STRUCTURAL GEOLOGY
OF SMITH-WEASEL CREEKS AREA,
LEWIS AND CLARK COUNTY, MONTANA

by

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INTRODUCTION

The Northern Disturbed Belt of Montana is part of an elongate trend of deformed rock extending from the Canadian Rockies southward into the United States. The Smith-Weasel creeks area ($57\ km^2$), about 23 km west-southwest of Augusta, Montana, and about 130 km south-southeast of Glacier National Park, is within the eastern imbricate thrust zone of the disturbed belt (Figs. 1 and 2).

The Smith-Weasel creeks area, lying in north central Lewis and Clark County between lat 47°20'N. and 47°26'N. and long 112°41'W. and 112°35'W., is almost totally contained within T.19 N., R.8 W. The research area is accessible with conventional automobile by traveling southwest from Augusta on U.S. Forest Service Route 434 for 5 km, then turning west-southwest for 12 km on an unpaved road used by local ranchers (Fig. 2). Haystack Butte, a prominent landmark that lies just east of the Smith-Weasel creeks area, is a post-thrusting rhyodacite porphyry plug 20 million years old (K-Ar date) that rises 550 m above the surrounding terrain (Mudge, 1972b, p. B47).

The structural trend is dominantly northeast-southwest in the northern half of the Smith-Weasel creeks area, whereas an east-west to northwest-southeast structural trend dominates in the

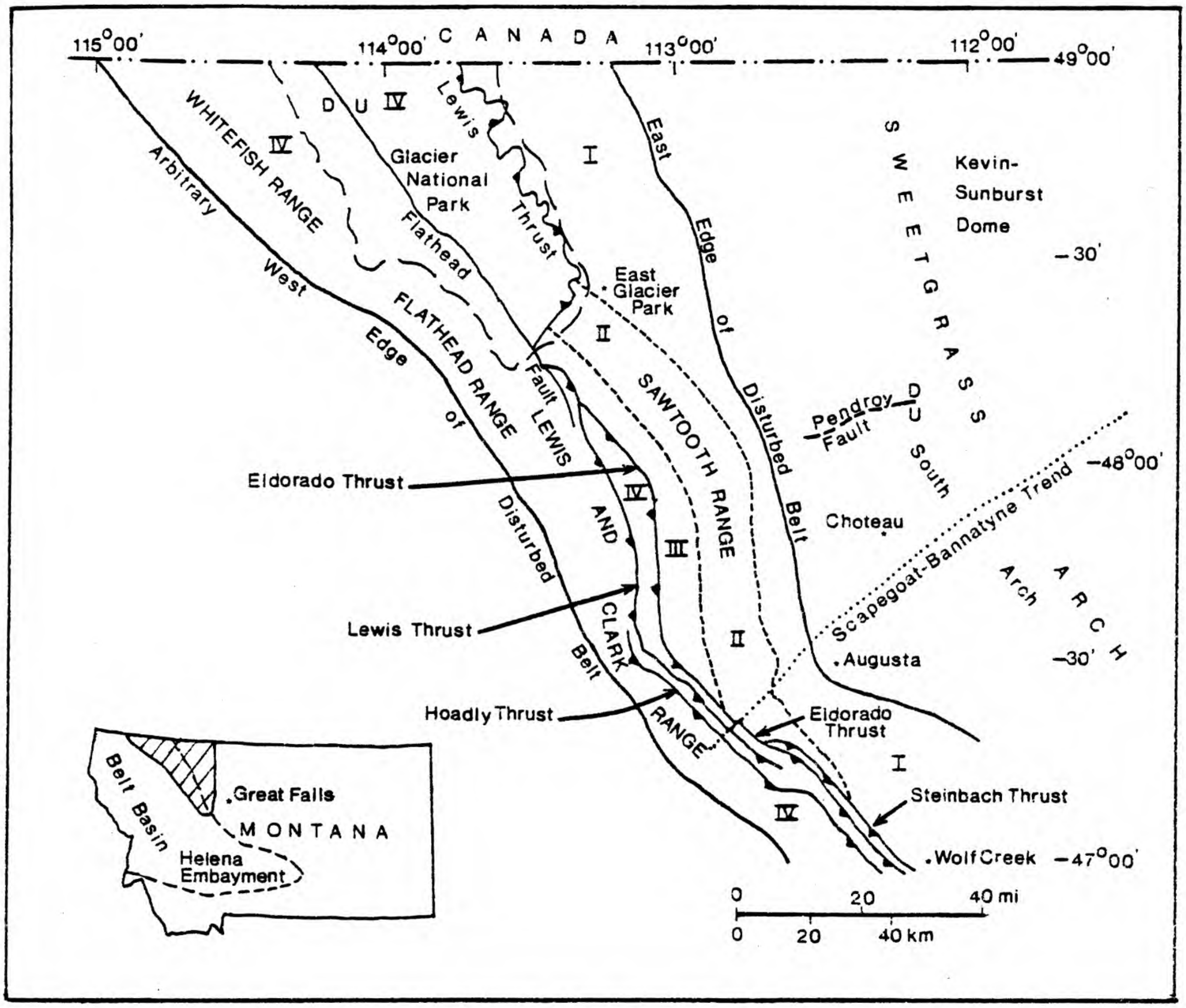

Figure 1. Structural features of the Montana Disturbed Belt and Sweetgrass Arch, northwestern Montana (from Mudge, 1982).

Subbelt I- consists of thrust-faulted and folded Mesozoic rocks. In the Smith-Weasel creeks area the subbelt is the region north of the Goss I thrust fault (Pl. 1; Fig. 3).

Subbelt II- consists of complexly thrust-faulted and folded Paleozoic and Mesozoic rocks. In the Smith-Weasel creeks area the subbelt is the region north of the Steinbach thrust and south of the Goss I thrust fault (Pl. 1; Fig. 3).

Subbelt III- is absent in the Smith-Weasel creeks area. The subbelt consists mostly of thrust faulted and folded Mesozoic rocks.

Subbelt IV- contains major thrust plates of Precambrian and Paleozoic rocks. In the Smith-Weasel creeks area the subbelt is the region south of the Steinbach thrust (Pl. 1; Fig. 3).

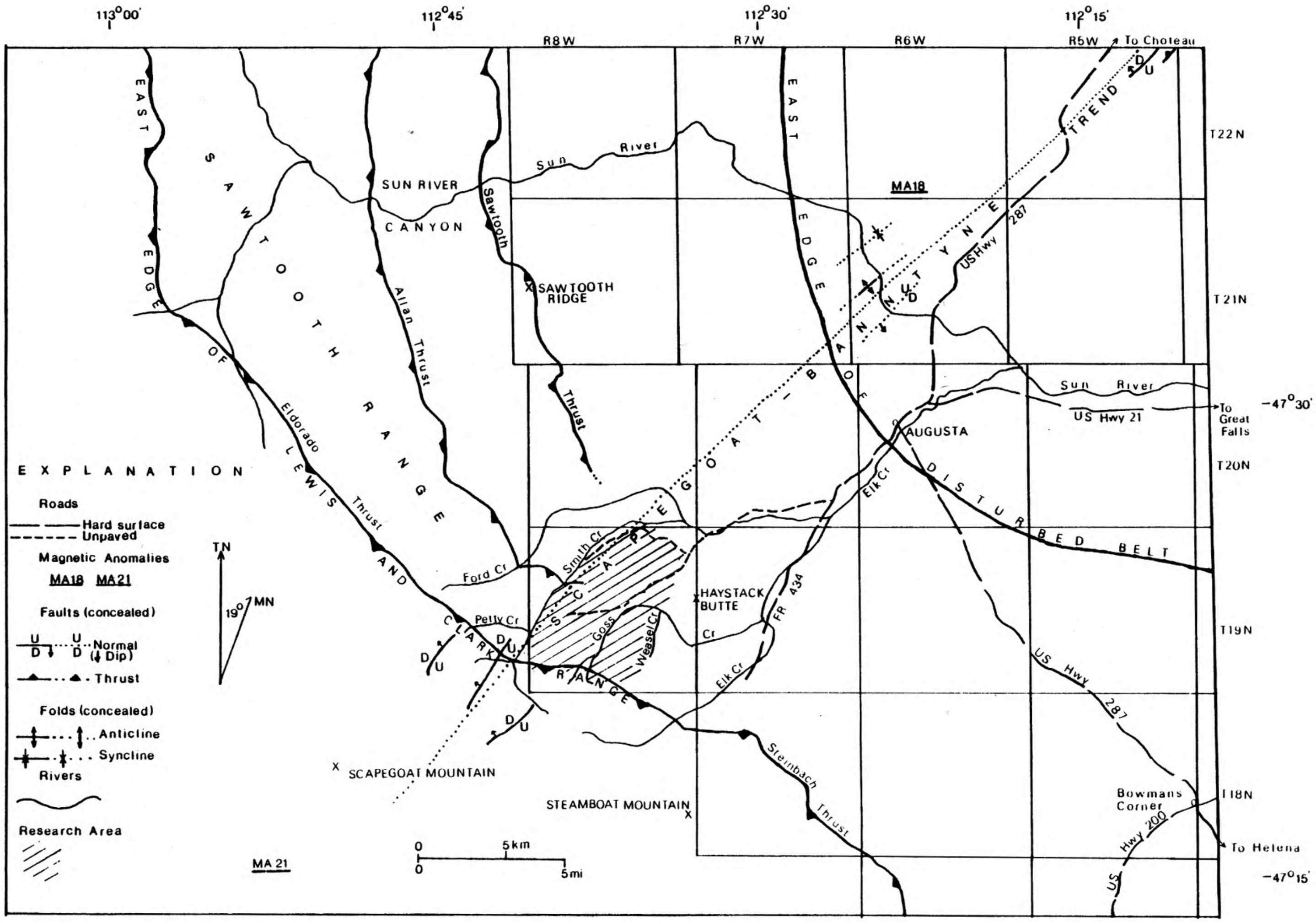

Figure 2. Geologic, geophysical, and geographic features near the Smith-Weasel creeks area (from Mudge and others, 1982).

southern half of the area (Pl. 1). A distinct shift in the structural trend from east-west to northeast-southwest, is recognized along the Smith, Weisner, and Johnston thrust fault traces in the northern part of the Smith-Weasel creeks area (Pl. 1; Pl. 3).

Purpose and Scope

The Smith-Weasel creeks area encompasses a region of the disturbed belt where the structural grain changes from nearly north-south to northwest-southeast and is located at the intersection of the disturbed belt and the southwest extension of the Scapegoat-Bannatyne trend. The Scapegoat-Bannatyne trend is defined by a series of northeast-trending gravity and magnetic anomalies (Kleinkopf and Mudge, 1972, p. A11, anomaly 4) and an associated northeast trending fracture system within the Precambrian crystalline basement (Alpha, 1955b, p. 131, 138; Mudge, 1982, p. 92). This report describes the structural geology of the Smith-Weasel creeks area based on a geologic map (Pl. 1, scale 1:20860) and cross-sections (Pl. 2) and assesses the influence of the Scapegoat-Bannatyne trend on the structural development of this part of the Montana Disturbed Belt.

Method of Investigation

During the summer of 1982 the research area was traversed on foot. Strike and dip measurements were collected with a Brunton compass set for 19° E. magnetic declination. Data for the geologic map were plotted on four U.S. Geological Survey 7.5-minute topographic quadrangles (Double Falls, Nilan Reservoir, Jakie Creek, and Steamboat Mountain) that were enlarged to a scale of 1:9600. Stereoscopic examination of aerial photographs (1:36,000) in the field assisted in finding locations and interpreting the geology.

The location of thrust faults was determined by observing repetition of the stratigraphic section and by cross-cutting relationships. Vegetative cover prevented direct observation of the actual fault surfaces. In a few locations the occurrence of a localized area of vegetation in an otherwise rocky terrain indicated a fault zone. All names of structural zones, thrust plates, and major folds, except for the Steinbach thrust, have been assigned informally (Fig. 3; Pl. 1; Pl. 3). Geologically important peaks are referred to in the text by their elevation in feet, as shown on the U.S. Geological Survey topographic maps of the study area.

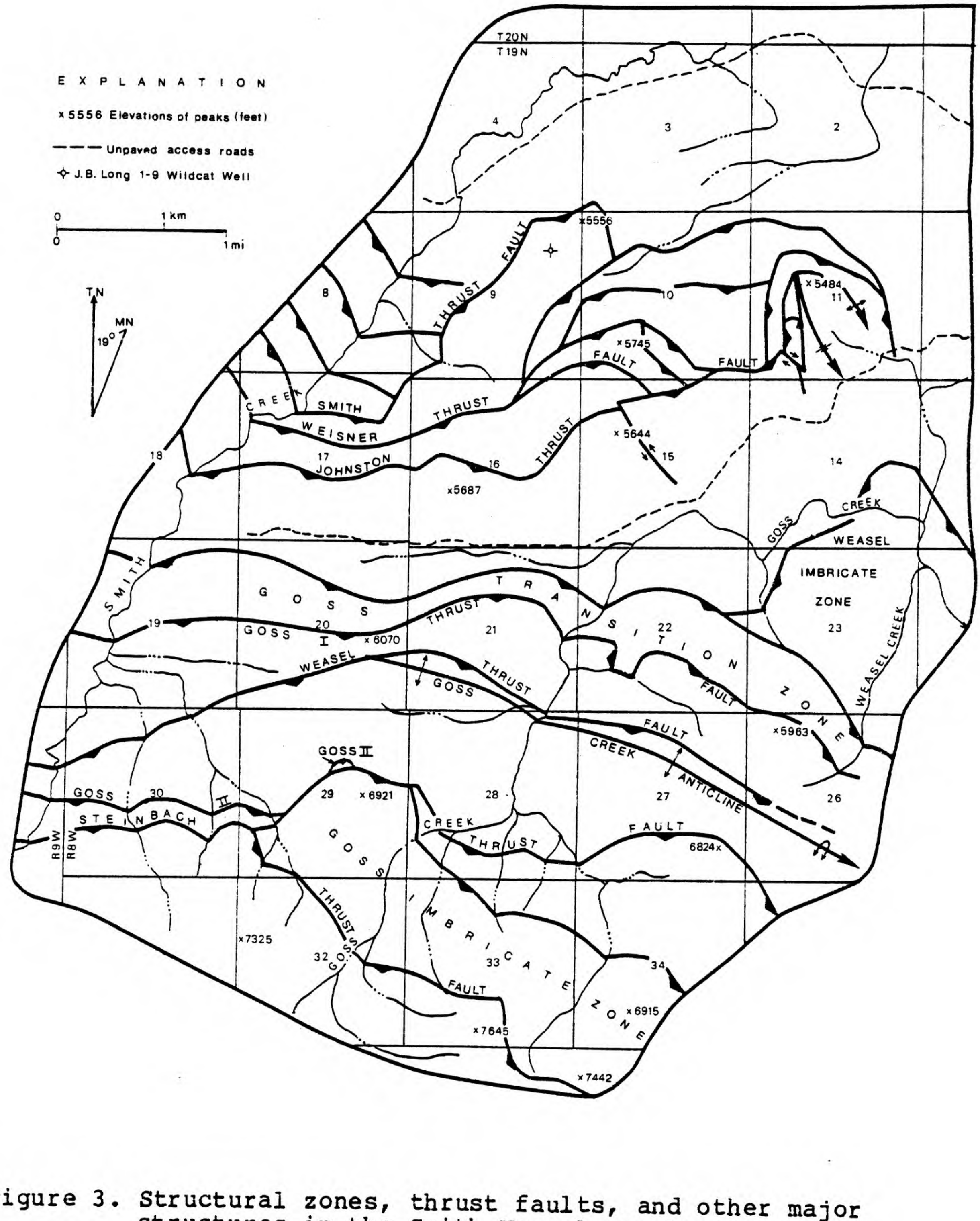

Figure 3. Structural zones, thrust faults, and other major structures in the Smith-Weasel creeks area.

Joint data were collected by taking the trend of the line formed by the intersection of the joint surface and the bedding plane. In most places the strike and dip of the joint surface were difficult to measure; the joint surface was assumed to be perpendicular, or nearly so, to the bedding plane. The bedding planes were rotated back to horizontal using a stereonet. When the bedding plane and the joint surface-bedding plane intersection are rotated back to horizontal, the trend of the bedding plane-joint surface line of intersection will become the strike of the rotated joint surface. The rotated data (Appendix 2) were grouped into 10-degree intervals and plotted on rose diagrams (Figs. 6, 7, 10, 13, and Appendix 4).

During the summer of 1982 seismic crews (Seismograph Services Corporation and HR Seismic Company, Denver) operated within T.19 N., R.8 W. and Sun Oil Company, Denver, drilled a dry hole (J.B. Long 1-9) in the northeast quarter of sec. 9. Because of the proprietary nature of the subsurface data, the cross-sections in Plate 2 are based soley on surface data. The cross-sections are, however, modeled to a degree after those constructed for nearby areas by Mudge (1972b, Pl. 3), who was permitted to view some seismic sections that assisted him in subsurface reconstructions (Mudge, 1983, written communication).

Previous Investigations

The earliest investigations into the structure and stratigraphy of the Montana Disturbed Belt began around 1900. These early investigations were discussed by Deiss (1943a, p. 209-211), and Mudge (1959, p. 18; 1972a, p. A2-A4). Reconnaissance geologic mapping by C.H. Clapp and C.F. Deiss of the Coopers Lake quadrangle (unpublished) resulted in the first geologic map to encompass the Smith-Weasel creeks area (Clapp, 1932). Other reconnaissance geologic maps that contain the Smith-Weasel creeks area are the "Structure Contour Map of the Montana Plains" by Dobbin and Erdmann (1955; scale 1:500,000), on which the base of the Colorado Group was contoured, and the "Tectonic Map of a Portion of North Central Montana" by Alpha (1955b; scale 1:563,200). Alden (1932) discussed the physiography and glacial geology of this part of the Montana Disturbed Belt.

The first detailed study of the Smith-Weasel creeks area was done by Holcombe (1963), whose work was largely descriptive and mainly emphasized the stratigraphy of the area. Research work in the immediate vicinity of the Smith-Weasel creeks area was carried out by Viele (1960) on the Flat Creek area to the southeast, by Langfield (1967) on the Ford Creek area to the west, by Merrill (1965) on the southern terminus of the Sawtooth Range to the northwest, and by Knapp (1963) on a diorite sill that extends northwest up Wood Canyon from the southwest corner of the Smith-Weasel creeks area.

A reconnaissance study of the geology, geophysics, and geochemistry of the southeastern part of the Lewis and Clark Range (Mudge and others, 1968) included the southern part of the Smith-Weasel creeks area. Kleinkopf and Mudge (1972) discussed the Bouguer gravity and aeromagnetic anomalies of the region. An extensive study of the stratigraphy and structure of the Sun River Canyon and adjacent areas was published by Mudge (1972a,b). Because of the close proximity of the Smith-Weasel creeks area to the Sun River Canyon, Mudge's work provided the foundation for the regional tectonic framework used in this thesis. Structural trends that surround the Smith-Weasel creeks area can be observed on the Choteau 1° x 2° quadrangle map complied by Mudge and others (1982) and on the bedrock geologic map of part of the Northern Disturbed Belt by Mudge and Earhart (1983).

Physiography

Slightly more than 950 m of topographic relief exist in the Smith-Weasel creeks area. Minimum elevations (1371 m MSL) occur in the northern half of the area along Smith Creek, whereas progressively higher elevations (maximum 2330 m MSL) occur toward the southern half of the area, particularly along the southern map boundary.

Northern Part of Research Area.--The northern area, which is northwest of the northeast-southwest unpaved access road (Fig. 3), consists of low-lying peaks and two northeast-trending ridges, all of which have an average topographic relief of about 150 m. Both northeast-trending ridges are composed of the resistant Kootenai Formation (Table 1) and reflect the orientation of the Smith and Johnston thrust plates (Pl. 1). Valleys in the northern area, e.g. the valley between the Goss I and Johnston thrusts, are underlain by less resistant units such as the Flood Member of the Lower Cretaceous Blackleaf Formation (Pl. 1). The northwest-facing slopes are covered with conifer forests, whereas the southeast-facing dip slopes are covered with grassland and small shrubs. The overall lower elevations and topographic relief of the northern area probably resulted from Wisconsin-age glacial scouring and the dominance there of less-resistant Cretaceous units.

Southern Part of Research Area.--The southern area consists of many prominent, near east-west trending ridges and more than 460 m of topographic relief. The higher elevations in the southern area can be attributed to the presence there of resistant Cambrian, Devonian, and Mississippian carbonate rocks.

Two of the most noticeable ridges in the eastern part of the southern area are composed of the Mississippian Castle Reef Dolomite, a resistant unit that constitutes the lower part of the Goss I and II thrust plates (Fig. 4). The trends of the Goss I and II thrust faults can be easily traced by following the two ridges composed of the Castle Reef Dolomite. In the Goss imbricate zone (Fig. 3), ridges composed of the Devonian Jefferson Formation do not reflect the general northwest trend of the thrust faults possibly because of dissection by Goss Creek and its minor tributaries. A distinct increase in topographic elevation associated with the Goss imbricate zone (Fig. 4) is attributed to the presence there of multiple thrust plates that contain the resistant carbonate rocks of the Devonian Jefferson Formation.

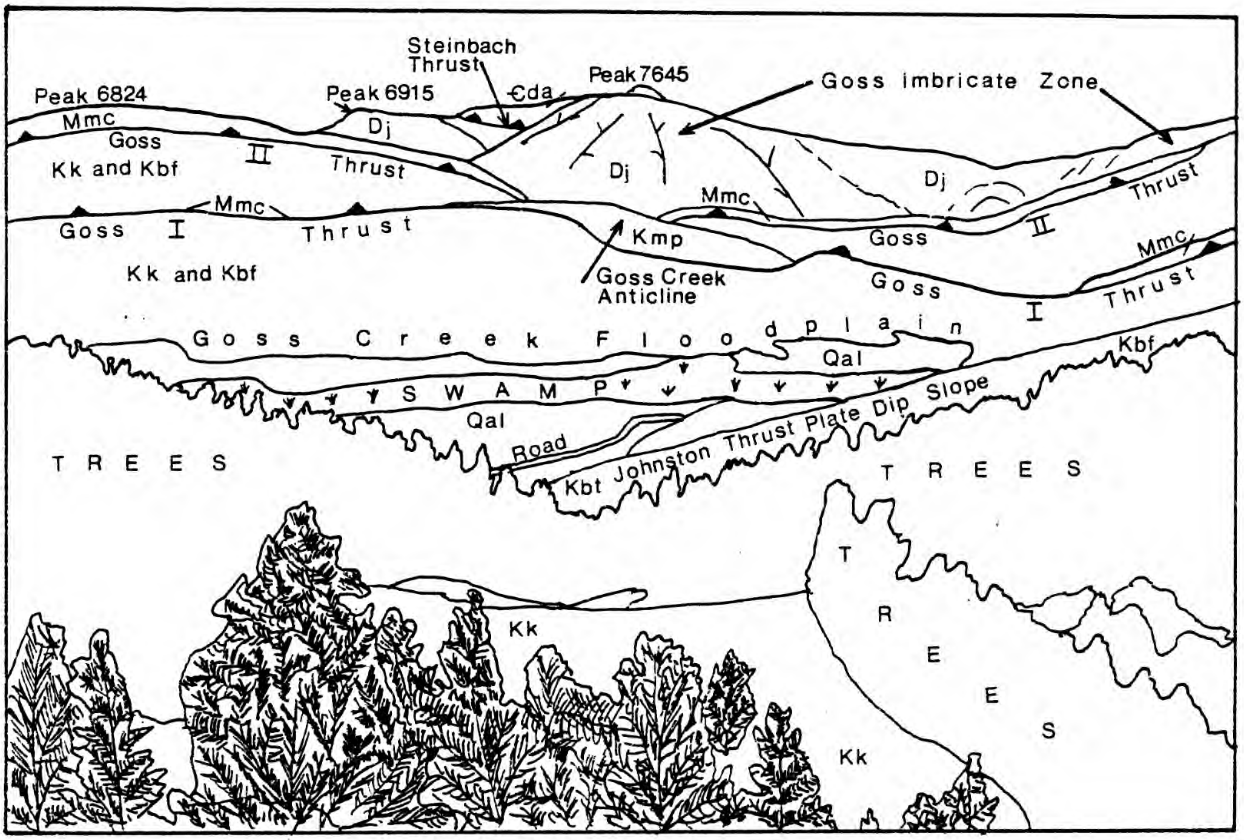

Figure 4. Photograph of southern part of Smith-Weasel creeks area.

View to the south from the southwest quarter of section 11. The south-dipping Goss I and Goss II thrust plates, the lower parts of which are composed of the Mississippian Castle Reef Dolomite (Mmc), form the first two ridges in the background. High ridge in left background is peak 6824 (SE1/4 sec. 27). The southeast-plunging (to the left) Goss Creek anticline, where the Cretaceous Mount Pablo Formation (Kmp) is exposed, is between the Goss I and Goss II thrust faults. Higher elevations in extreme background are in the Goss imbricate zone where the Devonian Jefferson Formation (Dj) has been repeated by multiple-thrust plates. The Cambrian Damnation Limestone (Ꞓda) is visible in the center background at the base of the Steinbach thrust plate. Low area in middle of picture is the Goss Creek floodplain (Qal). The Cretaceous Flood (Kbf) and Taft Hill members of the Blackleaf Formation are visible (right) on the dip slope of the southeast-dipping Johnston thrust plate (sec. 15). The Cretaceous Kootenai Formation (Kk) underlies the area in the foreground.

Acknowledgements

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State University, and by Mr. Mudge, who served as an ex-offico member of the thesis committee.

REGIONAL SETTING

The Montana Disturbed Belt follows approximately what was the eastern margin of the Cordilleran geosyncline from middle Proterozoic (1.5 billion years ago) through early Mesozoic (Mudge, 1970, p. 378; Harrison and others, 1974, p. 1). The stratigraphic section, from the Precambrian Belt Supergroup through lower Mesozoic rocks, thickens westward. The inferred erosional edge of the Precambrian Belt Supergroup is at or near the eastern edge of the disturbed belt (Mudge, 1970, p. 378). About 250 km westward, near the Idaho-Montana stateline, Belt rocks are more than 15,240 m thick (McMannis, 1965, p. 1806; Mudge, 1970, p. 378). Although this great thickness of Belt rock does exist in many areas as an unfaulted, continuous stratigraphic section, Cavanaugh and Cavanaugh (1982, p. 161) concluded that, based on drilling results, geophysical studies, and field observations, the Belt rocks in many places are part of an overlying thrust plate that conceals thick sections of Paleozoic reservoir rocks.

Paleozoic rocks thicken from 945 m at the eastern edge of the disturbed belt to 3700 m in western Montana, 250 km westward (Sloss, 1950, p. 425). In the eastern part of the Sawtooth Range Mesozoic rocks are 2800 m thick, whereas in the western part of the Sawtooth Range 40 km away, Mesozoic rocks are 3660 m thick (Mudge, 1970, p. 379).

The Sweetgrass Arch, which is east of the disturbed belt, contains the South Arch and the Kevin-Sunburst Dome, and is traversed by two northeast trending fracture zones, the Scapegoat-Bannatyne trend and the Pendroy fault (Fig. 1). The Sweetgrass Arch is a northwesterly plunging flexure involving all rocks including the Precambrian crystalline basement; it has been tectonically active several times since the Precambrian, attaining its present configuration near the end of the Cretaceous (Mudge, 1982, p. 91). The development of the Sweetgrass Arch and its associated structural elements thus preceded the development of the disturbed belt.

Uplift and erosion of the geosynclinal sedimentary rocks of western Montana began in the Late Jurassic; periodic uplift continued through the Cretaceous and into the Paleocene, at which time décollement-type faulting and folding began (Mudge, 1970, p. 384). To the west, the thrust fault planes developed at a relatively deep depth in the Precambrian Belt rocks; to the east the thrust-fault planes migrated upsection through the Paleozoic and Mesozoic rocks in a stairstep manner, by moving laterally within the incompetent units and cutting upsection at a high angle through competent units (Hume, 1957, p. 397; Dahlstrom, 1977, p. 412). Subsurface data in the Canadian Rockies on such structures as the Jumpingpound thrust fault (Hume, 1957, p. 400) indicate that, with increasing depth, the dip of the thrust fault decreases (Dahlstrom, 1977, p. 411; Price, 1981, p. 433). Mudge (1972b, p. B41) noted a similar relationship in the Sun River Canyon area where "... the faults appear to have the configuration of a 'lazy S' or an integral sign..."

Gravitational gliding triggered in the early Tertiary by the Laramide Orogeny moved the rocks above the sole fault eastward across a small Mesozoic basin. When the glide mass neared the erosional edge of the Belt Supergroup and the roughly coincident west edge of the craton, folding and imbricate thrust faulting of the strata of the eastern part of the overriding block took place (Mudge, 1970, p. 384). Hence, an east-to-west sequence of deformation, where the oldest deformation of the overriding block occurred in the eastern part of the Montana Disturbed Belt, is indicated (Mudge, 1972b, p. B34). Mudge (1982, p. 107) stated that all structures in the Northern Disturbed Belt "... formed mostly during the Paleocene and are equivalent in time to only the eastern-most thrust faults of the Idaho-Wyoming thrust belt."

The Precambrian crystalline basement was not involved in the décollement (Mudge, 1970, p. 384), but the regional slope of the basement controlled, to a great extent, the structural development of the Montana Disturbed Belt (Mudge, 1982, p. 91). The configuration of the Precambrian crystalline basement had little effect on the development of the southern Canadian Rockies (Mudge, 1982, p. 120).

Northwesterly trending normal faults that post-date the thrust faults may represent backsliding or the relaxation of the maximum principal compressive stress acting on the thrust plates (Mudge, 1970, p. 380). These listric normal faults do not involve the Precambrian crystalline basement (Mudge, 1983, written communication).

Two orientations of the maximum principal compressive stress are recognized in the Sun River Canyon area (Mudge, 1972b, p. B34). North of the Sun River (Fig. 1), a nearly east-west alignment of the maximum principal compressive stress resulted in an almost north-south alignment of fold axes and thrust-fault traces, whereas south of the Sun River the structural grain is approximately N.10°-20° W. as a result of a more northeasterly alignment of the maximum principal compressive stress (Mudge, 1972b, p. B34).

The Smith-Weasel creeks area is on the southeast margin of the Scapegoat-Bannatyne trend that, in most of the area, appears to be a hingeline along which the strike of the structures of the disturbed belt change markedly (Mudge and others, 1982). North of Ford Creek the structural trend is more northerly; at Ford Creek the structural trend becomes northwest-southeast. South of Smith Creek, in the northern part of the research area, thrust faults have northeast traces, whereas in the southern part of the research area thrust fault traces are east-west to northwest-southeast (Fig. 2; Pl. 1). South of the Smith-Weasel creeks area the structural grain of the disturbed belt is northwest-southeast.

STRATIGRAPHY

The stratigraphy of the Smith-Weasel creeks area is discussed by Zoe (in preparation) and is summarized in Table 1. Mudge (1972a) provided a detailed description of the pre-Quaternary rocks in the Sun River Canyon area, 25 km north of the Smith-Weasel creeks area. The newly established Mount Pablo Formation was described by Mudge and Rice (1982). These reports were invaluable in defining the rock units in the research area. Upper Cretaceous rocks were not included as part of the stratigraphic study and are therefore undifferentiated.

The pre-Quaternary rocks that crop out in the research area range from Precambrian Y (Upper Proterozoic) to Upper Cretaceous. Precambrian and Paleozoic rocks were deposited in a dominantly marine environment; westward, these rock units thicken toward the axis of the Cordilleran geosyncline (Mudge, 1972b, p. B1). Most of the Mesozoic rocks, which also thicken westward (Mudge, 1972b, p. B1), are terrigenous and were deposited mainly in a small marine basin (Imlay, 1957, p. 471; Mudge, 1970, p. 379). In the Canadian Rockies, Price (1981, p. 430) divided the stratigraphic record into tectonostratigraphic assemblages that also seem applicable to the Montana Disturbed Belt. A pre-orogenic stage, during which sediments were deposited in a western eugeoclinal

Era	System	Series	Group	Formation	Member	Thickness (meters)	Description
CENO-ZOIC	QUA-TERNARY					–	Alluvium, colluvium, glacial till, terrace gravels UNCONFORMITY
MESOZOIC	CRETACEOUS	Upper	Montana	Two Medicine Fm Virgelle Ss. Telegraph Cr. Fm		360+	Undifferentiated
		Upper	Colorado	Marias River Shale		360+	Undifferentiated UNCONFORMITY
		Lower	Colorado	Blackleaf Fm.	Vaughn Mbr.	55	Olive gray sandstone and siltstone, locally small- to medium-scale cross bedding
					Taft Hill Mbr.	30	Olive gray mudstone, locally small- to medium-scale cross bedding
					Flood Mbr.	60	Dark gray shale with thin- to medium-beds of sandstone UNCONFORMITY
				Kootenai Fm.		240	Greenish gray sandstone with dark reddish brown and greenish gray mudstone UNCONFORMITY
				Mount Pablo Fm.	Cut Bank Ss.	65	Thinly laminated moderate red mudstone and grayish green siltstone UNCONFORMITY
	JURASSIC	Upper	Ellis	Swift Fm.		30	Calcareous, salt and pepper sandstone, small- to medium-scale cross bedding UNCONFORMITY
				Rierdon Fm.		40	Alternating thin beds of limestone and medium gray calcareous mudstone UNCONFORMITY
		Middle		Sawtooth Fm.		20	Medium gray thinly laminated shale UNCONFORMITY
PALEOZOIC	MISSISSIPPIAN	Upper	Madison	Castle Reef Dolomite	Sun River Mbr.	60	Finely crystalline dolostone with chert bands
		Lower		Allan Mountain Limestone *		150	Medium gray cherty limestone, some shale in lower part UNCONFORMITY
	DEVONIAN	Upper		Three Forks Fm. *		75	Mostly evaporite-solution breccia
				Jefferson Fm.		120	Very finely crystalline grayish brown limestone, fetid oder
		Middle		Maywood Fm.		35	Thinly bedded dolomitic mudstone and grayish brown limestone UNCONFORMITY

* Present in thesis area only in subsurface

TABLE 1.
Stratigraphy of Smith-Weasel Creeks Area (after Zoe, in preparation; Mudge, 1972a, p. A6-A7; Mudge, 1982, p. 98-99), with colors according to the Rock-Color Chart (Goddard and others, 1980) and thickness terminology from McKee and Weir (1953) and Ingram (1954).

Era	System	Series	Group	Formation	Member	Thickness (meters)	Description
PALEOZOIC	CAMBRIAN	Upper		Devils Glen Dolomite *		75	Very light gray finely crystalline massive dolomite
		Middle		Switchback Shale *		55	Greenish gray mudstone
				Steamboat Limestone *		75	Thinly bedded limestone and dolomite
				Pagoda Limestone *		90	Grayish brown dolomitic limestone and lower grayish green shale
				Dearborn Limestone		60	Pale yellowish brown limestone, calcite-filled veins abundant
				Damnation Limestone		65	Brownish gray limestone, heavy mottling with yellowish gray siltstone
				Gordon Shale		60	Thinly laminated green shale
				Flathead Sandstone		50	Yellowish brown, iron-stained sandstone UNCONFORMITY

P R E C A M B R I A N

Eon	Era	Super Group	Group	Formation	Member	Thickness (meters)	Description
PROTEROZOIC	UPPER	BELT	Missoula	McNamara Fm.*		80	Siltite and metaquatzite
				Bonner Quartzite *		230	Medium gray metaquartzite
				Mount Shields Fm. *		510	Dark reddish brown siltite
				Shepard Fm. *		160	Grayish yellow dolomitic siltite
				Snowslip Fm.*		150	Grayish red and grayish green siltite
				Helena Fm.		30+	Medium gray dolostone, argillite in lower part
			Ravalli	Empire and Spokane Fms.		370	Dark reddish brown, grayish green, and medium gray thinly bedded siltite

* Present in thesis area only in subsurface

TABLE 1 - Continued

domain and in an eastern platformal and miogeoclinal domain, existed from late Proterozoic to Middle Jurassic. During the following synorogenic stage, late Jurassic to Paleogene, sediments were deposited in an exogeoclinal domain.

Pre-Quaternary Rocks of the Northern Area

Pre-Quaternary rocks of the thrust plates in the northern area consist entirely of the Lower Cretaceous Mount Pablo, Kootenai, and Blackleaf formations and undifferentiated Upper Cretaceous rocks. The Blackleaf Formation is further subdivided into the Flood, Taft Hill, and Vaughn members (Table 1).

Excellent marker horizons are formed by the well-indurated basal sandstone of the Flood Member and by the gastropod-rich limestone in the upper part of the underlying Kootenai Formation. Where exposed these two beds, separated only by 2-3 m of mudstone, form a 1-2 m high, easily traced ridge that marks the contact between the Kootenai and Blackleaf formations.

Pre-Quaternary Rocks of the Southern Area

Pre-Quaternary rocks of the southern area range from the Precambrian Y (Upper Proterozoic) Empire and Spokane formations to undifferentiated Upper Cretaceous rocks. In general, older rock units in a thrust plate are to the south. The youngest rocks in the southern area are in the Weasel imbricate zone (Fig. 3), where the Vaughn Member of the Cretaceous Blackleaf Formation and other Cretaceous units are repeated by many imbricate thrust faults.

Precambrian Y (Upper Proterozoic) rocks include the Empire and Spokane formations and the Helena Formation. In the northwest quarter of sec. 31, a Precambrian Z (Upper Proterozoic) diorite sill, greater than 30 m thick, was intruded along the contact between the Empire and Spokane formations and the Helena Formation (see Knapp, 1963; McGill and Sommers, 1967, Wood Creek Hogback section, Figure 2a on Pl. 1; Kleinkopf and Mudge, 1972, p. A13, magnetic anomaly 19).

Paleozoic formations in the research area include the Cambrian Flathead Sandstone, Gordon Shale, Damnation Limestone, and Dearborn Limestone; the Devonian Jefferson and Maywood formations; and the Castle Reef Dolomite of the Mississippian Madison Group. Some rock units not exposed in the Smith-Weasel creeks area because of truncation by thrust faults or removal by erosion, are present in the Sun River Canyon area (Mudge, 1972a, p. A6-A7) and are interpreted to occur in the subsurface of the Smith-Weasel creeks area. These units are: the Precambrian Y (Upper Proterozoic) Missoula Group; the Cambrian Pagoda Limestone, Steamboat Limestone, Switchback Shale, and Devils Glen Dolomite; the Devonian Three Forks Formation; and the Mississippian Allan Mountain Limestone.

Jurassic rock units in the southern part of the research area include the Swift, Rierdon, and Sawtooth formations of the Ellis Group. Only the Swift Formation forms numerous outcrops. The Jurassic Morrison Formation was not recognized in the Smith-Weasel creeks area, although the formation forms part of the thrust plates of the Sawtooth Range (Mudge, 1972a, p. A49). The thrust plates in the Smith-Weasel creeks area may have been transported from points too far west for Morrison rocks to have been present, as compared to the thrust plates of the Sawtooth Range that had their origins farther east. Pre-Cretaceous uplift, however, may have removed the Morrison Formation prior to deposition of the Mount Pablo Formation (Mudge and Rice, 1982, p. 10).

STRUCTURAL GEOLOGY

Based on the dominant structural trend of the thrust-fault traces, the Smith-Weasel creeks area can be divided into north and south areas by the northeast-southwest unpaved access road (Fig. 5). The northern area has a dominantly northeast-southwest structural trend, whereas in the southern area an east-west to northwest-southeast structural trend is more common. There is a general increase in stratigraphic throw from north to south.

Northern Part of Research Area

The northern area includes the Smith, Weisner, and Johnston thrust plates (Fig. 5). Eastward from Smith Creek these three almost northwest striking thrust plates with southwesterly dips become near-northeast striking with southeasterly dips (Pl. 1; Pl. 2; A-A', B-B'). Joint data from the northern area are summarized in Figure 6. Stratigraphic throw in the northern area is less than 450 m and, along most faults, is less than 300 m.

<u>Smith Thrust</u>.--The trace of the Smith thrust exhibits the greatest change in orientation of any thrust-fault trace within the research area, with a near-90° rotation occurring in the

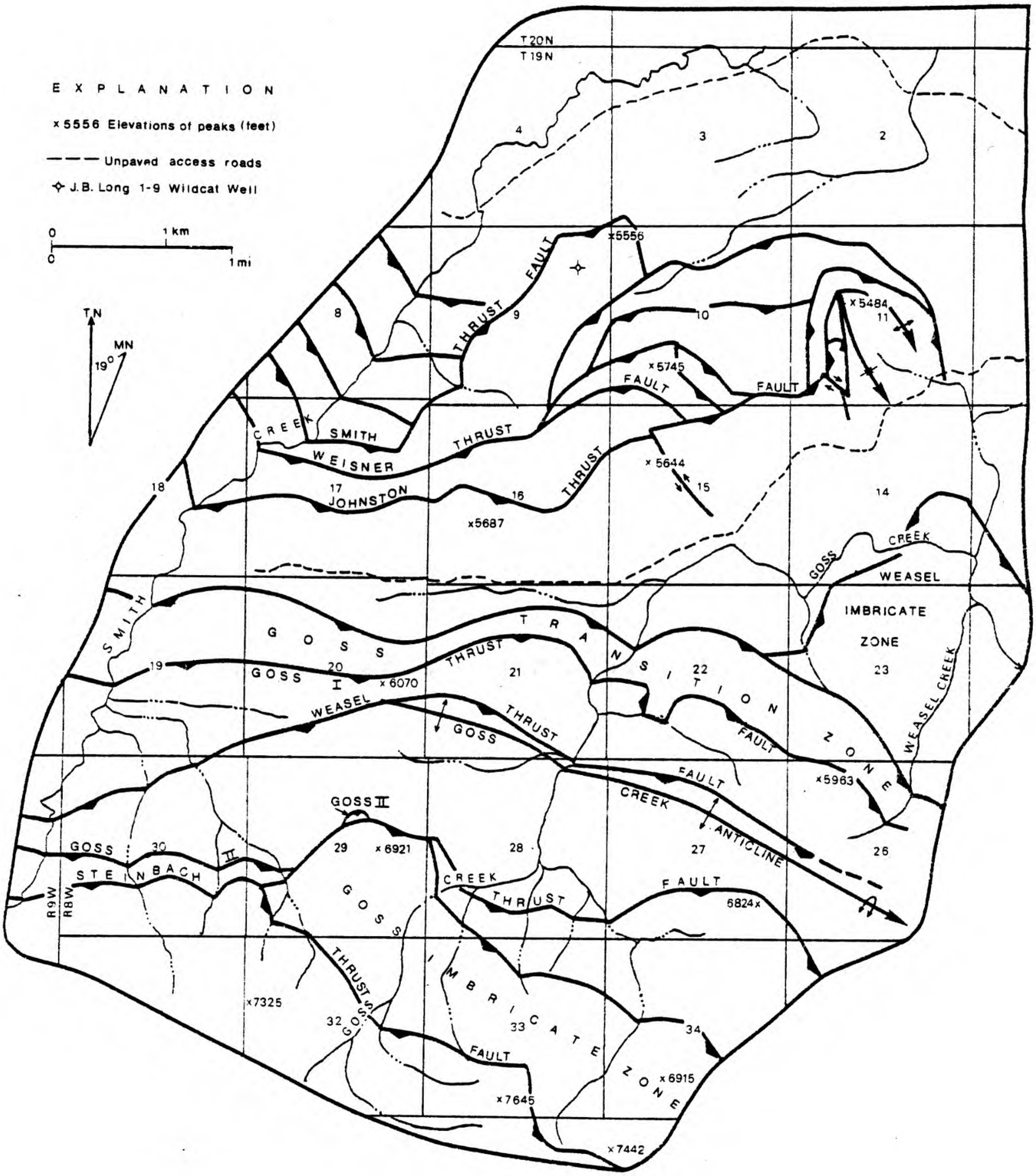

Figure 5. Structural zones, thrust faults, and other major structures in the Smith-Weasel creeks area.

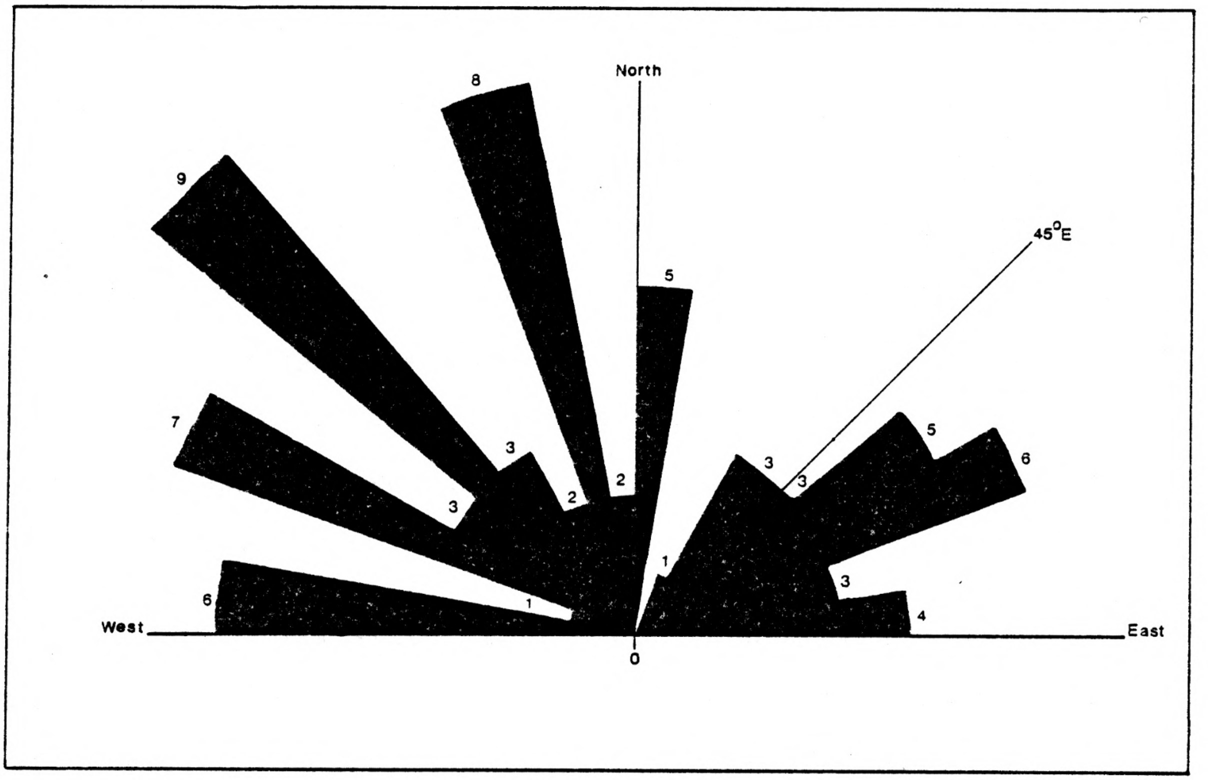

Figure 6. Summary of joint data for the northern area.

Rose diagram for the strike of 71 joint measurements collected in the northern area. Numbers represent the actual number of joint directions measured in a particular 10° interval. Strike of joints was determined by using the stereonet to rotate the strata to the horizontal.

northeast quarter of sec. 17 (Pl. 1; Pl. 3). At the hinge point the orientation of the trace of the Smith thrust fault changes from northwest-southeast to northeast-southwest. In sec. 9 the northwestern edge of the Smith thrust plate forms a prominant ridge that overlooks the Weisner Ranch. Although the Smith thrust fault was nowhere clearly seen, the trace of the Smith thrust fault is approximately parallel to the ridge formed by the Kootenai Formation. This ridge was not broken by other faults and is well-exposed except in a small northwest-trending drainage (SW1/4 sec. 9).

Extending across Smith Creek from the northwest, three westerly-to-northwesterly trending thrust faults repeat only Lower Cretaceous units. These faults, together with some unmapped thrust faults that are assumed to exist in the undifferentiated Upper Cretaceous units, are truncated by the Smith Thrust (Pl. 1; Pl. 3). The geologic map of Mudge and others (1982) indicates that one of these three northwest-trending thrust faults may be the southern extension of the Allan thrust (Fig. 2); in the research area, however, which of these three thrust faults, if any, is the Allan thrust is unclear. The thrust plates that are truncated by the Smith thrust and contain only Lower Cretaceous rocks may continue a limited distance (probably less than 500 m) in the subsurface beneath the erosional edge of the Smith thrust plate (Pl. 2; A-A' and B-B').

Northwest-southeast trending folds occur in two of the thrust plates that contain only Lower Cretaceous rocks (S1/2 sec. 8 and NE1/4 sec. 17); southeast-trending folds occur in the Smith thrust plate west of Smith Creek (NW1/4 sec. 17). In sec. 9, three southeast-plunging folds reflect the warping of the Smith thrust plate that developed when the plate overrode underlying thrust plates or folds. In the northeast quarter of sec. 9, a syncline affects the total thickness of the Smith thrust plate; this fold, together with subsequent erosion, has resulted in the curvilinear trace of the Smith thrust.

Weisner Thrust.--South of the Smith thrust is the Weisner thrust. Eastward from Smith Creek the trace of the Weisner thrust changes orientation gradually from west-northwest to east-northeast to northeast, subparalleling the change in orientation of the trace of the Smith thrust. The Weisner thrust splays into several imbricate thrust faults near peak 5745 (SW1/4 sec. 10); these thrust faults are, in turn, truncated by the Johnston thrust fault. Two of the imbricate thrust fault plates on peak 5745 contain the distinctive medium-crystalline, gray limestone bed of the upper part of the Mount Pablo Formation (Mudge and Rice, 1982, p. 5).

Two smaller thrust plates (sec. 10; Pl. 2; C-C') are truncated by the Weisner thrust in the southeast quarter of sec. 9. These thrust plates may once have been a part of the Weisner thrust plate before becoming detached from it. Three south-plunging folds with approximate north-south axes occur in the southernmost of these two thrust plates (SE1/4 sec. 10). These folds may reflect the deformation or warping of the total thickness of the thrust plate responding, perhaps, to irregularities of the underlying surface.

Johnston Thrust.--The Johnston thrust is south of the Weisner thrust. The Johnston thrust plate, because of its topographic expression, is one of the most accurately defined thrust plates in the research area. The trace of the Johnston thrust is nearly east-west at Smith Creek, but changes to a northeasterly orientation near a southeast plunging anticline and syncline in the southeast quarter of sec. 16 (Pl. 1; Pl. 3). East of this hinge point the dips of strata in the Johnston thrust plate change from southerly to southeasterly and increase 10°-20°. The anticline and syncline in secs. 15 and 16 represent a response to the change in orientation of the Johnston thrust plate. These folds are restricted to the Johnston thrust plate and do not affect the Weisner thrust. Minor warping of the Johnston thrust plate in the southeast quarter of sec. 18 resulted in two small southeast plunging folds. These folds may reflect the influence of underlying structures overridden by the Johnston thrust plate. At Smith Creek the Johnston thrust has cut downsection along strike to the Mount Pablo Formation.

Two tear faults break the Johnston thrust plate; a left-lateral tear fault with approximately 60 m of displacement in sec. 15, and on peak 5484 in sec. 11, a right-lateral tear fault, with no more than 9 m of strike-slip displacement. These kinds of tear faults would be classified by Dahlstrom (1977, p. 429) as secondary transverse tear faults. No slickensides were observed; if the movement on the faults was dip-slip, the block between the tear faults would be down-dropped.

Immediately north of the right-lateral tear fault in sec. 11, along the north-south trending ridge, the Kootenai gastropod limestone and the basal sandstone of the Flood Member are overturned (Inset, Pl. 1). The north-south trending overturned syncline, of which the Kootenai Formation and Flood Member are a part, may have developed because of the fold's proximity to the Johnston thrust (Pl. 2; E-E'). South of the right-lateral tear fault the syncline is not overturned and plunges southward. Northward along the north-south trending ridge, the main part of the Johnston thrust plate thins to an erosional remnant that partly obscures a southeast plunging syncline (Inset, Pl. 1; Pl. 2; E-E'). The Johnston thrust fault either terminates in, or is replaced by, a complex system of faults and folds on peak 5484 in sec. 11 (Inset, Pl. 1).

Zones or Horizons of Weakness.--Mudge (1972b, p. B38) discussed the zones or horizons of weakness in the Sun River Canyon area and summarized them on his Plate 5. In the northern area, most major thrust faults lie in the lower part of the Kootenai Formation in the upper plate and in the upper part of the Kootenai Formation or in the Flood Member of the Blackleaf Formation in the lower plate. The Kootenai Formation, a competent unit because of its thickness and lithology, apparently transmitted the stresses that formed the Johnston, Weisner, and Smith thrust faults (Pl. 2; A-A', B-B', and C-C').

Southern Part of Research Area

Structural elements of the southern area are the Weasel imbricate zone, Goss transition zone, Goss I and II thrust plates, Weasel thrust plate, Goss Creek anticline, Goss imbricate zone, and the Steinbach thrust plate (Fig. 5). Thrust-fault traces in the southern area are generally east-west to northwest-southeast (Pl. 1; Pl. 3). Joint data for the southern area are summarized in Figure 7.

Weasel Imbricate Zone.--The Weasel imbricate zone comprises rocks of an erosional remnant of a once more extensive thrust plate with a northwest structural grain. The Weasel imbricate

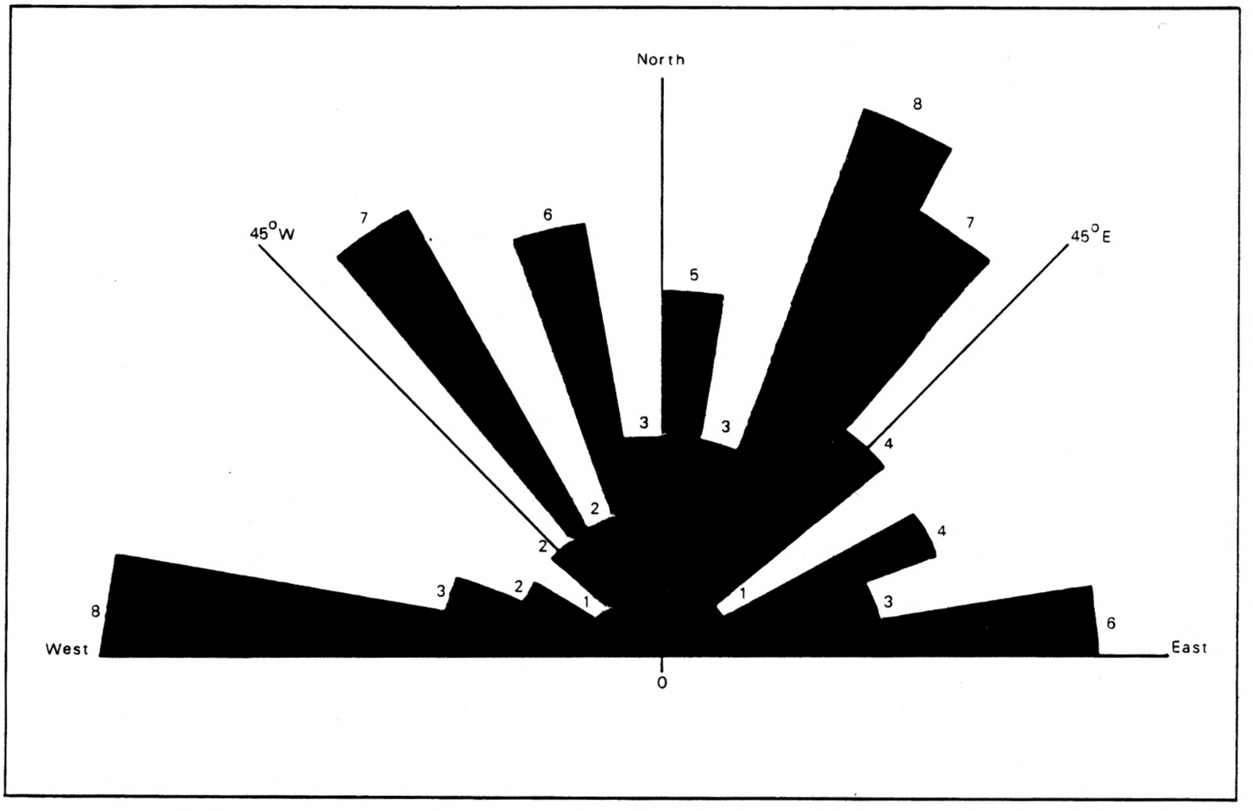

Figure 7. Summary of joint data for the southern area.

Rose diagram for the strike of 75 joint measurements collected in the southern area. Numbers represent the actual number of joint directions measured in a particular 10° interval. Strike of joints was determined by using the stereonet to rotate the strata to the horizontal.

zone (Fig. 5) contains many northwest-trending imbricate thrust faults (stratigraphic throw less than 150 m) that repeat the Vaughn Member of the Cretaceous Blackleaf Formation. Also repeated by the faults are other Cretaceous units that display southeast-plunging folds (SE1/4 sec. 14), i.e. a syncline flanked by two northwest-trending anticlines. The northwest boundary of the Weasel imbricate zone is defined by the northeasterly trending segments of these imbricate thrust faults, which dip approximately 40° SE. (Pl. 2; D-D'). The rocks of the Weasel imbricate zone truncate the northeast structural trend of some of the rocks in the northern area (Pl. 1; Pl. 2; D-D').

Goss Transition Zone.--The east-west trending Goss transition zone is bounded on the south by the Goss I thrust and on the north by a series of parallel to sub-parallel thrust faults that truncate the Johnston thrust plate and rocks of the Weasel imbricate zone (Fig. 5). Two fractured, overturned anticlines (N1/2 sec. 19) occur in the western part of the Goss transition zone. The exposed core of one of the anticlines lies within the Jurassic Rierdon Formation (Fig. 8); this fold is informally designated the Smith Creek anticline (NW1/4 sec. 19).

The origin of the Smith Creek anticline is unclear. The anticline may be a small drag fold that formed when the Goss I thrust plate overrode the Rierdon Formation. The complete

Figure 8. Photograph of core of Smith Creek anticline

Photograph looking west across Smith Creek at core of Smith Creek anticline (NW1/4 sec. 19). All rock visible in the photograph is the alternating limestone and mudstone of the Jurassic Rierdon Formation. The fold is parallel, overturned, and formed mainly by flexural slip. Some flexural flow is visible at the crest of the anticline. The fold plunges slightly southeast by an unknown angle. At water level the Smith Creek anticline is approximately 7 m wide.

overturned stratigraphic section (Swift, Mount Pablo, and Kootenai formations) just north of the Smith Creek anticline, however, suggests a much larger overturned anticline. It is unclear whether the Goss I thrust is a back-limb thrust that originated from the Smith Creek anticline or is simply a thrust fault that overrode a previously fractured overturned anticline. The geologic map of Mudge and Earhart (1983) indicates that the Goss I thrust continues northwest, with approximately the same relative displacement, after crossing Smith Creek; therefore, the second explanation is favored.

Northeast of the Smith Creek anticline the other overturned anticline is fractured by a fore-limb thrust fault in the western part of sec. 20. The thrust fault formed nearly parallel to the axial surface between the isoclinal limbs of the fold (Pl. 2; A-A'). Rocks in the upper part of the Kootenai Formation were placed above overturned rocks in the middle part of the Kootenai Formation by the fore-limb thrust fault, which is truncated by the Goss I thrust in the eastern part of sec. 20.

The eastern part of the Goss transition zone contains two minor thrust faults that repeat Lower Cretaceous rock units. Stratigraphic throw within this part of the transition zone ranges from 150 m to 335 m. An anticline and syncline with west-northwest trending fold axes occur in the northwest quarter of sec. 22.

Goss I Thrust.--The Goss I thrust transported the Mississippian Castle Reef Dolomite to a postion that is now its northernmost surface exposure in the research area. A near-100 m increase in topographic elevation occurs at the escarpment formed by the northern edge of the Goss I thrust plate, except where dissection by Goss and Smith creeks has occurred. Stratigraphic throw along the Goss I thrust ranges from 450 m in the eastern part of the research area to near zero in the western part of the research area. At the surface the Goss I thrust fault dips approximately 30° SW.; subsurface reconstructions suggest that the dip increases to about 60° SW. (Pl. 2; A-A', B-B', C-C', D-D'). In the west half of sec. 21, the Goss I thrust changes stratigraphic position along strike, cutting upsection westward from near the base of the Mississippian Castle Reef Dolomite to a position just above the base of the Jurassic Swift Formation. The small west-northwest trending syncline (SW1/4 sec. 22) in the Mount Pablo Formation (Pl. 2; C-C') may have developed prior to the Weasel thrust fault.

Goss Creek Anticline and Weasel Thrust.--The Goss Creek anticline (secs. 20, 21, 26, 27), a major fold plunging 15° east-southeast (Fig. 9), is broken by the fore-limb Weasel thrust fault (Pl. 2; D-D'). The Weasel thrust probably originated from

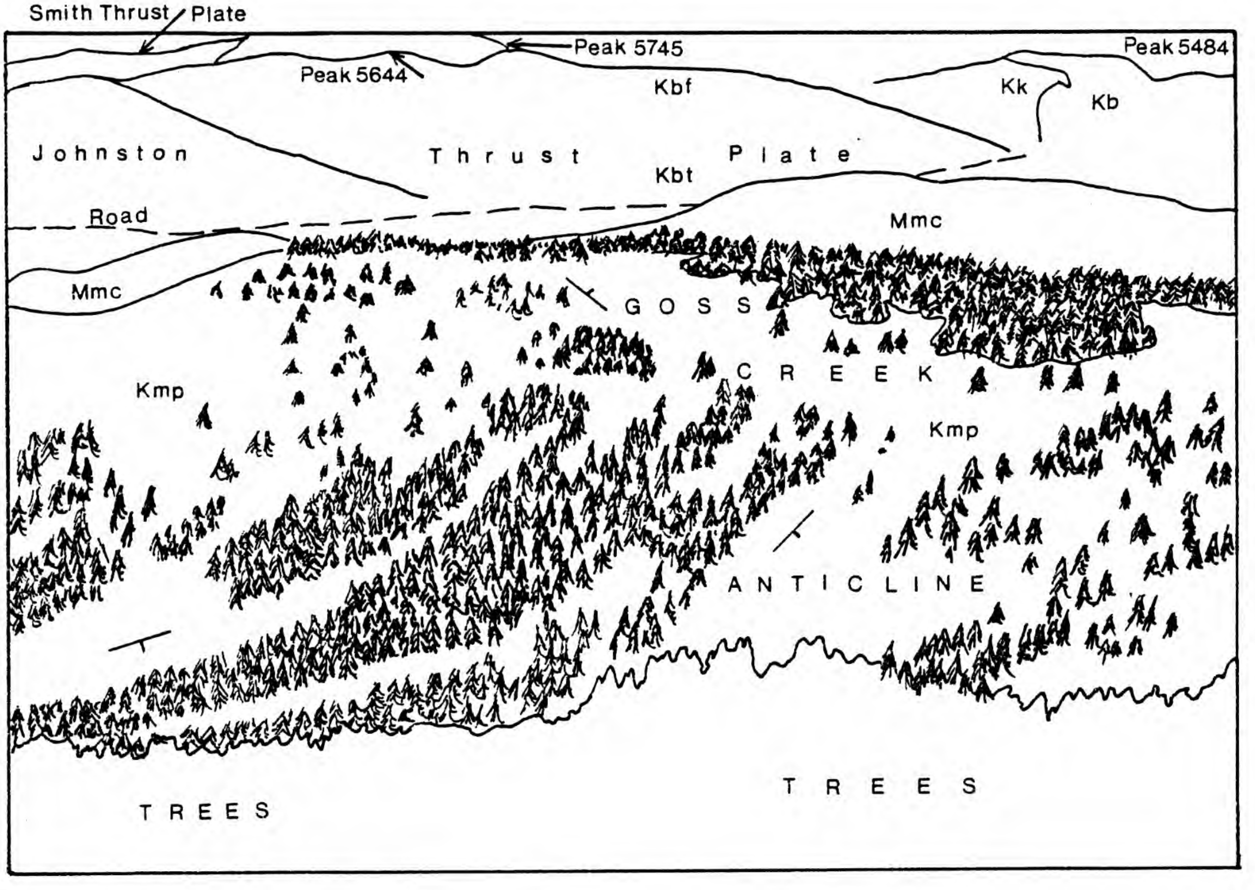

Figure 9. Photograph of Goss Creek anticline

Photograph looking northwest from just west of peak 6824 (SE1/4 sec. 27). In foreground the vegetation pattern indicates the southeast-plunging (to the right) Goss Creek anticline (NW1/4 sec. 27). Rock in foreground is the Cretaceous Mount Pablo Formation (Kmp). Above the Goss Creek anticline is the Mississippian Castle Reef Dolomite (Mmc) dip slope at the base of the Goss I thrust plate. In right background is peak 5484 (sec. 11) where Lower Cretaceous rocks (Kb and Kk) crop out. In center and left background the dip slope of the Johnston thrust plate (sec. 15) composed of the Flood (Kbf) and Taft Hill (Kbt) members of the Lower Cretaceous Blackleaf Formetion (Kb).

fractures in the overturned northeast limb of the Goss Creek anticline (S1/2 sec. 26). In sec. 20 the Weasel thrust fault cuts upsection so that at Smith Creek only the southern limb remains in the thrust plate (Pl. 2; A-A'). At Smith Creek the Weasel thrust fault truncates a small imbricate thrust zone in the northern half of sec. 30 and the southern half of sec. 19 where parts of the Kootenai and Mount Pablo formations have been repeated (Pl. 2; A-A'). This imbricate thrust zone probably is contemporaneous with the Weasel thrust fault (Pl. 2; A-A').

Goss II Thrust.--The Goss II thrust fault truncates the south limb of the Goss Creek anticline by placing the Castle Reef Dolomite onto strata of the Blackleaf Formation (Pl. 2; A-A', C-C', D-D'). Jurassic and Lower Cretaceous rocks that are part of the Goss II thrust plate in sec. 34 are progressively truncated westward by the northernmost thrust fault of the Goss imbricate zone, so that west of sec. 28 only the Castle Reef Dolomite remains exposed in the Goss II thrust plate. The Castle Reef Dolomite forms a prominent east-west trending escarpment, which is absent in sec. 29 because the northernmost thrust fault of the Goss imbricate zone has truncated the Goss II thrust plate (Pl. 2; B-B'). The dip of the Goss II thrust fault ranges from 20°-60° SW., with steeper dips occurring toward Smith Creek (Pl. 2; A-A', D-D'). The dips of strata in the Goss II thrust plate increase westward from approximately 23° SW. (secs. 27,

34) to approximately 55° SW. at Smith Creek (Pl. 1; Pl. 3). Three minor splay faults occur along the Goss II thrust, two in the southwest quarter of sec. 28 and one along Smith Creek. Stratigraphic throw along the thrust trace ranges, west-to-east, from 450 m to 670 m. Joint data collected from the Castle Reef Dolomite in the Goss II thrust plate are summarized in Figure 10.

Goss Imbricate Zone.--Within the Goss imbricate zone the Devonian Jefferson Formation has been repeated by four thrust faults with northwest-southeast fault traces (Pl. 2; B-B', C-C', and D-D'). At the base of one of the thrust plates (Pl. 2; B-B') the rocks of the oldest Devonian unit, the Maywood Formation, are exposed (SE1/4, sec. 29). Stratigraphic throw along the northern boundary of the Goss imbricate zone ranges from 550 m in the west to 1050 m in the east.

The Goss imbricate zone ends abruptly in the western half of sec. 29; truncation by the Steinbach thrust resulted in a marked decrease in topographic elevation and the absence of Devonian rocks toward Smith Creek (Pl. 2; A-A'). Following the general structural trend of the southern area, the traces of thrust faults in the Goss imbricate zone may have at one time curved so that they continued westward past their present position.

Steinbach Thrust.--The trace of the Steinbach thrust follows the general structural grain of the southern area and represents

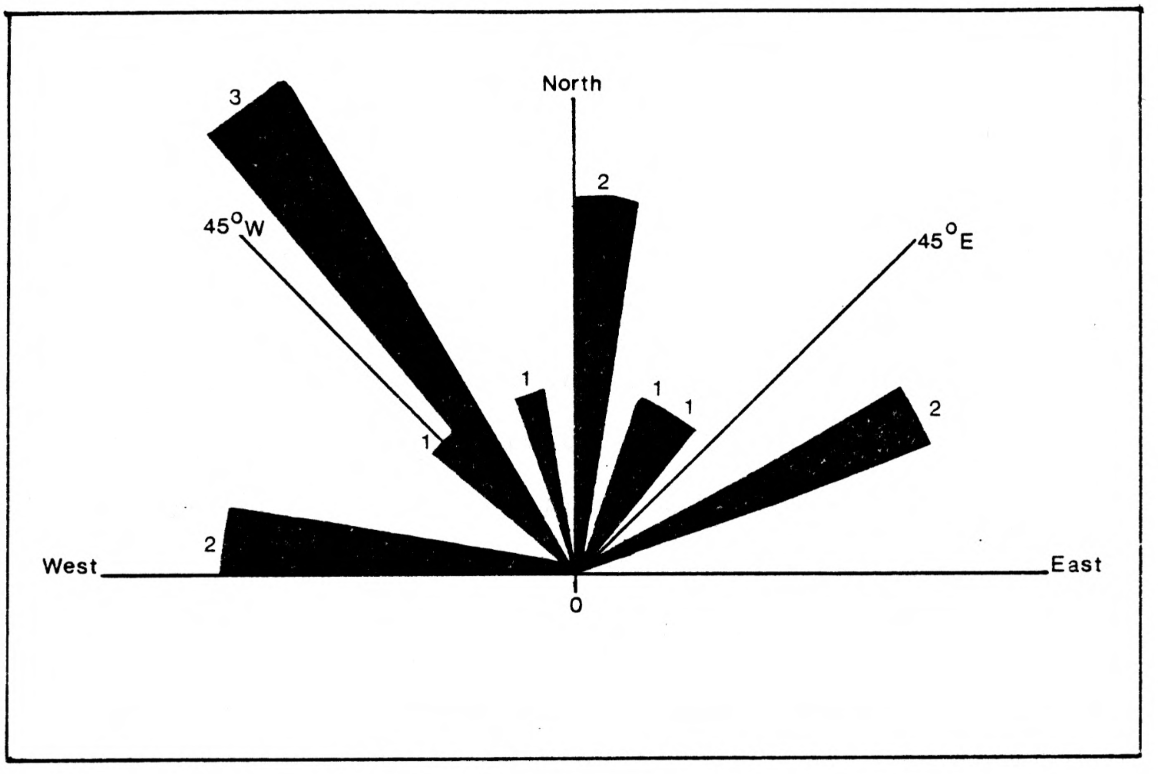

Figure 10. Summary of joint data collected along the Goss II thrust.

Rose diagram for the strike of 13 joint measurements collected along the Goss II thrust plate at stations 45-47 and 51-52 (Appendix 2) in the southern area. Numbers represent the actual number of joint directions measured in a particular 10° interval. Strike of joints was determined by using the stereonet to rotate the strata to the horizontal.

the northernmost boundary of the Lewis and Clark Range in the research area (Fig. 1). Stratigraphic throw along the Steinbach thrust ranges from approximately 1830 m in the west to 800 m in the east. In the western part of the research area, where the Steinbach thrust has an east-west fault trace, the Precambrian Y Empire and Spokane formations are in contact with the Castle Reef Dolomite. In the eastern part of the research area the Steinbach thrust cuts upsection along strike, placing the Cambrian Damnation Limestone in fault contact with the Devonian Jefferson Formation (Pl. 2; C-C', and D-D'). The dip of the Steinbach thrust fault is greater than 60° SW. at Smith Creek (Pl. 2; A-A') but decreases eastward to approximately 40° SW. (PL. 2; C-C'). The dips of strata eastward in the Steinbach thrust plate decrease 20°-30°. A small imbricate thrust fault north of peak 7325 (sec. 32) repeats part of the Empire and Spokane formations, Flathead Sandstone, and Gordon Shale. East-west and northwest-southeast trending folds occur on peak 7325 in sec. 31 and 32.

Cambrian formations that crop out in the northeast quarter of sec. 31 are absent in the northwest quarter between the Precambrian Z diorite sill and the Empire and Spokane formations (Pl. 1). The diorite sill and Helena Formation were not found in the east half of sec. 31. No tight folds, which might explain the absence of the missing formations, were observed. Therefore, based on the observed stratigraphic relationships, a pre-Steinbach transverse fault is inferred to exist within the Steinbach thrust plate. If displacement along the transverse fault was by dip-slip movement then the east side would be down-dropped, whereas if displacement was by strike-slip movement then the tear fault would be left-lateral.

<u>Zones or Horizons of Weakness</u>.--In the southern area the surface of dislocation along the Goss I and II thrusts is in the lower part of the Castle Reef Dolomite. West of sec. 21, the Goss I thrust has cut upsection along strike to a position that is slightly above the base of the Swift Formation. Mudge (1972b, p. B38) noted that the underlying Rierdon Formation "... is the most common locus of thrusts, especially back-limb thrusts, in the Jurassic strata."

Mudge (1972b, p. B38) noted that thrust faults in Devonian strata in the Sun River Canyon area "... are restricted mostly to an evaporite solution breccia in the lower part of the lower member of the Jefferson Formation." Although this relationship was not directly observed in the Smith-Weasel creeks area, the thrust faults at the base of overriding plates in the Goss imbricate zone occur near the base of the Jefferson Formation and are probably restricted to the evaporite solution breccia. A thin remnant of the underlying Maywood Formation is brought to the surface in secs. 29 and 32 by one of the imbricate thrusts.

From a position within the Precambrian Empire and Spokane formations the trace of the Steinbach thrust cuts upsection, from west to east (Pl. 1; Pl. 2; A-A', B-B', C-C', D-D), to a postion near the base of the Cambrian Damnation Limestone. Because of this change in stratigraphic position, no single Cambrian or Precambrian unit appears to be a preferred transmitter of stress in this area. Competent rock units that transmitted the stress in the southern area are the Mississippian Madison Group (Goss I and II thrust faults; Pl. 2; A-A', B-B', C-C', and D-D'), and the Devonian Jefferson Formation (Goss imbricate zone; Pl. 2; B-B', C-C', and D-D').

Scapegoat-Bannatyne Trend

Geologic Expression.--The northeasterly trending Scapegoat-Bannatyne trend was named by Dobbin and Erdmann (1955) on their 1955 revision of their "Structure Contour Map of the Montana Plains." Alpha (1955a, p. 133) designated the feature the Genou trend on the Sweetgrass Arch. He (1955b, p. 131) suggested that the trend was "... a system of fractures which extended from the basement rocks." The fracture system has remained periodically active since the Precambrian (Alpha, 1955b, p. 138) and "...

apparently has had some movement during or after the early Tertiary orogeny as indicated by northeast trending faults and fold axes on the trend [Fig. 11] ..." (Mudge, 1982, p. 121). The magma that cooled to form the body now known as Haystack Butte, just east of the map area, intruded 20 million years ago at what may have been a point of weakness in the reactivated northeast trending Scapegoat-Bannatyne basement fractures (Mudge, 1982, p. 92, 121).

On the Sweetgrass Arch, at the northeastern end of the Scapegoat-Bannatyne trend, the faults of the fracture system formed a northeast-trending, weathered, Precambrian igneous ridge on which several structural highs (horsts?) with more than 430 m of relief are characterized by the absence of Cambrian and Lower Devonian rocks (Alpha, 1955a, p. 133). Alpha defined the southwestern termination of the Scapegoat-Bannatyne trend as a set of northeast-trending normal faults (Mudge and others, 1968, p. E4). These faults, transverse to the northwest trend of the disturbed belt in this area, apparently were first discussed by Clapp (1932, p. 26). The northeast alignment of the Scapegoat-Bannatyne fracture system seems to parallel the structural grain of, and to have roots in, rocks equivalent to those of the Hudsonian (1820 to 1640 million years ago) Churchill Province of the Canadian Shield (Alpha, 1955a, p. 133; Stockwell, 1965, p. 890; Muehlberger and others, 1967, p. 2375; King, 1969,

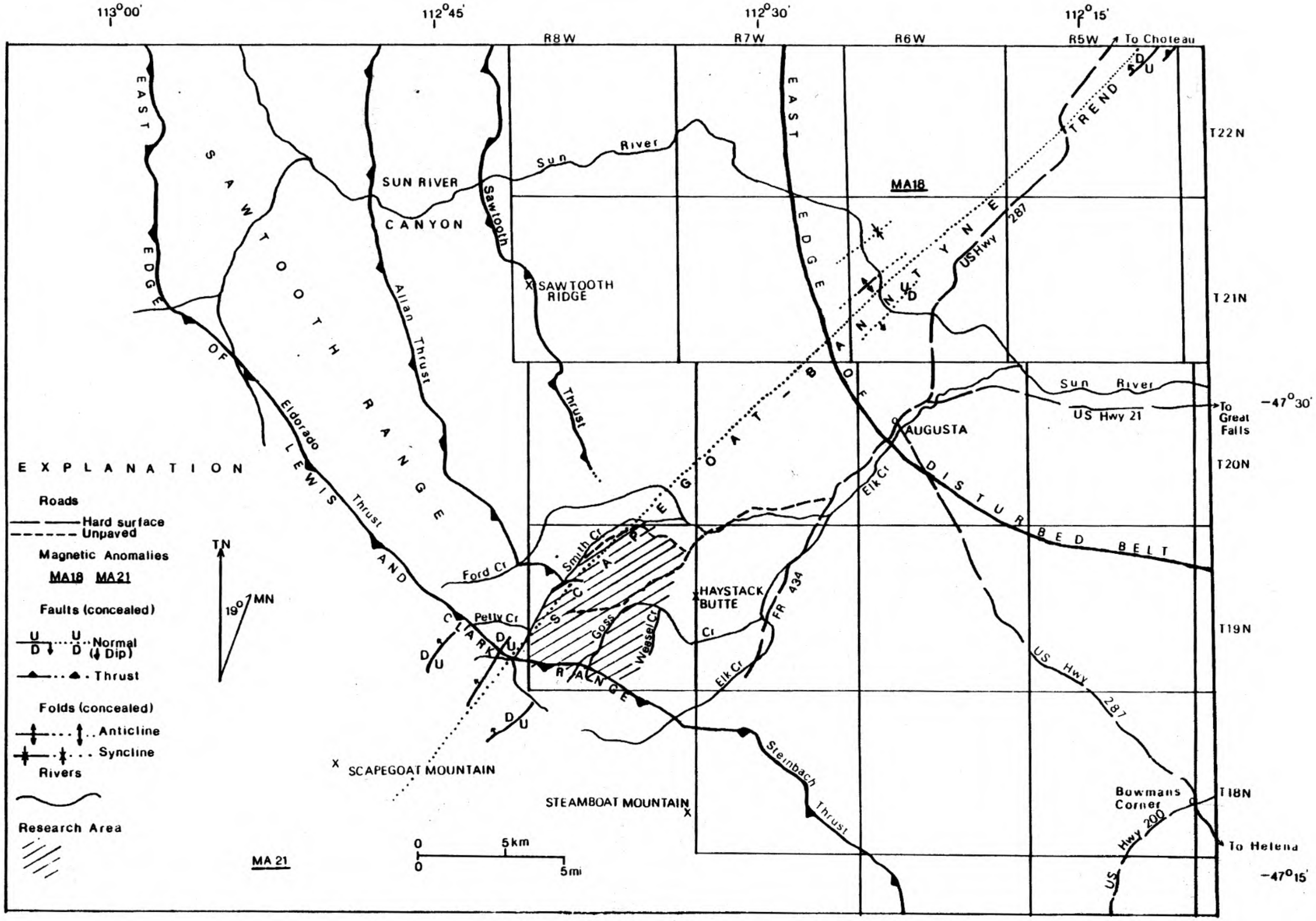

Figure 11. Geologic, geophysical, and geographic features near the Smith-Weasel creeks area (from Mudge and others, 1982).

p. 38-39; King, 1976, p. 76; Price 1981, p. 433).

The Scapegoat-Bannatyne trend has been detected at the surface on Landsat images. Saunders and others (1973, p. 18) used Landsat images to study lineament directions, but were able to distinguish only the part of the trend that lies across the Sweetgrass Arch. For the Montana region they (1973, p. 23) found that the trend of one set of major lineaments indicated a preferential orientation about a N.62° E. axis. These lineaments probably reflect the structural grain of the Precambrian crystalline basement. Stone (1974, p. 4) and Mudge (1983, written communication), based on a study of lineaments, were able to distinguish the entire Scapegoat-Bannatyne trend on Landsat images.

Geophysical Expression.--Smith (1970, p. 1179) and Kleinkopf and Mudge (1972, p. A11) interpreted the Scapegoat-Bannatyne trend as a northeast-trending fracture system that controlled the emplacement of igneous plutons that are the sources of two magnetic anomalies. Magnetic anomalies 18 and 21 of Kleinkopf and Mudge (1972, p. A13), which are evident on the aeromagnetic map of Zietz and others (1980), have been suggested by Kleinkopf and Mudge (1972, p. A13) to reflect, respectively, a gabbroic body at a computed depth of 1830 ± 335 m below the surface and a buried pluton of intermediate composition at a computed depth of

3200 ± 365 m below the surface (Fig. 11).

Kleinkopf and Mudge (1972, p. A13) recognized a 5- to 10-mgal gravity low (their anomaly 14) where the Scapegoat-Bannatyne trend intersects the disturbed belt. They interpreted the gravity minimum as a broad structural low. Smith (1970, p. 1179) suggested that the Scapegoat-Bannatyne gravity anomaly on the Sweetgrass Arch represents the southeastern structural high of two northeast-trending structural highs that border a structural downwarp or down-faulted block.

Thus, it appears that the Scapegoat-Bannatyne trend is a narrow, northeast-trending Precambrian fracture system where an alignment of Precambrian structural highs and lows (horsts and grabens?) and intrusions (pre-Middle Cambrian plutons and Haystack Butte) occur. Part of the Scapegoat-Bannatyne trend may be reflected on an isopach map constructed by Mudge (1972b, p. B8, Fig. 3) of the interval from the top of the Three Forks Formation (Upper Devonian) to the top of the Cone Calcareous Member of the Marias River Shale (lower Upper Cretaceous). The southwesternmost center of thinning on this isopach map appears to be roughly coincident with magnetic anomaly 18 (Fig. 11); this thinning may reflect the periodic tectonic activity along the Scapegoat-Bannatyne trend referred to by Alpha (1955b, p. 138).

Intersection with Montana Disturbed Belt.--South of a point due west of Choteau, Montana, the autochthonous Mississippian rocks and the top of the Precambrian crystalline basement change strike from nearly north-south at the South Arch to northwest-southeast (Mudge, 1982, p. 96, 121), thus causing the contours on top of the basement to shift eastward. The trend of the Montana Disturbed Belt, however, remains nearly north-south (Mudge and Earhart, 1983). Therefore, southward toward the Scapegoat-Bannatyne trend the southerly trending east edge of the allochthonous Mississippian rocks in the subsurface and the top of the Precambrian crystalline basement beneath the southerly trending Montana Disturbed Belt become progressively deeper (Mudge, 1982, p. 96, 121). Collinear with the southwest extension of the Scapegoat-Bannatyne trend, the north-south trending east edge of allochthonous Mississippian rocks attains its deepest position, nearly 1676 m below mean sea level (Fig. 12), then changes orientation to northwest-southeast and rises in elevation southward.

At the southern terminus of the Sawtooth Range, on the northwest flank of the Scapegoat-Bannatyne trend, folds become tighter and plunge southward toward the Scapegoat-Bannatyne trend (Merrill, 1965, p. 45; Mudge 1972b, p. B10-B11). The orientation of the traces of the thrust faults begins to assume a more southeasterly direction, and thrust plates in the eastern part of

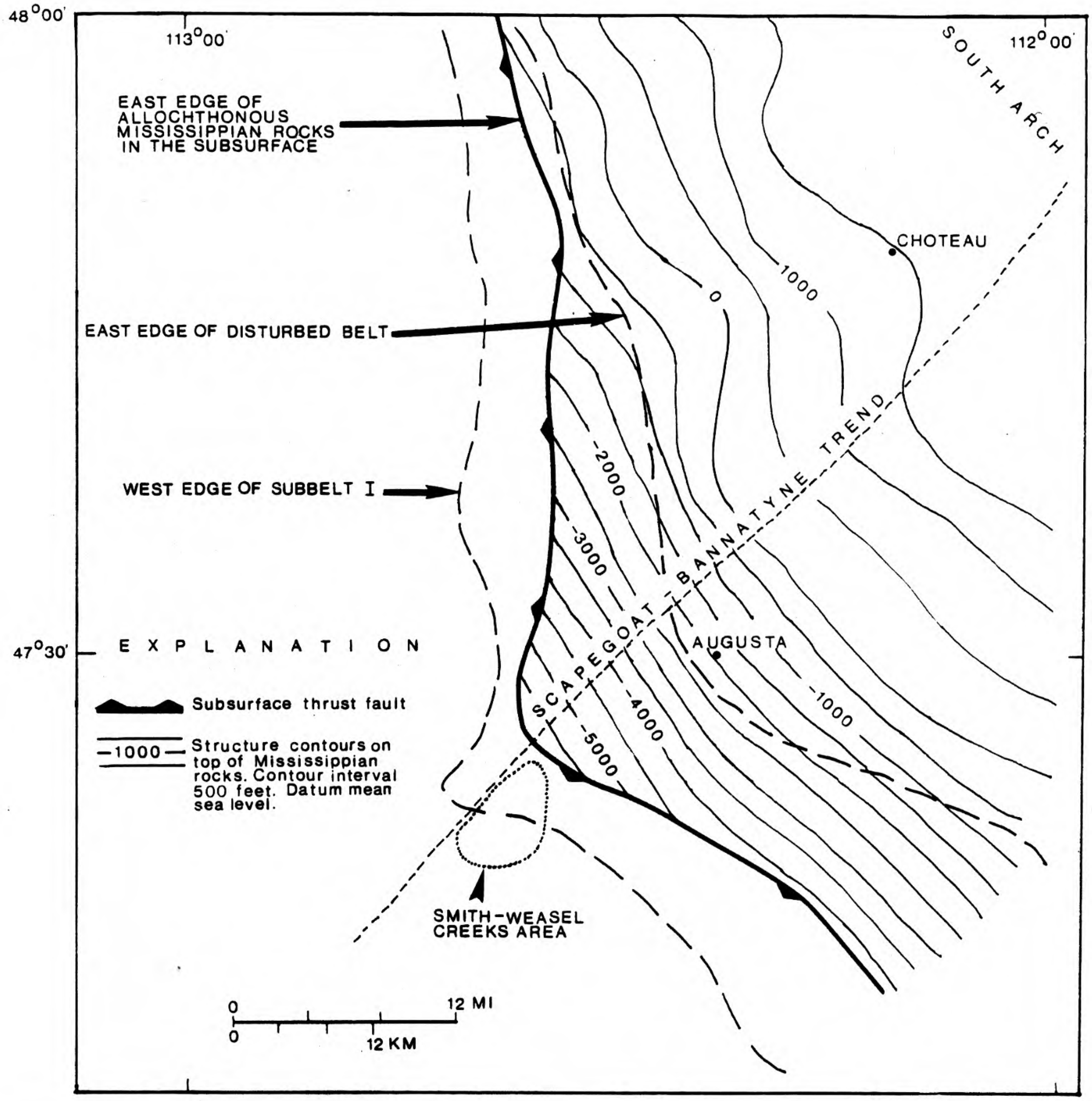

Figure 12. Structure map on top of Mississippian rocks in Sweetgrass Arch area, Montana (from Mudge, 1982, p. 95).

The east edge of allochthonous Mississippian rocks in the subsurface is interpreted mostly from drill-hole data. The Precambrian crystalline basement is approximately 1067 m (3500 ft) below the top of Mississippian rocks (Mudge, 1982, p. 96, Fig. 5).

the Sawtooth Range begin to plunge southward toward the Scapegoat-Bannatyne trend (Merrill, 1965, p. 48; Mudge, 1982, p. 121; Mudge and others, 1982; Mudge and Earhart, 1983). The southerly plunge of the thrust plates caused the thrust faults to cut upsection along strike and lose stratigraphic throw southward. In the northern half of the Smith-Weasel creeks area, on the southeast flank of the Scapegoat-Bannatyne trend, the traces of the Smith, Weisner, and Johnston thrust faults are northeast-southwest, thus forming a part of the convex-cratonward structural grain (structural salient) mapped by Mudge and others (1982) and by Mudge and Earhart (1983).

Southward from the Scapegoat-Bannatyne trend, the trends of the east edge of the Montana Disturbed Belt, the east edge of allochthonous Mississippian rocks in the subsurface, and the west edge of Subbelt I are oriented northwest-southeast (Fig. 12). Mudge (1983, written communication) believed that the Scapegoat-Bannatyne trend is a hingeline where the trends of fold axes and thrust-fault traces of the disturbed belt change from a north-south orientation to a northwest-southeast orientation, the result of thrust faults in the Helena embayment to the south (Fig. 1) moving farther east than the structures of the Sawtooth Range to the north (Harrison and others, 1974, p. 4, Fig. 3; Woodward, 1981, p. 292). Lying 160 km southeast of the Smith-Weasel creeks area (Fig. 1), the eastern part of the Belt basin, also known as the Central Montana trough or Helena embayment, in the late Precambrian was a region of slow subsidence where 20 km of low grade metasedimentary rocks of the Belt Supergroup accumulated and are still preserved (Harrison and others, 1974, p. 2).

MECHANICS AND HISTORY OF DEFORMATION

Smith-Weasel Creeks Area

Sequence of Thrust-Fault Development.--Because the thrust faults in the Smith-Weasel creeks area are consecutively truncated from north to south, i.e. from the margin of the disturbed belt inward (Fig. 3; Pl. 1), the ages of the thrust faults are interpreted to decrease from north to south. The oldest thrust faults are truncated by the Smith thrust whereas the youngest thrust faults are south of the Steinbach thrust. The north-to-south sequence of development of thrust faults in the Smith-Weasel creeks area corresponds to the east-to-west sequence of development of the imbricate thrust faults in the Sun River Canyon area.

Boyer and Elliott (1982, p. 1209) believed that the Montana Disturbed Belt formed by duplex thrust faulting. This style of faulting would produce a west-to-east sequence of deformation like that proposed for the thrust faults of the Canadian Rockies; there the youngest deformation occurred in the east (Hume, 1957, p. 411; Price and Mountjoy, 1970, p. 18; Price, 1981, p. 428). Like the Montana Disturbed Belt, however, the westerly dips of the thrust faults in the Canadian Rockies indicate a west-to-east movement of the individual thrust plates. If the duplex style of thrust faulting occurred in the Montana Disturbed Belt, the Lewis thrust fault would represent an older roof thrust (Boyer and Elliott, 1982, p. 1209) that covered a younger internal duplex structure. Subsequent erosion of the Lewis thrust has exposed this younger internal duplex structure, which is represented by the fault blocks of the Sawtooth Range. The east-to-west sequence of deformation in the Smith-Weasel creeks area, precludes the occurrence there of duplex thrusts, which would require west-to-east fault development.

Principal-Stress Orientations.--The orientation of the maximum principal compressive stress was inferred from thrust fault traces, the trends of fold axes, and joint data. The directions of complimentary shear fractures are observed to be oriented 30° on either side of the maximum principal compressive stress direction (Anderson, 1951, p. 11-15; Hubbert, 1951, p. 362; Moody and Hill, 1956, p. 1210; Hodgson, 1961, p. 33; Badgley, 1965, p. 101; Price, 1966, p. 141). The bisectrix of the acute angle formed by the two most common joint directions will approximate the maximum principal compressive stress orientation.

Eastward from Smith Creek the fault traces of the Smith, Weisner, and Johnston thrust faults exhibit a change in orientation from east-west to northeast-southwest. This change in orientation becomes less abrupt, and occurs farther east, in progressively younger thrust faults (compare older Smith thrust trace with younger Johnston thrust trace). Fold axes in two of the thrust plates truncated by the Smith thrust (S1/2 sec. 8 and N1/2 sec. 17) and fold axes in the Smith thrust west of Smith Creek indicate a northeast-southwest maximum principal compressive stress. This stress orientation differs from the northwest-southeast maximum principal compressive stress indicated by joint data (Appendices 1,2,3) collected from the Kootenai Formation along the northeast trending part of the Smith thrust plate east of Smith Creek in sec. 9 (Fig. 13).

In the southern part of the research area, westerly and northwesterly trending fold axes and thrust fault traces indicate that a noteable change in the stress field occurred. This change occurred after movement along the Johnston thrust and along two minor thrust faults that lie southeast of the Johnston thrust plate beneath the Quaternary alluvium, but prior to movement along the thrust faults in the Weasel imbricate zone. This change may have occurred during an orogenic hiatus, at which time the stress field affecting this part of the disturbed belt was modified. A second possibility is that the more southerly thrust faults formed during during the later stages of continuous orogeny, when the stress field was altered locally because of a change in the influence of the Scapegoat-Bannatyne trend. The

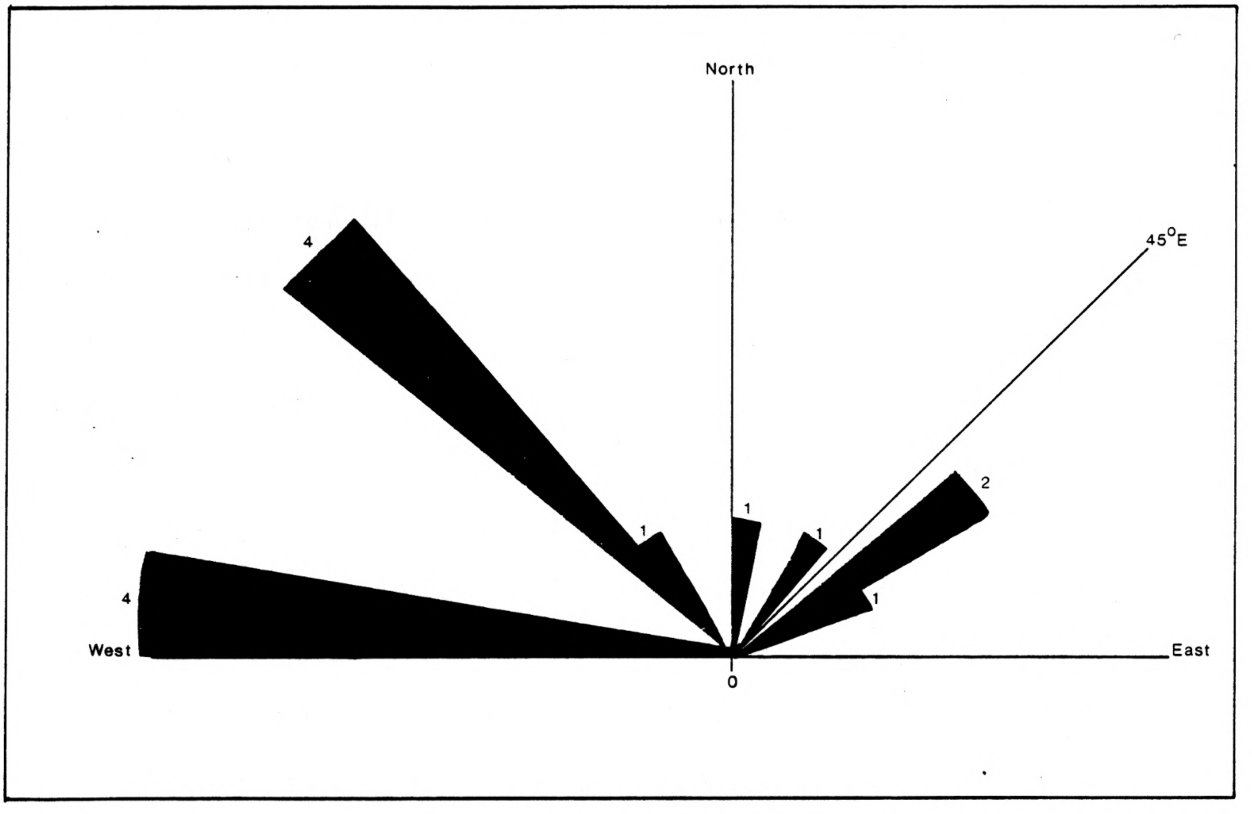

Figure 13. Summary of joint data collected along the Smith thrust.

Rose diagram for the strike of 14 joint measurements collected along the Smith thrust plate at stations 4-10 in the northern area. Numbers represent the actual number of joint directions measured in a particular 10° interval. Strike of joints was determined by using the stereonet to rotate the strata to the horizontal.

second alternative is preferred because regionally there is no evidence of a major realignment of the stress field (Mudge and Earhart, 1983).

Relative Intensities of Principal Stress.--Westward in the southern part of the research area, toward the Scapegoat-Bannatyne hingeline, a greater level of maximum principal compressive stress is suggested by:

1. The increase of 20°-40° in the dips of the Goss II and Steinbach thrust faults (Pl. 2; A-A', B-B').
2. The increase of 20°-30° in the dips of strata in the Goss II and Steinbach thrust plates (Pl. 1; Pl. 3).
3. The truncation of the Goss II thrust plate by thrust faults of the Goss imbricate zone.
4. The truncation of the Goss imbricate zone by the Steinbach thrust fault in the southwest quarter of sec. 29.

The two overturned anticlines along Smith Creek (N1/2 sec. 19) and the truncation of the Steinbach thrust fault by the Eldorado thrust fault (Fig. 1) may also indicate a locally higher level of maximum principal compressive stress westward toward the Scapegoat-Bannatyne hingeline.

Conditions of Folding.--In the Goss transition zone the exposed part of the Smith Creek anticline can be classified as a tight to isoclinal, overturned, parallel fold that formed mainly by the process of flexural slip (Donath and Parker, 1964, p. 50-52), although a small amount of flexural flow may have occurred (Fig. 8). The alternating limestone and mudstone sedimentary sequence of the Rierdon Formation produces a high ductility contrast within the unit. As a consequence of this lithologic property, the Rierdon Formation would undergo flexural slip only under conditions favoring brittle- to moderately brittle-rock behavior (Donath and Parker, 1964, p. 51). Brittle-rock behavior occurs at the low temperatures and confining pressures characteristic of shallow depths, i.e. depths less than 3500 m. The Goss Creek anticline, like the Smith Creek anticline, is assumed to have formed by flexural slip under near-surface temperatures and pressures.

Basement Configuration in Vicinity of Smith-Weasel Creeks Area

Deiss (1943b, p. 1160) and Mudge (1982, p. 121) noted that the most intense deformation in the Sawtooth Range is in the central part west of Choteau. In this part of the Sawtooth Range, fault blocks are more closely spaced and the fault planes dip at higher angles than elsewhere. Structure contours on top of Mississippian rocks indicate that the Precambrian crystalline basement beneath the South Arch forms a westerly plunging salient

(Mudge, 1982, p. 95). Mudge (1982, p. 121) suggested that the South Arch acted as a buttress against which the early Tertiary structures were compressed. The thrust plates of Subbelt I "... moved topographically higher onto the South Arch as compared with the adjacent areas" (Mudge, 1982, p. 121). Holocene erosion has exposed older rocks in the thrust plates of Subbelt I over the South Arch, whereas north and south of the South Arch younger rocks are exposed in the same thrust plates (Mudge, 1982, p. 121).

A larger-scale analogy has been suggested by Thomas (1983) for the Appalachian-Ouachita Paleozoic orogenic belt. Thomas noted a relationship between the occurrence of "external basement massifs" (rocks older than one billion years and low in the stratigraphic section) and points occupied by pre-orogenic continental salients. Areas that lacked these basement massifs were interpreted as the location of pre-orogenic continental structural embayments. The difference in the geologic setting for the model proposed by Thomas and the geologic setting for the Montana Disturbed Belt is that the Thomas model is one for a closing ocean basin. Both orogenic events however occurred along the Precambrian cratonic margin.

At the Sun River the structural grain of the Sawtooth Range changes from a near north-south orientation to a more northwesterly orientation (Mudge, 1972b, p. B43). Because of the northwest strike of the upper surface of the Precambrian crystalline basement (Mudge, 1982, p. 96, Fig. 5), the top of the basement south and west of the South Arch is lower (Fig. 12). The lower position of the Precambriam crystalline basement south of the Sun River allowed the thrust faults of the Sawtooth Range to move farther east, thus causing the change in structural grain. The change in orientation of the Sawtooth Range, therefore, may represent an adjustment to the northwest strike of the Precambrian crystalline basement.

Southward from the Sun River, many of the eastern thrust plates of the Sawtooth Range plunge toward the Scapegoat-Bannatyne trend (Mudge, 1982, p. 121). The southerly plunge of the thrust plates caused the thrust faults to cut upsection along strike (Gwinn, 1964, p. 891; Dahlstrom, 1977, p. 434, Fig. 48) and to lose stratigraphic throw southward. This change in the stratigraphic position of the thrust faults probably represents the increasing depth to the top of the crystalline basement southward beneath the Sawtooth Range toward the Scapegoat-Bannatyne trend (Mudge, 1982, p. 121). The low position of the Precambrian basement where the Scapegoat-Bannatyne trend intersects the Sawtooth Range may have reduced or eleminated a buttressing effect. The maximum principal compressive stresses, therefore, could only concentrate sufficiently to form small-scale thrust faults and tight folds in the eastern part of the southern terminus of the Sawtooth Range. At the northern terminus of the Sawtooth Range, near Glacier National Park, folds plunge northwestward (Childers, 1964, p. 379, Fig. 1) into the structural low beneath the Lewis thrust plate (Mudge, 1977, p. 747) in a manner similar to that seen at the southern terminus of the Sawtooth Range near the Scapegoat-Bannatyne trend (Mudge and Earhart, 1983).

South of the southern termination of the eastern part of the Sawtooth Range, the eastward movement of the thrust plates in the western part of the Sawtooth Range was no longer obstructed. The western thrust faults of the Sawtooth Range were able to move farther east and "wrap-around" the southern termination of the eastern part of the Sawtooth Range. This "wrapping-around" effect, which involves the east-west to northeast-southwest change in orientation along the Smith, Weisner, and Johnston thrust plates in the northern area of the Smith-Weasel creeks area, produced a convex-cratonward structural grain (Fig. 14b).

A gelatin-slab experiment (Fig. 14a) discussed by Beutner (1977, p. 362) indicated that lines of equal intermediate principal stress are convex toward a clay foreland in the vicinity of a structural low or foreland recess (Fig. 14a). The basement configuration that underlies the Smith-Weasel creeks

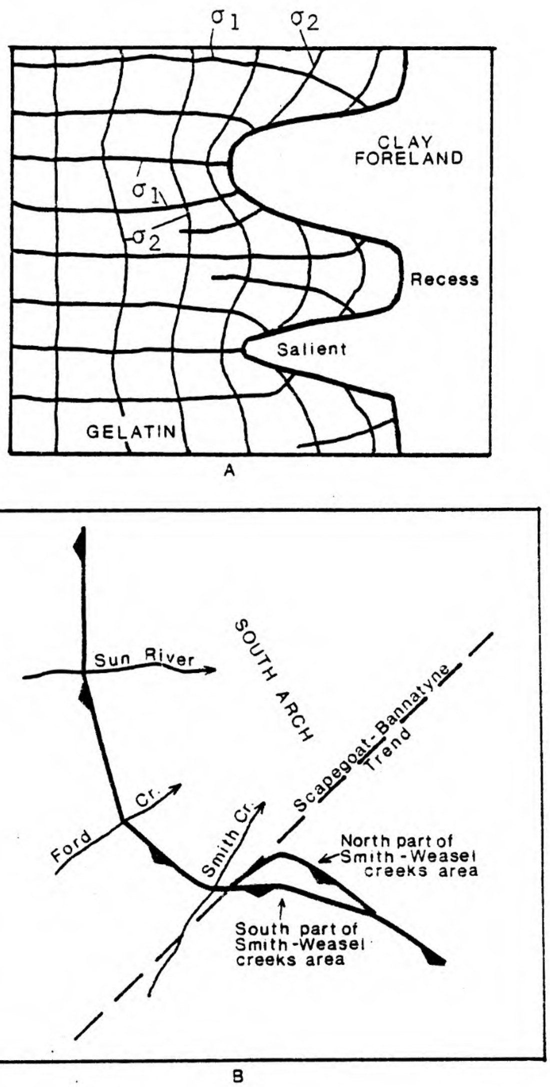

Figure 14(A). Stress trajectory, gelatin-slab model;
Figure 14(B). Structural grain in vicinity of southern terminus of Sawtooth Range.

(A) Sketch of gelatin-slab experiment of Beutner (1977, p. 362). Stress trajectory lines for maximum principal stress (σ_1) and intermediate principal stress (σ_2) are shown. Faults will tend to form parallel to the σ_2 trajectory line (Billings, 1972, p. 231). (B) Structural grain in vicinity of Scapegoat-Bannatyne trend and southern termination of Sawtooth Range (not to scale). Note similarity of the convex nature of the σ_2 trajectory lines toward the clay foreland in the vicinity of a clay recess (14A), and the convex-cratonward nature of the structural grain in the Smith-Weasel creeks area where the Scapegoat-Bannatyne trend intersects the Montana Disturbed Belt (14B). In the younger faults in the southern part of the Smith-Weasel creeks area the convexity decreases.

area may have altered the stress field in a manner similar to that shown by Beutner's (1977, p. 362) gelatin-slab model (Fig. 14a), so that the altered stress field affected the orientation of the Smith, Weisner, and Johnston thrust faults as they were forming. Therefore, the greater amount of convexity in the structural grain (Fig. 14b) at the intersection of the Scapegoat-Bannatyne trend and the disturbed belt may reflect the much deeper position of the Precambrian crystalline basement, or the "wrapping-around" effect about the southern termination of the Sawtooth Range, or both. Mudge (1982, p. 121) noted that "... the southerly abrupt plunge of the fault plates of subbelt II [see Fig. 1] in the Ford-Smith Creek area may reflect [the presence there of] a much deeper part of the basement ..."

Southwest along the Scapegoat-Bannatyne trend from the northern part of the Smith-Weasel creeks area, there is a decrease in the hinging effect of the Scapegoat-Bannatyne trend on the traces of progressively younger thrust faults because the older thrust faults have masked the influence (possibly by the "filling-in") of the low basement. This relationship is apparent on a relatively small scale in the Smith-Weasel creeks area by comparing the older Smith thrust with the younger Johnston thrust, or at a relatively large scale by comparing the structural trend of the older Sawtooth Range with the younger Lewis and Clark Range (Mudge and others, 1982; Mudge and Earhart, 1983). The easternmost thrust faults of the Montana Disturbed Belt are not affected by the the Scapegoat-Bannatyne trend and do not show a convex-cratonward structural grain because the faults formed at a higher level and were not as strongly influenced by the stress patterns generated by interaction with the Precambrian basement.

The eastward movement of the thrust plates of the Lewis and Clark Range was obstructed by the thrust blocks of the Sawtooth Range. South of the southern termination of the Sawtooth Range, the thrust plates of the Lewis and Clark Range were able to move farther east. The easternmost thrust faults of the Lewis and Clark Range appear to have interacted with the Scapegoat-Bannatyne trend, although to a lesser degree than the older, westernmost thrust faults of the Sawtooth Range. The northeast-trending normal faults that Alpha (1955a, p. 133) defined as the southwestern termination of the Scapegoat-Bannatyne trend, may be tensional fractures in the more competent lower Paleozoic and Precambrian thrust plates of the Lewis and Clark Range produced by a lessened, but still significant, change in orientation along the Scapegoat-Bannatyne hingeline. The set of transverse fractures may also represent Scapegoat-Bannatyne basement fractures reactivated because of crustal loading or because of repeated orogenic activity. According to Mudge (1983, written communication), however, surface offset on the transverse fractures is only a meter to as much as 7-10 m. The transverse fractures, therefore, are not considered to extend into the crystalline basement.

Thus, the intersection of the Scapegoat-Bannatyne trend with the Montana Disturbed Belt seems to be a region where the structural grain of the disturbed belt adjusts to the northwest-southeast trend that is characteristic of the top of the Precambrian crystalline basement southward toward the Helena embayment. The Scapegoat-Bannatyne trend is a preferred hingeline in the region of adjustment because periodic activity along the trend has weakened the overlying sedimentary rocks. In the Smith-Weasel creeks area the change in orientation in the northern part of the research area of the Smith, Weisner and Johnston thrust faults, and the locally higher level of maximum principal compressive stress suggested in the western part of the southern part of the research area by the increased dip and closer spacing of thrust faults, seems to indicate that the Scapegoat-Bannatyne hingeline affects the north and west parts of the research area to a greater degree. The Scapegoat-Bannatyne trend is not a structural embayment in the Precambrian craton, rather the trend is coincident with an increased depth to the top of the crystalline basement because the south trending part of the disturbed belt overlies a northwest-southeast trending basement. The crystalline basement may be slightly deeper along the Scapegoat-Bannatyne trend (Mudge, 1983, written communication).

Scapegoat-Bannatyne Trend

Ancient Aulacogen or Wrench Fault.--Some characteristics of the Scapegoat-Bannatyne trend resemble those of aulacogens, e.g.: (1) the Scapegoat-Bannatyne trend is a Precambrian zone of weakness that extends northeastward into the craton, roughly perpendicular to the north-northwesterly trending rifted Precambrian craton margin (King, 1976, p. 76; Sears and Price, 1978, p. 268), and (2) the northeast trending zone of weakness defines an alignment of intermediate and mafic pre-Middle Cambrian plutons and a northeast trending en echelon basement fracture system along which structural highs and lows developed.

The Scapegoat-Bannatyne trend is not considered to be an aulacogen because the dimensions of the trend (approximately 12 km wide and 155 km long) define a long, narrow form that differs from the roughly triangular shape of aulacogens such as the Mississippi embayment (Burke and Dewey, 1973, p. 420), the Belt Basin (Harrison and others, 1974, p. 3, Fig. 2), and the "Southern Oklahoma aulacogen" (Hoffman and others, 1974, p. 40). Aulacogens are the failed third arm of the classic triple junction that develops over a hot spot (Burke and Wilson, 1976, p. 55). If the Scapegoat-Bannatyne trend is a failed third arm, then the hot spot that produced the triple junction must have been extremely small. Although subsurface data are scarce, no abnormally thick sedimentary sequences or unusual facies (such as deltaic or fluvial facies) that might suggest a cratonic trough undergoing long and continuous subsidence have been reported in the vinicity of the Scapegoat-Bannatyne trend.

The Scapegoat-Bannatyne trend may represent a zone where vertical stresses created by the thermal expansion and uplift of the crust during the initial stages of the Precambrian rifting event that formed the Cordilleran geosyncline (Kanasewich, 1968; Burchfield and Davis, 1975, p. 364; Stewart, 1976; Sears and Price, 1978) caused failure along the northeast structural grain of the Churchill Province. Thermal expansion of the crust could have been aided by the proximity of the Scapegoat-Bannatyne trend to the Belt basin, a possible aulacogen (Harrison and others, 1974, p. 1), where a hot spot may once have existed. If a transform fault from the juvenile proto-Pacific plate intersected the craton, the fault may have caused the initial failure of the Scapegoat-Bannatyne fracture system. Mudge (1983, written communication) suggested that the Scapegoat-Bannatyne trend may be a fracture system that resulted from the downwarping of the Helena embayment during deposition of the Belt Supergroup.

The tectonic setting required for the Scapegoat-Bannatyne trend to be considered part of a wrench fault system (Moody and Hill, 1956, p. 1213) must include a component of north-northeasterly or east-northeasterly directed maximum principal compressive stress in order to account for the northeasterly trend of the Scapegoat-Bannatyne trend. The stress field that formed the north-northwesterly cratonic margin may have contained this north-northeast or east-northeast directed maximum principal compressive stress, so that the stress field was partially responsible for the initial failure along the northeast trending structural grain of the Churhill Province. The component of north-northeasterly or east-northeasterly directed maximum principal compressive stress could have been generated by a convergent plate margin or by a strike-slip plate margin similar to that which formed the San Andreas fault (Moody and Hill, 1956, p. 1216). The western cratonic edge is, however, believed to have formed under a tensional environment that resulted in the Precambrian rifting event that formed the Cordilleran geosyncline (Burchfield and Davis, 1975, p. 364). Therefore, other than Stone (1974, p. 4), who used Landsat images to classify the Scapegoat-Bannatyne trend as a right-lateral wrench fault (which would favor a east-northeasterly maximum principal compressive stress), geologists have not interpreted the Scapegoat-Bannatyne trend as part of a wrench-fault system.

Comparison to Similar Structures, Southern Canadian Rockies.--In the southern Canadian Rocky Mountains, west of Pincher Creek, Alberta, at lat 49°20'N. and long 114°00'W. (Price, 1981, p. 428, Fig. 1), a change in structural trend exists that appears to exhibit many of the characteristics of the intersection of the Scapegoat-Bannatyne trend and the Montana Disturbed Belt. Price (1981, p. 432) noted that "... most [of the distinct linear tectonic subprovinces in the southern Canadian Rocky Mountains] change abruptly along ... strike [southward from nearly north-south to northwest-southeast] at about 49°20'N. latitude because of changes in sedimentary facies and thicknesses resulting from the influence of the transverse, northeasterly trending structures that were active during Proterozoic and Paleozoic time." Price (1981, p. 431-432) indicated that the area northwest of the transverse, northeasterly trending structures was down-dropped. This is contrary to the observation to the south where the Lewis thrust plate is preserved because the plate lies in a structural depression within the Precambrian basement (Mudge, 1977, p. 747)

Price (1981, p. 432) noted that south of the change in structural trend, the structural style characteristic of the eastern Main Ranges tectonic subprovince (Lower Paleozoic and Proterozoic miogeoclinal carbonate facies) extended farther eastward to the edge of the Foothills tectonic subprovince (platformal Paleozoic and exogeoclinal Upper Cretaceous rocks). These geologic relationships possibly are analogous to the eastward shift of the Lewis and Clark Range south of the Scapegoat-Bannatyne trend. The eastward shift of the eastern Main Ranges tectonic province may have been related to the southward termination of "... the steeply-dipping, moderately thick thrust slices of Paleozoic platformal to miogeoclinal carbonate rocks that form the characteristic linear mountain ranges of the Front Ranges [tectonic subprovince]..." (Price, 1981, p. 432). The geologic setting there is possibly analogous to that of the southern termination of the Sawtooth Ranges in the vicinity of the Scapegoat-Bannatyne trend. The Sawtooth Range, however, is correlative with the western part of the Foothills tectonic subprovince in southern Alberta, and the Lewis and Clark Range is correlative with the Front Range tectonic subprovince (Mudge, 1983, written communtcation). The southerly plunging structures north of the change in structural trend of the Canadian Rockies (Dahlstrom, 1977, p. 423, Fig. 28) are comparable to the southerly plunging structures in the Sawtooth Range that lie north of the Scapegoat-Bannatyne trend.

Gravity and magnetic anomalies, which lie along a northeast trending line that intersects the change in structural trend in Canada, appear similar to the gravity and magnetic anomalies that are collinear with the Scapegoat-Bannatyne trend. Bouguer gravity anomalies along the Scapegoat-Bannatyne trend define a southwesterly trending gravity high with associated gravity lows to the northwest and southeast (Kleinkopf and Mudge, 1972, Pl. 2). An almost identical setting exists in the southern Canadian Rockies where a southwest trending gravity high, with associated gravity lows to the northwest and southeast, intersects the change in structural trend (Price, 1981, p. 435, Fig. 4). Lower Bouguer gravity values may represent tectonic thickening of the supracrustal rocks (Price, 1981, p. 433), possibly because of a structurally low Hudsonian basement.

Northeast of the change in structural grain in the Canadian Rockies, a magnetic high exists that may represent an intrusion into a zone of weakness--a geologic setting possibly similar to the intrusion of the gabbroic body that served as the source of magnetic anomaly 18 along the Scapegoat-Banatyne trend (Kleinkopf anf Mudge, 1972, p. A13). Just north of the change in structural trend in the southern Canadian Rockies, a magnetic low exists that is similar to the magnetic low that underlies the southern termination of the Sawtooth Range between magnetic anomalies 18 and 21 (Kleinkopf and Mudge, 1972, p. A13).

In summary, other than the lack of a convex-cratonward structural grain at the change in trend of the southern Canadian

Rockies, and a gravity low at the southern termination of the Front Ranges tectonic subprovince, the intersection of the Scapegoat-Bannatyne trend with the Montana Disturbed Belt and the area west of Pincher Creek, Alberta, share the following characteristics:

1. An abrupt southward change in structural trend from nearly north-south to northwest-southeast occurs in both areas.

2. Both the Front Range tectonic subprovince and the Sawtooth Range terminated near a change in structural trend.

3. The eastward shift of the eastern Main Ranges tectonic subprovince may be a response to the southern termination of the Front Ranges tectonic subprovince, and the eastward shift of the Lewis and Clark Range may be a response to the southern termination of the Sawtooth Range.

4. Northeast of the change in structural trend in both the southern Canadian Rockies and the Montana Disturbed Belt, gravity data indicate southwesterly trending gravity highs, with associated gravity lows to the northwest and southeast, that trend toward the two respective changes

in structural trend.

5. A magnetic high underlies both the area northeast of the change in structural trend in the southern Canadian Rockies and along the Scapegoat-Bannatyne trend northeast of the change in structural trend in the Montana Disturbed Belt.

6. A magnetic low underlies both the southern termination of the Sawtooth Range and the southern termination of the Front Ranges tectonic subprovince.

7. In the southern Canadian Rockies structures that are north of the change in structural trend plunge southward, as do many of the structures near the southern terminus of the Sawtooth Range.

8. Both areas are influenced by the northeast trending structural grain characteristic of the Hudsonian Churchill Province basement and by northeasterly trending structures or zones of weakness that were active during the Proterozoic and Paleozoic.

PETROLEUM PROSPECTS

The structural target of the Sun Oil Company J.B. Long 1-9 wildcat well (Fig. 3) apparently was a structurally thickened section of the Sun River Member of the Castle Reef Dolomite (Mississippian Madison Group) resulting from repetition of the Mississippian rocks by a thrust fault. The Sun River Member is a proven oil and gas horizon 60 km to the north (T.26 N., R.8 W., Teton County) in the Blackleaf Canyon field (McCaslin, 1981, p. 121). The J.B. Long 1-9 wildcat well was plugged and abandoned December 25, 1982 after reaching a total depth of 3690 m.

In general, favorable conditions for petroleum accumulation could exist in the Montana Disturbed Belt where: (1) structures occur beneath thrust plates, (2) blind thrusts (Boyer and Elliott, 1982, p. 1197) have created folds in overlying units, (3) repetition of units cause abnormally thick reservoir rocks, or (4) a fold was produced when one thrust plate overrode another (Hume, 1957, p. 411; Dahlstrom, 1977, p. 412, Fig. 6). More specifically, in the region of the Smith-Weasel creeks area: (1) structural highs along the Scapegoat-Bannatyne trend may have been the depositional centers for reef-like structures, (2) movement along the Scapegoat-Bannatyne fracture system may have sealed a reservoir rock, thus forming a trap, (3) periodic movement along the Scapegoat-Bannatyne fracture system may have added a component of fracture porosity to the rock units that overlie the trend, or (4) basement highs may cause structural highs to form in the overlying sedimentary rocks because of sedimentary draping or periodic basement uplift.

SUMMARY

The following relationships have been noted in and near the Smith-Weasel creeks area.

1. Northeast-southwest structural trends dominate the northern part of the area (Smith, Weisner, and Johnston thrusts), whereas in the southern part of the area an east-west to northwest-southeast structural trend is more common.

2. Thrust faults become progressively younger, and stratigraphic throw generally increases, southward.

3. The Scapegoat-Bannatyne trend, defined by several collinear structures as well as by gravity and magnetic anomalies, seems to be a narrow, northeast-trending Precambrian fracture zone where an alignment of structural highs and lows (horsts and grabens?) and points of intrusion (Haystack Butte and plutons) occurs.

4. In the Smith-Weasel creeks area, where the Scapegoat-Bannatyne trend intersects the Montana Disturbed Belt, the convex-cratonward structural grain either reflects the influence of the structurally lower position of the Precambrian basement or the "wrapping-around" effect

about the southern termination of the eastern part of the Sawtooth Range, or both.

5. In the Smith-Weasel creeks area, the change in orientation in the northern part of the research area of the Smith, Weisner, and Johnston thrust faults and a locally higher level of maximum principal compressive stress suggested in the western part of the southern area by the increased dip and closer spacing of thrust faults, seems to indicate that the Scapegoat-Bannatyne hingeline affected the north and west parts of the research area to a greater degree.

6. The intersection of the Scapegoat-Bannatyne trend with the Montana Disturbed Belt is a region where the structural grain of the disturbed belt adjusts to the northwest-southeast trend that is characteristic of the top of the Precambrian crystalline basement southward toward the Helena embayment. The Scapegoat-Bannatyne trend is a preferred hingeline in the region of adjustment because periodic activity along the trend weakened the overlying sedimentary rocks.

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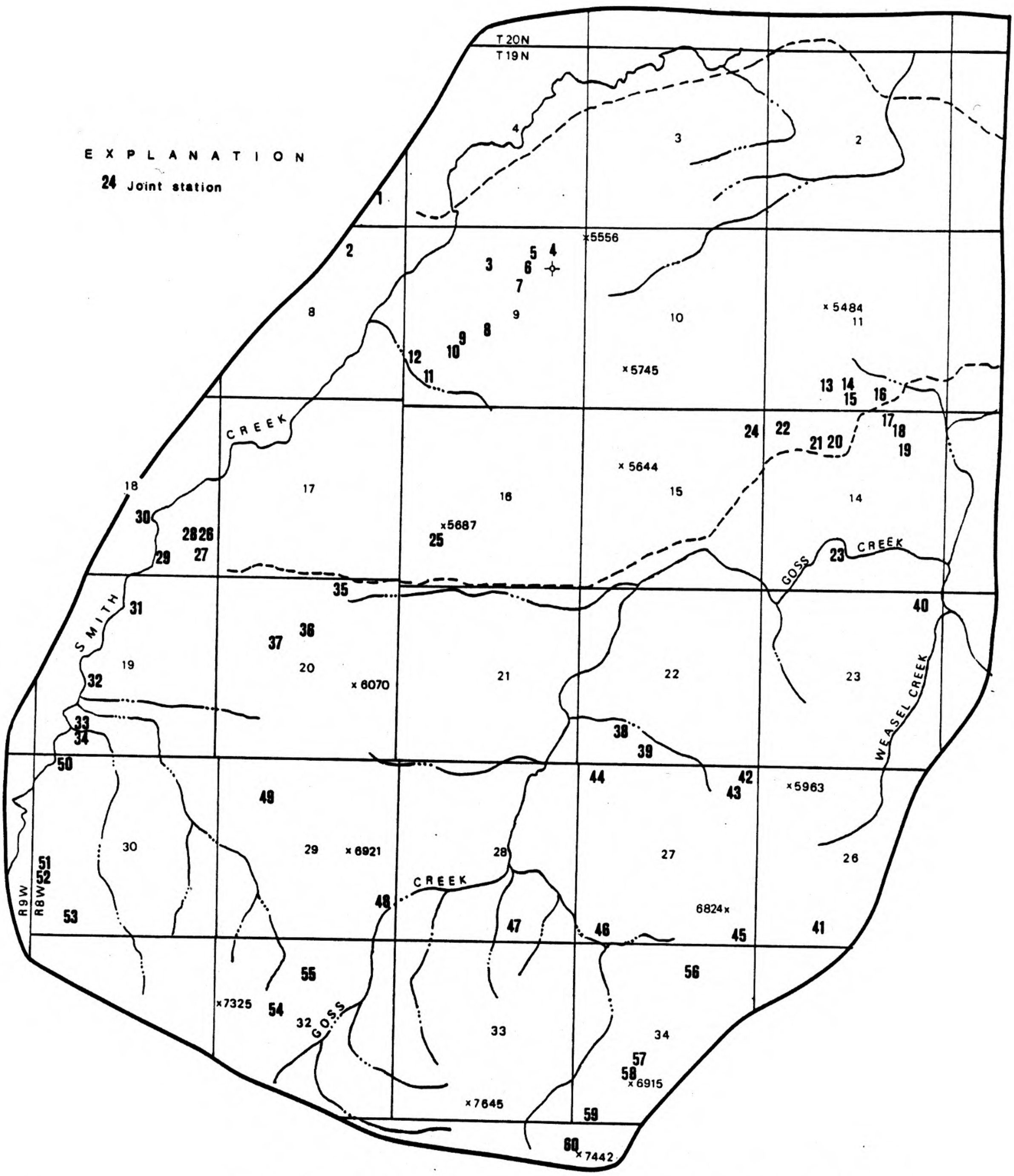
APPENDICES



Appendix 1. Location of joint stations in the Smith-Weasel creeks area.

APPENDIX 2

Joint Data Collected in the Smith-Weasel Creeks Area

Northern Area

Section	Station	Bed Orientation	Strike of Joint
5	1	N.35° W., 23°SW.	N.35° W.
			N.50° E.
8	2	N.45° W., 50°SW.	N.02° E.
			N.62° E.
9	3	N.84° W., 40°SW.	N.06° W.
			N.81° E.
	4	N.15° W., 15°SW.	N.01° E.
			N.81° W.
	5	N.50° W., 26°SW.	N.50° W.
			N.68° E.
	6	N.10° E., 15°SE.	N.31° W.
			N.86° W.
	7	N.20° E., 21°SE.	N.48° W.
			N.56° E.
	8	N.83° W., 20°SW.	N.33° W.
			N.85° W.
	9	N.10° E., 25°SE.	N.56° E.
			N.43° W.
	10	N.40° E., 23°SE.	N.48° W.
			N.83° W.
	11	N.42° W., 55°SW.	N.25° E.
			N.75° E.
	12	N.60° W., 30°SW.	N.76° E.
			N.26° W.
11	13	N.40° E., 35°SE.	N.67° W.
			N.42° W.
	14	N.80° W., 30°SW.	N.16° W.
			N.56° E.
	15	N.85° W., 17°SW.	E.- W.
			N.01° E.
	16	N.84° E., 41°SE.	N.73° E.
			N.58° W.
			N.13° W.
14	17	N.34° E., 39°SE.	N.62° W.
			N.67° W.
	18	N.47° E., 41°SE.	N.53° W.
			N.38° E.

Section	Station	Bed Orientation	Strike of Joint
	19	N.78° W., 47°SW.	N.68° W.
			N.11° W.
			N.54° E.
	20	N.60° E., 45°SE.	N.82° E.
			N.20° W.
	21	N.49° W., 16°SW.	N.52° E.
			N.61° W.
			N.04° E.
	22	N.75° E., 32°SE.	N.50° W.
			N.87° E.
15	24	N.75° E., 32°SE.	N.50° W.
			N.35° E.
16	25	N.70° E., 27°SE.	N.68° E.
			N.87° W.
			N.53° W.
			N.04° E.
18	26	N.72° W., 38°SW.	N.12° W.
			N.35° E.
			N.50° W.
	27	N.70° W., 33°SW.	N.15° W.
			N.70° W.
			N.50° E.
	28	N.70° W., 34°SW.	N.15° W.
			N.65° E.
	29	N.68° E., 42°SE.	N.74° W.
			N.28° W.
	30	N.78° W., 47°SW.	N.67° W.
			N.12° W.
			N.62° E.
19	31	N.75° E., 35°SE.	N.47° W.
			N.69° E.
20	35	N.57° E., 9°SE.	N.10° W.
			N.85° E.

Southern Area

Section	Station	Bed Orientation	Strike of Joint
14	23	N.61° W., 31°SW.	N.21° E.
19	32	N.65° W., 31°SW.	N.12° E.
			N.82° E.
	33	N.84° W., 34°SW.	N.72° E.
			N.03° W.
	34	N.56° W., 26°SW.	N.82° W.
			N.34° W.
20	36	N.20° W., 45°SW.	N.70° W.
			N.30° E.
			N.06° E.
	37	N.45° W., 48°SW.	N.49° E.
			N.17° W.
22	38	N.60° W., 34°SW.	N.32° E.
			N.10° W.
			N.82° W.
	39	N.70° W., 10°SW.	N.57° E.
			N.85° W.
			N.30° W.
23	40	N.35° E., 24°SE.	N.35° W.
			N.85° E.
			N.30° E.
26	41	N.70° W., 29°SW.	N.79° W.
			N.40° E.
			N.06° E.
27	42	N.55° W., 38°SW.	N.14° W.
			N.88° W.
			N.49° E.
			N.35° E.
	43	N.30° W., 23°SW.	N.18° E.
			N.72° W.
	44	N.21° W., 20°NE.	N.48° E.
			N.80° E.
	45	N.66° W., 28°SW.	N.40° E.
			E.-W.
			N.49° W.
	46	N.70° W., 35°SW.	N.82° W.
			N.40° W.
			N.-S.
28	47	N.72° W., 40°SW.	N.64° E.
			N.15° W.

Section	Station	Bed Orientation	Strike of Joint
29	48	N.70° W., 51°SW.	N.23° E.
			N.89° E.
			N.01° E.
			N.43° W.
	49	N.80° W., 28°SW.	N.28° E.
			N.37° E.
			N.16° W.
			N.32° W.
30	50	N.84° E., 60°SE.	N.38° E.
			N.07° W.
	51	N.40° E., 10°SE.	N.36° W.
			N.22° E.
	52	N.45° W., 44°SW.	N.69° E.
			N.04° E.
	53	N.40° W., 29°SW.	N.87° W.
			N.38° E.
32	54	N.35° W., 31°SW.	N.84° E.
			N.26° W.
			N.72° W.
	55	N.39° W., 12°SW.	N.67° E.
			N.83° W.
			N.13° W.
34	56	N.85° W., 24°SW.	N.78° E.
	57	N.46° W., 51°SW.	N.58° W.
			N.81° E.
			N.17° E.
	58	N.48° W., 44°SW.	N.64° E.
			N.29° E.
	59	N.57° W., 25°SW.	N.44° E.
			N.66° W.
	60	N.15° W., 32°SW.	N.83° E.
			N.12° W.
			N.38° W.
			N.24° E.

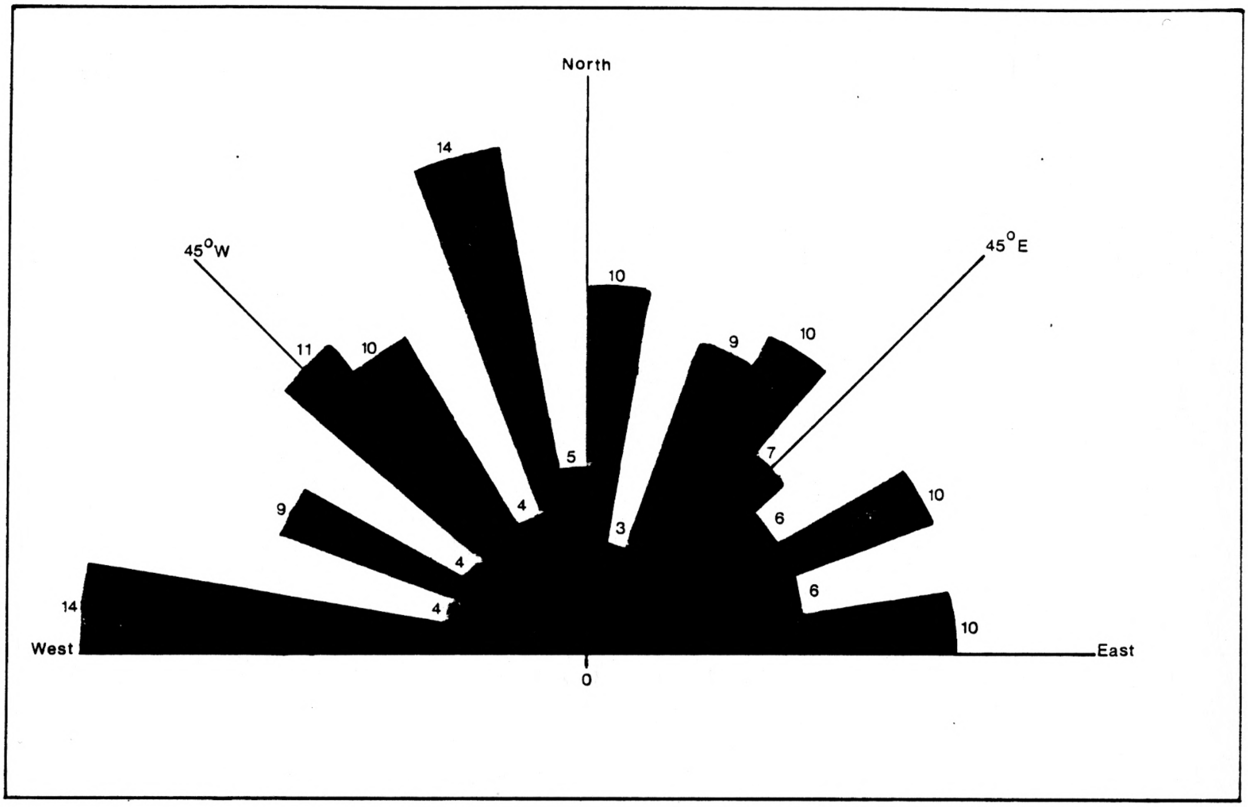
NUMBER OF MEASUREMENTS

Degrees East	Northern Area	Southern Area	Total	Smith Thrust	Goss II Thrust
0-10	5	5	10	1	2
11-20	0	3	3	1	2
21-30	1	8	9	0	0
31-40	3	7	10	1	1
41-50	3	4	7	0	0
51-60	5	1	6	2	0
61-70	6	4	10	1	2
71-80	3	3	6	0	0
81-89	4	6	10	0	0
Subtotal:	30	41	71	5	6

Degrees West	Northern Area	Southern Area	Total	Smith Thrust	Goss II Thrust
1-10	2	3	5	0	0
11-20	8	6	14	0	1
21-30	2	2	4	0	0
31-40	3	7	10	1	3
41-50	9	2	11	4	1
51-60	3	1	4	0	0
61-70	7	2	9	0	0
71-80	1	3	4	0	0
81-90	6	8	14	4	2
Subtotal:	41	34	75	9	7
Total:	71	75	146	14	13

Appendix 3. Summary of 146 joint measurements collected in the Smith-Weasel creeks area.

Data for Smith thrust is included in northern area and data for Goss II thrust is included in southern area.



Appendix 4. Rose diagram of 146 joint measurments collected in the Smith-Weasel creks area.

Numbers represent the actual number of joint directions measured in a particular 10° interval. Strike of joints was determined by using the stereonet to rotate the strata to the horizontal.

STRUCTURAL GEOLOGY
OF SMITH-WEASEL CREEKS AREA,
LEWIS AND CLARK COUNTY, MONTANA

by

Kurt Manfred Reinecke

B. S., Texas Christain University, 1981

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

Kansas State University
Manhattan, Kansas

1984

ABSTRACT

The Smith-Weasel creeks area (T.19 N., R.8 W.), 23 km southwest of Augusta, Montana, lies in the eastern imbricate thrust zone of the Montana Disturbed Belt. In the structurally older northern part of the research area, northeast structural trends dominate. Eastward from Smith Creek the three major thrust faults of the northern area exhibit a change in orientation from east-west to northeast-southwest. This change in orientation becomes less abrupt in younger thrust faults. In the structurally younger southern part of the research area thrust fault traces are east-west to northwest-southeast. Thrust faults become progressively younger, and stratigraphic throw generally becomes greater southward.

The Smith-Weasel creeks area encompasses the intersection of the Montana Disturbed Belt and the Scapegoat-Bannatyne trend, where the orientation of the structural grain shifts from nearly north-south to northwest-southeast. The Scapegoat-Bannatyne trend, defined by several collinear structures and by gravity and magnetic anomalies, appears to be a narrow northeast-trending Precambrian fracture zone characterized by an alignment of structural highs and lows (horsts and grabens?) and intrusions (plutons and Haystack Butte). The convex-cratonward structural grain in the research area either reflects the structurally low

position of the Precambrian basement or a "wrapping-around" effect about the southern termination of eastern part of the Sawtooth Range, or both.

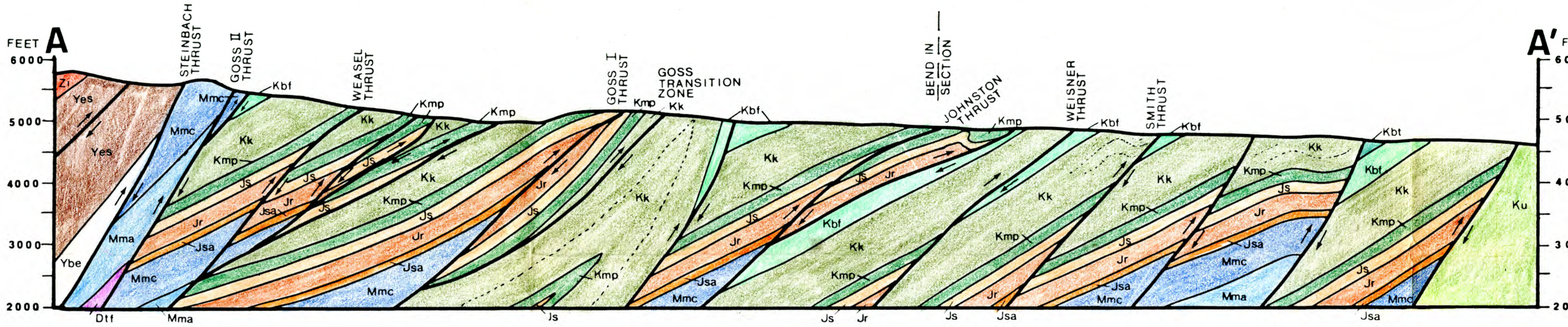
The thrust faults in the western part of the Sawtooth Range and in the Lewis and Clark Range do not terminate at the Scapegoat-Bannatyne trend, rather these thrust faults adjusted to the northwest-southeast strike of the crystalline basement by moving farther east and wrapping around the southern termination of the eastern part of the Sawtooth Range before continuing southeastward toward the Helena embayment. The Scapegoat-Bannatyne trend is a preferred hingeline in the region of adjustment because periodic activity along the trend has weakened the overlying sedimentary rocks. In the Smith-Weasel creeks area the change in orientation of thrust faults in the northern part of the research area and the locally higher level of maximum principal compressive stress suggested in the western part of the southern area by the increased dip and closer spacing of thrust faults, seem to indicate that the Scapegoat-Bannatyne hingeline effected the north and west parts of the research area to a greater degree.

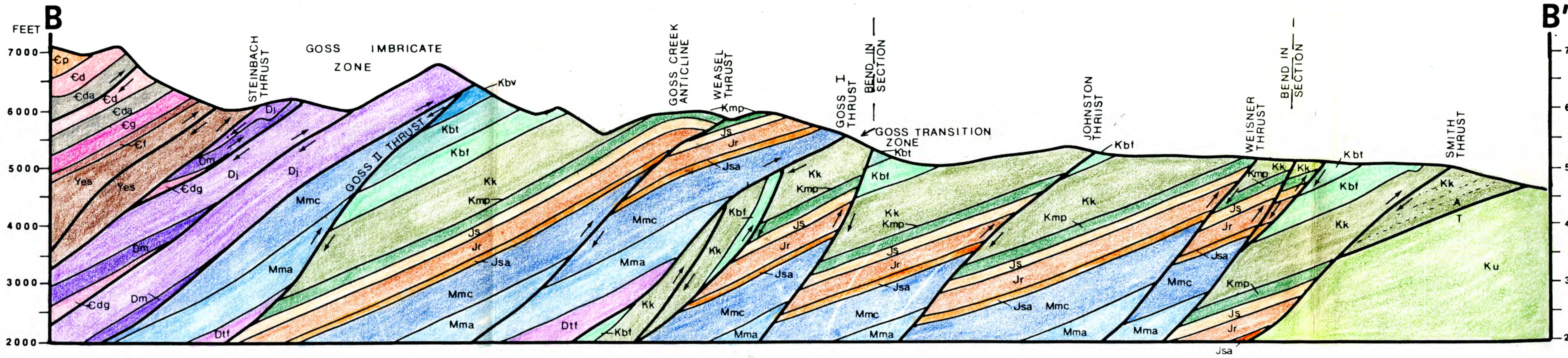
Plate 2

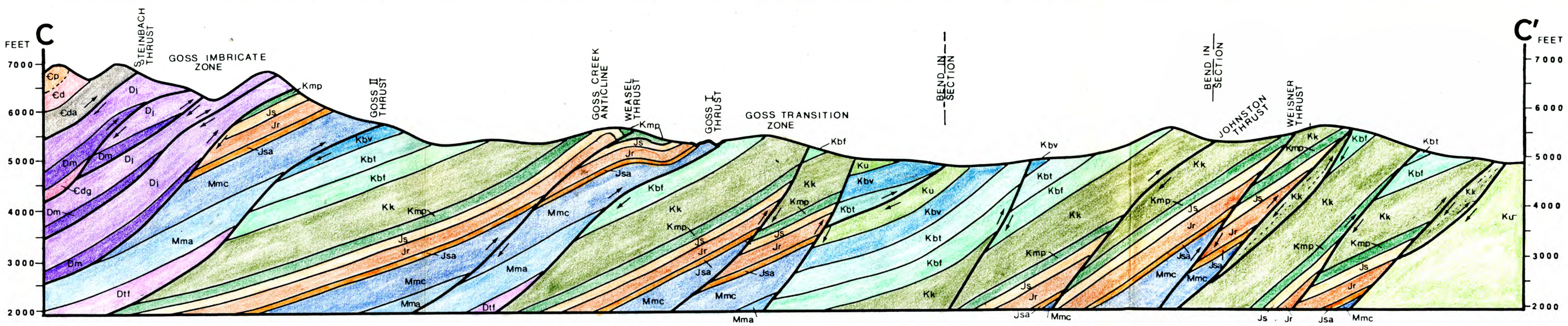
GEOLOGIC CROSS SECTIONS IN SMITH-WEASEL CREEKS AREA, LEWIS AND CLARK COUNTY, MONTANA

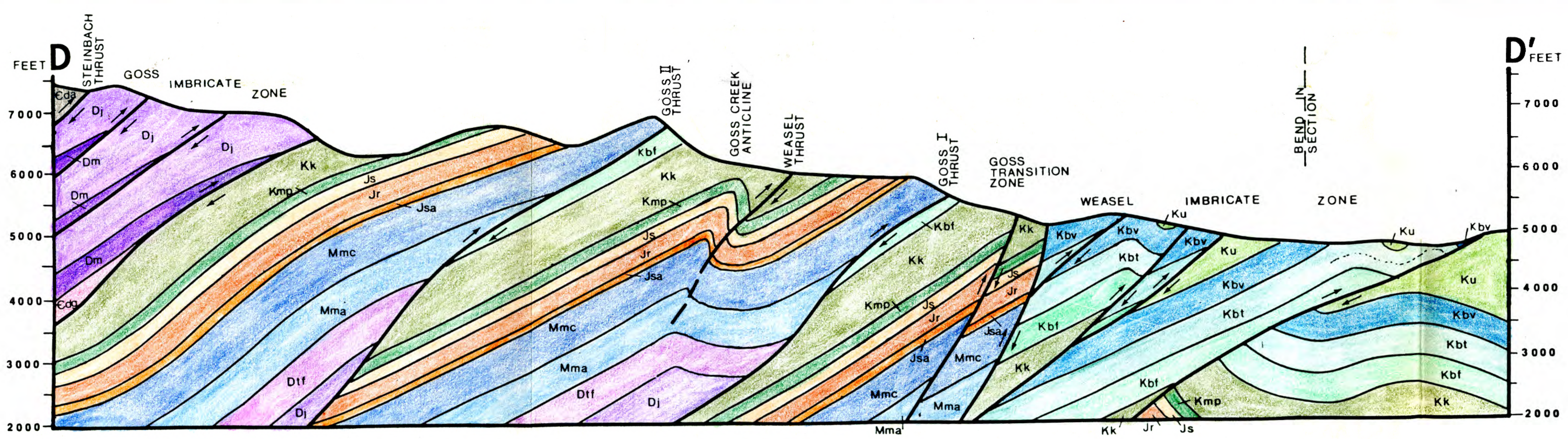
BY KURT M. REINECKE

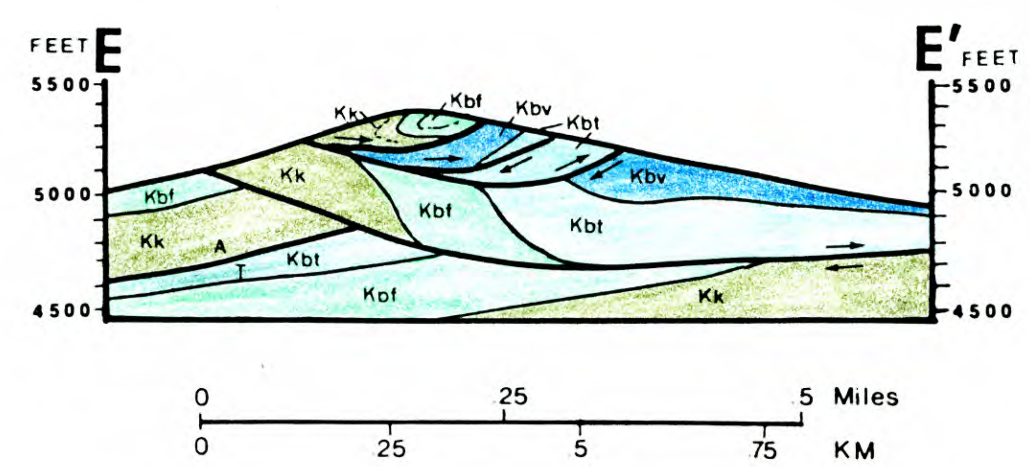
1984











E X P L A N A T I O N

Fault, showing direction of relative movement

Fault, A = away, T = toward

Form lines

Scale

0 .5 1 Miles

0 .5 1 KM

No vertical exaggeration

Quaternary deposits not shown

CRETACEOUS

- Montana Gp.
  - Ku — Upper Cretaceous
- Colorado Gp. — Blackleaf Fm.
  - Kbv — Vaughn Mbr.
  - Kbt — Taft Hill Mbr.
  - Kbf — Flood Mbr.
- Kk — Kootenai Fm.
- Kmp — Mount Pablo Fm.

JURASSIC — Ellis Gp.

- Js — Swift Fm.
- Jr — Rierdon Fm.
- Jsa — Sawtooth Fm.

MISSISSIPPIAN — Madison Gp.

- Mmc — Castle Reef Dolomite
- Mma — Allan Mountain Limestone

DEVONIAN

- Dtf — Three Forks Fm.
- Dj — Jefferson Fm.
- Dm — Maywood Fm.

CAMBRIAN

- Єdg — Devils Glen Dolomite
- Єs — Switchback Shale
- Єst — Steamboat Limestone
- Єp — Pagoda Limestone
- Єd — Dearborn Limestone
- Єda — Damnation Limestone
- Єg — Gordon Shale
- Єf — Flathead Sandstone

PRECAMBRIAN

- Zi — Diorite Sill
- Belt Supergroup
  - Yh — Helena Fm.
  - Ravalli Gp.: Yes — Empire and Spokane Fms.
  - Ybe — Older Belt rocks

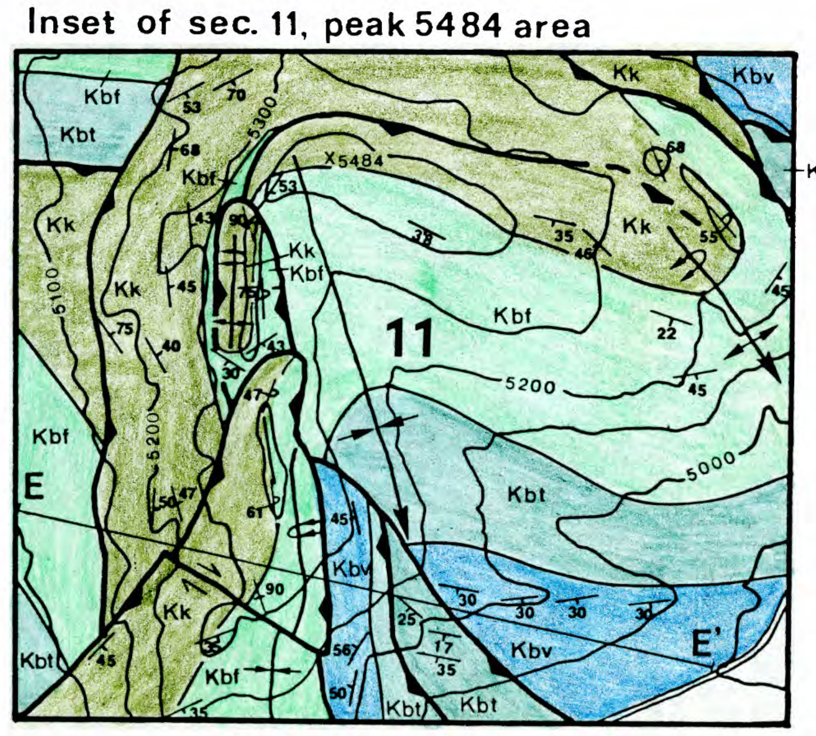
Plate 1

GEOLOGIC MAP OF SMITH-WEASEL CREEKS AREA, LEWIS AND CLARK COUNTY, MONTANA

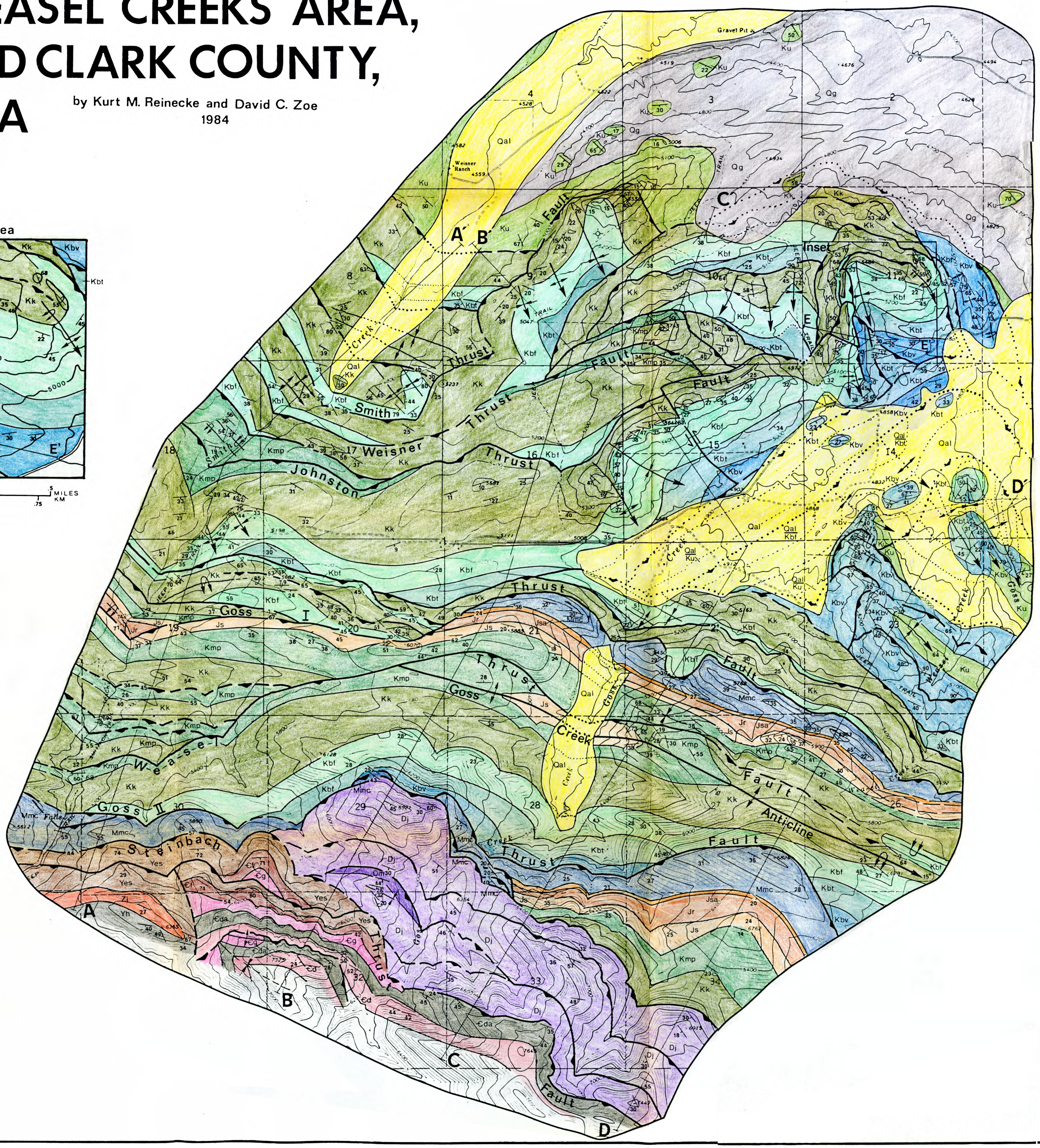
by Kurt M. Reinecke and David C. Zoe

1984

Inset of sec. 11, peak 5484 area



Scale 0 .25 .5 MILES; 0 .25 .5 .75 KM



EXPLANATION

SEDIMENTARY ROCKS IN THE SMITH-WEASEL CREEKS AREA

QUATERNARY

- **Qal** — ALLUVIUM: Unconsolidated stream derived mud, silt, sand and gravel. Thickness up to 52m (16 feet)
- **Qg** — GLACIAL DEPOSITS: Glacial till forming hummocky topography. Poorly sorted mixture of rock fragments and silt. Thickness undetermined

UPPER CRETACEOUS

- **Qal/Ku, Qal/Kbf** — CRETACEOUS UNITS INFERRED BENEATH QUATERNARY ALLUVIUM
- **Ku** — UPPER CRETACEOUS ROCKS UNDIVIDED: Includes TWO MEDICINE FORMATION, VIRGELLE SANDSTONE, TELEGRAPH CREEK FORMATION, AND MARIAS RIVER SHALE. Thickness 110+m (360+ feet)

LOWER CRETACEOUS

COLORADO GROUP

- **Kbv** — BLACKLEAF FORMATION, VAUGHN MEMBER: Olive gray sandstone and siltstone, sandstone coarse-grained, locally cross bedded. Siltstone thinly bedded, locally calcitic. Thickness 55m (180 feet)
- **Kbt** — BLACKLEAF FORMATION, TAFT HILL MEMBER: Olive gray mudstone interbedded with thinly bedded sandstone. Sandstone locally cross bedded. Thickness 30m (98 feet)
- **Kbf** — BLACKLEAF FORMATION, FLOOD MEMBER: Alternating sequence of dark gray shale and thinly bedded sandstone. Basal sandstone very thickly bedded and contains worm trails. Thickness 58m (190 feet)

- **Kk** — KOOTENAI FORMATION: Very thickly bedded grayish green sandstone interbedded with thinly bedded maroon and grayish green mudstone. Upper unit muddy limestone. Thickness 242 m (794 feet)
- **Kmp** — MOUNT PABLO FORMATION: Alternating beds of thinly laminated moderate red mudstone and grayish green siltstone. Siltstone well-indurated. Thickness 56 m (184 feet)

ELLIS GROUP

UPPER JURASSIC

- **Js** — SWIFT FORMATION: Salt and pepper calcitic sandstone. Sandstone cross-bedded, iron-stained throughout. Thickness 27 m (89 feet)

MIDDLE JURASSIC

- **Jr** — RIERDON FORMATION: Alternating sequence of thinly laminated limestone and gray calcitic mudstone. Pelecypods (Gryphaea) are common. Thickness 40m (131 feet)
- **Jsa** — SAWTOOTH FORMATION: Medium gray, thinly laminated micaceous shale. Iron nodules occur locally. Thickness 18 m (59 feet)

MADISON GROUP

UPPER AND LOWER MISSISSIPPIAN

- **Mmc** — CASTLE REEF DOLOMITE: Very thickly bedded, excellent ridge former, finely crystalline with chert bands abundant throughout. Thickness 61+m (200+ feet)

UPPER DEVONIAN

- **Dj** — JEFFERSON FORMATION: Very finely crystalline, dense, dark brownish gray limestone. Fetid odor on broken surface. Grayish yellow mottling abundant. Thickness 122 m (400 feet)

MIDDLE DEVONIAN

- **Dm** — MAYWOOD FORMATION: Thinly bedded dolomitic mudstone interbedded with brownish gray limestone. Mudstone dark grayish green. Thickness 37 m (121 feet)

MIDDLE CAMBRIAN

- **Єd** — DEARBORN LIMESTONE: Very thickly bedded, yellowish brown, closely spaced fractures filled with calcite occur throughout. Thickness 58 m (190 feet)
- **Єda** — DAMNATION LIMESTONE: Dark brownish gray, heavily mottled with yellowish gray siltstone. Strong fetid odor on broken surface. Thickness 67m (220 feet)
- **Єg** — GORDON SHALE: Thinly laminated dark gray containing beds of thinly bedded micaceous sandstone. Thickness 60 m (197 feet)
- **Єf** — FLATHEAD SANDSTONE: Yellowish brown, iron-stained, interbedded with dusky brown shale. Sandstone well-indurated and non-calcareous. Thickness 48m (157 feet)

PROTEROZOIC (Y)

- **Yh** — HELENA FORMATION: Very thickly bedded dolomitic limestone containing abundant stromatolites. Thickness 27+m (90+ feet)

RAVALLI GROUP

- **Yes** — SPOKANE AND EMPIRE FORMATIONS UNDIVIDED: Very thick sequence maroon, green, and gray thinly bedded siltstone. Thickness 367m (1204 feet)

IGNEOUS ROCKS IN THE SMITH-WEASEL CREEKS AREA

PROTEROZOIC (Z)

- **Zi** — DIORITE SILL: Massive diorite and quartz diorite. Thickness 90m (295 feet)

THRUST FAULT: dashed where inferred, dotted where concealed. Sawteeth on upper plate

TEAR FAULT: arrows show relative movement

TRANSVERSE FAULT: inferred, relative movement uncertain

ANTICLINE: showing direction of plunge

SYNCLINE: showing direction of plunge

OVERTURNED ANTICLINE: showing direction of dip of limbs

OVERTURNED SYNCLINE: showing direction of dip of limbs

STRIKE AND DIP OF BEDS

11 Inclined — 90 Vertical — 88 Overturned

J B LONG 1-9 WILDCAT WELL

A — A' LINE OF CROSS SECTION

Contour interval 20 feet north and east, 40 feet elsewhere

SCALE 0 .5 1 MILES; 0 .5 1 KM

Base map from U.S. Geological Survey 7.5-minute topographic quadrangles, 1970

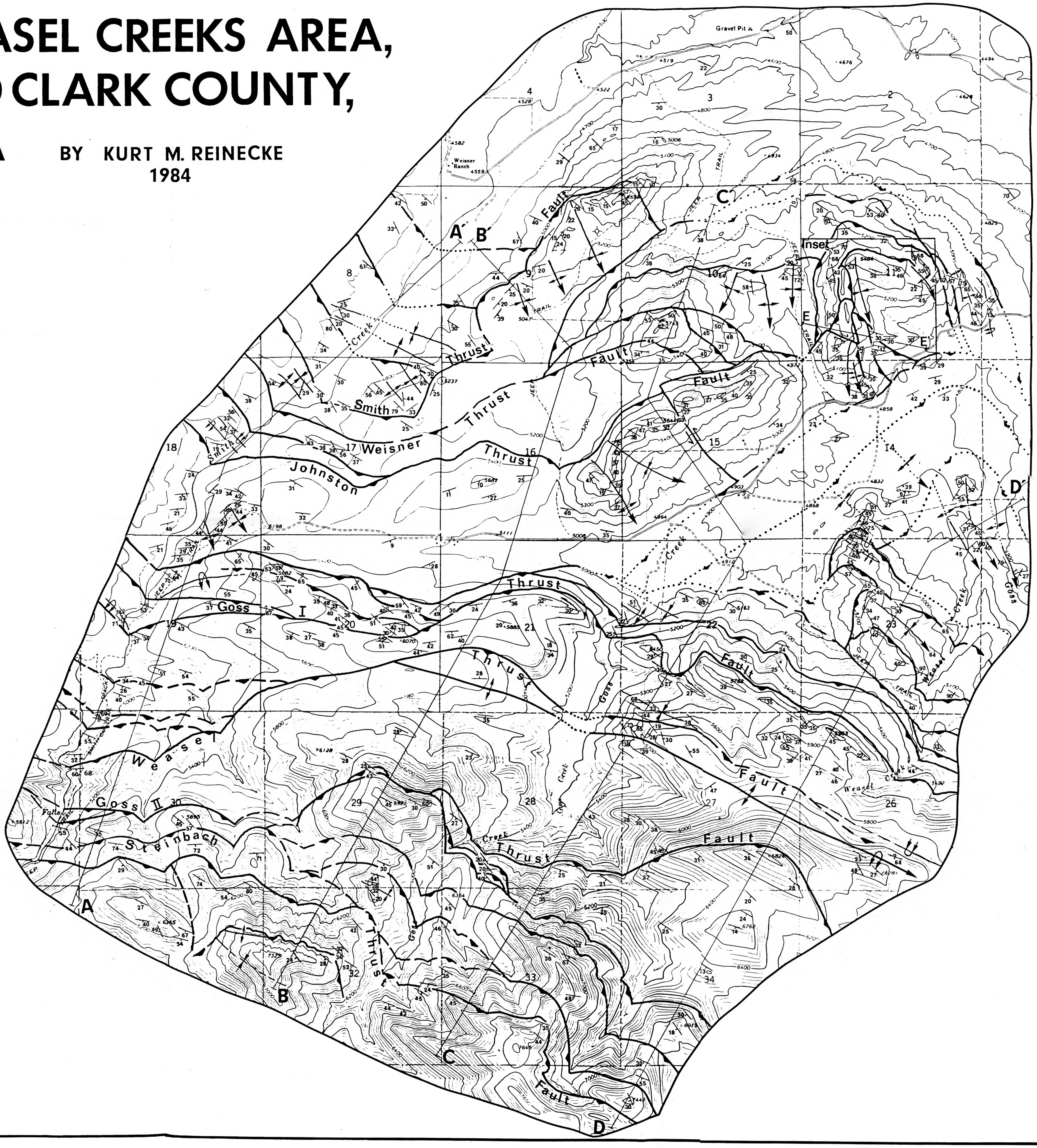
DOUBLE FALLS	NILAN RESERVOIR
JAKIE CREEK	STEAMBOAT MTN

TN — MN 19°

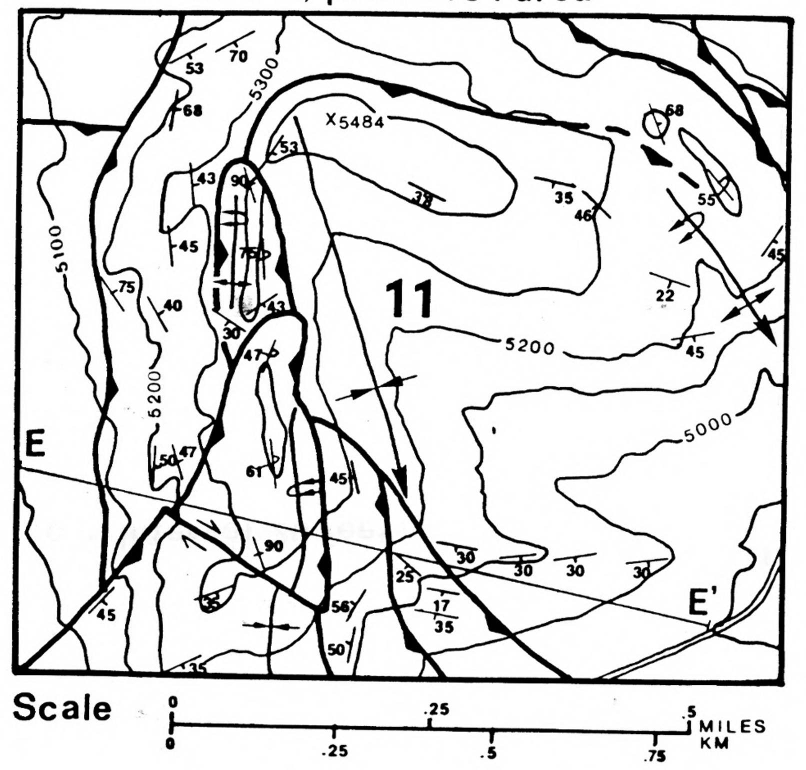
Plate 3

STRUCTURE MAP OF SMITH-WEASEL CREEKS AREA, LEWIS AND CLARK COUNTY, MONTANA

BY KURT M. REINECKE
1984



Inset of sec. 11, peak 5484 area



EXPLANATION

Thrust Fault–dashed where inferred, dotted where concealed. Sawteeth on upper plate.

Tear Fault–arrows show direction of relative movement.

Transverse Fault, inferred– relative movement uncertain.

Anticline– showing direction of plunge.

Syncline–showing direction of plunge.

Overturned anticline–showing direction of dip of limbs.

Overturned syncline–showing direction of dip of limbs.

STRIKE AND DIP OF BEDS

Inclined   Vertical   Overturned

J.B. Long 1-9 wildcat well

A — A' Line of cross section shown on Plate 2

Contour Interval 20 feet, north and east; 40 feet elsewhere

Scale 0 .5 1 MILES
0 .5 1 KM

TN
MN
19°

Base map from U.S. Geological Survey 7.5-minute topographic quadrangles, 1970.

Double Falls	Nilan Reservoir
Jakie Creek	Steamboat Mtn.