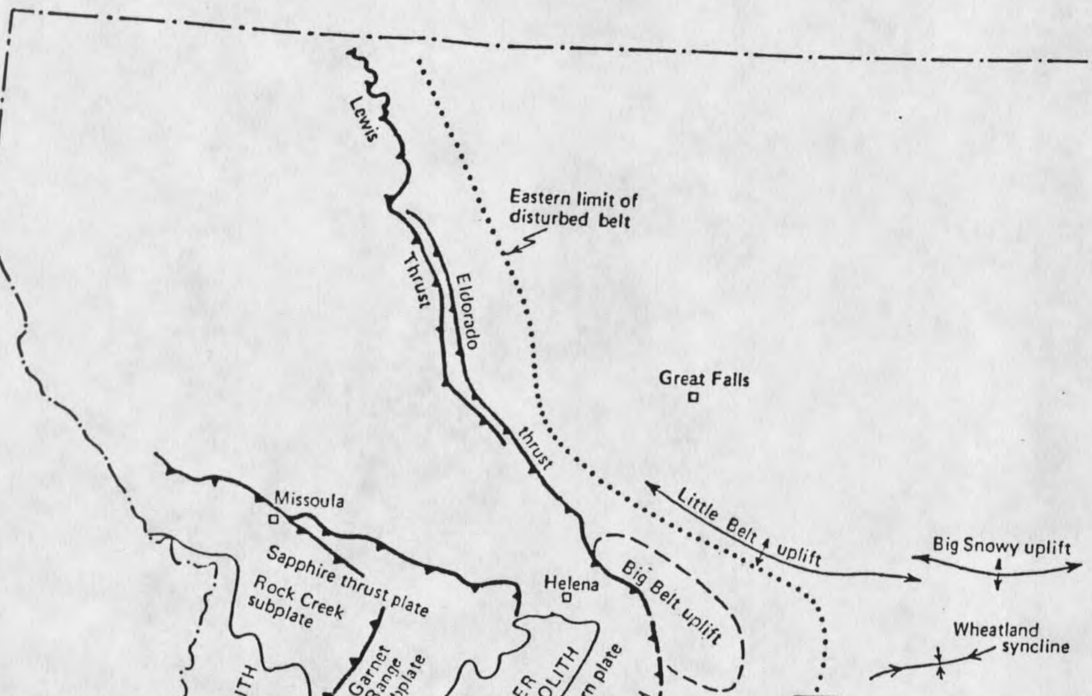

Figure 1. Map showing the location of the study area and its relationship to the major structural and tectonic features of western Montana (modified from Woodward, 1983).

The purpose of this study is threefold: 1) to present new paleomagnetic and radiometric age date data which, in combination with existing stratigraphic data, more accurately constrains the timing of fold and thrust belt deformation in the Crazy Mountains Basin; 2) to present a geochronological synthesis of the major tectonic events in the evolution of the Crazy Mountains Basin; and 3) to compare the timing of decollement-style fold and thrust belt deformation with other similar areas of the Cordilleran fold and thrust belt.

Methods of Investigation

Fieldwork was conducted during parts of the summers of 1983 and 1984. Reconnaissance mapping of the Robinson anticline area at a scale of 1:24,000 on standard U.S.G.S 7.5 minute quadrangles and 1:24,000 U.S. Forest Service airphotos was conducted to check and supplement previously published maps (Simms, 1966).

Simms' map was transferred from a U.S.F.S. 1:20,000 planimetric map to a standard U.S.G.S. 7.5 minute 1:24,000 base using a Salzman projector. Location of contacts and structures were then checked using airphotos and U.S.G.S. orthophoto quadrangles, and by comparison with reconnaissance mapping.

Paleomagnetic analysis utilizing Graham's (1949) fold test was used in order to determine whether sills in the Robinson anticline area were intruded pre-, syn-, or post-tectonically with respect to fold and thrust belt deformation. Oriented samples were collected in the field, and analyzed under the direction of Dr. John W. Geissman during the fall of 1984 at the University of New Mexico.

Radiometric dating of igneous rocks by the K-Ar method was performed by Geochron Laboratories of Cambridge, Massachusetts.

Previous Investigations

The earliest work in the Crazy Mountains Basin was conducted in 1882 by A.D. Wilson who mapped topography in the area at a scale of 1:250,000 for the Northern Transcontinental Survey. Early geologic reconnaissance studies were conducted by Iddings and Weed (1894), who mapped the Livingston 60 minute quadrangle, and by Weed (1899) who mapped the Little Belt 60 minute quadrangle.

Early stratigraphic contributions were made by Weed (1893) and by Stone and Calvert (1910). More recent stratigraphic studies include Simpson (1937), Vhay (1934; 1939), Parsons (1949), Stow (1938; 1946), Richards and Prichard (1950), McMannis (1955; 1957), Fields (1957), Andrichuk (1957), Hanson, (1957), Sims (1964; 1967), McMannis (1965), Skipp and McGrew (1972), Roberts (1972), and Piombino (1972).

Detailed geologic mapping has been conducted by Richards (1957), Sims (1967), Roberts (1972), Skipp and Petersen (1959), Skipp (1977), Skipp and Hepp (1968), Skipp and McMannis (1971), and McGrew (1977a; 1977b; 1977c; 1977d).

The geologic occurrences of hydrocarbons in the Crazy Mountains Basin has been considered by Hannock (1918), and by Hadley (1972).

Early contributions to an understanding of the igneous geology of the area were made by Pirrsson (1905), and by Wolff (1885; 1892; 1893; 1898). More recent contributions include Daly (1933), Johansen (1937), Wolff (1938) and Larsen (1940). Detailed studies and mapping of the igneous intrusions of the Crazy Mountains has been conducted under the direction of Dr. Leonard Larsen of the University of Cincinnatti. These include Simms (1966), Tappe (1966), Starmer (1972), Fink (1975), and Garner (1984, in preparation). Recently, Dudas and Eggler (1984) and Dudas et al. (1985) have conducted geochemical studies in the Crazy Mountains Basin.

Papers dealing with the structural geology and tectonic evolution of the Crazy Mountains Basin and adjacent areas include Bowen (1918), Thom (1923), Wilson (1936), Tanner (1949), McMannis (1955), Harris (1957), Foose et al. (1961), McMannis (1965), Smith (1965), Simms (1966), Garret (1972), Roberts (1972), Woodward (1981), Harlan and Lageson (1983), Woodward (1983), Lageson et al. (1984), and Lageson and Zim (in press). Tectonic maps of the Crazy Mountains Basin and surrounding areas have been prepared by Roberts (1972), Woodward (1983), and Lageson (1985). Gravity studies have been conducted by Kelly (1966), Sims (1967), and Bonini et al. (1971; 1972).

GENERAL GEOLOGY

Stratigraphic Framework

Sedimentary rocks in the Crazy Mountains Basin range in age from late Precambrian to Quaternary, and are floored everywhere by a basement of Archean continental crust. Following the classifications of Robinson (1959) and Woodward (1981), the sedimentary succession in the Crazy Mountains Basin can be divided into three main assemblages: 1) a late Precambrian to mid-Cretaceous miogeoclinal shelf assemblage; 2) a Late Cretaceous to mid-Paleocene, syn-tectonic clastic-wedge assemblage; and 3) a late Tertiary to Holocene, post-orogenic assemblage. The miogeoclinal shelf sequence is dominated by carbonates and shales, with subordinate sandstones. These sediments were deposited during numerous transgressions and regressions (McMannis, 1965) following the inferred rifting of western North America during Proterozoic time (Burchfiel, 1975; Dickinson, 1977). The synorogenic assemblage is dominated by marine and non-marine clastic sediments shed from orogenic uplifts to the west (McGookey, 1972). Rocks of the pre-orogenic assemblage are exposed only along the basin margins and in surrounding uplifts, while the syn-orogenic units comprise the exposed basin-fill. Post-orogenic strata are represented by late Tertiary to early Quaternary gravel-capped pediments which flank the mountain ranges and by Quaternary glacial deposits (Mansfield, 1909; Alden, 1932; Bluemle, 1962).

A composite stratigraphic column for the Crazy Mountains Basin is presented in Figure 2. For more detailed lithologic descriptions of sedimentary units exposed in and around the Crazy Mountains Basin see McMannis (1964; 1965), Sims (1964; 1967), Roberts (1963; 1972), Skipp and McGrew (1972), and Piombino (1972).

Igneous Geology

Tertiary igneous rocks, intruded into Late Cretaceous to middle Paleocene sedimentary rocks, form rugged peaks and foothills in the approximate center of the Crazy Mountains Basin. The igneous rocks, known as the Crazy Mountains intrusive complex, are part of Pirsson's (1905) central Montana petrographic province and Chadwick's (1972) central Montana alkalic province (Figure 3). The central Montana petrographic province generally consists of two distinct subprovinces or successions of igneous rocks: 1) subalkaline igneous centers; and 2) alkaline igneous centers (Larsen, 1940). Most of the igneous activity has been demonstrated to post-date Laramide orogenic activity (Marvin et al., 1980; Diehl et al., 1983), and belong temporally to the Challis igneous episode as defined by Armstrong (1978).

The Crazy Mountains intrusive complex consists of five main igneous centers including the: 1) Big Timber stock and associated dike swarm; 2) Loco Mountain stock and associated dike swarm; 3) Robinson anticline intrusive complex; 4) Comb Creek stock and associated dike swarm; and 5) Gordon Butte - Elk Mountain anticline complex (Figure 4). Petrologically, the rocks of the Crazy Mountains

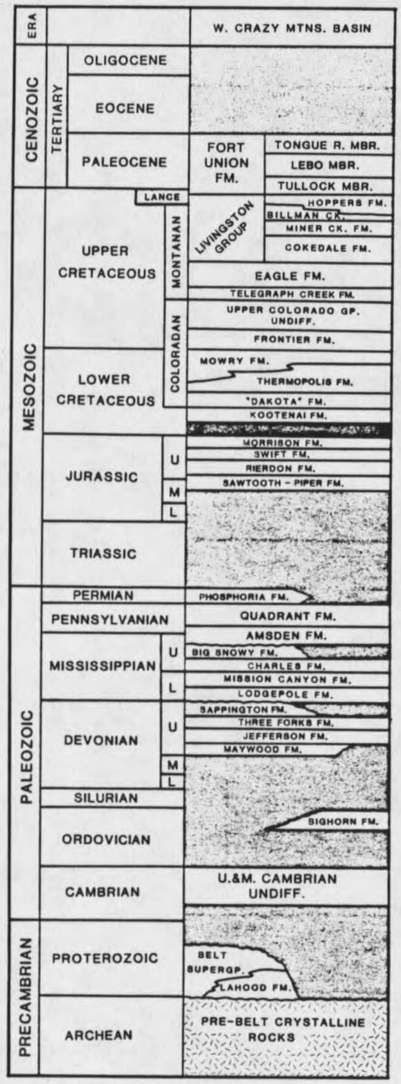

Figure 2. Generalized stratigraphic column for the western Crazy Mountains Basin (modified from McMannis, 1965; Roberts, 1963).

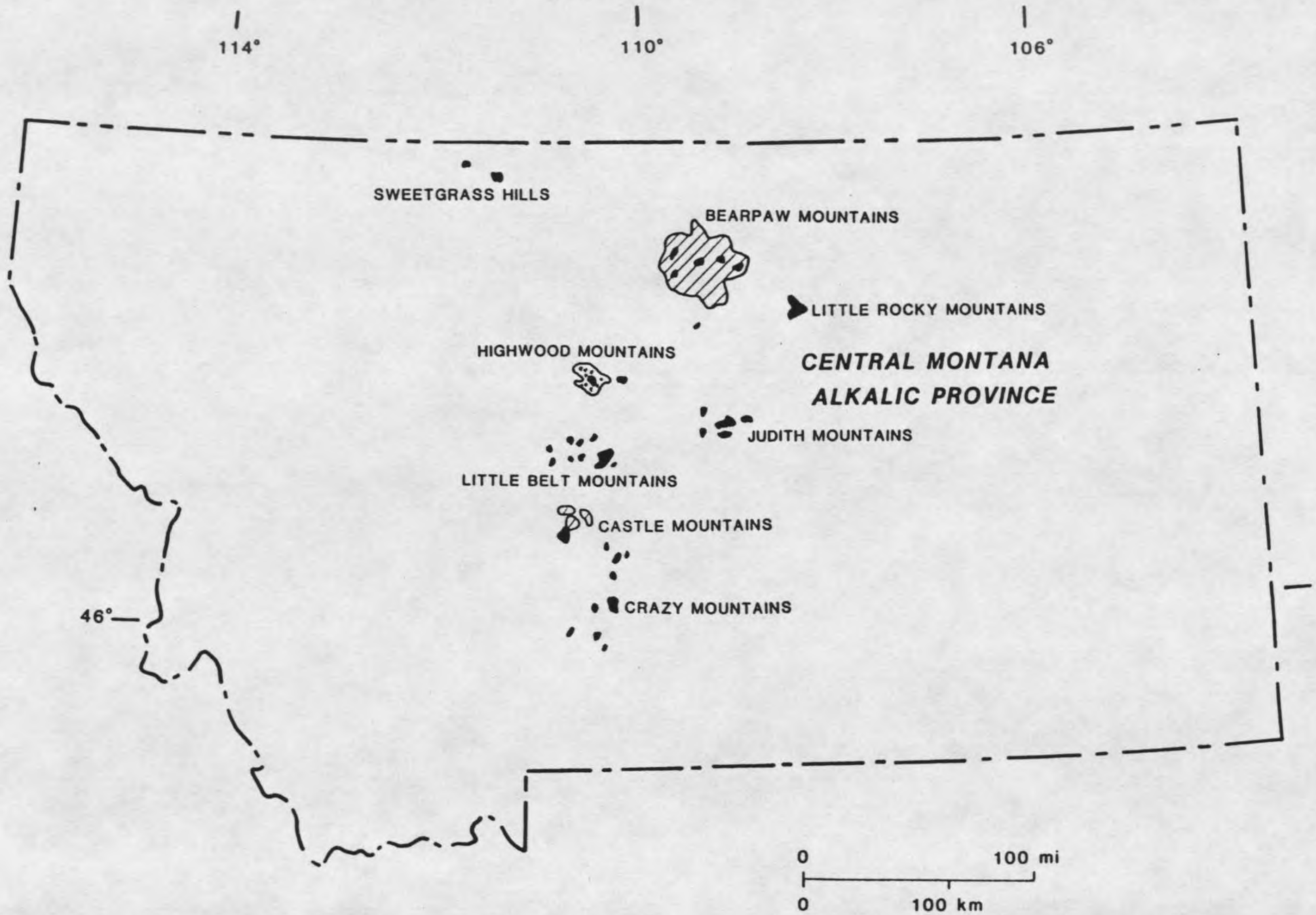

Figure 3. Map showing distribution of major igneous centers of the central Montana alkalic province. Solid pattern = intrusive center; ruled pattern = andesitic volcanic field; stippled pattern = rhyolitic volcanic field. Figure modified from Stewart (1978).

may be divided into two distinct magma series (Larsen and Simms, 1972; Dudas and Eggler, 1984). The Big Timber and Loco Mountain stocks are characterized by a subalkaline, silica-saturated to over-saturated series, while those of the Robinson anticline intrusive complex, Comb Creek stock, and Gordon Butte - Elk Mountain complex belong to a sodium-rich, silica-under saturated, strongly alkaline series. This is in contrast to the remainder of the central Montana alkaline igneous centers which are potassium-rich. Igneous centers of the alkaline series, with the exception of the sill at Ibex Mountain (also known as Theralite Butte), are restricted to north and northeast of the Shields River drainage, while the subalkaline intrusives are generally east and south of the Shields River (Roberts, 1972; Simms, 1966). Because only the Comb Creek stock and Robinson anticline intrusive complex intrude fold and thrust structures of the Disturbed Belt, they will be described in detail below.

Comb Creek Stock

The Comb Creek intrusive complex, originally mapped by Sims (1967) and studied intensively by Fink (1975), consists of a poorly exposed central intrusive body and contact aureole surrounded by an associated dike and sill swarm which has intruded sedimentary rocks of the Late Cretaceous Livingston Group and Late Cretaceous-middle Paleocene Fort Union Formation (Figure 4). The intrusion, subcircular in plan view and with a diameter of 3.5 km, is approximately coincident with the hingeline of Robinson anticline. The body consists of a felsic augite nepheline syenite porphyry (laurvikite of Fink (1975)).

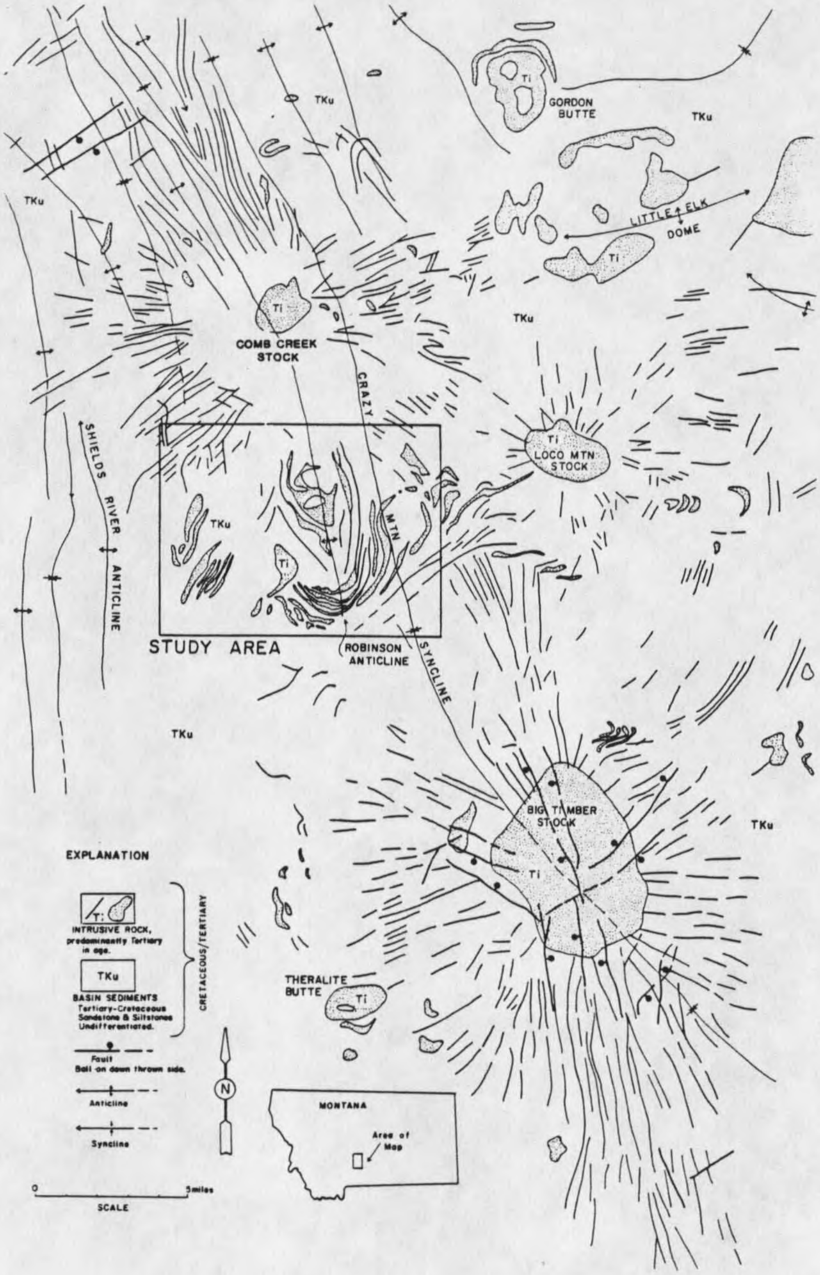

Figure 4. Map showing the distribution of igneous rocks of the Crazy Mountains intrusive complex (modified from Roberts, 1972).

No dikes from the associated swarm are observed to cut the stock, suggesting that intrusion of the stock post-dated emplacement of the dike swarm (Sims, 1967).

The true nature of this intrusive body has not been determined. Previous workers (Wolff, 1938; Simms, 1966; Larsen and Simms, 1972; and Sims, 1967) considers the central intrusion to be a laccolith; Sims (1967) presents a gravity model which supported this hypotheses. Fink (1975) however, points out that gravity data in the immediate area of the intrusive are lacking, and prefers to describe the body as a stock since no floor to the pluton has been observed. No conclusive evidence has been presented for either interpretation, but for the purposes of this study, Fink's stock hypothesis is accepted.

The dike swarm is distributed approximately radially to the Comb Creek stock. Most dikes are vertical ($\pm 10^{\circ}$) and their thickness ranges from 0.5-10 meters, thickness being largely a function of rock type. Compositions of the dikes range from mafic augite-rich nepheline syenite, to trachyte and syenite. Sills associated with the dike swarm are generally restricted to the area north of the stock.

Robinson Anticline Intrusive Complex

The Robinson Anticline intrusive complex consists of numerous concordant igneous bodies and dikes which have intruded Late Cretaceous-middle Paleocene sandstones and shales of the Fort Union Formation, on or near the nose of the south-plunging Robinson anticline (Figure 4, Plate 1). This area has been studied extensively by Simms (1966). Concordant intrusions include a nested sill and/or phaccolithic complex, numerous laccoliths, and dikes. According to Simms (1966), more than 530 meters of concordant intrusions in at least 72 separate bodies occur on the nose of the anticline. Mafic augite-rich nepheline syenites (malignites of Simms (1966)) are present at lower stratigraphic levels and are restricted to the anticline, while felsic feldspathoidal syenites are exposed at higher stratigraphic levels on the anticline, and to the east on a poorly defined east-trending monocline (Simms, 1966).

Dikes are numerous throughout the area and include two main types: 1) single dikes, usually less than 8-10 meters thick; 2) complex dikes, usually less than 30-35 meters thick. In many areas field relationships suggest that the dikes probably acted as feeders to the sills (Simms, 1966).

Six distinct lithologic units have been defined in or near the Robinson anticline intrusive complex: 1) rhyolite-quartz latite; 2) felsic feldsphathoidal syenites and their variants; 3) latites; 4) trachytes; 5) basalts and andesites; 6) mafic augite-rich nepheline syenites (Simms, 1966). Subalkaline silica saturated to oversaturated dikes and sills in this area are related to the adjacent Big Timber and Loco Mountain stocks.

Structural Geology

Regional Structural Setting

The Crazy Mountains Basin is a structural and physiographic basin located in west central Montana (Garret, 1972). It is bordered on the west by the Bridger Range and Big Belt uplift, to the north by the

Little Belt-Castle Mountains uplift, to the east by the Big Coulee - Hailstone dome, and to the south by the Beartooth Range and the Nye-Bowler Lineament (Figure 5).

Structurally, the Crazy Mountains Basin represents the intersection of four distinct structural entities: 1) the southern margin of the fault-bounded Proterozoic Belt embayment; 2) the Sevier-style thin-skinned fold and thrust belt structures of the Montana Disturbed Belt (Woodward, 1981; Garret, 1972); 3) the Rocky Mountain foreland province characterized by basement-involved, low to high angle reverse and thrust faults and associated folds (Schmidt and Garihan, 1983); and 4) a northwest trending wrench fault system comprising the Lake Basin Fault Zone and Nye-Bowler Lineament.

Structural Geology of the Disturbed Belt in the Crazy Mountains Basin

Major folds along the easternmost margin of the Disturbed Belt in the Crazy Mountains Basin are the Sixteen Mile, Elkhorn, Ringling, Potter Basin-Loweth, Shields River, and Robinson anticlines (Sims, 1967; Skipp and Hepp, 1968; Skipp, 1978; Garret, 1972; Woodward, 1981) (Figure 6). Structures along the western margin of the basin are north-south trending, east verging folds and associated thrust faults. Evidence for thrust faults that cut surface exposures of late Precambrian to late Cretaceous sedimentary rocks along the western margin of the basin has been described by Skipp, et. al. (1968). The eastern folds of the Helena salient are slightly asymmetrical, open structures that are convex eastward in map view (Figure 6), and are postulated

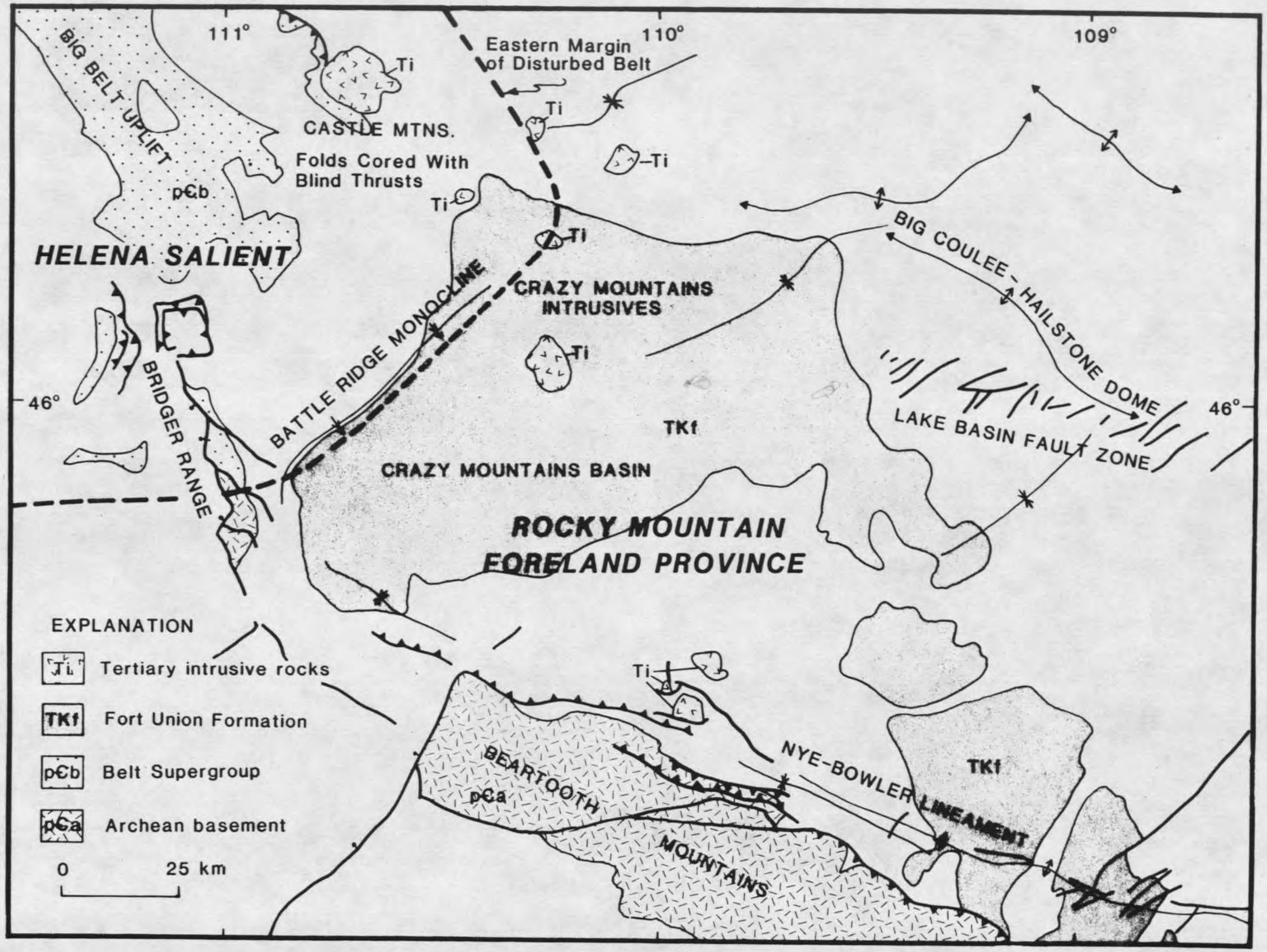

Figure 5. Tectonic map of the Crazy Mountains Basin and surrounding uplifts (modified from Roberts, 1972).

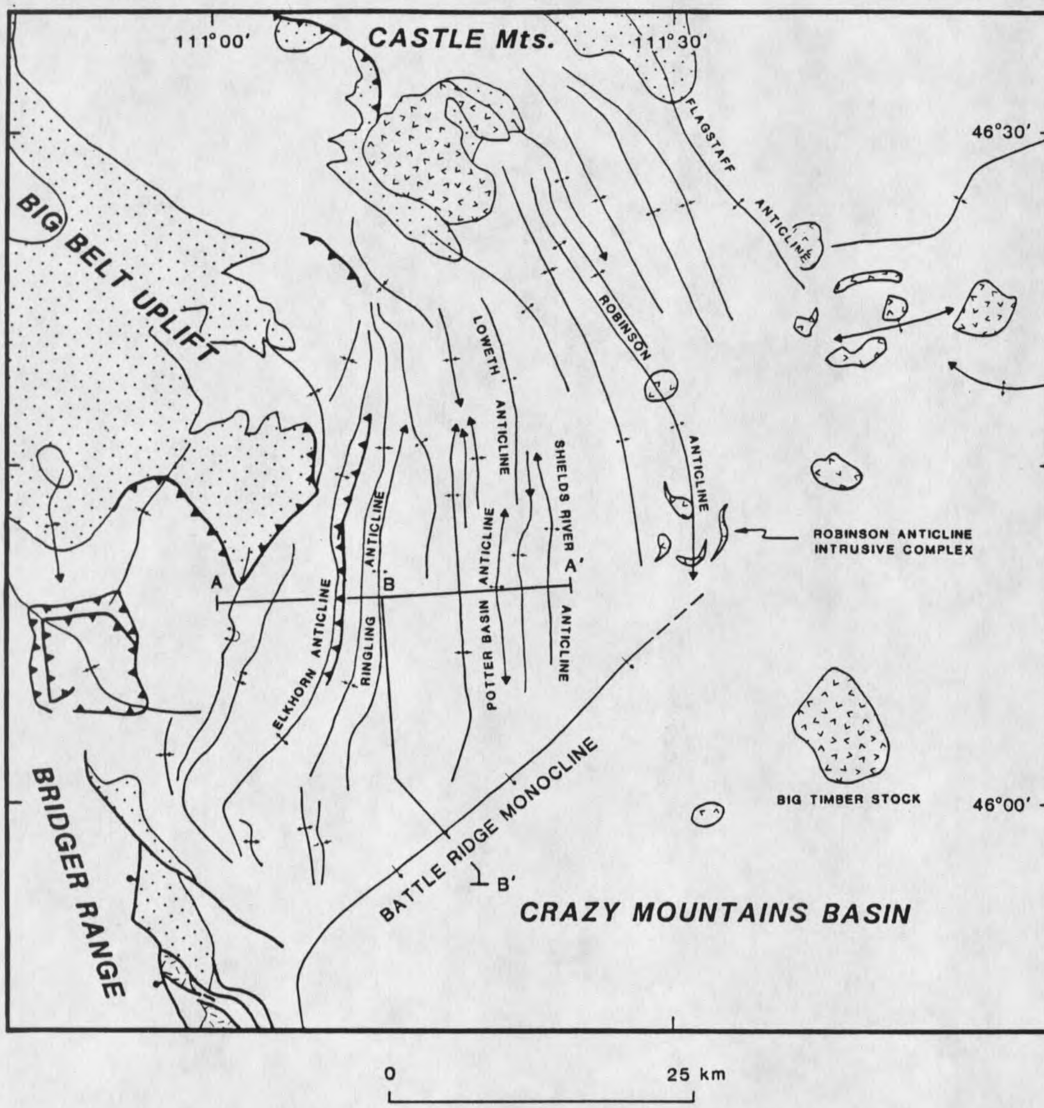

Figure 6. Map showing major folds and faults of the northern Crazy Mountains Basin. Also shown are lines of cross-section A-A' and B-B' of Figures 7 and 11 respectively. Locations of cross-section lines are approximate. Dotted pattern = Precambrian Belt Supergroup; random dash pattern = Precambrian crystalline basement; and random v pattern = Tertiary intrusive centers. Figure modified from Roberts (1972).

by Garret (1972), based on reflection seismic data, to be cored with blind thrusts in the subsurface (Figure 7).

Easternmost folds of the salient, as well as foreland structures immediately adjacent to the Disturbed Belt, are intruded by Tertiary age igneous bodies. Intrusive centers which cut fold and thrust belt structures are the Robinson anticline intrusive complex, and the Comb Creek stock (Larsen and Simms, 1972; Fink, 1975).

Structural Geology of the Robinson Anticline Area

Folds

Robinson Anticline. Robinson anticline is the main structural feature in the study area. The fold trends northwest in the Castle Mountains and Comb Creek stock area, and approximately north-south at its southern termination, just north of the Shields River. At the southern end of the fold, the fold axis plunges 20-25°, S2° E (Figure 8); elsewhere fold plunge is variable and poorly constrained. Geometrically, Robinson anticline is an open, east-verging, concentric to chevron style fold which formed through a combination of flexural slip and flexural flow folding (Donath and Parker, 1964). Evidence of flexural slip folding through layer parallel shortening is demonstrated by the numerous, non-faulted, slickensided sandstone outcrops, both near the southern end of the fold and in the Comb Creek area (Fink, 1975).

Because concentric folds maintain constant bed thickness, the fold shape cannot be maintained upwards or downwards in the folded sequence (Dahlstrom, 1969; Davis, 1984). Therefore, a concentric fold

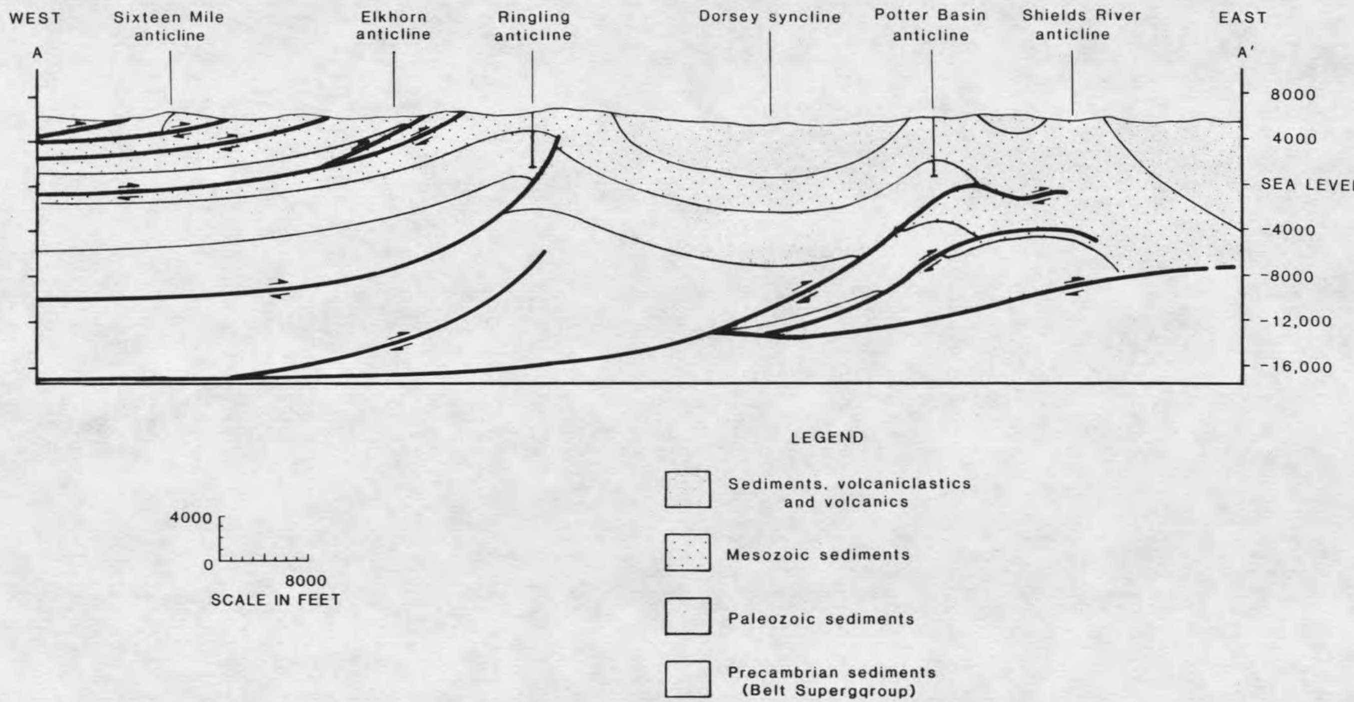

Figure 7. Structural cross-section A-A' (Figure 6) from the northern Crazy Mountains Basin. Structural interpretations are based on seismic profiles. The Shields River anticline is immediately west of the area of this report (modified from Garret, 1972; Woodward, 1981).

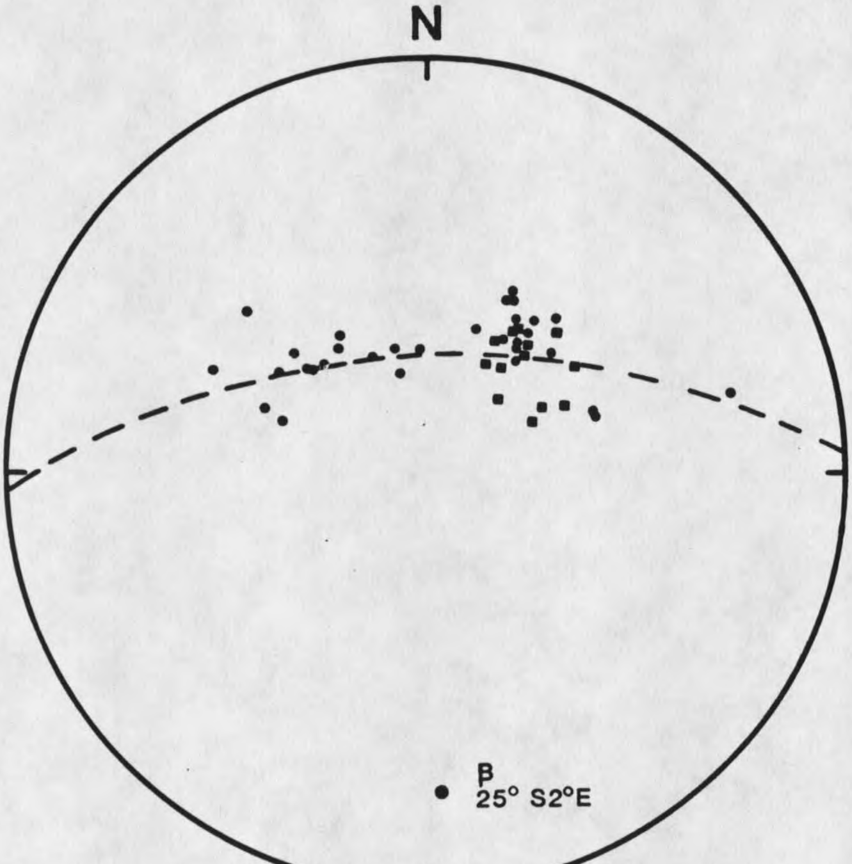

Figure 8. Beta diagram from the southern termination of Robinson anticline. Circles = poles to bedding; squares = poles to base of sills which parallel bedding. The diagram indicates that the fold axis plunges 25° in a S2° direction.

must detach at depth or be cored with a thrust fault (Dahlstrom, 1969). Depth to detachment calculations on form lines in cross-section A-A' (Figure 9) were conducted using the principle of constant area and line length balancing (Dahlstrom, 1969; Burchfiel, 1981). The calculation predicts a detachment at a depth of approximately 5.75 kilometers. This depth seems unreasonable for a fold of this size, especially with respect to the depth of folded and faulted strata immediately west of the study area (Figure 9). Therefore, it is proposed that rather than dying out in a simple detachment at a depth of 5.75 kilometers, the fold is cored with a blind thrust or thrusts at a shallower depth. Fault displacement and shortening at depth is accommodated higher in the section by fold shortening (Dahlstrom, 1969). This type of displacement transfer is very common along the leading edges of foreland fold and thrust belts, and is in accordance with structural interpretations of folds west of Robinson anticline which have been based on seismic profiling (Garret, 1972).

Within the core of Robinson anticline incompetent shales and siltstones of the Fort Union Formation probably deformed by flexural flow and disharmonic folding. Similar structures have been observed as parasitic folds along structures elsewhere in the basin (Figure 10).

Target Rock Monocline. Target Rock monocline is a poorly defined, east to northeast-trending, south-dipping structure immediately east of Robinson anticline (Plate 1). Dip of bedding ranges from 20°N to 70°N; Simms (1966) attributes the discrepancy in dip to be due to the effects of minor normal faults along the west

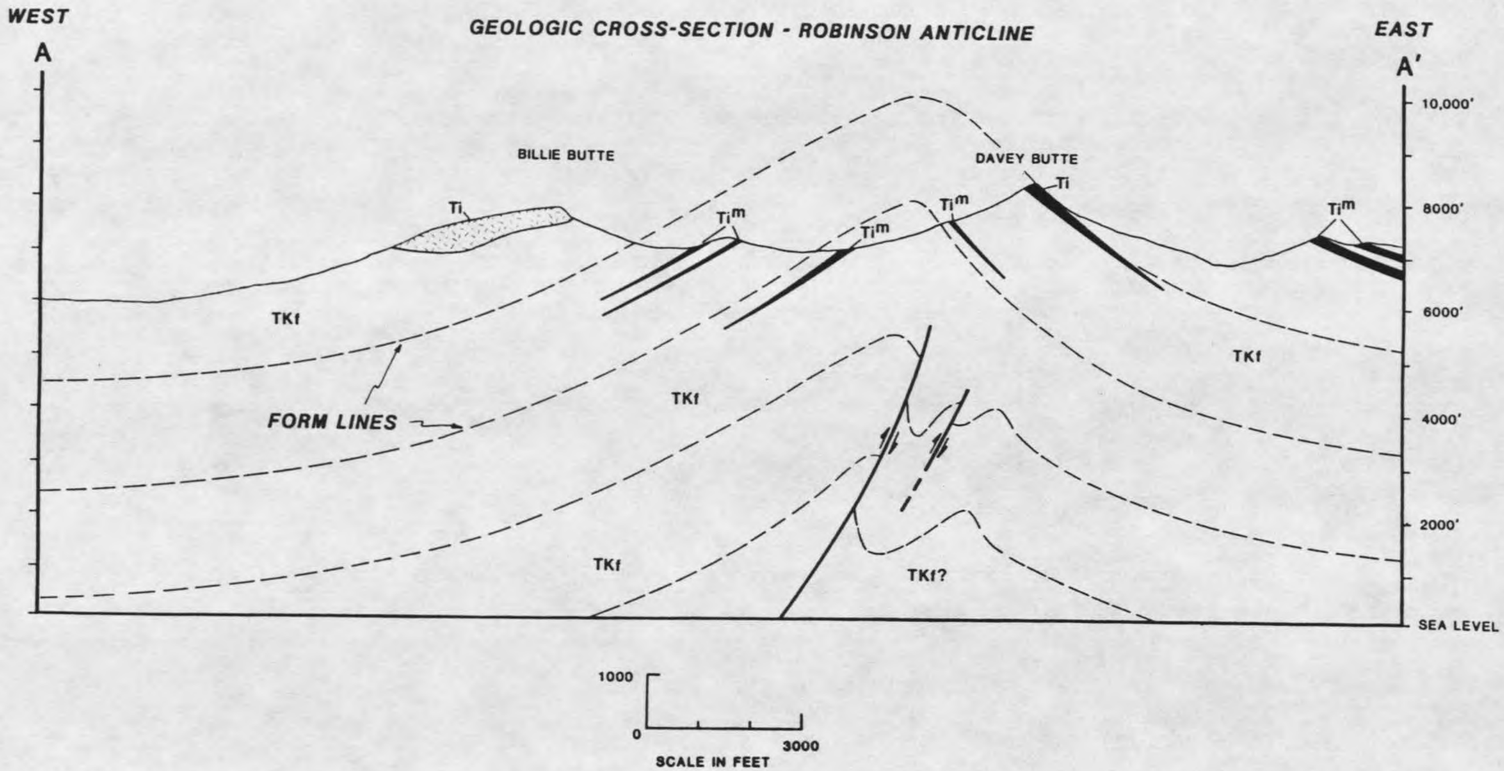

Figure 9. Structural cross-section A-A' (Plate 1) of Robinson anticline. The fold is interpreted to be cored with blind thrust faults at depth, and incompetent sandstones and siltstones of the Fort Union Formation within the core of the fold have deformed by flexural flow and disharmonic folding. Since distinctive stratigraphic boundaries are not present, gross geologic structure has been indicated by form lines. See Plate 1 for an explanation of sysmbols.

Figure 10. Small scale parasitic disharmonic fold and thrust faults in Livingston Group sedimentary rocks exposed in a highway cutslope one mile west of Lennep, Montana.

end of the monocline. Alternatively, variation in dip may be due to slight overturning of the fold along strike. Below the Target Rock intrusion, Simms (1966) reports the presence of a minor "downfold" or syncline.

The trend of Target Rock monocline is similar to that of east-trending foreland anticlines which occur east of the study area (Shawmut anticline and Little Elk dome), suggesting that they may be genetically related. Alternatively, Simms (1966) notes that the monocline trend is approximately on line with vertical sedimentary beds near Wilsall, Montana, which are related to the Battle Ridge monocline. This suggests that Target Rock monocline may be similar in structure and origin to Battle Ridge monocline, which is discussed below.

Battle Ridge Monocline. Battle Ridge monocline is a northeast trending structure adjacent to the east flank of the Bridger Range. Regionally this structure defines the southeastern margin of the Helena salient of the fold and thrust belt (Figure 5). Recent interpretations, based on seismic and structural data (Garret, 1972; Woodward, 1981; and Lageson and Zim, in press), suggest that this structure represents the surface expression of a right-lateral, oblique-slip, ramp anticline (Figure 11). This late Cretaceous to early Tertiary contraction structure is thought to be the result of reactivation of a Proterozoic age normal fault associated with the Belt Basin.

The presence of a northeast trending dike swarm south of Robinson anticline and which parallels the Battle Ridge monocline trend

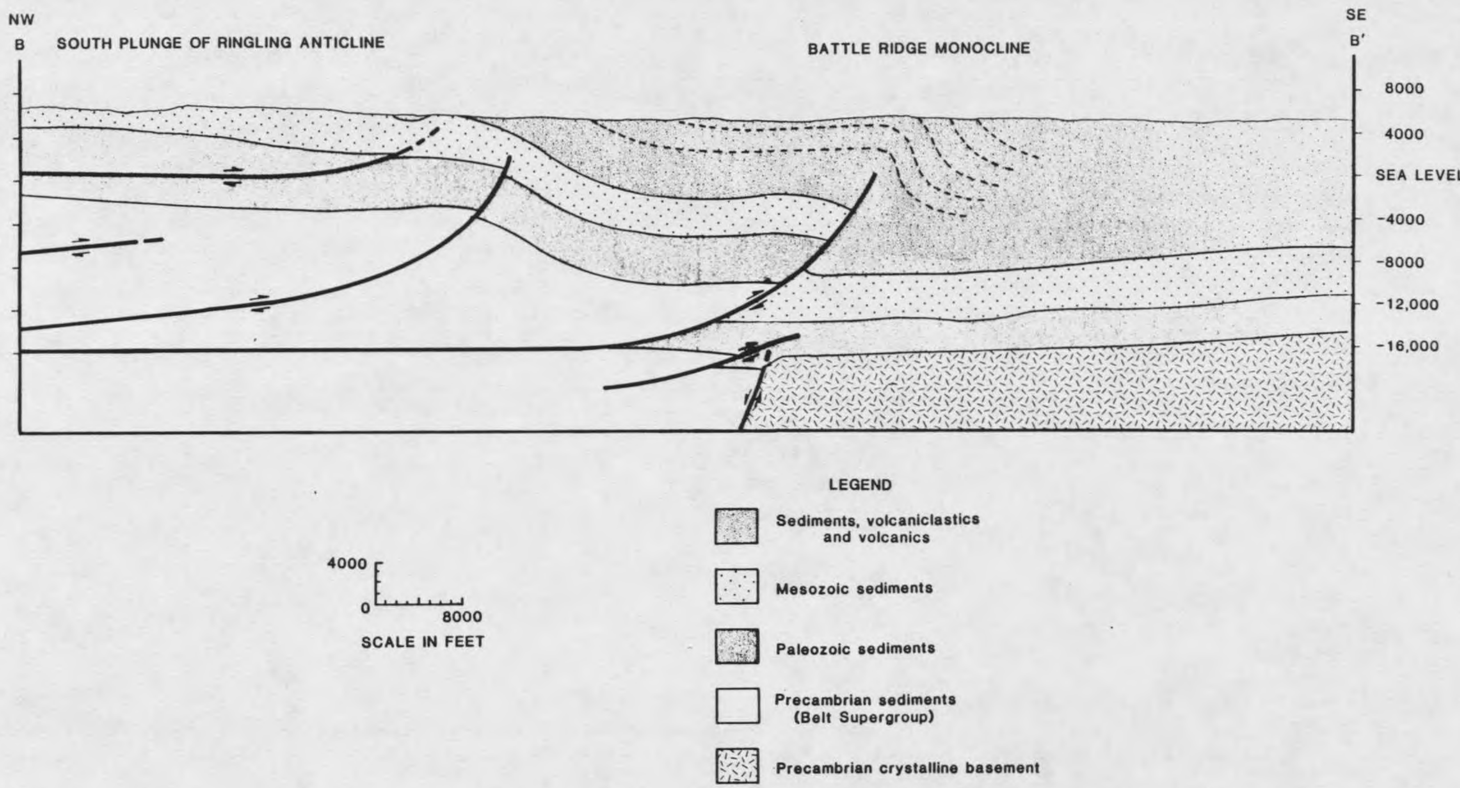

Figure 11. Structural cross-section B-B' (Figure 6) of the Battle Ridge monocline. Structural interpretations are based on seismic profiling. Battle Ridge monocline is interpreted to represent the surface expression of a right-lateral, oblique-slip, ramp anticline. Note that the location of this structure corresponds to the inferred location of the southern margin of the Proterozoic Helena embayment. Figure modified from Garret (1972) and Woodward (1981).

suggests that the monocline may extend into the study area. Presumably, the Battle Ridge structure may have been a line of weakness along which the igneous bodies intruded. In addition, Target Rock monocline may be an extension of, or related to, the Battle Ridge monocline. Unfortunately, overlying late Tertiary/Quaternary surficial deposits obscure any possible relationship between the Battle Ridge monocline and structures in the study area.

A northeast extension of the Battle Ridge monocline into the Crazy Mountains also serves to divide the Crazy Mountains petrologically. In general, sodium-rich strongly alkaline rocks are found only north of the Battle Ridge trend, with the exception of the mafic nepheline syenite sill at Ibex Mountain (Theralite Butte). Subalkaline igneous rocks, although present north of this line, predominate south of the Battle Ridge trend (Roberts, 1972) What relationship, if any, exists between the location of this structure and the emplacement of the two distinct magma series is open to conjecture.

Faults

Faults within the study area, with the exception of blind thrusts at depth, are either not present or have not been recognized due to poor stratigraphic control. The one exception is the minor reverse fault exposed in the headwall of the Great Cliffs landslide (Plate 1). This east-trending fault dips 65^{o} to the north and may have controlled emplacement of a mafic nepheline syenite sill (Simms, 1966). To the east, a continuation of this fault coincides with abrupt the bend in the Virginia Peak laccolith and the presence of slickensided Virginia Peak talus (Simms, 1966).

Simms (1966) reports the presence of minor normal faults (displacement less than three meters) near the western end of the Target Rock Monocline. These faults are not included on his geologic map.

RADIOMETRIC AGE DETERMINATIONS

General Statement

Although the petrology and geochemistry of igneous rocks in the Crazy Mountains Basin have been extensively studied in the last 20 years, radiometric dates of the various igneous centers are either scarce or lacking. In contrast, other igneous centers in the central Montana alkalic province have been extensively dated (Marvin et al., 1973; Marvin et al., 1980). Prior to this study, only one often cited date from the Crazy Mountains intrusive complex had been reported (Larsen and Simms, 1972). This date, a fission-track age of 58.0 ± 6 Megannum (Ma), is from a latite dike associated with the Big Timber stock (Leonard Larsen, personal communication, 1975). Unfortunately, the specific location of this sample is not mentioned, nor is the analytical data used in calculating this age presented in any report. In addition, an unpublished K-Ar date of 50.5 ± 0.6 Ma has been obtained on a biotite separate from the mafic nepheline syenite sill at Ibex Mountain (Theralite Butte) (Larry Snee, personal communication, 1985).

In order to constrain the timing of deformation along the leading edge of the Disturbed Belt in the Crazy Mountains Basin, this study presents new radiometric (K-Ar) dates from the Comb Creek stock and the Robinson anticline intrusive complex. The Robinson anticline intrusive complex has been variously described as pre- or syn-tectonic with respect to folding (Wolff, 1938; Larsen and Simms, 1972; Harlan and Lageson, 1983). Paleomagnetic analysis of the intrusions (discussed in a subsequent section) was proposed by Harlan and Lageson (1983) in order to determine the timing of intrusion relative to the folding event. If the igneous rocks are pre- or syn-tectonic, then radiometric dating of these rocks would allow a lower bracketing age to be placed on the deformation. Radiometric dating of the post-tectonic Comb Creek stock (Fink, 1975), would then provide an upper bracketing age to be placed on fold and thrust deformation in the Crazy Mountains Basin.

In addition to dates used in determination of timing of deformation within the Disturbed Belt, two new radiometric (K-Ar) dates were determined for the Big Timber stock. A map showing the location of the samples is shown in Figure 12, and results of radiometric dating of the samples from the Crazy Mountains intrusive complex are presented in Table 1 and Figure 13. Analytical data used in calculating age of the samples is provided in the Appendix.

Comb Creek Stock

Two samples from the Comb Creek stock and dike swarm were collected for radiometric dating. The first sample (location 1, Figure 12) is from a mafic nepheline syenite dike from the Comb Creek dike swarm and yields a biotite age of 50.3 ± 2.0 Ma. The second date (location 2, Figure 12) is from the nepheline syenite stock and dates as 48.0 ± 1.9 Ma. The older age for the mafic dike is consistent with Sims'

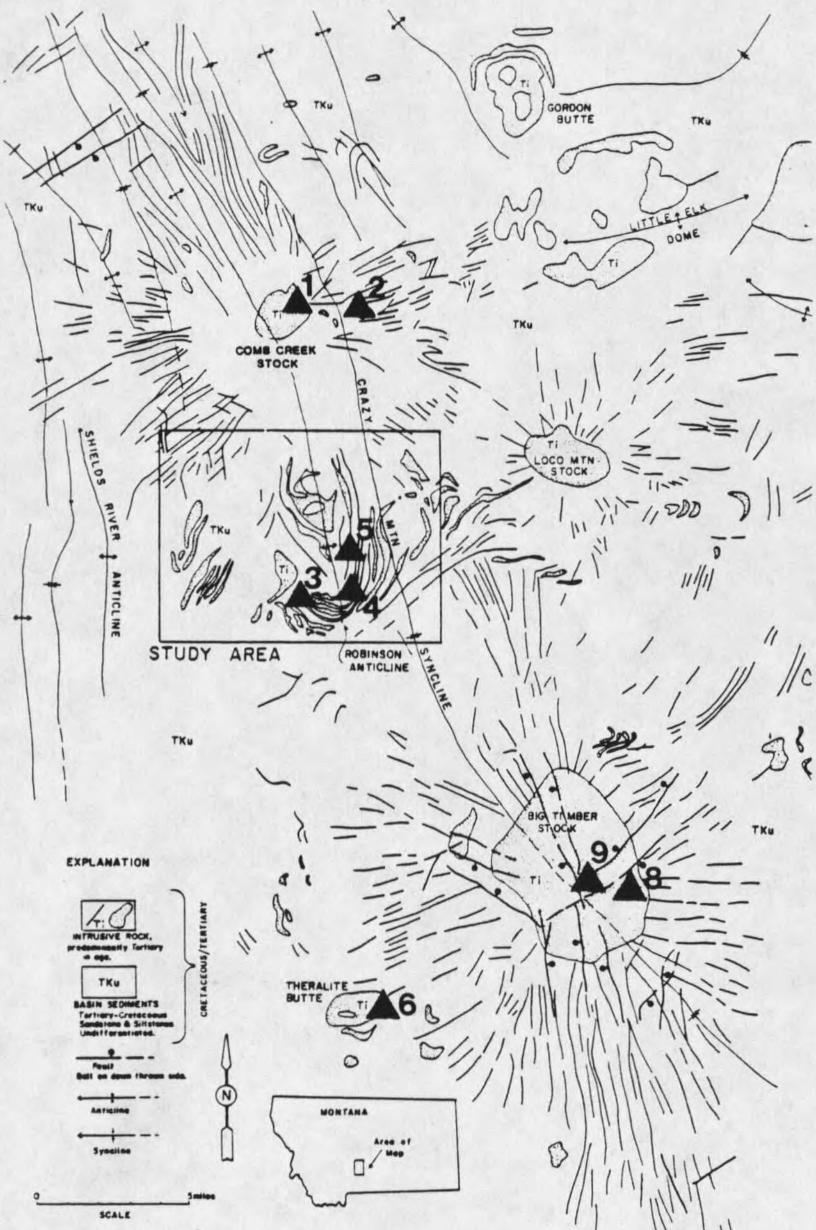

Figure 12. Location of radiometric age determinations from the Crazy Mountains intrusive complex. Figure modified from Roberts (1972).

Sample location (Figure 13)	Sample no.	Material dated/Rock type	Age (Ma)
1	84CC12	Biotite/Nepheline Syenite	48.0 ± 1.9
2	83VPCC1	Biotite/Mafic Nepheline Syenite	52.3 ± 2.0
3	83VP65	Biotite/Mafic Nepheline Syenite	50.6 ± 1.9
4	83VP75	Biotite/Mafic Nepheline Syenite	49.3 ± 1.9
5	82VP2	Hornblende/Trachyte	58.5 ± 4.6
6[1]	008	Biotite/Mafic Nepheline Syenite	50.5 ± 0.6
7[2]	-----	Zircon/Latite	58.0 ± 6.0
8	83BT3	Hornblende/Hornblende Gabbro	50.4 ± 2.5
9	83BTTP1	Hornblende/Granodiorite	43.8 ± 2.7

[1] Larry Snee, personal communication, 1985.

[2] Larsen and Simms (1972). The location of this sample is unknown and does not appear in Figure 13.

Table 1. Radiometric age determinations from the Crazy Mountains intrusive complex, Montana.

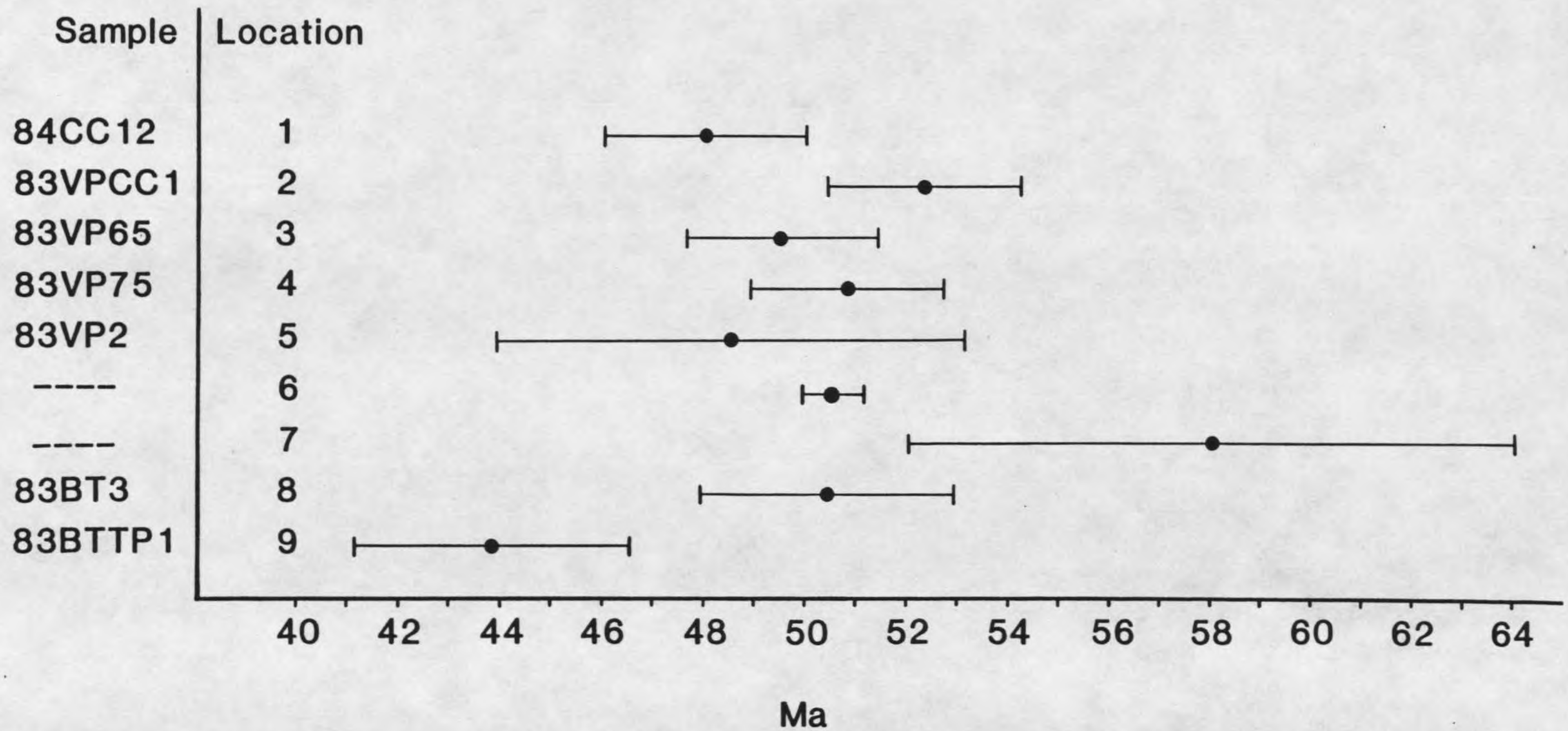

Figure 13. Graphical representation of radiometric age determinations from the Crazy Mountains intrusive complex and their analytical uncertainties.

(1967) interpretation that dike swarm emplacement preceded intrusion of the stock.

Robinson Anticline Intrusive Complex

Radiometric age determinations for three sills from the Robinson anticline intrusive complex (locations 3,4, and 5 of Figure 12) range from 50.6 $\pm$ 1.9 Ma to 48.5 $\pm$ 4.6 Ma for biotite and hornblende separates (Table 1). These ages overlap with those of the Comb Creek stock, and are in good agreement with the 50.6 Ma date determined for the mafic nepheline syenite sill at Ibex Mountain (location 6, Figure 12) (Larry Snee, personal communication, 1985). Thus the radiometric dating of alkaline igneous rocks from the Crazy Mountains intrusive complex provides an average age of 50 Ma, which is in good agreement with rocks of similar composition elsewhere in the central Montana alkalic province.

Big Timber Stock

Two new radiometric dates were obtained from the Big Timber stock. These dates are of interest in regard to the relative timing of emplacement of the two chemically distinct, but spatially overlapping magma series. Early workers in the Crazy Mountains proposed that the subalkaline igneous rocks of the Big Timber and Loco Mountain stocks pre-date emplacement of the alkaline igneous centers, and that the two magma series are genetically related. Recent work by Simms (1966) and Fink (1975) has demonstrated, on the basis of cross-cutting relationships, that the two magma series overlap temporally.

Geochemical studies (Simms, 1966; Fink, 1975; Dudas and Eggler, 1984) further indicate that the magma series are not genetically related, and that they have different source areas.

Tappe (1966) demonstrated that the igneous activity of the Big Timber stock was characterized by six distinct intrusive episodes. These are from oldest to youngest: 1) emplacement of a mafic border phase; 2) emplacement of a phase of intermediate composition; 3) emplacement of a terminal stock phase of felsic composition; 4) intrusion of mafic dikes; 5) net-veining of the stock by numerous generations of aplite dikes; and 6) a final andesitic dike phase (Tappe, 1966). Radiometric dates obtained from hornblende and biotite separates from hornblende gabbro of the mafic border phase and granodiorite of the terminal stock phase (locations 8 and 9, Figure 12) provide ages of 50.4 $\pm$ 2.0 Ma and 43.8 $\pm$ 2.7 Ma respectively. No dates were obtained from the dikes because all sites examined proved to be too weathered to provide reliable dates.

The 50.4 Ma date for the first phase of activity in the Big Timber stock supports cross-cutting relationships which indicate that the two magma series overlap temporally. The recent discovery from this study of a mafic nepheline syenite xenolith within the intermediate phase of the Big Timber stock indicates that alkaline igneous activity may have slightly pre-dated subalkaline igneous activity.

The 43.8 Ma age for the terminal phase of the stock indicates a period of activity for the Big Timber stock and dike swarm of longer than 6 Ma. Since igneous activity for individual igneous centers within the central Montana alkalic province average 3-5 Ma in duration, and major igneous activity in the province ceased by about 46 Ma, the 43.8 Ma date may be too young. This could be the result of radiogenic argon loss due to weathering. Because the population of radiometric ages from the Crazy Mountains is small, additional dates are necessary in order to more accurately assess the duration of igneous activity in the Crazy Mountains intrusive complex.

The 58 Ma age for the latite dike reported in Larsen and Simms (1972) is too old with respect to dates obtained in this study. This date may be spurious for the following reasons: 1) the andesite dike phase (of which the latite dike is most probably associated) is the last phase of igneous activity to occur in the emplacement of the Big Timber stock; hence it is older than the first phase of emplacement; 2) the date is older than those obtained for mafic nepheline syenites which, based on cross-cutting relationships, pre-date at least the intermediate phase of the Big Timber stock; and 3) there is a high degree of analytical uncertainty associated with the date ($\pm$ 6 Ma). Since Larsen and Simms (1972) provide no analytical data for the acquisition of the date, it is difficult to evaluate its geological accuracy.

PALEOMAGNETIC ANALYSIS

Approach and Methods

The purpose of the paleomagnetic analysis of intrusive rocks from the Robinson Anticline intrusive complex was to determine whether they were pre-, syn-, or post-tectonic with respect to fold and thrust belt deformation. This was accomplished using the principles of Graham's (1949) fold test. In this technique, the natural remanent magnetization (NRM) of samples that are distributed about a fold are measured. If the magnetization due to the cooling of the sills has been acquired prior to folding, then the in situ site mean directions are scattered when plotted in stereographic projection. Structural correction for bedding dips "unfolds" the fold, which should result in the clustering of site mean directions. Conversely, if the magnetization has been acquired subsequent to folding, then the in situ directions are well-grouped and structural correction results in the dispersion of site mean directions. A third case, magnetization acquired synchronous with folding is recognized by site mean directions which are not well-grouped either in situ or after structural correction, but cluster when the fold is only partially restored (Brown, 1982).

In order to determine whether improvements in grouping with application of tilt corrections are "real", and not the result of some random mechanism, statistical tests have been devised to analyze fold test data (Watson, 1956a, 1956b; Watson and Irving, 1957; McIlhinny, 1964; McFadden and Jones, 1981).

Nine sites distributed around the nose of the south-plunging Robinson anticline were sampled for paleomagnetic analysis (Plate 1). Due to poor exposure of surrounding sedimentary beds, sampling was restricted to the uppermost mafic nepheline syenite sill (the anticlinal phaccolith of Simms (1966)). The base of this unit is generally well exposed and structural measurements of the sedimentary units are easily obtained. Between 3-7 samples per site were collected by the block method (Tarling, 1983), and were usually taken near the base of the unit in order to avoid the effects of lightning strikes. Orientations were made using a Brunton compass, and backsitings were taken at each site. Samples were reoriented in the laboratory, and cores were drilled using a drill press equipped with a water-cooled diamond drill bit.

Analysis of the samples was conducted at the University of New Mexico during the fall of 1984. Measurements of the natural remanent magnetization were made with a Schonstedt SSM-1a spinner magnetometer interfaced with a Cromenco-two microprocessor, and a Hewlett-Packard (HEDS-500) 500 count/rotation optical shaft encoder. Progressive alternating field (AF) and thermal demagnetization techniques were employed to resolve all magnetic components. AF demagnetization was conducted using a Schonstedt GSD-1 single-axis demagnetizer, and thermal demagnetization was done in a Schonstedt TSD-1 furnace.

Results of demagnetization runs were plotted on Zijderveld (1967) orthogonal vector diagrams. Magnetic components were resolved using standard vector subtraction techniques.

Paleomagnetic Data

Demagnetization of samples by AF and thermal methods was straightforward. In most cases it was possible to isolate a single component of magnetization (Figure 14). Secondary components, generally characterized by northerly directions with moderate to steep inclinations, were generally removed by AF fields of 10-20 millitesla (MT) and by temperatures of 180-270°c. These secondary components are interpreted to suggest a present-day viscous overprint. No other consistent secondary component was observed.

Samples which did not show a single component of magnetization, or which consisted of numerous random components, were generally characterized by intense magnetizations (> 10 Am^{-1}) and probably reflect isothermal remanent magnetization (IRM) induced by lightning-strikes (Cox, 1961). Specimens for which a single vector (defined by three or more colinear points in orthogonal projection (Zijderveld, 1967; Dunlop, 1979) could not be established, or which gave totally random results, were rejected for statistical analysis; this includes the entire sample collection from site 2.

In situ and structurally corrected stereographic projections of the eight site mean directions are shown in Figure 15, and additional statistical data is presented in Table 2. Structural corrections were

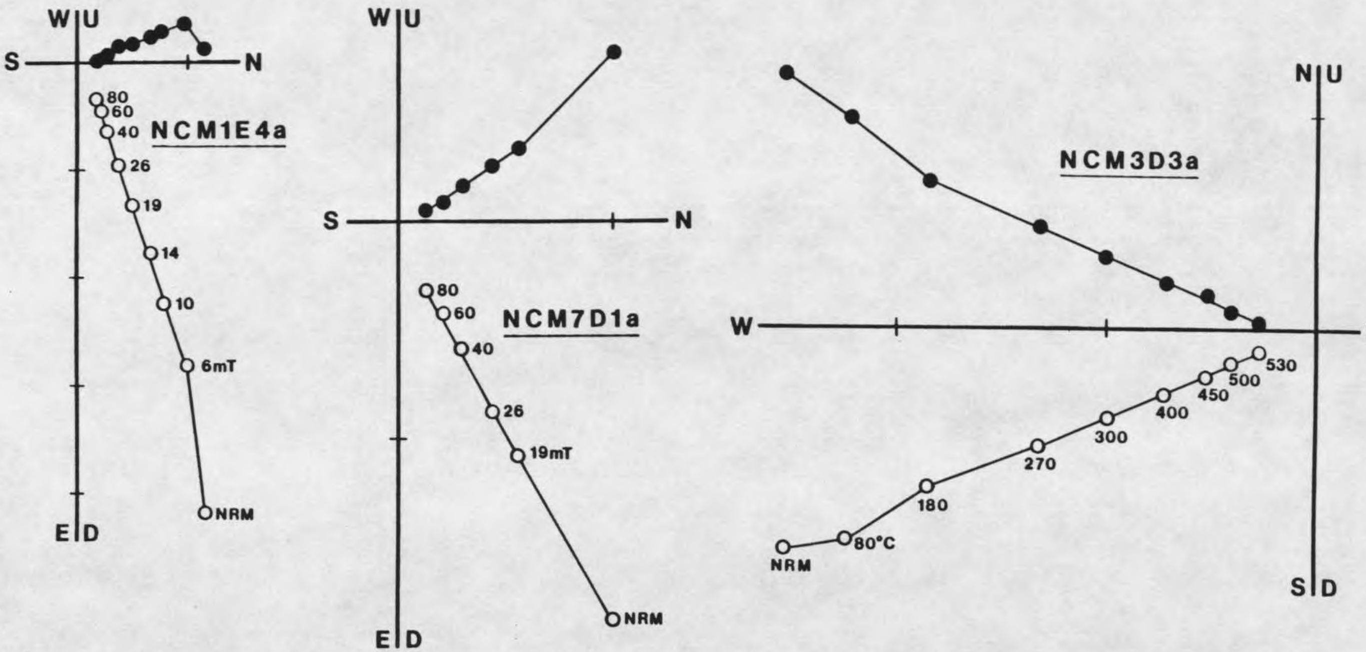

Figure 14. Orthogonal progressive demagnetization projections (Zijdervedld, 1967) of the successive endpoints of the remanence vector during progressive thermal and alternating field demagnetization of mafic nepheline syenite samples from the Robinson anticline intrusive complex. Projections of the endpoints onto the vertical plane is indicated by open circles, projections onto the horizontal plane by closed circles. Each unit = 1.0 X 10^{-3} Am^{-1}.

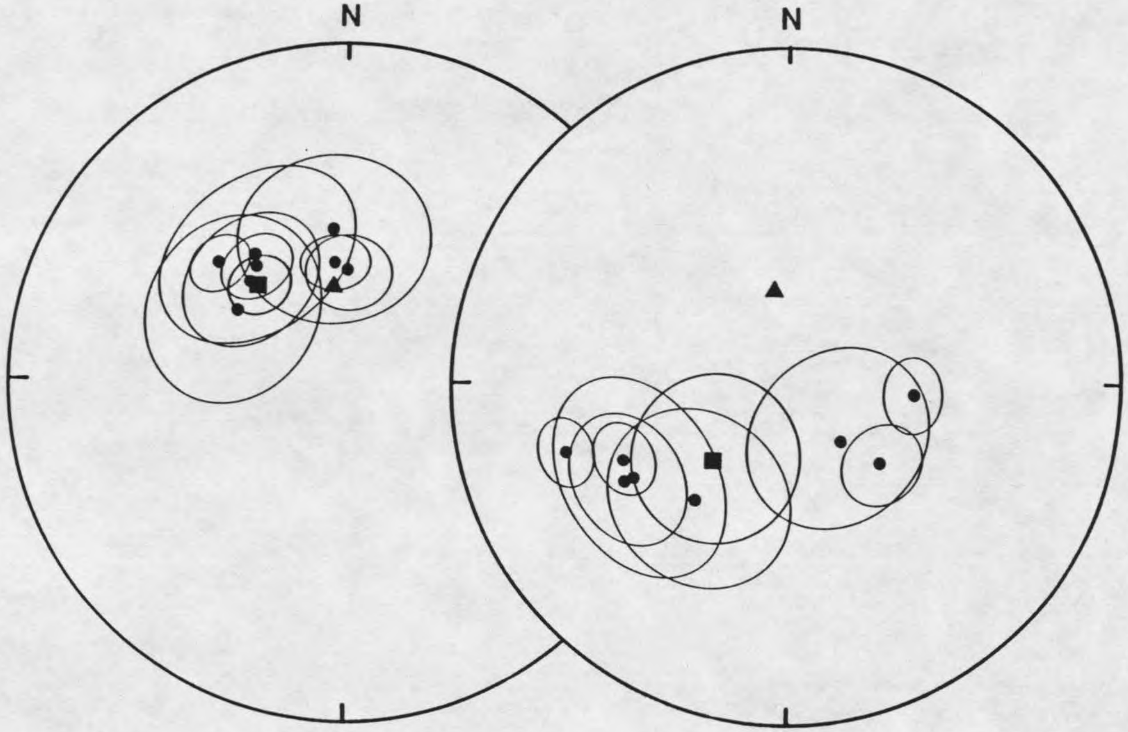

Figure 15. In situ and structurally corrected stereographic projections of the eight site mean directions and their associated ovals of confidence from the Robinson anticline intrusive complex. In situ and structurally corrected group mean directions are indicated by squares; triangle denotes the expected Eocene pole position for central Montana.

Table 2. Summary of site mean results from the Robinson anticline intrusive complex, northern Crazy Mountains, Montana.

Site	Uncorrected		Corrected		Attitude(°)	a_{95}	k	R	N/N_0
	I(°)	D(°)	I(°)	D(°)					
1	61	354	60	095	010, 35	8.5	54	4.93	5/7
2	magnetic components not separated								0/5
3	55	354	75	166	055, 29	23.0	13	2.84	3/4
4	63	001	61	126	042, 31	9.0	61	3.95	4/5
5	57	303	54	219	076, 25	22.0	10	3.70	4/4
6	47	314	36	257	310, 38	7.2	75	4.95	5/5
7	56	316	45	240	300, 32	15.0	22	3.86	4/5
8	54	321	42	249	305, 34	8.0	47	5.90	6/6
9	51	324	44	242	295, 38	23.0	12	2.84	3/3

a_{95} = semi-angle of 95% confidence level.
N/N_0 = ratio of samples used in calculation to samples collected
k = precision parameter (Fisher, 1953)
R = resultant vector

Table 2. Summary of site mean results from the Robinson anticline intrusive complex, northern Crazy Mountains, Montana.

made by first removing the 25° $S2^{\circ}E$ plunge of the fold, and then correcting for bedding tilt.

Examination of Figure 15 indicates that the in situ mean directions are well-grouped and that restoration of the fold produces a scattering of the site mean directions. Note, however, that the grouping of sites 7, 8, and 9 vary little with respect to each other regardless of their configuration. This is because the three sites were sampled along strike and have nearly identical structural corrections (Table 2). They therefore cannot be expected to diverge appreciably when the fold is restored.

Table 3 shows the averaged group mean directions for the in situ and structurally corrected configurations. Again, the in situ orientation has the highest value of the precision parameter (Fishers "k"), and the smallest value of alpha-95 (a95). Application of tectonic correction reduces the value of k and increases the value of a95, suggesting that the in situ position is the correct configuration. In addition, the in situ group mean direction of 58°, 333°, is more nearly coincident with the expected Tertiary pole position for central Montana (66°, 350°) (Diehl et al., 1983), than that of the structurally corrected group mean direction.

In order to determine whether the results of the fold test are statistically distinguishable, an f-test originally derived by Watson (1956) and using values formulated by McIlhinny (1964), was performed. This test compares the precision paramater k (essentially equivalent to the invariance of the mean directions) of the corrected and in situ group mean directions. The formulation of the test is as follows:

Table 3. Paleomagnetic group mean directions and Mchilhinny (1964) fold test statistics from the Robinson anticline intrusive complex.

Sample Collection	D	I	N	R	K	a95
In situ	326.9	57.5	8	7.85	46.5	7.25
Structural Correction	224.6	63.7	8	6.89	6.30	19.7

k1 = 46.5 k2 = 6.30

f = k1/k2 = 7.386

For N = 8 f must exceed 3.70 at the 99% confidence limit

Table 3. Paleomagnetic group mean directions and Mchilhinny (1964) fold test statistics from the Robinson anticline intrusive complex.

$$\frac{k1}{k2} = \frac{\text{Variance with 2(N-1) degrees of freedom before folding}}{\text{Variance with 2(N-1) degrees of freedom after folding}}$$

where N = number of NRM directions, and k1 and k2 represent the best estimates of the precision parameter k for the in situ group mean directions. When k1/k2>>1 then the two populations do not have the same directional dispersion within a given confidence limit (Collinson, 1983). The calculated f-value is then compared to table values computed by McIlhinny (1964). If the ratio of k1/k2 exceeds that of the tabulated value for a given N at a given probability level, then the difference in precision between the in situ and structurally corrected group mean configurations is significant at that level (McIlhinny, 1967; Collinson, 1983).

A McIlhinny fold test analysis (Table 3) indicates that the ratio of k1 to k2 is 7.836. For N = 8, k1/k2 must exceed 3.70 at the 99% confidence limit. The results of the f-test therefore indicate that the fold test has failed, and that the difference between the in situ and structurally corrected configurations are significant at the 99% confidence level.

Conversely, McFadden and Jones (1981), suggest that a McIlhinny (1964) f-test is not valid due to incorrect basic assumptions. This results in the need for a far greater degree of fold distortion than that which should be necessary for statistical significance (McFadden and Jones, 1981). They propose that a test which compares the directional dispersion of a group of sites from each limb of the fold is the correct statistical procedure for analyzing fold test data. In this analysis, the hypothesis that the two limbs of a fold contain a common true mean direction may be rejected if:

$$\frac{(R1 + R2) - (R^2/R1 + R2)}{2(N - Ra - Rb)} > (1/P)^{1/(N-2)} - 1$$

where R is the resultant vector of the site mean directions, Ra and Rb are the resultant vectors of the group mean vectors from each limb of the fold, P is the desired level of significance, and N is the number of sites.

For N = 8 sites from Robinson anticline, the hypothesis of a common mean direction may be rejected at the 95% confidence level if:

$$\frac{7.83 - R^2/7.83}{0.34} > 0.6475$$

substituting R = R1 (the uncorrected resultant vector), the left side of the equation equals 0.304. Thus the hypothesis of a true common mean direction before structural correction is not rejected. For R = R2 (the structurally corrected resultant vector) the left side of the equation equals 5.202 and the hypothesis of a common true mean direction after folding is rejected. A McFadden and Jones (1981) fold test analysis thus indicates that the fold test has failed and that the results are significant at the 95% confidence level.

Discussion of Results

Paleomagnetic data from the Robinson anticline intrusive complex thus indicate that the characteristic NRM of the sill was acquired subsequent to formation of the fold. Intrusion of sills from the Robinson anticline intrusive complex thus post-dates fold and thrust belt deformation. Intrusion of other sills of similar age and composition elsewhere in the Crazy Mountains Basin can also be considered to post-date folding. A minimum age for fold and thrust deformation along the leading edge of the Disturbed Belt can be established by the radiometric dating of post-tectonic sills of the Robinson anticline intrusive complex, as discussed in detail in the next section.

TIMING OF DEFORMATION

The purpose of this section is to review the late Cretaceous to Eocene structural and tectonic evolution of the Crazy Mountains Basin and surrounding uplifts. Although the emphasis of this discussion is on events which began in Late Cretaceous time, a brief review of late Precambrian to mid-Cretaceous events is provided for consistency. Major events from oldest to youngest include the following:

1) The structural and tectonic evolution of western North America began with the inferred rifting of the proto-North American continent during Proterozoic time (Stewart and Suczek, 1977; Dickinson, 1977; Burchfiel, 1975). In western Montana this event is recorded by a westward thickening sequence of quartzite, carbonate rocks, and argillite of the Belt Supergroup. In central Montana, near the Crazy Mountains Basin, a prominent east-trending embayment extended into the craton. This feature, the Helena Embayment, is considered by some workers (Harrison et al., 1974; Stewart and Suczek, 1977; Burchfiel, 1975) to represent an aulacogen which developed in association with the rifting event. Along the southern margin of the Helena embayment, coarse clastic sediments were shed from a fault-bounded crystalline highland into a rapidly subsiding trough (McMannis, 1963). This fault zone, known as the "Willow Creek fault zone" or "Perry Line" (Harris, 1957; Robinson, 1961; Winston et al., in preparation), as well as other Proterozoic structures in Montana, have played a

significant role in controlling subsequent Phanerozoic depositional patterns and tectonic events (for a discussion of Belt age structures and their role in the tectonic evolution of Montana, refer to Winston et al., in preparation, and Harrision et al., 1974).

During Paleozoic time, following the rifting of the proto-North American continent, the western margin of North America was a passive or trailing continental margin (Stewart and Suczek, 1977; Dickinson, 1977). Transgression of the continent began along western North America in early to mid Cambrian time, and deposition throughout Paleozoic time was characterized by carbonate sedimentation with subordinate amounts of shale and sandstone. The change in thickness of various Paleozoic units across the Perry line in southwestern Montana indicates that this structure continued to be active throughout the Paleozoic (McMannis, 1965; Winston et al., in preparation).

2) Beginning in Late Jurassic time, the nature of sedimentation along the western margin of North America changed from predominately carbonate deposition to clastic deposition. This change in sedimentation records the onset of the Sevier orogeny (Armstrong 1968). During this time, the central interior of the North American continent was inundated by a vast, intracratonic, epeiric sea which extended from the Arctic ocean to the Gulf of Mexico (Kauffman, 1977). The western boundary of this seaway was formed by the highlands of the Sevier orogenic belt. Tectonically, the western part of the Cretaceous Interior Seaway can be classified as a foredeep, foreland, or retroarc basin (Dickinson, 1977) that formed eastward of the Sevier fold and thrust belt (Jordan, 1981) (Figure 16). Clastic sediments were shed

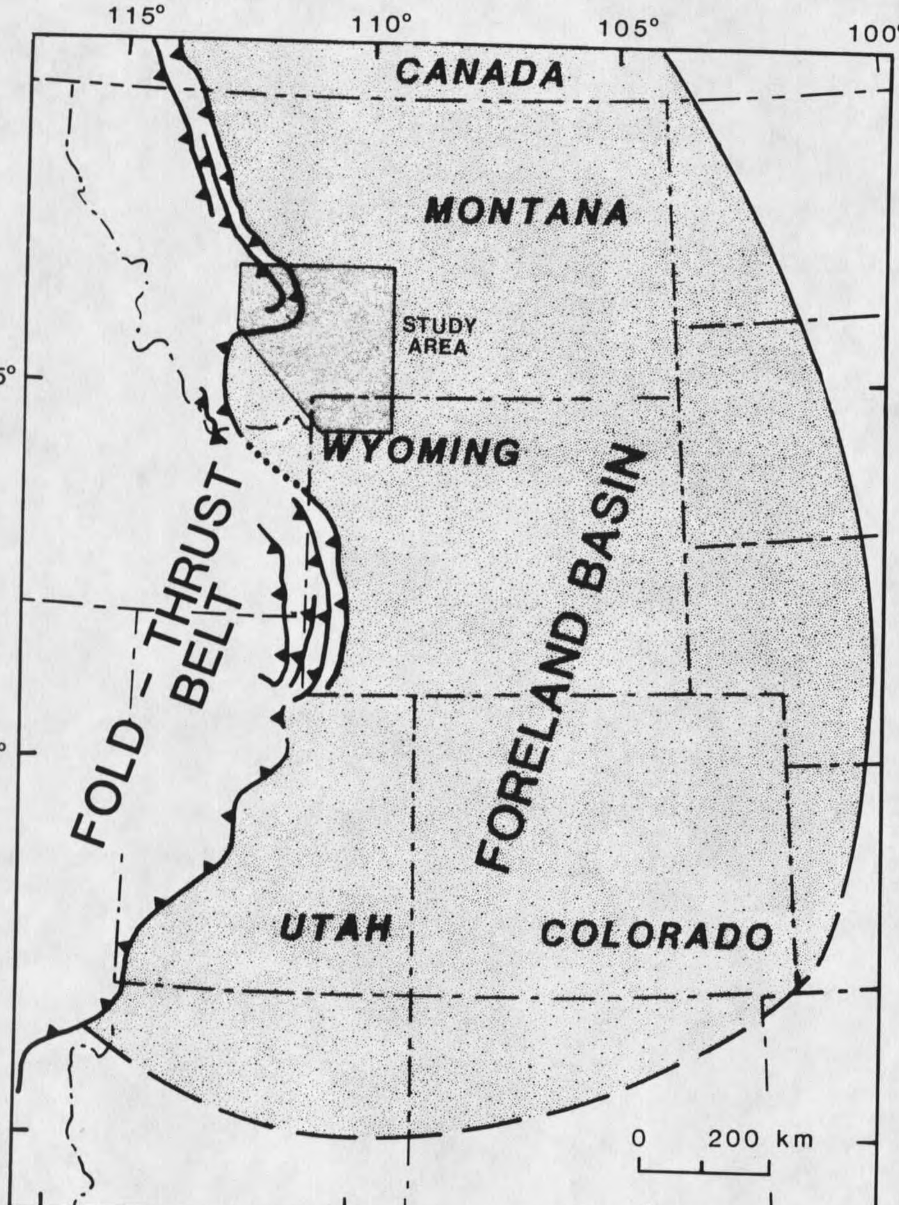

Figure 16. Map showing the location of the Cretaceous foreland basin and the fold and thrust belt (modified from Lawton, 1985).

eastward from the Sevier highland as terrigenous alluvial fans and aprons which interfingered with the marine sediments of the seaway. As deformation in the Sevier orogenic belt migrated from west to east through time, so too did the basin axis. These events are recorded in the late Jurassic to Cretaceous sedimentary rocks of the Crazy Mountains Basin (Roberts, 1972).

3) In the Late Cretaceous, following the retreat of the Eagle sea, the site of the present day Crazy Mountains Basin was warped downward into an asymmetric, northwest-trending basin (Roberts, 1972). Commensurate with downwarping was deposition of the thick volcaniclastic sediments of the Livingston Group. The Livingston Group has been demonstrated to be the eastward lateral equivalent of the Elkhorn Mountains volcanics, which were emplaced contemporaneously with fold and thrusting in the vicinity of the Boulder Batholith (Robinson et al., 1968).

4) During Late Cretaceous to early Paleocene time, a major change in the character of sedimentation in the Crazy Mountains Basin occurred. This change in sedimentation is recognized by the deposition of a thick sequence of conglomerate and conglomeratic sediments of the Fort Union Formation, which were conformably deposited above the Livingston Group. The Fort Union Formation was deposited as a series of coalescing alluvial fans which graded east and southeastward into a low-gradient, marginal marine setting (Piombino, 1979).

A change of provenance between Livingston and Fort Union deposition is recognized by the following characteristics: 1) conglomerates of the Fort Union Formation are much coarser than those of the underlying Livingston Group (Roberts, 1972; Piombino, 1979); and 2) the change in clast composition from Livingston Group rocks which are composed almost entirely of volcanic rock fragments, while Fort Union sediments also contain lithic fragments of Precambrian crystalline and Belt rocks, Paleozoic, and Mesozoic strata (Roberts, 1963; Roberts, 1972; Piombino, 1979). Furthermore, the proportion of non-volcanic detritus in the Fort Union increases higher in the section (Piombino, 1979). Fragments of Archean rocks in the Fort Union Formation are limited to the southwestern part of the Crazy Mountain basin, while Belt clasts tentatively identified as Spokane Shale have been observed only in the northern part of the basin (Sims, 1967).

The change in provenance between the Livingston Group and Fort Union Formation is significant because it indicates the onset of a Late Cretaceous-early Paleocene uplift proximal to the present-day Crazy Mountains Basin. Determining the approximate location of the uplift which acted as a source for Fort Union sedimentation is important in determining the relative timing of tectonic events within and adjacent to the Crazy Mountains Basin. In considering possible uplifts, a source area which contains Archean crystalline and Proterozoic Belt rocks is necessary. Furthermore, the source area must have been unroofed sufficiently by Late Cretaceous to early Paleocene time to expose Paleozoic and older rocks to erosion. Five possible sources are considered: a) uplift of the ancestral Bridger and Gallatin-Beartooth Ranges (Roberts, 1972); b) uplift and erosion of a crystalline cored basement uplift west of the Bridger Range (Piombino, 1979); c) uplift and erosion of the Tobacco Root uplift, with eastward transport of sediments to the Crazy Mountains Basin (Lageson and Zim, in press); d) uplift of the basement-involved Little Belt Mountains; and e) uplift and erosion of a source area containing the Proterozoic LaHood Formation (Figure 17). Each of these possible sources will be considered below.

a) Roberts (1972) has proposed that deposition of the Fort Union Formation was accompanied by uplift of the ancestral Bridger and Gallatin-Beartooth Ranges. Non-volcanic rock fragments in the Fort Union were considered to be derived from the erosion of the developing uplifts. This argument however, is based primarily on the observation that present-day outcrops of the Livingston Group extend beyond the margins of the Crazy Mountains Basin, while those of the Fort Union do not. He does not, in proposing his hypothesis, take into account the possibility that the depositional record of Fort Union sedimentation outside the margins of the Crazy Mountains basin may have been stripped by subsequent uplift and erosion. Furthermore, it is doubtful whether uplift of these ranges was sufficient by Late Cretaceous-early Paleocene time to expose their crystalline cores. For example, initial uplift of the Bridger Range anticline post-dates deposition of the Fort Union Formation (discussed in item 7 below) (Lageson and Zim, in press). Initial uplift of the ancestral Gallatin-Beartooth uplift may have begun by Late Cretaceous-early Tertiary time, but Paleocene sediments along the northern flank of the Beartooth uplift do not indicate unroofing of metamorphic rocks until mid-Paleocene time

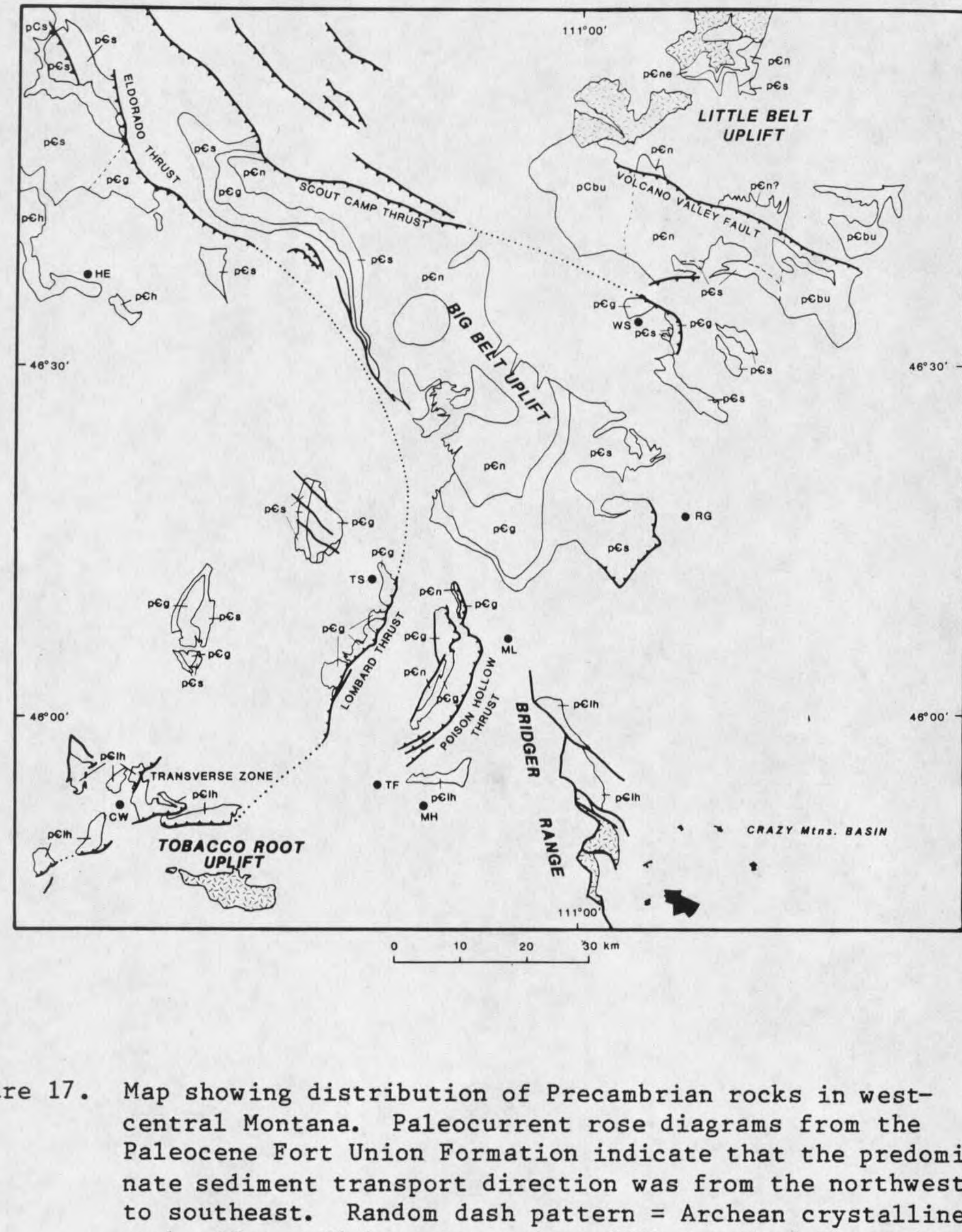

Figure 17. Map showing distribution of Precambrian rocks in west-central Montana. Paleocurrent rose diagrams from the Paleocene Fort Union Formation indicate that the predominate sediment transport direction was from the northwest to southeast. Random dash pattern = Archean crystalline rock; PЄne = Niehart Quartzite; PЄlh = LaHood Formation; PЄn = Newland Limestone; PЄg = Grayson Shale; PЄs = Spokane Shale; PЄh = Helena Limestone; and PЄbu = Belt Supergroup undifferentiated. Locations are: HE = Helena; TS = Toston; CW = Cardwell; TF = Three Forks; MH = Manhattan; ML = Maudlow; RG = Ringling; and WS = White Sulphur Springs. Figure modified from Ross (1963) and Piombino (1979).

(discussed in item 8 below). Therefore, an ancestral Bridger Range and Gallatin-Beartooth Range source is not considered as a possible source area for Fort Union sedimentation.

b) Piombino (1979) agrees with Roberts' hypothesis that the ancestral Bridger Range had been uplifted by Late Cretaceous-early Paleocene time. He recognized however, on the basis of paleocurrent data that exposures of crystalline rock in the Bridger Range are too far south to have contributed material to Fort Union sediments. He proposed instead that the Precambrian rock fragments were derived from the erosion of a crystalline cored uplift in the vicinity of the present Three Forks Basin. He states:

> "Precambrian exposures in the Bridger Range are too far south to have provided detritus to the extensive Battle Ridge conglomerates. Perhaps during Fort Union deposition the crystalline basement was exposed west of the present Bridger Range and in the later Tertiary a portion of this highland was down dropped forming the Three Forks Basin (Piombino, 1979, page 25)."

Sediments containing Archean clasts were then by-passed through the ancestral Bridger Range and deposited in the Crazy Mountains Basin (Piombino, 1979, Figure 25). Paleozoic and Mesozoic components were postulated to be derived from either the flanks of the Bridger Range or from near the Maudlow Basin.

Piombino's model requires a basement-cored uplift northwest of the crystalline exposures in the southern Bridger Range. Since these exposures are just south of the fold and thrust belt structures of the Transverse Zone, such an uplift must lie within the Helena salient. Unfortunately there is no geological or geophysical evidence to suggest the presence of a buried basement-cored uplift within the Helena salient. Furthermore, as stated previously, there is no evidence to suggest that the Bridger Range was a positive element at this time.

c) Uplift of the Precambrian-cored Tobacco Root mountains in late Cretaceous time has been well documented (Schmidt and Garihan, 1983). Erosion of this uplift has been proposed by Lageson and Zim (in press) as a possible source area for the non-volcanic components of the Fort Union Formation. Presumably, sedimentary detritus was transported eastward across the site of the present-day Three Forks Basin and deposited in the Crazy Mountains Basin. There is no evidence at this time to discount the Tobacco Root uplift as possible source of Archean rock fragments within the Fort Union Formation.

d) Uplift and erosion of the Little Belt uplift is proposed as a possible source for Fort Union deposition, but is not considered likely because of the following: 1) paleocurrent evidence (Piombino, 1979) in the Crazy Mountains Basin does not indicate south or southwestern transport of Fort Union sediments; and 2) no Archean clasts have been reported in Fort Union sediments from the northern part of the Crazy Mountains Basin;

e) Archean clasts in the Fort Union Formation need not have been derived directly from uplifts cored with Archean crystalline rocks. Rather, the Archean clasts may have been derived from the sedimentary recycling of clasts from the Proterozoic LaHood

Formation. Uplift and erosion of thrust sheets in the Helena salient which carry LaHood strata in their hanging walls may have provided a portion of the non-volcanic fraction of the LaHood Formation. This hypothesis is favored over the previous four for the following reasons: 1) Exposure of LaHood strata, presently exposed in the Horseshoe Hills along the Transverse Zone, are relatively close (within 15-25 km) to the present day outcrops of the Fort Union; 2) present day outcrops are west and northwest of Archean-bearing outcrops of Fort Union Formation in the Crazy Mountains Basin; and 3) there is evidence to suggest that fold and thrust belt deformation had progressed as far east as the Maudlow Basin by late Cretaceous-early Paleocene time (discussed in item 5 below) and this deformation may have uplifted hanging wall thrust sheets sufficiently to erode LaHood strata. Although the author favors this hypothesis for the occurrence of Archean clasts in the Fort Union Formation, it must be noted that there have been no reports of recycled, second-generation, conglomeratic clasts from the Fort Union conglomerates. Further study of the Fort Union is necessary before any firm conclusion concerning a source area can be made.

5) Uplift of the Big Belt Mountains is also proposed to have begun in Late Cretaceous-early Paleocene time. Evidence includes the presence of lithic fragments tentatively identified as Spokane Shale within the uppermost units of the Livingston Group, and throughout the Fort Union Group in the northern Crazy Mountains Basin (Sims, 1967). Examination of Figure 17 indicates that the Spokane Shale is exposed

in the Big Belt Mountains, and uplift and erosion of the Big Belt uplift may have shed detritus southeastward into the Crazy Mountains Basin. Furthermore, Piombino (1979) reports lithic fragments of a blue-green, vitric crystal tuff within the basal Fort Union conglomerate. These fragments are reportedly derived from a tuff within Maudlow Formation E (Skipp and Petersen, 1959), which is exposed in the Maudlow Basin at the southern edge of the Big Belt Mountains (Piombino, 1979). This suggests uplift and erosion of Late Cretaceous volcaniclastic sediments in the Maudlow basin during Late Cretaceous-early Paleocene time, perhaps concurrently with uplift of the Big Belt Mountains. Simultaneous uplift of the Big Belt Mountains and movement of thrusts along the southern edge of the salient could easily have provided the nonvolcanic detritus which was shed east and southeastward into the Crazy Mountains Basin. Continued uplift, combined with erosion of progressively older sediments could also account for the increase in the non-volcanic detritus upwards in the Fort Union Formation.

6) In post middle Paleocene time, Sevier-style folds and thrust faults of the Disturbed Belt deformed the Late Cretaceous to middle Paleocene Fort Union Formation (Newman, 1969; Newman, 1972; and Roberts, 1972), and older sediments in the Castle Mountains, northern Crazy Mountains Basin and along the southeast margin of the Helena salient at the Battle Ridge monocline.

Along the easternmost edge of the salient, several of the folds have been intruded by dikes, sills, and stocks of the Crazy Mountains intrusive complex. Sills exposed within Robinson anticline have been demonstrated on the basis of paleomagnetic fold test data to be post-tectonic with respect to fold and thrust belt deformation. Radiometric age determinations from the northern Crazy Mountains have yielded ages that range from 52-48 Ma., or early Eocene. Intrusions of similar composition in the foreland Little Elk and Big Elk domes east of the Disturbed Belt are probably post-folding as well.

Sevier-style fold and thrust belt deformation along the eastern margin of the Helena salient, as well as foreland deformation immediately east of the Helena salient, ranges from post mid Paleocene to pre-early Eocene, or latest Paleocene to earliest Eocene in age.

7) Folding of the Late Cretaceous to mid-Paleocene Fort Union Formation conglomerates by the oblique-slip, lateral ramp of Battle Ridge monocline indicates that initial fold and thrust belt deformation in the immediate area of the Bridger Range is post-middle Paleocene in age. Subsequent deformation of the fold and thrust belt structures by the Laramide-style foreland uplift of the Bridger anticlinorium has been demonstrated by Lageson and Zim (1984; in press). Although no precise date for the timing of this deformation can be established at this time, it must be no older than latest Paleocene to very earliest Eocene in age; an upper limit of pre-early Eocene is proposed based on the cesstation of compressional deformation in the Disturbed Belt to the east (discussed in item 6 above) and in the ancestral Gallatin-Beartooth uplift to the south and southeast (discussed in item 8 below).

8) A maximum age for the timing of uplift of the ancestral Gallatin-Beartooth Block is provided by intrusive relationships of

sills near McLeod, Montana, along the northern edge of the Beartooth Mountains. At this location, faults of the Nye-Bowler lineament cut diorite sills and stocks (Rouse et al., 1937). Radiometric age determinations yield ages of approximately 80 Ma (Marvin and Dobson, 1979). This relationship indicates that fault activity along the Nye-Bowler lineament, probably associated with initial uplift of the ancestral Gallatin-Beartooth uplift, is post-Late Cretaceous in age.

Corroboration of a Late Cretaceous to early Tertiary uplift of the ancestral Gallatin-Beartooth uplift is provided by Stow (1938; 1946) who studied heavy mineral assemblages of sediments in the Crazy Mountains and Bighorn Basins. He recognized the appearance of heavy minerals of metamorphic origin in sedimentary rocks of Tullock age in the Bighorn Basin, and concluded that uplift of the ancestral Gallatin-Beartooth uplift had begun by Late Cretaceous time. Sediments from the Crazy Mountains Basin however, were not found to contain heavy mineral assemblages of metamorphic origin until after early Tongue River time, or until after mid-Paleocene time (Stow, 1946). The discrepancy between the apparent timing between these two areas was thought by Stow (1946) to be the result of: 1) a greater amount of structural relief along the eastern flank of the Beartooth Range, thus resulting in more rapid denudation and unroofing of the sedimentary cover than along the northern flank; and 2) a greater thickness in the sedimentary cover along the northern flank of the Beartooths, due largely to the eruption of the Late Cretaceous Deer Park Volcanics.

Tertiary sediments in the Clark's Fork Basin (a northwest extension of the Bighorn Basin) along the northeast corner of the Beartooth Mountains, have been extensively studied by Fluekinger (1970) and Jobling (1974). Here, intensely folded and faulted alluvial fan deposits, identified as a proximal facies of the Fort Union Formation associated with the initial uplift of the Beartooth massif, have been thrust over more distal facies of the Fort Union Formation during the major uplift of the Beartooth Block. The Fort Union at this location is overlain unconformably by what Jobling (1974) has described as a post-tectonic conglomerate, the Linely Conglomerate. An inverted stratigraphic sequence has been demonstrated both in the Fort Union and Linely Conglomerates, which records progressive uplift of the Beartooth massif.

Both the Fort Union Formation and the lower part of the Linely Conglomerate have been dated as Paleocene by faunal and palynological methods. No more precise date has been established.

Elsewhere in the Clark's Fork Basin, Gingerich (1983) has studied the sedimentology of the Fort Union and Willwood Formations. He has proposed the existence of the Clarks Fork Basin as a structural entity and thus the initial uplift of the ancestral Gallatin-Beartooth block extends to Torrejonian or possibly Puercan time. Major uplift of the Beartooth Range however, occurred from latest Paleocene (mid-Tiffanian) through earliest Eocene (Clarkforkian), or approximately 57-53 Ma. Initial uplift of the Beartooth Range therefore began in early middle Paleocene, with major uplift culminating in late Paleocene to earliest Eocene time.

A minimum age for deformation of the ancestral Gallatin-Beartooth uplift is provided by radiometric dates of volcanic rocks of the Absaroka Supergroup, which have been demonstrated to be undeformed and hence post-date uplift (Chadwick, 1972; Smedes and Protska, 1972). These dates range from 52 to 44 Ma.

In summary, a lower limit to deformation of the ancestral Gallatin-Beartooth uplift has not been well constrained. Movement along the Nye-Bowler lineament and early uplift of the Beartooth Range may have begun as early as Late Cretaceous or early Paleocene time. Initial uplift of the Beartooths had definitely occurred by early to middle Paleocene, as evidenced by the deposition of proximal alluvial fan deposits along the eastern flank of the Beartooth Range. The major culminating uplift however, occurred in late Paleocene to very earliest Eocene time. By earliest Eocene (approximately 50 Ma) uplift of the range had ceased prior to the onset of igneous activity in the Absaroka volcanic field.

9) In Latest Cretaceous to early Paleocene time, plutono-volcanic activity began in the northwestern United States that was substantially different in character than that of the Late Cretaceous synorogenic magmatic activity associated with the Idaho and Boulder Batholiths. This igneous activity, defined by Armstrong (1978) as the Challis volcanic episode (Figure 18), is considered to be post-orogenic (with the possible exception of the Adel Mountains volcanics and related intrusions in northwestern Montana) with respect to Sevier- and Laramide-style deformation. In Montana, this activity consisted of generally intermediate composition calc-alkaline plutonic

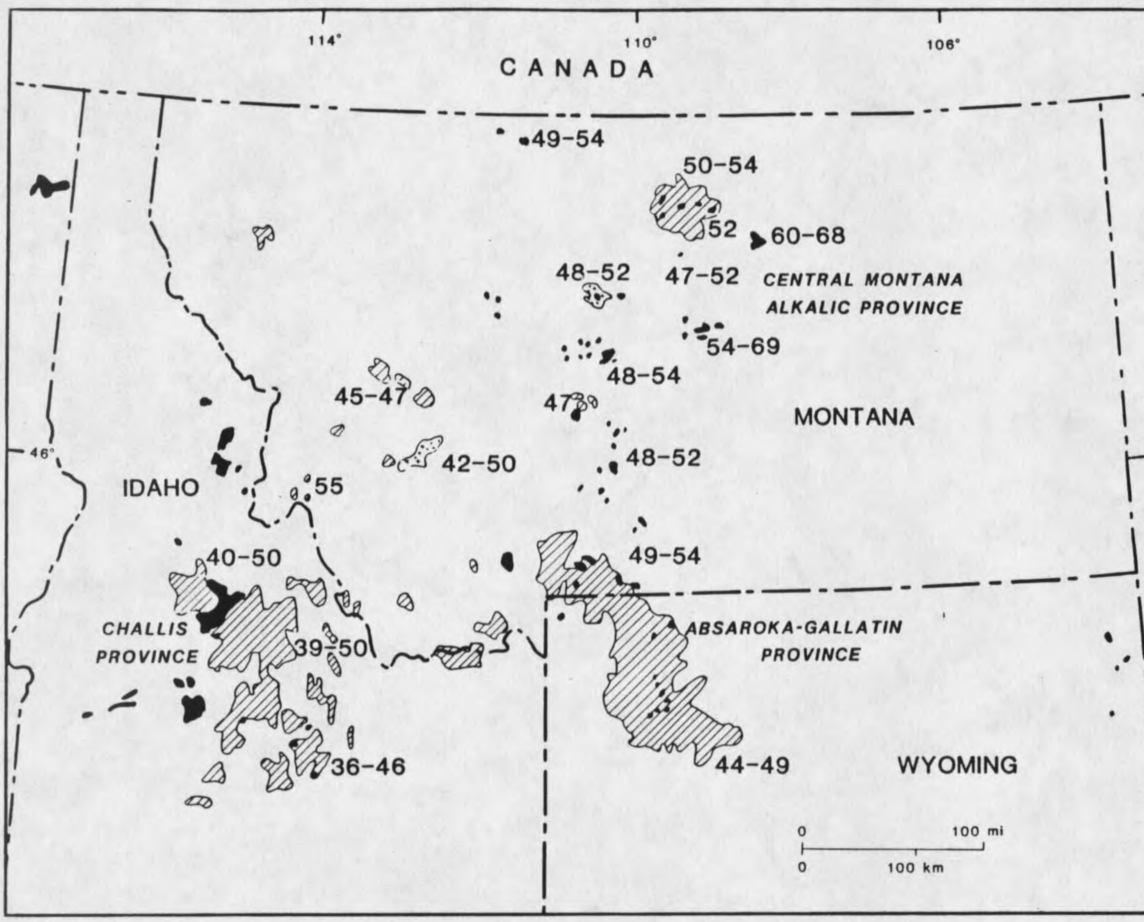

Figure 18. Map showing distribution and ages of igneous activity of the Challis igneous episode in Montana, Idaho, and Wyoming. Age in Ma. Solid pattern = intrusive center; ruled pattern = andesitic volcanic field; and stippled pattern = rhyolitic volcanic field. Figure modified from Stewart (1978). Radiometric ages from Stewart (1978); Marvin et al, 1973; Marvin et al, 1980; Chadwick (1980); this report.

and volcanic activity, and the emplacement of strongly alkaline, silica-undersaturated igneous centers.

The Challis episode, as originally defined by Armstrong (1978), spans the period from 55 Ma to 46-43 Ma. However, recent radiometric dating of igneous rocks from the central Montana alkalic province indicates that activity within parts of the province had begun by 68 Ma (Marvin et al., 1980).

Widespread volcanism in the Absaroka-Gallatin province resulted in the eruption of hundreds of meters of flat-lying to moderately tilted calc-alkaline volcanic rocks over an area of 16,000 square kilometers (Chadwick, 1972). The volcanics were erupted over an irregular topography, which had been carved into strongly deformed Precambrian to Mesozoic rocks, and have been demonstrated to post-date the Laramide-style deformation of the Gallatin and Beartooth Ranges (Roberts, 1972). Radiometric age determinations from the Absaroka-Gallatin field indicate that activity began at 53 Ma and persisted to 43 Ma (Chadwick, 1969; Chadwick, 1972; Smedes and Protska, 1972). In general, the oldest dates are found in the northern part of the field.

In the Crazy Mountains, plutonic activity of the Challis episode is represented by the intrusion of two compositionally distinct, temporally and spatially overlapping magma series: a subalkaline silica-saturated to over-saturated series, and a sodium rich, silica-undersaturated, strongly alkaline series. These magmas were intruded as a complex of stocks, sills, laccoliths, and dikes. Sills of the Robinson anticline complex have been demonstrated to post-date thin-skinned fold and thrust belt deformation, and other intrusives in the complex are probably post-orogenic as well. Radiometric dates indicate that igneous activity spanned the period from 58 to 43 Ma, but generally occurred from 52-48 Ma.

In the Castle Mountains, subalkaline and alkaline stocks, sills, and dikes, have also been intruded subsequent to the fold and thrust belt deformation of the Disturbed Belt. Timing of the intrusive activity is poorly constrained, but a rhyolite flow which post-dates the intrusion of the Castle Mountains stock has been dated as 48 Ma (Chadwick, 1980). In addition, dikes related to the Comb Creek stock, dated as 49-52 Ma extend into the southern part of the Castle Mountains Uplift.

COMPARISON OF CRAZY MOUNTAINS DISTURBED BELT TIMING WITH OTHER AREAS OF THE FORELAND FOLD AND THRUST BELT

Northern Disturbed Belt

General

The Northern Disturbed Belt, as defined by Mudge (1972; 1982) is an arcuate, generally convex eastward zone of intense fold and thrust deformation in Montana along the eastern Rocky Mountain front (Figure 19). Its western border is arbitrarily defined by the Flathead River, and its eastern boundary is defined by northerly-trending fold axes which occur eastward of the mountains. Structurally the Disturbed Belt is characterized by closely spaced, imbricate, west-dipping thrust faults, folds, longitudinal faults, and northeast-trending transverse faults. In general, the intensity of deformation decreases from west to east. For a detailed discussion of the structural geology of the northern Disturbed Belt, the reader is referred to Mudge (1970; 1972; 1982).

Timing of Deformation

Hoffman and others (1976) have presented K-Ar age dates of Cretaceous bentonites from various areas within the Northern Disturbed Belt. The ages, which range from 72 to 56 Ma $\pm$ 2% presumably reflect burial metamorphism by overriding thrust sheets. Mudge (1982), in reviewing this data, has suggested that Disturbed Belt deformation began no earlier than 72 Ma. Hoffman et al. (1976) point out that the

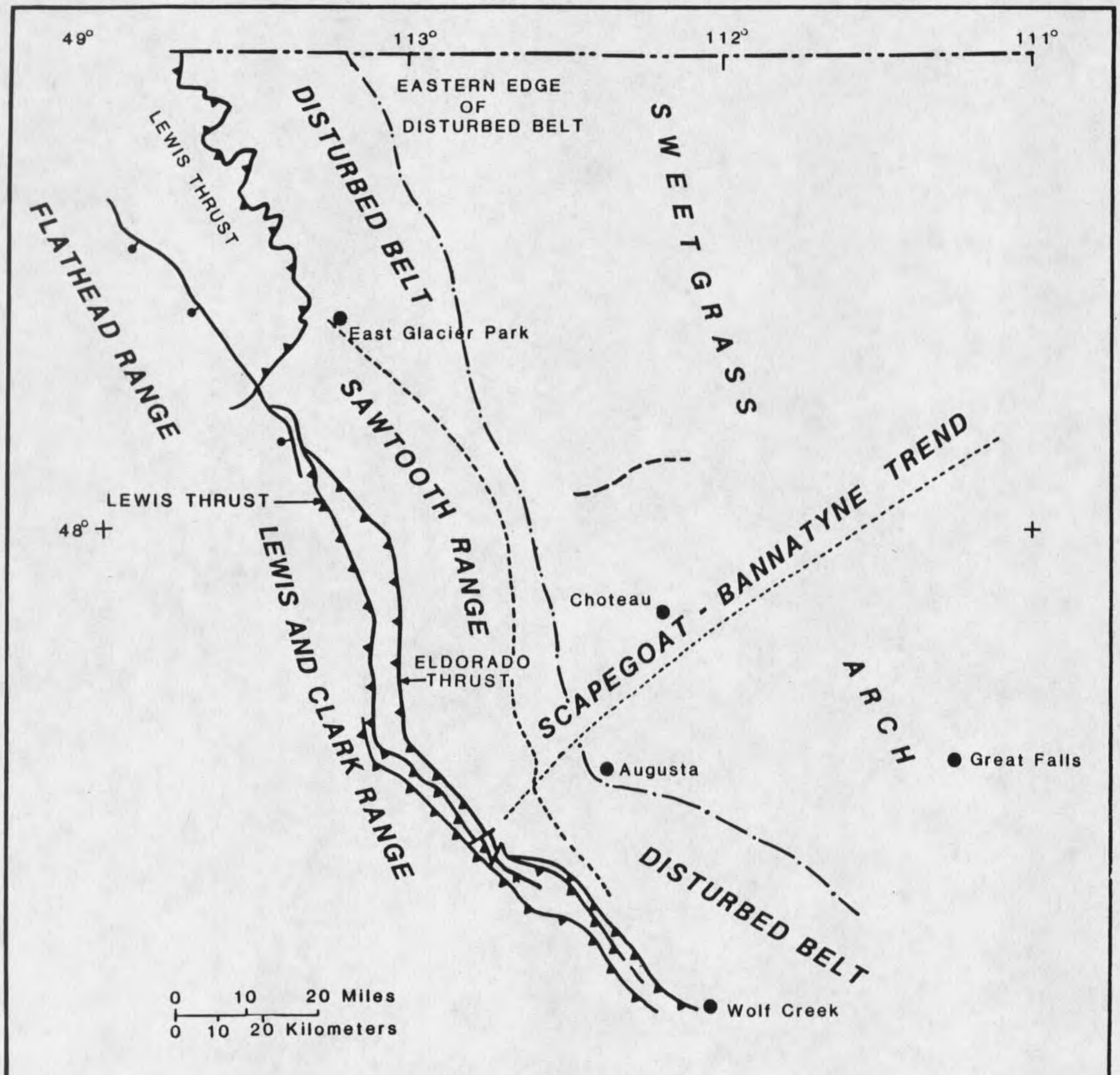

Figure 19. Map showing the location of the northern Disturbed Belt and associated major structural features. Modified from Mudge (1982)

radiometric dates represent the range in time in which maximum burial temperatures were reached; they do not necessarily record the point at which thrusting began or ended. A minimum age for thrusting of 56 Ma is suggested by Hoffman et al. (1976) thereby indicating that fold and thrust belt deformation continued to post-latest Paleocene time.

According the Schmidt (1979), igneous rocks in the western part of the Adel Mountains volcanic field have been overridden by thrusts which carry the Upper Cretaceous Two Medicine Formation in their hanging wall. The Adel Mountains volcanics, although not isotopically dated (Armstrong, 1978), have been tentatively assigned a Latest Cretaceous age (Lyons, 1944; Chadwick, 1972). Schmidt (1978) however, suggests that emplacement occurred between Late Cretaceous and late Paleocene time, and that they are probably early Paleocene in age. Schmidt (1978) further notes that the Adel Mountains volcanics are intratectonic with respect to deformation, and that they lie with angular unconformity on Early to mid-Cretaceous sedimentary rocks of the Kootenai and Blackleaf Formations. This relationship led Schmidt to conclude that considerable deformation occurred prior to the deposition of the volcanic rocks; hence fold and thrust deformation may date to Late Cretaceous time (Schmidt, 1978). Clearly radiometric dating of volcanic units cut by thrusts could help resolve the age of thrust faulting in this area.

Near the Canadian border, sedimentary rocks of the Willow Creek Formation have been folded and thrusted along the leading edge of the Disturbed Belt (Mudge, 1982). The Willow Creek Formation has been dated by Tozer (1953) as very Late Cretaceous to early Paleocene, indicating that deformation occurred in post early Paleocene time.

Elsewhere in the northern Disturbed Belt, radiometric (K-Ar) dating has been used to date fold and thrust deformation. An age of 58.3 Ma is reported for a quartz monzonite sill which intrudes the Steimbach thrust plate, thereby cutting the Lombard thrust (Mehnert and Schmidt, 1971; Mudge, 1982; Mudge, 1983). In the central part of the Comb Rock quadrangle (Schmidt, 1972), however, quartz monzonite dikes and sills of similar composition and believed to be the same age as those dated by Mehnert and Schmidt (1971), appear to be cut by thrust faults. These dikes may therefore both pre- and post-tectonic with respect to fold and thrust deformation. In the same area, hornblende monzonite dikes date as 46.3 Ma cut folds and thrust faults and clearly are post-tectonic.

Although Mudge (1982) considers that most, if not all, deformation in the northern Disturbed Belt occurred during the Paleocene, fold and thrust deformation beginning in Late Cretaceous time cannot be ruled out. Furthermore, radiometric dating of bentonites (Hoffman et al., 1976) and the possibility that late Paleocene dikes are both pre- and post-tectonic, suggests that Disturbed Belt deformation may have continued to latest Paleocene-earliest Eocene time. Radiometric dating of post-tectonic intrusions however, provides and upper limiting age of pre-middle Eocene for fold and thrust deformation in the northern Disturbed Belt.

A lower limit of Late Cretaceous age for early deformation in the northern Disturbed Belt indicates a longer period of activity than that of the eastern Disturbed Belt structures of the Helena salient. In addition, northern Disturbed Belt deformation may have slightly post-dated activity in the Crazy Mountains Basin, which had clearly ended by earliest Eocene time.

Utah-Idaho-Wyoming Salient

General Statement

The Utah-Idaho-Wyoming salient of the foreland fold and thrust belt is a broadly arcuate, convex eastward zone, which consists of 6-7 major west-dipping, low-angle thrust faults and associated folds (Beutner, 1977; Blackstone, 1977) (Figure 20). The salient extends southeastward from the Snake River Plain, to the vicinity of Salt Lake City, Utah. The western boundary is poorly defined, due to the dissection of the westernmost Sevier-style structures by late Cenozoic Basin and Range extensional normal faults (Blackstone, 1977). The eastern boundary is defined by thrusts along the western boundary of the Green River Basin. A detailed discussion of the structural geology of the Utah-Idaho-Wyoming salient is provided by Royse et al., (1975) and Blackstone (1977).

The Utah-Idaho-Wyoming salient is perhaps the most extensively studied fold and thrust belt in the world, and for this reason, dating of deformational events is the most refined of any thrust belt (Wiltschko and Dorr, 1983). An extensive review of the timing of deformation within the salient and adjacent foreland areas is presented by Wiltschko and Dorr (1983) in their report on the thrust belt. This discussion will recount only the timing of activity of the

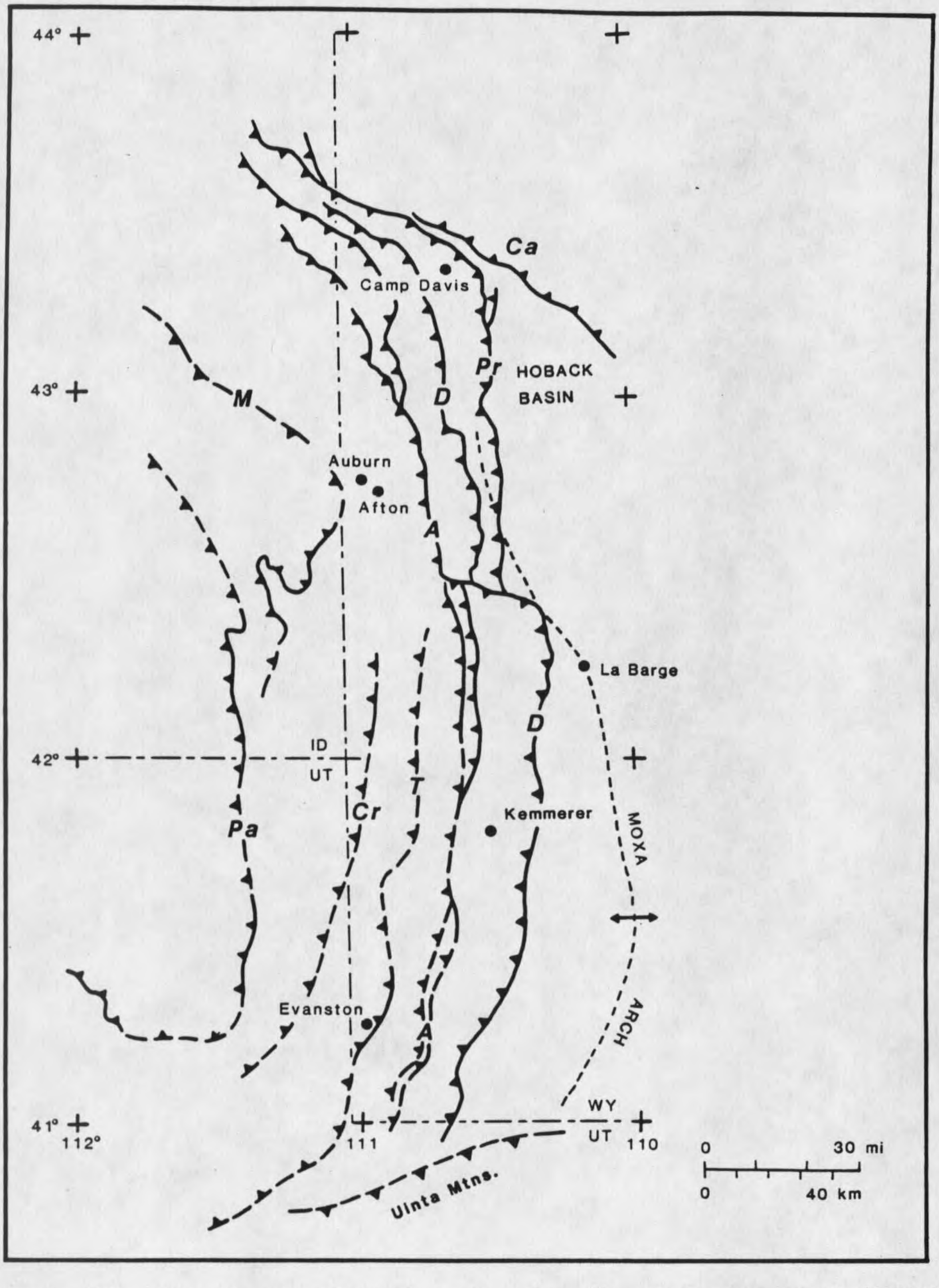

Figure 20. Map showing location of major thrust faults of Utah-Idaho-Wyoming salient of the fold and thrust belt. Major faults are: Pa = Paris thrust; M = Meade thrust; Cr = Crawford thrust; T = Tunp thrust; A = Absaroka thrust; D = Darby thrust; Pr = Prospect thrust; and Ca = Cache Creek reverse fault. Figure modified from Wiltschko and Dorr (1983).

frontal, easternmost thrusts of the salient, an area roughly comparable to Disturbed Belt structures in the northern Crazy Mountains Basin.

Timing of Deformation

The oldest thrust in this discussion is the Darby thrust. This thrust is difficult to date with certainty, and the proposed ages of movement may be complicated due to recurrent movement (Wiltschko and Dorr, 1983). Ages of movement range from Late Cretaceous (Santonian) to late Paleocene (Clarkforkian) time (Wiltschko and Dorr, 1983). Wiltschko and Dorr (1983) argue that thrust movement is middle Paleocene (Torrejonian) to middle Tiffanian in age. Royse (1985), however, demonstrated that Darby thrust movement was transferred to a previously unrecognized "cryptic" thrust sheet that Royse refers to as the Granite Creek thrust. The Granite Creek thrust is overlapped by mid-Paleocene sediments thus dating Darby thrust movement as pre-middle Paleocene in age (Royse, 1985).

In the northern segment of the salient, the Prospect thrust was the next fault in the sequence to move. Along the western margin of the Green River Basin, the thrust cuts late Paleocene (middle Tiffanian) strata of the Hoback Formation and is overlapped by earliest Eocene (early Graybullian) strata of the Lookout Mountain conglomerate. Thrust movement is thus placed at the Paleocene-Eocene transition (Wiltschko and Dorr, 1983). Subsequent hanging wall imbrication resulted in the emplacement of the Lookout Mountain thrust, which has been shown to cut the Lookout Mountain conglomerate (Dorr et al., 1977) Sevier-style fold and thrust belt deformation along the northern Utah-Idaho-Wyoming salient is thus post-early Eocene in age.

Near La Barge Wyoming, in the central segment of the salient, Darby thrust movement was followed by the emplacement of the La Barge thrust. The La Barge thrust, a blind thrust known only from subsurface data, deformed Graybullian or possible Lysitian strata of the Wasatch Formation. Final deformation along the central part of the salient is therefore middle-early Eocene in age.

Movement of the frontal, easternmost zone of Sevier-style fold and thrust belt deformation of the Utah-Idaho-Wyoming salient ranges from middle to late Paleocene to middle-early Eocene, at which time compressional deformation was accommodated entirely by Laramide-style structures elsewhere in the foreland. In the northern segment of the salient, final movement was characterized by hanging wall imbrication west of the easternmost thrust of the salient. In the central segment final movement resulted in footwall deformation which progressed from west to east. The latter situation is roughly analogous to the style of deformation observed along the easternmost margin of the Helena salient of the Disturbed Belt. The post-early Eocene to early middle Eocene age for deformation for the Sevier-style folds and thrusts of the Utah-Idaho-Wyoming salient suggests a slightly younger, although broadly contemporaneous, period of activity than that of the Disturbed Belt in the northern Crazy Mountains Basin.

CONCLUSIONS

The following conclusions may be made with respect to this study:

1) Paleomagnetic fold test data from the northern Crazy Mountains Basin indicate that sills of the Robinson anticline intrusive complex post-date Sevier-style or detachment-style fold and thrust belt deformation. Radiometric dates of intrusives from the Crazy Mountains indicate that igneous activity ranged from 52 to 48 Ma.

2) Paleomagnetic studies and radiometric dates from this study, combined with pre-existing stratigraphic data, indicate a late Paleocene age for Sevier-style or decollement-style fold and thrust belt deformation along the leading edge of the Montana Disturbed Belt in the northern Crazy Mountains Basin and Castle Mountains Uplift. This is in relatively good agreement with the timing of fold and thrust belt deformation in the northern Disturbed Belt, and along the leading edge of the Utah-Idaho-Wyoming salient.

3) The broad timing of deformational events within and adjacent to the Crazy Mountains Basin has been demonstrated to span the period from Late Cretaceous to earliest Eocene. Post-orogenic igneous activity of the Challis Episode within the Crazy Mountains Basin and surrounding uplifts indicate that compressional deformation in southwestern Montana had clearly ended by early Eocene time.

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APPENDIX

APPENDIX A

Radiometric Age Determinations

1. 83VPCC1 (Geochron B-6649) K-Ar
Dark gray porphyritic biotite-pyroxene nepheline syenite (46^{o} 18'N, 110^{o}26'30"W; NW1/4 S11 T6N R10E; Forest Lake Road; Lebo quad.; Meagher Co., MT). *Analytical data:* K_2O = 6.453%, $*Ar^{40}$ = .02443 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 66.30%. *Collected by:* Stephen S. Harlan. *Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is from a mafic dike from the Comb Creek dike swarm.
(biotite) 52.3 ± 2.0 Ma

2. 84CC12 (Geochron B-7132) K-Ar
Light gray biotite-pyroxene nepheline syenite porpyhry (46^{o} 18'30"N, 110^{o}29'30"W; S4 T6N R10E; Lebo 7.5' quad.; Meagher Co., MT). *Analytical data:* K = 6.923%, $*Ar^{40}$ = .02336 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 69.60%. *Collected by:* Stephen S. Harlan and Jenny Fryxell. *Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is from the felsic central intrusion of the Comb Creek stock.
(biotite) 48.0 ± 1.9 Ma

3. 83VP65 (Geochron B-7130) K-Ar
Dark green olivine-biotite-pyroxene nepheline syenite (46^{o} 12'N, 110^{o}27'20"W; SW1/4 S16 T5N R10E; Virginia Peak 7.5' quad.; Park Co., MT). *Analytical data:* K_2O = 7.380%, $*Ar^{40}$ = .02589 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 59.25%. *Collected by:* Stephen S. Harlan. *Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is from a mafic nepheline syenite sill from the Robinson anticline intrusive complex.
(biotite) 50.6 ± 1.9 Ma

4. 83VP75 (Geochron B-7131) K-Ar
Dark green olivine-biotite-pyroxene nepheline syenite (46^{o} 12'N, 110^{o}27'30"W; SW1/4 S15 T5N R10E; Virginia Peak 7.5' quad.; Park Co., MT). *Analytical data:* K_2O = 6.718%, $*Ar^{40}$ = .02328 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 59.25%. *Collected by:* Stephen S. Harlan. *Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is from a mafic nepheline syenite sill from the Robinson anticline intrusive complex.

(biotite) 49.3 ± 1.9 Ma

5. 83VP2 (Geochron A-6412) K-Ar
Gray platy hornblende-pyroxene porphyritic trachyte (46°12'N, 110°27'30"W; NW1/4 SE1/4 S10 T5N R10E; Davey Butte Ridge; Virginia Peak 7.5' quad.; Meagher Co., MT). *Analytical data:* K_2O = 0.167%, $*Ar^{40}$ = .00584 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 18.3%. *Collected by:* Stephen S. Harlan and David R. Lageson. *Analyzed Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is from a trachyte sill from the Robinson anticline intrusive complex.

(hornblende) 48.5 ± 4.6 Ma

6. 83BT3 (Geochron A-6756) K-Ar
Dark gray hornblende gabbro (46°2'N, 110°16'W; NE1/4 S6 T3N R12E; Crazy Peak 7.5' quad.; Sweetgrass Co., MT). *Analytical data:* K_2O = 0.771%, $*Ar^{40}$ = .002814 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 41.7%. *Collected by:* Stephen S. Harlan. *Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is believed to be from the mafic border phase of the Big Timber stock.

(hornblende) 50.4 ± 2.5 Ma

7. 83BTTP1 (Geochron A-6634) K-Ar
Light gray biotite-hornblende granodiorite (46°2'N, 110°18'45"W; SE1/4 S35 T4N R11E; Crazy Peak 7.5' quad.; Park Co., MT). *Analytical data:* K_2O = 0.421%, $*Ar^{40}$ = .001333 ppm, $*Ar^{40}/\Sigma Ar^{40}$ = 29.7%. *Collected by:* Stephen S. Harlan. *Analyzed by:* Geochron Laboratories, Inc. *Comment:* Sample is believed to be from the felsic terminal phase of the Big Timber stock.

(hornblende) 43.8 ± 2.7 Ma

Constants use in calculating radiometric ages:
$\lambda_\beta = 4.72 \times 10^{-10}$/year
$\lambda_e = 0.585 \times 10^{-10}$/year
$K^{40}/K = 1.22 \times 10^{-4}$ g./g.
Note: $*Ar^{40}$ = radiogenic Ar^{40}

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PLATE 1

GEOLOGY OF THE ROBINSON ANTICLINE AREA, NORTHERN CRAZY MOUNTAINS, MONTANA

GEOLOGY MODIFIED FROM SIMMS (1966)

SCALE 1:24,000

0 — 1 mi

1 km

EXPLANATION

MAP UNITS

PLEISTOCENE to RECENT
- Qls — Landslide and rockfall deposits
- Qal — Unconsolidated alluvium, terrace deposits

EOCENE — Hypabyssal igneous intrusions
- Ti^a — Andesite porphyry
- Ti^b — Basalt
- Ti^r — Quartz latite and rhyolite porphyry
- Ti^t — Mafic trachytes and latites
- Ti^f — Feldspathoidal syenite, trachyte, and variants
- Ti^m — Mafic nepheline syenites

PALEOCENE
- Tfu — Fort Union Formation (sandstone and shale)

SYMBOLS

- CONTACT, length of contact lines indicate accuracy of contact
- U/D REVERSE FAULT (inferred)
- ANTICLINE (showing direction of plunge), dashed where approximate
- 35 STRIKE and DIP (bedding)
- ▲ 48.5±4.5 RADIOMETRIC AGE DETERMINATION, age in Ma
- ● 3 PALEOMAGNETIC SAMPLE LOCATION, all site numbers pre-fixed by "NCM"
- A — A' LINE OF CROSS-SECTION

N, GN, MN, 17.5°

MONTANA

MAP LOCATION

BASE MAP - U.S.G.S. 7.5' TOPOGRAPHIC QUADRANGLES: Virginia Peak, Scab Rock Mountain, Rimrock Divide, and Lebo