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A REVIEW OF THE GEOLOGY AND PETROLEUM RESOURCE POTENTIAL OF THE MONTANA THRUST BELT

BY

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WITH A SECTION ON

GEOLOGY OF POTENTIAL MISSISSIPPIAN RESERVOIR ROCKS, DISTURBED BELT SECTOR OF THE MONTANA THRUST BELT

BY

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INTRODUCTION

The Montana thrust belt province, 41,400 square miles in area, lies in the generally mountainous terrain of western Montana, adjoining Idaho on the east and northeast (Fig. 1). It is coterminous with that part of the Cordilleran fold-and-thrust belt which occurs within the State of Montana. The purpose of this report is to provide the geologic basis for that portion of the U. S. Geological Survey's national oil and gas assessment which deals with the Montana thrust belt (Province 98, Fig. 1A).

STRUCTURAL SETTING

The Montana thrust belt province consists of numerous thrust sheets and intrusive bodies. Thrusting generally took place from west to east during Late Cretaceous and Paleocene time, between 88 and 57 Ma (million years) (Ruppel and others, 1981; Harlan and others, 1988). The structure of much of this province is exceedingly complex, and many structural and stratigraphic relationships remain obscure or are the subject of controversy. In this report, the province is subdivided into three subprovinces (Fig. 1A) based on differences in structural setting and history: (1) Montana disturbed belt and Belt basin, north and northwest of Helena, (2) Helena salient and hinterland[1], east, west and south of Helena and north of the southwest Montana transverse zone, and (3) southwest Montana recess southwest of Dillon, south of the transverse zone (Fig. 1B). Although the entire province was part of the craton during Paleozoic time, the eastern part of subprovince 1 was a positive element during late Paleozoic time; here Jurassic clastic rocks of the Ellis Group rest unconformably on the Mississippian Madison Group carbonate sequence. The western part of subprovince 1, including the upper plates of the Lewis and Eldorado thrusts ('B' and 'C', Fig. 2), was originally part of the Middle Proterozoic Belt basin (Harrison, 1972; Harrison and others, 1974), which subsided between 1,500 and 900 Ma (Reynolds, 1984), preserving more than 46,000 ft of Proterozoic sedimentary rocks west of the Libby trough and in the western part of the Purcell anticlinorium (Fig. 2; Harrison and Cressman, 1985). Thrusting involving Belt basin rocks is discussed by Harrison and others (1980, 1985). These Proterozoic rocks were stripped off of the eastern part of subprovince 1 by pre-Middle Cambrian uplift and erosion (Reynolds, 1984). The westernmost part of subprovince 1 contains the Cambrian Libby trough (Fig. 2) of Harrison and others (1974). Farther east, in the region of the present Rocky Mountain trench, a Cambrian through Middle Devonian high was present ('A' of Fig. 2); Devonian rocks rest directly on the Middle Proterozoic Belt Supergroup sequence on the east side of the Rocky Mountain trench near the International Boundary with Canada. The western part of subprovince 1 is suspected to have subsided more rapidly during Paleozoic time than the eastern part (Peterson, 1985, 1986), although all but the early part of the Paleozoic sequence has been subsequently stripped by erosion west of the Rocky Mountain trench. The trench is one of a number of Tertiary

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[1] Hinterland, for purposes of this report, is that portion of subprovince 2 west of which only Proterozoic rocks are involved in the footwalls of thrust sheets. The hinterland thrust plates (west of dotted line, Fig. 1B) are primarily composed of Proterozoic Belt Supergroup.

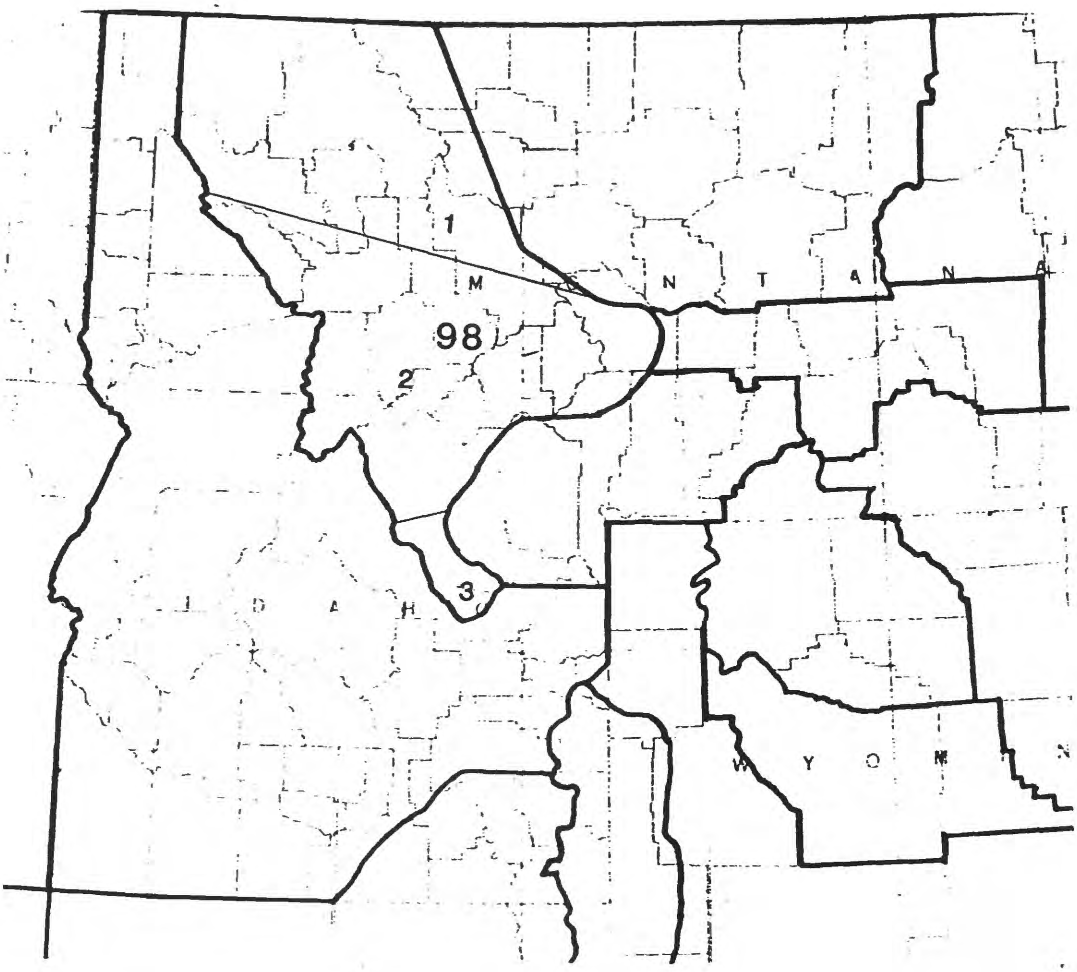
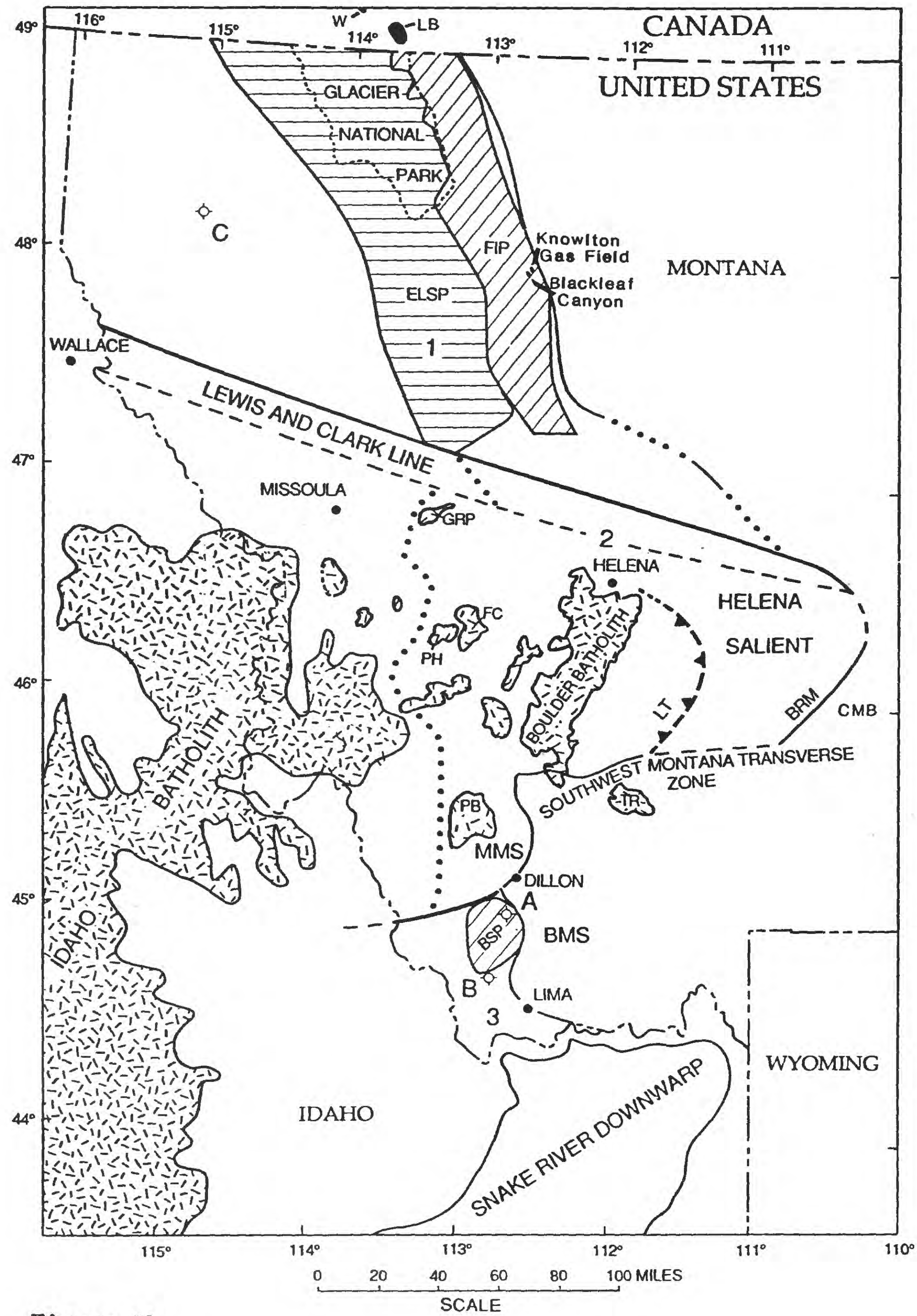


Figure 1a. Outline map showing location and boundary of the Montana thrust belt province and three subprovinces within this province discussed separately in this report. Eastern boundary modified slightly from that of Province 98 in Dolton and others (1981).

Figure 1b. Map of the Montana thrust belt province and environs showing (1) hydrocarbon plays considered in this report: BSP - Blacktail salient play, ELSP - Eldorado-Lewis subthrust play, and FIP - frontal imbricate play; (2) drill-holes mentioned in this report: A - American Quasar no. 9-1 May-Federal, B - Amoco no. 1 McKnight Canyon Unit, and C - ARCO no. 1 Paul Gibbs; (3) Canadian gas fields: LB - Lookout Butte, and W - south end of Waterton; (4) structural features: BMS - Blacktail Mountains salient, BRM - Battle Ridge monocline, CMB - Crazy Mountains basin, LT - Lombard thrust, and MMS - McCartney Mountain salient, and (5) intrusive bodies: FC - Flint Creek batholith, GRP - Garnet Range pluton, PB - Pioneer batholith, PH - Philipsburg batholith, and TR - Tobacco Root batholith. Thick lines separate subprovinces 1, 2, and 3. Boundary between subprovince 1 and 2 is approximate northern boundary of the Lewis and Clark 'line', a transverse zone of west-northwest-trending strike-slip faults. The approximate southern boundary of the zone is shown by short dashes. The western edge of Eldorado-Lewis subthrust play, subprovince 1, and dotted line west of Boulder batholith, subprovince 2, are the approximate western limit of subthrust post-Cambrian Phanerozoic rocks. Narrow line along eastern margin is eastern limit of allochthonous rocks of Montana thrust belt, dotted where inferred, rather than the province boundary shown in Figure 1a. Fault symbols as in Figure 2. Limits of Canadian gas fields from Wallace-Dudley (1981).



CANADA
UNITED STATES
W
LB
GLACIER
NATIONAL
PARK
FIP
ELSP
1
C
Knowlton Gas Field
Blackleaf Canyon
MONTANA
WALLACE
LEWIS AND CLARK LINE
MISSOULA
GRP
2
HELENA
HELENA
SALIENT
FC
PH
BOULDER BATHOLITH
LT
BRM
CMB
BATHOLITH
SOUTHWEST MONTANA TRANSVERSE ZONE
TR
PB
MMS
DILLON
A
BSP
BMS
B
LIMA
3
IDAHO
IDAHO
WYOMING
SNAKE RIVER DOWNWARP
0 20 40 60 80 100 MILES
SCALE

Figure 1b.

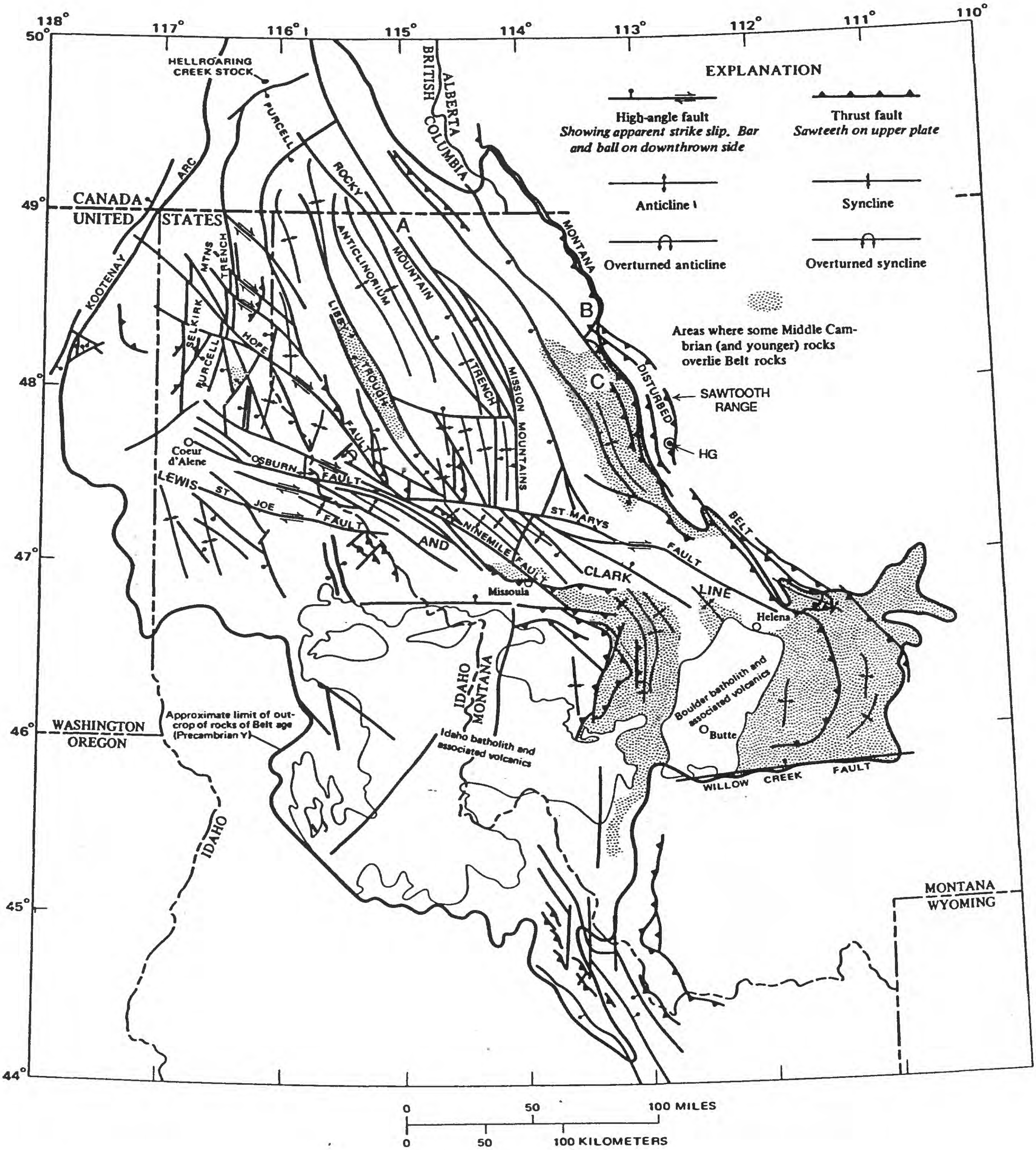


Figure 2. Index map of the Belt basin from Harrison and others (1974, Fig. 3), showing principal folds and faults recognized at the time. A - locality on east side of Rocky Mountain trench with anomalous Lower Paleozoic sequence. B - Lewis thrust plate, southern part of Glacier National Park. C - Eldorado-Lewis thrust plate. HG - Hannah Gulch.

extensional features west and southwest of Glacier Park (Fig. 2). These features are bounded by normal faults which are suspected to merge with the older thrust faults at depth (Fig. 3; Kulik, 1983; Fritts and Klipping, 1987a, 1987b). The best known example is the late Eocene to Oligocene Kishenehn basin in the western part of and just west of Glacier Park (Constenius, 1983). The eastern part of subprovince 1 is termed Montana disturbed belt (Fig. 2). The disturbed belt includes the Lewis thrust plate, of which the bounding thrust is exposed along the eastern and southern margin of Glacier Park (Willis, 1902; Davis and Jardine, 1984). South of Glacier Park, stacked imbricate thrusts involving the Devonian through Cretaceous sequence are exposed within the Sawtooth Range (Fig. 2) and along the eastern and northern margin of the Range (Mudge, 1972b, 1983; Mudge and Earhart (1983). This thrust complex is bounded on the west by the Eldorado thrust and plunges northward beneath the Lewis thrust (Kulik, 1983); the relationship of the Eldorado and Lewis thrusts was investigated by Mudge and Earhart (1980). Fritts and Klipping (1987a, 1987b) indicate that two duplexes are present beneath the Lewis-Eldorado thrust plate, as shown earlier by Kulik (1983) beneath Glacier Park (Fig. 3). These are inferred from seismic data to involve the Paleozoic carbonate sequence. The footwall cutoff of Paleozoic rocks beneath the Lewis-Eldorado thrust system is shown by Fritts and Klipping (1987a, 1987b) to occur beneath the eastern part of the Rocky Mountain trench (western edge of Eldorado-Lewis subthrust play, Fig. 1B). The Lewis and Clark line (Fig. 1B), a complex cross-structural zone active intermittently from Proterozoic to Holocene time (Reynolds, 1979, 1984) at the southern margin of subprovince 1, marks the southern terminus of the Rocky Mountain trench. This cross-structure was a transform fault during Laramide crustal compression and subsequent Tertiary extension (Lorenz, 1984; Sheriff and others, 1984).

In subprovince 2, south of the Lewis and Clark line (Fig. 1B), more than 28,000 ft of Middle Proterozoic Belt sedimentary rocks are preserved locally west of the Boulder batholith in major thrust plates which are composed almost entirely of Belt rocks (Ruppel and others, 1981). The eastern part of subprovince 2, the Helena structural salient, is the locus of the Proterozoic Belt embayment of McMannis (1963), which was later reactivated as the upper Paleozoic Central Montana trough (Peterson, 1985, 1986). Subprovince 2 occupies the major portion of the batholithic province of McMannis (1965) and is characterized by an abundance of Cretaceous and Tertiary intrusive and extrusive igneous rocks emplaced during and subsequent to thrusting (Tilling and others, 1968; Hyndman, 1979; Ruppel and others, 1981; Snee and others, 1983; Harlan and others, 1988). Ruppel and others (1981) tentatively distinguished two major thrust plates and a thrust zone in the central and western part of subprovince 2, based on distinctive sequences of sedimentary rocks and by distinctive patterns of folding and imbricate thrust faulting: the Grasshopper and Sapphire plates and Elkhorn thrust zone (Fig. 4). They tentatively considered the Sapphire plate to include the entire deformed belt between the Bitterroot lobe of the Idaho batholith and the Boulder batholith. They subdivided the Sapphire plate into two major subplates: a western Rock Creek subplate and eastern and northern Garnet Range subplate. The Rock Creek subplate is composed almost entirely of Middle Proterozoic rocks, intruded by Cretaceous igneous rocks. This subplate represents the Sapphire tectonic block of Hyndman (1980) and the Sapphire plate of Sears (1985). The Garnet Range subplate of Ruppel and others (1981), between the Philipsburg and Boulder batholiths, is tightly imbricated and folded and also intruded by Cretaceous igneous rocks. Folds and imbricate thrusts of this region are similar to those of the Elkhorn thrust zone east of the Boulder batholith. A

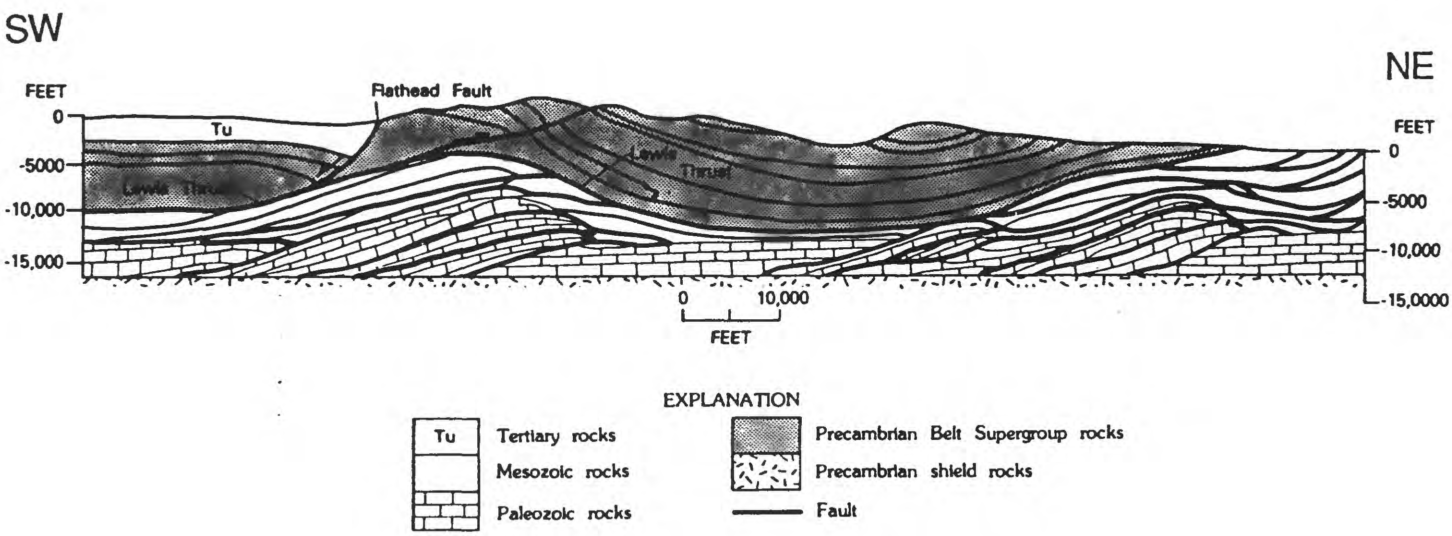


Figure 3. Geologic cross section inferred from gravity modeling across central portion of Glacier National Park (from Kulik, 1983, Fig. 6).

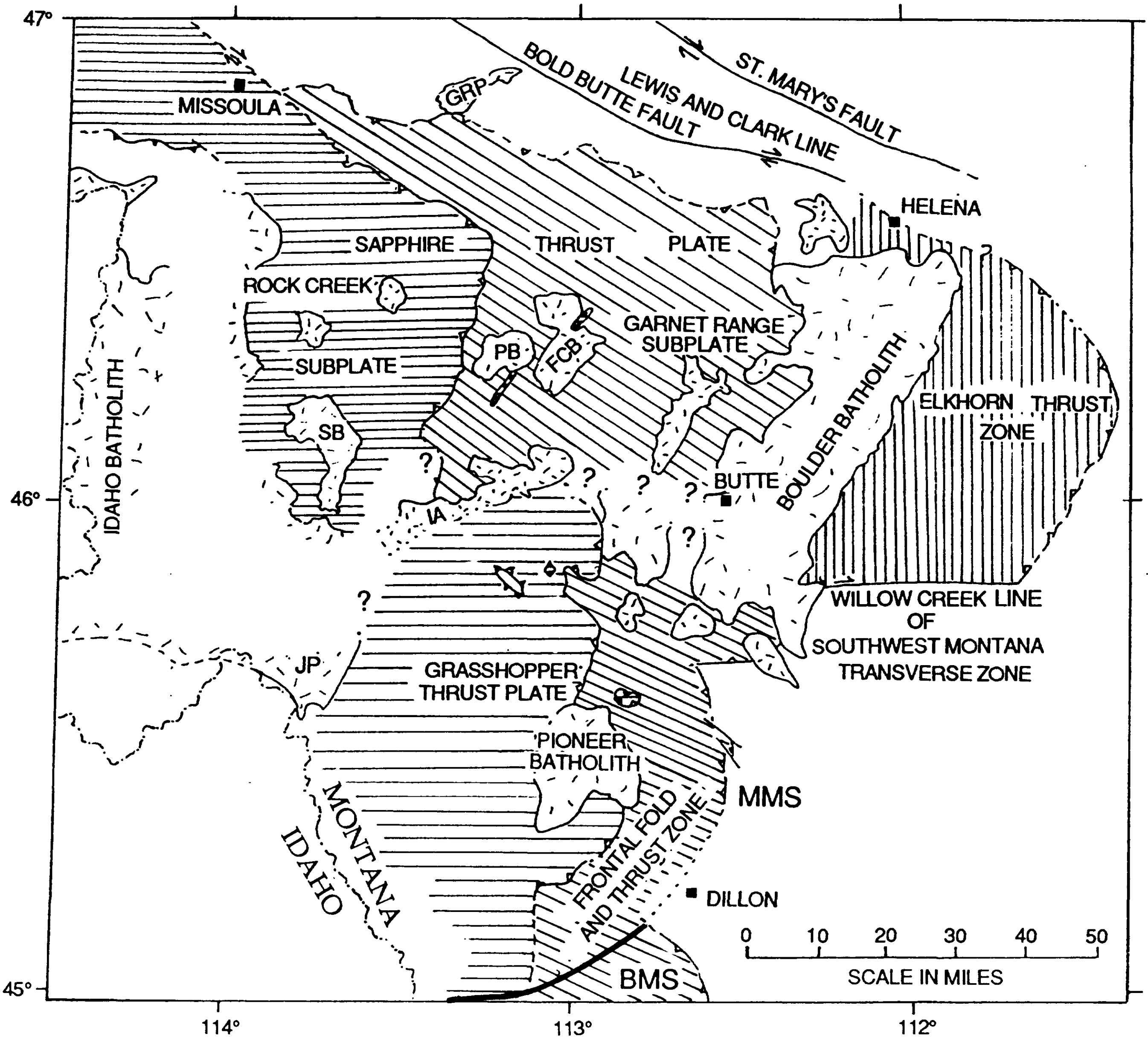


Figure 4. Generalized tectonic map of central and western part of subprovince 2 (simplified from Ruppel and others, 1981, Fig. 1). Second-order salients: MMS - McCartney Mountain salient and BMS - Blacktail Mountains salient. Intrusive masses: FCB - Flint Creek batholith, GRP - Garnet Range pluton, IA - intrusive suite of the Anaconda Range (informal usage, J. E. Elliot, oral communication, 1988), JP - Joseph pluton, PB - Philipsburg batholith, and SB - Sapphire batholith. All intrusive bodies shown in randomly oriented dash pattern. Fault symbols as in Figure 2. Thick line represents boundary between subprovince 2 (to north) and subprovince 3 (to south), based in part on the southern edge of Grasshopper plate as defined by Ruppel and others (1981). Southeastern boundary of MMS is modified from Ruppel and others (1981) based on subsurface data and my field observations northwest of Dillon. Horizontal ruled lines - Rock Creek subplate (Sapphire block of Hyndman, 1980) and Grasshopper thrust plate; diagonal ruled lines - Garnet Range subplate and frontal fold and thrust zone of Ruppel and others (1981); vertical ruled lines - Elkhorn thrust zone of Ruppel and others (1981).

thick sequence of Paleozoic and Mesozoic rocks is preserved in both areas. Structurally the Garnet Range subplate - Elkhorn thrust zone of Ruppel and others (1981) is footwall to the Sapphire block of Hyndman (1980), as indicated by Sears (1985). This structural complex is re-evaluated by Sears (1988). The southern part of subprovince 2 is occupied by the Grasshopper thrust plate to the west and frontal fold and thrust zone to the east (Ruppel and others, 1981). The former is chiefly composed of Middle Proterozoic Belt Supergroup with thin Cambrian to Devonian cover preserved locally. The latter preserves a thick sequence of Paleozoic and Mesozoic rocks involved in tight folding and imbricate thrusting similar to the Garnet Range subplate to the north (Fig. 4). The relationship of the Grasshopper plate and Sapphire plate is obscured by intervening Tertiary intrusive rocks of the Anaconda Range (D. J. Lidke and C. A. Wallace, oral communication, 1988). Lidke and Wallace, as well as J. M. O'Neill and other workers, are currently re-evaluating a number of structural relationships within subprovince 2 west of the Boulder batholith. The frontal zone of the thrust belt in subprovince 2, the Helena salient, extends eastward to the margin of the Crazy Mountains basin, where it abuts the Battle Ridge monocline along its southeastern margin (Fig. 1b; Garrett, 1972).

The southwest Montana recess (subprovince 3) is comprised of a complex of thrust sheets (Perry and Sando, 1983; Ruppel and Lopez, 1984; Skipp, 1985, and 1988; Perry and others, 1988) which generally are younger to the east. The frontal Tendoy plate near Lima (Fig. 5) has been folded by later thrusting involving the frontal fold and thrust zone of the Blacktail Mountains salient as well as late deformation of the Rocky Mountain foreland (Perry and others, 1983a and 1988). Various structural relationships in this subprovince are being re-evaluated and geologic mapping is in progress. The older geologic maps of this subprovince, prepared during the 1950's or earlier, do not reflect current thinking.

Both subprovinces 2 and 3 and the western part of subprovince 1 are overprinted by Tertiary to Quaternary basin-range extension faulting (Reynolds, 1979). Many of these faults have breached the older thrust-belt structures and appear to have destroyed many of the possible structural traps for hydrocarbons formed during thrusting.

STRATIGRAPHY

Strata ranging from Precambrian to Holocene are present in the Montana thrust belt province. The pre-Tertiary Phanerozoic stratigraphic sequence of the eastern (subsurface) part of the disturbed belt (subprovince 1, Figs. 1 and 2) is shown in Figure 6. The oldest sedimentary rocks, those of the predominately siliciclastic Middle Proterozoic Belt Supergroup, were deposited between 1,500 to 900 Ma over a broad area of western Montana (Reynolds, 1984). The precise age, thickness, and depositional setting of the Belt Supergroup is still a subject of controversy, but great strides have been made recently in understanding the distribution and correlation of stratigraphic units (Hobbs, 1984). The Belt Supergroup in the main part of the Belt basin (Fig. 2) is subdivided into, from base to top: (1) the Prichard Formation, 23,000 ft thick near the western edge of subprovince 1 (Cressman, 1984), (2) the overlying Ravelli Group, nearly 13,000 ft thick from near Helena (Fig. 1b) to Glacier Park and in northeastern Idaho (Conner and others, 1984), (3) the overlying middle Belt carbonates (Helena Formation to the east, Wallace Formation west of the Rocky Mountain trench, subprovince 1), more than 40,000 ft thick near Wallace, Idaho (Fig. 1) (Harrison, 1984), but only 3,000 to 5,000 ft thick in the western part of subprovince 2 between the Boulder and Idaho batholiths

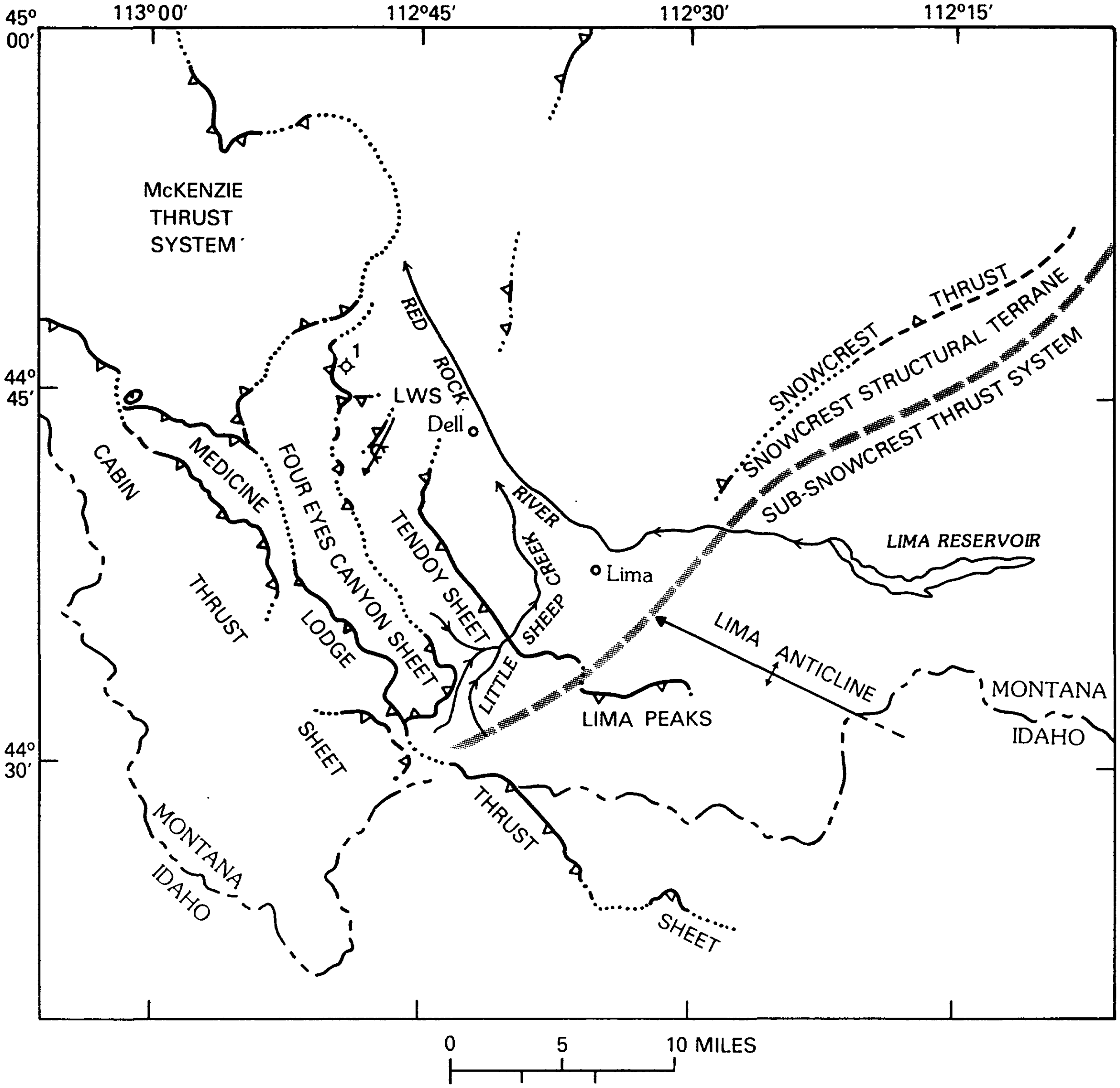


Figure 5. Generalized tectonic map of central and southern part of subprovince 3 from Perry and others (in press, Fig. 1b), showing area of structural interactions of sub-Snowcrest thrust system of Rocky Mountain foreland with the frontal zone of the Montana thrust belt. McKenzie thrust system, northwest of Dell, is a highly imbricated plate bearing offbank Mississippian rocks of the Tendoy Group (Sandberg and others, 1985; Sando and others, 1985). Dry hole symbol labelled "1" is the location of Amoco no. 1 McKnight Canyon Unit drill-hole, summarized in the Appendix. Structural symbols as in Figure 2.

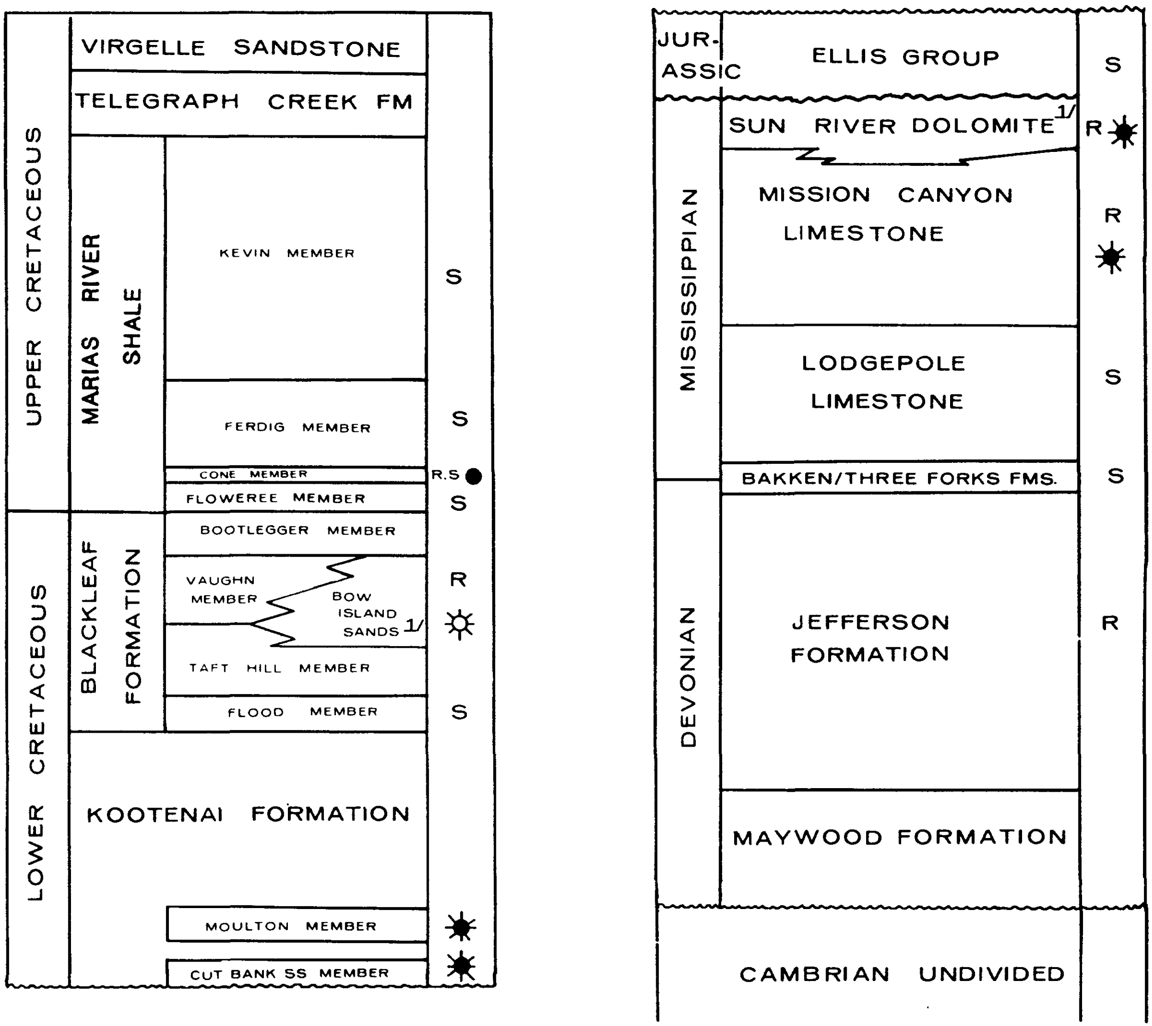


Figure 6. Subsurface stratigraphic usage for pre-Tertiary rocks of the eastern Montana disturbed belt sector of the Montana thrust belt, eastern part of subprovince 1 (from Perry and others, 1983b). Superscript 1/ denotes an informal drillers term in this area. Abbreviations and symbols in right-hand column are as follows: S - known or potential source rock, R - known or potential reservoir rock, solid circle - oil productive, open circle with rays - gas productive, and solid circle with rays - both oil and gas productive. Mission Canyon and Lodgepole Limestones comprise the Madison Group. The dolomitic upper Mission Canyon is commonly termed Sun River dolomite by drillers in the area. Within the exposed Madison Group of the disturbed belt farther west, Mississippian rocks are subdivided into the Allan Mountain Formation, equivalent to the Lodgepole Limestone (W. J. Sando, oral communication, 1987), and overlying Castle Reef Formation. See discussion below by K. M. Nichols and Figures 10 and 11.

(Ruppel and others, 1981; D. A. Lidke, oral communication, 1988), and (4) Missoula Group, more than 20,000 ft thick in the same part of subprovince 2 (Ruppel and others, 1981). The latter pinches out eastward in the disturbed belt (subprovince 1), suggesting proximity to the margin of the Belt basin (Wallace and others, 1984). Although the Belt Supergroup extends east of the Helena salient (Fig. 1b), it thickens westward into the interior of the salient (Harris, 1957) to a thickness of more than 25,000 ft in the western part of subprovince 2 (Sapphire block and Grasshopper plate, Fig. 4; Ruppel and others, 1981) and at least 46,000 ft thick in the Libby trough area of the Belt basin (Harrison and others, 1985) north of the Lewis and Clark line (Figs. 1 and 2), the western part of subprovince 1. Middle Proterozoic rocks are present only along the western margin of subprovince 3, where they are assigned to the Yellowjacket Formation and Lemhi Group (Ruppel and others, 1975; Skipp, 1985, and 1988).

In the eastern part of subprovince 1 (Montana disturbed belt), Deiss (1939) showed a northward thinning of the Cambrian sequence from nearly 2300 ft in the southern disturbed belt to less than 1700 ft on the Lewis thrust plate southwest of Glacier park. These rocks consist of limestones with several interbedded green and red shale units above the basal Flathead Sandstone; the abruptly northward thinning Devils Glen Dolomite forms the top of the sequence (Deiss, 1939, Fig. 5). Cambrian rocks appear to be absent by erosion and/or nondeposition on the east side of the Rocky Mountain trench (locality 'A', Fig. 2) on the thrust plate above and west of the Lewis plate, although they are present and more than 3,000 ft thick farther west in the Libby trough (Fig. 2) (Chesson and others, 1984). The former area appears to represent the "Montana Island" of Walcott, discussed by Deiss (1939), a pre-Middle Devonian high which extends northward into the southern Canadian Rocky Mountains, similar to the "Lemhi arch" of Sloss (1954) which affects the western part of subprovince 3. The latter has been re-evaluated by Mapel and Sandberg (1968) and Ruppel (1986). As a complete Cambrian section is missing in much of the western part of subprovince 2, a gradual westward thickening such as pictured by Peterson (1985, 1986) cannot be adequately documented. However a thick sequence of Cambrian carbonate rocks near Missoula is described by Chesson and others (1984), similar to those of the Libby trough. Cambrian rocks are absent along the western edge of subprovince 3 but are nearly 900 ft thick along the northeastern margin of subprovince 3 (Pecora, 1981; Peterson, 1985). Lower Mesozoic and Paleozoic rocks younger than Cambrian are not preserved in subprovince 2 west of the dotted line (Fig. 1b) and in subprovince 1 west of the Eldorado-Lewis subthrust play (Fig. 1b).

Ordovician rocks are present in the Montana thrust belt province in the western part of subprovince 3 and adjacent east-central Idaho (Ruppel and others, 1975), where they form an eastward thinning wedge. These are predominately quartzites which rest unconformably on Precambrian Archean(?) gneiss to the east in the northern part of the Cabin thrust sheet and far western part of the McKenzie thrust system (Fig. 5) and on Precambrian sedimentary rocks to the west in east-central Idaho. Silurian rocks are absent by erosion and/or nondeposition throughout the Montana thrust belt province.

In the central and eastern part of the McKenzie thrust system (subprovince 3, Fig. 5), east of the area of preserved Ordovician rocks, Devonian rocks appear to locally rest on Archean(?) basement (C. A. Sandberg, oral communication, 1984). On the east side of the Rocky Mountain trench (locality 'A', Fig. 2), Devonian(?) sandstone rests directly on the Middle Proterozoic Belt Supergroup. Elsewhere in the Montana thrust belt, Devonian rocks rest unconformably on Cambrian carbonates; Ordovician through Middle Devonian rocks are absent by erosion and/or nondeposition. Devonian rocks in the Montana thrust belt province form two stratigraphic sequences. The lower sequence is predominately dolostone with some interbedded evaporites, with siltstone and sandstone locally at the base. This sequence, up to 1,100 ft thick in the Montana disturbed belt (subprovince 1, Figs. 1 and 2) and locally more than 1,500 ft thick in the western part of subprovince 2, is subdivided into the Upper Devonian Jefferson Dolomite and underlying Middle and Upper Devonian Maywood Formation (Sandberg and Mapel, 1967). The upper sequence, the Upper Devonian and Lower Mississippian Three Forks Formation, is locally more than 800 ft thick in the disturbed belt but generally only 200 to 300 ft thick in subprovinces 2 and 3 (Sandberg and Mapel, 1967). The Three Forks contains widely traceable marker units of from base to top: Upper Devonian carbonate and evaporite (Logan Gulch Member) and shale (Trident Member), and Upper Devonian and Lower Mississippian fine-grained calcareous sandstone and sapropelic shale (Sappington Member) (Sandberg and Mapel, 1967). Locally in subprovince 3, the Three Forks contains a polymictic conglomerate unit with Archean(?) gneissic clasts (northwestern part of McKenzie thrust system, Fig. 5; M'Gonigle, 1983) derived from a nearby paleotopographic and paleostructural high. The Three Forks thus forms a heterogeneous stratigraphic sequence; the Sappington Member is equivalent to much of the Upper Devonian and Lower Mississippian Bakken Formation of the Williston basin (Macqueen and Sandberg (1970).

Mississippian rocks, dominantly limestones, occur in two depositional sequences. The lower sequence consists of Upper Devonian and Lower Mississippian sapropelic shales of the Sappington Member of the Three Forks Formation, overlain by Lower Mississippian carbonate ramp deposits (in the sense of Read, 1985) of the Lodgepole Formation, capped by the Mission Canyon carbonate bank of subprovince 1 and the eastern parts of subprovinces 2 and 3 (Gutschick and others, 1980). In the latter two subprovinces, the bank margin and transition westward to deepwater-deposited carbonates is currently under study by W. J. Sando. The transitional sequence is best exposed in the McKenzie thrust system (Fig. 5; Perry and others, 1985; Sandberg and others, 1985) of subprovince 3, where it has recently been described (Sando and others, 1985; Tendoy Group). The carbonate bank deposits of the upper part of the Madison Group have been a primary target for oil and gas exploration in the Montana thrust belt province. The geology of the Madison Group in the Montana disturbed belt sector (eastern part of subprovince 1) is summarized by K. M. Nichols, below. The upper sequence, equivalent to the Upper Mississippian Big Snowy Group of central Montana, is absent in the disturbed belt sector (subprovince 1, Figs. 1 and 2) and thin to absent in subprovince 2. In subprovince 3, this sequence is composed of a thin basal sandstone and overlying shale and limestone up to 2,000 ft thick near the depocenter of the upper Paleozoic Snowcrest trough (Perry, 1986) in rocks of the southern part of the Four Eyes Canyon thrust sheet (Fig. 5). These have recently been assigned to the Kibbey Sandstone and Lombard Limestone of the Snowcrest Range Group in southwestern Montana (Wardlaw and Pecora, 1985). Mississippian limestones, very similar to those of the southern Canadian Rocky Mountains, are present east of the Rocky Mountain trench (Fig.2) and west of Glacier Park in subprovince 1 (Johns, 1970) but have not been identified elsewhere in the Montana thrust belt province. These limestones are quite different from partially equivalent rocks of the Montana disturbed belt (W. J. Sando, oral communication, 1985) summarized in Figure 6. The differences between the two sequences may have a marked effect on the hydrocarbon potential of the bulk of subprovince 1 (excepting the area studied by Johns (1970) which lies on the original hanging wall of the Lewis thrust, dropped during Tertiary extension faulting) and that of the southern Canadian Rocky Mountains. The Canadian sequence is not known to be present in the subsurface in the Montana thrust belt province. It could be expected in lower plate rocks only under the northern part of Glacier Park, where the base of the Lewis thrust and presumably the lower plate section dip regionally to the south (Gordy and others, 1977).

Pennsylvanian sandstones are also present in the area studied by Johns (1970), although absent in the disturbed belt to the east (subprovince 1, Figs. 1, 2, and 6). Lower Pennsylvanian sandstone, red mudstone, and limestone, overlain by younger Pennsylvanian orthoquartzite and sandy dolostone thicken southward from a wedge-edge near the Lewis and Clark line (Fig. 1b) to a thickness of more than 2,500 ft in the Tendoy thrust sheet of subprovince 3 (Fig. 5). This great thickness of Pennsylvanian rocks was deposited near the depocenter of the Snowcrest trough (Maughan and Perry, 1982; Saperstone and Ethridge, 1984; Perry, 1986). The sharp southern boundary of this paleotectonic feature is shown in Figure 7. The younger Pennsylvanian sequence, entirely Quadrant Formation (Saperstone and Ethridge, 1984; Saperstone, 1986), is considered a possible reservoir rock and has been a target for oil and gas exploration in subprovince 3. The older sequence, which may be locally Late Mississippian in age at the base, has been placed in the Conover Ranch Formation at the top of the Snowcrest Range Group by Wardlaw and Pecora (1985). This older sequence rests with slight angular unconformity on the subjacent Lombard Formation in the northeastern part of subprovince 3, where a basal polymictic conglomerate, composed primarily of rounded limestone clasts, is present at the type section of the Conover Ranch Formation designated by Wardlaw and Pecora (1985).

Permian rocks of the Phosphoria and Park City Formations also thicken southward from a wedge-edge in or near the Lewis and Clark line to a maximum thickness of more than 800 ft (McKelvey, 1959) in the southern Tendoy thrust plate of subprovince 3 (Fig. 5). These rocks consist of a lower sequence of interstratified dolostone and sandstone and an upper sequence of chert, limestone, shale, organic-carbon rich phosphatic mudstone, and sandstone. These units can be traced laterally over long distances (McKelvey, 1959).

Triassic rocks are restricted to the southern edge of subprovince 2 and thicken southward toward the southern edge of subprovince 3. In the Exxon no. 1 Myers-Federal (drillhole no. 3, Fig. 7) at the southern edge of subprovince 3 these rocks are more than 1200 ft thick. These are predominately silty limestones, with redbed units at the top and middle: from base to top, the Dinwoody Formation, overlying redbeds of the Woodside Shale, Thaynes Limestone, and redbeds possibly equivalent to the Ankareh Formation of Wyoming (Perry, 1986). In the Tendoy thrust sheet to the north (Fig. 5), where only the lower three formations are recognized, a thickness of 1650 ft has been measured (Sadler, 1980); here 240 ft of redbeds beneath the Jurassic Ellis Group are considered to be "Gypsum Spring Tongue of the Twin Creek Formation" (Sadler, 1980, p. 136-153), a contention not supported by biostratigraphy. Only limestones and siltstones of the Dinwoody Formation are present to the northeast in the Blacktail Mountains salient (Fig. 1b; Pecora, 1981), where the middle and upper parts of the Triassic sequence have been removed by pre-Jurassic erosion. Farther north, the entire Triassic sequence has been removed by pre-Jurassic erosion (Peterson, 1985, 1986). Redbeds in the middle and top of this sequence thicken eastward from the southern part of subprovince 3 into the Rocky Mountain foreland (see drillhole summaries in

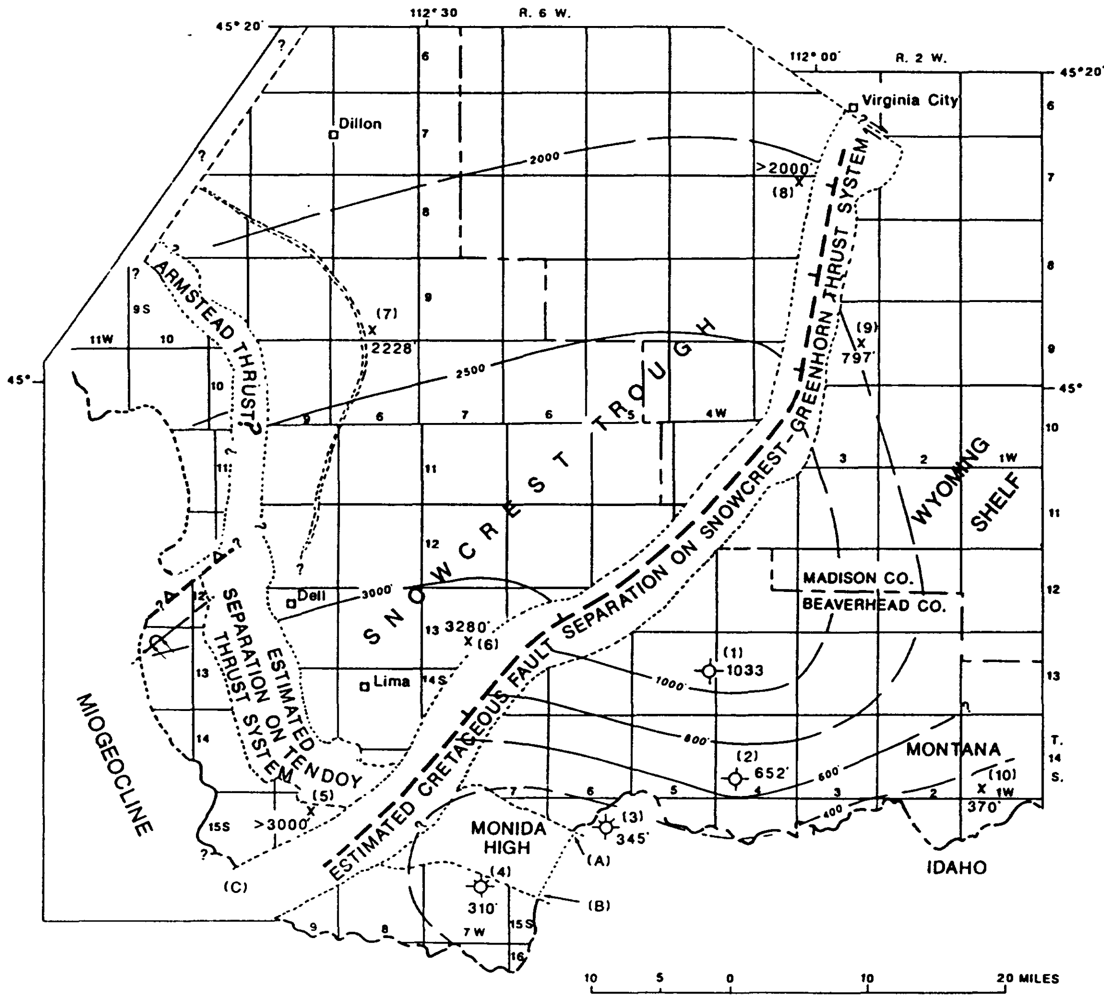


Figure 7. Palinspastic map of Lima region (subprovince 3) showing the Snowcrest trough, the inferred position of down-to-north normal faults (heavy dashed line), and the adjacent Wyoming shelf (from Perry (1986). Structural symbols as in Figure 2. Combined thicknesses of Upper Mississippian through Permian formations are contoured in feet. Dry hole symbols indicate locations of drillholes; x - locations of surface measured thicknesses. Drillholes 1 through 4 are briefly described and the sources of measured thicknesses 5 through 10 are given by Perry (1986). Drillhole 3 is the Exxon no. 1 Myers-Federal, TD 18,540 ft, which penetrated nearly to the base of the Cambrian Flathead Sandstone and indicates a westward thinning Devonian sequence as well as a very thin Upper Paleozoic sequence. Drillhole 4, the Amoco no.1 Snowline Grazing-Federal, TD 14,369 ft, encountered a very thin Upper Paleozoic sequence similar to that of drill-hole no. 3. Together these drillholes define the western part of the Upper Paleozoic Monida high of Perry (1986) and Saperstone (1986). Both encountered subcommercial quantities of natural gas in the upper part of the Mississippian Madison Group.

Perry, 1986).

Jurassic rocks, predominately shale and sandstone of the marine Ellis Group overlain by nonmarine Morrison Formation, occur in the Montana disturbed belt of subprovince 1, primarily east of, but partly beneath the Eldorado-Lewis subthrust play (Fig. 1b). The Ellis Group thickens westward from less than 200 ft to more than 600 ft in the disturbed belt sector (Peterson 1986, Fig. 15) and is absent throughout much of subprovince 2 where it pinches out against several paleohighs or welts (Boulder high and Belt Island complex of Peterson, 1985, 1986). In subprovince 3, Jurassic rocks are present at the surface only east of the Medicine Lodge, Four Eyes Canyon, and McKenzie thrust plates (Fig. 5). Jurassic rocks rest unconformably on a variety of older rocks in the Montana thrust belt province; the pre-Jurassic erosion surface represents a major unconformity in subprovinces 1 and 2. This unconformity diminishes in magnitude southward through subprovinces 2 and 3 with respect to pre-Jurassic rocks and does not form a major break in sequence in the southern part of subprovince 3 (see Peterson, 1985, 1986). Unlike the upper Paleozoic and Triassic sequences, which are absent by pre-Jurassic erosion in the disturbed belt (subprovince 1, Figs. 1, 2, and 6), the Jurassic sequence is thickest here and has been extensively described by Mudge (1972a).

Lower Cretaceous Neocomian rocks appear to be absent throughout the Montana thrust belt province. The Cretaceous sequence is generally floored by an undated chert-pebble conglomerate overlain conformably by redbeds and freshwater limestones of Aptian age assigned to the Kootenai Formation in western Montana (Peterson, 1985, 1986). These form the classic foreland basin sequence of Suttner and others (1981). In the disturbed belt (subprovince 1), the lower part of this sequence has been separated out as the Mount Pablo Formation (Mudge and Rice, 1982). The Kootenai is overlain by the Blackleaf Formation throughout the central and eastern parts of the thrust belt where not removed by subsequent erosion. The Blackleaf is composed of siliciclastic rocks including the oldest marine and marginal marine Cretaceous rocks in the Montana thrust belt (Flood and Taft Hill Members, Cobban, 1955; Mudge, 1972a). The upper part of the Blackleaf is dominated by nonmarine volcaniclastic rocks in subprovinces 2 and 3 (see for example Dyman, 1985). In the disturbed belt of subprovince 1, equivalent rocks are marine in part but also contain some material of volcanic origin (Mudge, 1972a). The overlying lower Upper Cretaceous Marias River Shale in the disturbed belt (subprovince 1) is 1,200 to 1,300 ft thick (Mudge, 1972a). Here it contains two calcareous black shale members which correlate to the Greenhorn and Niobrara Formations farther east (Cobban and others, 1976) and which may be classified as oil shales (W. A. Cobban, oral communication, 1988). This marine facies extends southeastward into the Helena salient east of the Boulder batholith (Cobban, written communication, 1988), where it is markedly thinner than in the disturbed belt (less than 600 ft on the eastern margin of the Boulder batholith, Klepper and others, 1971). The lower Upper Cretaceous sequence is predominately nonmarine to the south where it is being studied by T. S. Dyman and R. G. Tysdal. This sequence is assigned to the Frontier Formation in subprovince 3 (Perry and others, 1983a; Dyman and others, 1988) where locally it appears to be more than 7,000 ft thick. Younger Cretaceous sedimentary rocks are predominately nonmarine throughout the Montana thrust belt province (Peterson, 1985, 1986). They are composed chiefly of sandstone and conglomerate in subprovince 3, where thicknesses locally exceed 10,000 ft (Ryder and Scholten, 1973; Perry and others, 1983a). In the southern part of subprovince 2, they are intercalated with volcanic rocks. Thick sequences of volcanic rocks of this age are present in the neighborhood of the Boulder batholith (Fig. 1b)

(Klepper and others, 1971). A thick sequence of Upper Cretaceous volcaniclastic and siliciclastic nonmarine rocks is present west of the Boulder batholith (Gwinn, 1965). Farther north in the disturbed belt, these rocks are chiefly sandstones and red and green mudstones, with a few thin coal seams (Mudge, 1972a). A thin marine shale tongue, the Bearpaw Shale, thins and wedges out westward and southward in the eastern part of the disturbed belt (Cobban, 1955; Mudge, 1972a). In subprovince 2, the Upper Cretaceous sequence is dominated by volcanics and volcaniclastic rocks chiefly derived from the Pioneer and Boulder batholiths.

Tertiary rocks consist of nonmarine intermontane basin fill (Fields and others, 1985). Lake deposits are locally present above Eocene volcanic rocks in many of the basins. These grade upward into tuffaceous sandstone and mudrock, conglomerates, agglomerates and younger Tertiary lava flows in subprovinces 2 and 3. Oil shales are locally present. Distribution of the basins is shown in Figure 8.

SOURCE ROCKS

The occurrence of potential hydrocarbon source rocks in the Middle Proterozoic Prichard Formation of the lower part of the Belt Supergroup is discussed by Boberg (1985). This discussion is summarized below in the section on the Eldorado-Lewis subthrust play. Euxinic black shales are locally present near the top of the Belt Supergroup in the northwestern part of subprovince 1 (upper part of the Libby Formation, Wallace and others, 1984). These rocks are low in organic carbon (Harrison, oral communication, 1982) and have not been considered source rocks for hydrocarbons. On the southeastern flank of the Boulder batholith, in subprovince 2, several hundred feet of black calcareous argillite and carbonaceous limestone (unit 2C of Thorson, 1984) is reported in the lower part of the Belt Supergroup. These Belt rocks were formerly deeply buried, were intensely heated during Late Cretaceous igneous activity, and are not considered a likely source of hydrocarbons the Montana thrust belt province. In general, the middle and upper parts of the Belt Supergroup appear to be low in organic carbon.

Cambrian carbonate rocks throughout the Montana thrust belt province lack identified source rock potential. Interbedded with these carbonates are several green and red shale units which appear to lack source rock potential. In general, Ordovician through Middle Devonian rocks are absent by unconformity throughout the province, with the exception of a small area of subprovince 3, discussed above, where the relatively thin Ordovician sequence present appears to lack source rock potential.

The upper Middle and lower Upper Devonian rocks, primarily fetid dolostones, may have had limited source rock potential in the Montana thrust belt province, but are now generally supermature with respect to oil generation based on studies of the overlying Upper Devonian and Lower Mississippian Exshaw Formation and related rocks (Clayton and others, 1983; Perry and others, 1983a and unpublished data). Hydrogen sulfide gas is commonly emitted when fresh samples of these impermeable dolostones are crushed. The Exshaw in the northern part of subprovince 1 and equivalent carbonaceous shales in the southern part of subprovince 2 and throughout subprovince 3 are believed equivalent in part to the Bakken Shale of the Williston basin (Macqueen and Sandberg, 1970). These units have demonstrated source rock potential for gas generation but are generally supermature with respect to oil generation (Clayton and others, 1983; Perry and others, 1983a and unpublished data). Dark gray somewhat carbonaceous limestones are present in the lower part of the Madison Group in the disturbed belt, subprovince 1,

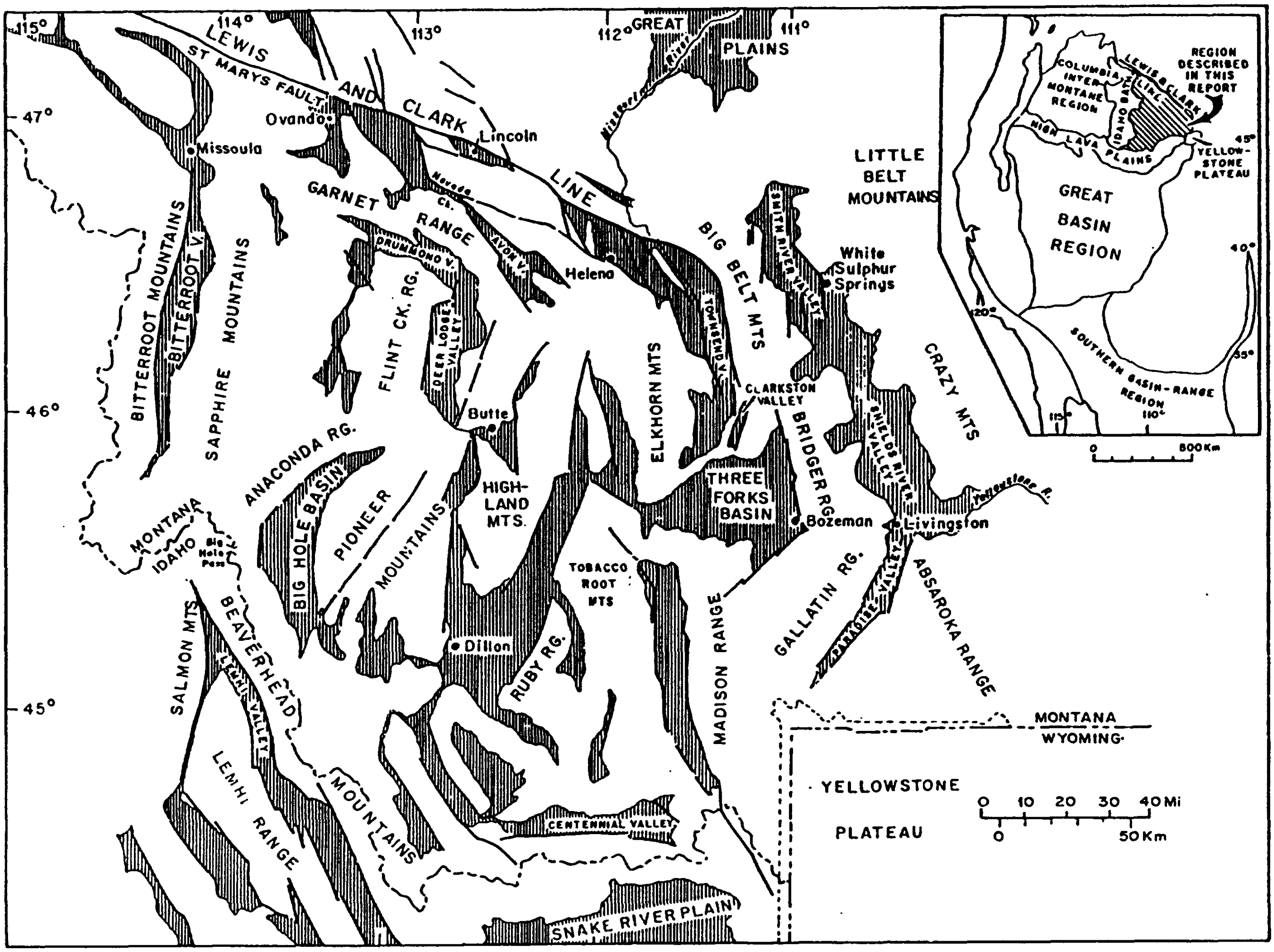


Figure 8. Generalized map of Tertiary to Quaternary basins (ruled) and ranges in western Montana and east-central Idaho, primarily south of Lewis and Clark line, from Reynolds (1979, Fig. 1). Extensional and transtensional basins are primarily west of Big Belt Mountains and Bridger Range.

west of the Boulder batholith in subprovince 2, and throughout most of subprovince 3. However, these appear to have limited source rock potential in the Montana thrust belt province. Dark-gray calcareous mudstones in the upper part of the Mississippian sequence in subprovince 3 contain up to 3% total organic carbon, have woody to herbaceous kerogen, and are gas-prone (Perry and others, 1983a). These rocks pinch out northward in subprovince 3, away from the depocenter of the upper Paleozoic Snowcrest trough (Perry, 1986), and are not found elsewhere in the Montana thrust belt province. Pennsylvanian rocks lack demonstrated source rock potential in the province.

The Retort Phosphatic Shale Member of the Permian Phosphoria Formation is a demonstrated oil shale in the northeastern part of subprovince 3 (Pecora, 1981) and is considered to be an oil-prone potential source rock in that region (Perry and others, 1981, 1983a). This unit is locally present west of the Boulder batholith in subprovince 2, but is absent in subprovince 1. Triassic rocks lack demonstrated source rock potential and are present only in subprovince 3 and the southern part of subprovince 2. Black shale units in the Jurassic Ellis Group appear to have hydrocarbon source-rock potential in the disturbed belt, subprovince 1 (Clayton and others, 1983) but do not have demonstrated potential elsewhere in the province.

Lower Cretaceous rocks are generally nonmarine throughout the province and lack demonstrated hydrocarbon source-rock potential except for the Flood Member of the Blackleaf Formation which is generally present throughout the eastern part of the province. This unit contains woody kerogen in the southern part of subprovince 3 (Perry and others, 1983a) and is there considered gas-prone. The lower Upper Cretaceous Marias River Shale of the disturbed belt (eastern part of subprovince 1) contains two calcareous black shale members which may be classified as oil shales (W. A. Cobban, oral communication, 1988). The lower, the Cone Member, averages 2.4% organic carbon and is oil-prone based on numerous samples analyzed and tabulated by Clayton and others (1983). The Marias River Shale thickens westward in the disturbed belt and is present beneath the Lewis thrust plate (Kulik, 1983; Mudge, 1983). This formation is mature with respect to liquid hydrocarbon generation in the eastern part of the disturbed belt and submature farther east (Clayton and others, 1983). The formation thins southward and may have limited source-rock potential in the eastern part of subprovince 2, east of the Boulder batholith. Overlying and laterally equivalent Upper Cretaceous rocks are generally nonmarine throughout the province and generally appear to lack source-rock potential.

The presence of oil shales in lake-bed deposits of Oligocene age in Tertiary basins in the Montana thrust belt province (Constenius, 1983; Fields and others, 1985; Peterson, 1985, 1986) caused a flurry of exploration activity during the early 1980's. No economic discoveries were generated, and the Tertiary rocks were found to lack effective porosity.

BURIAL HISTORY, THERMAL MATURITY, AND TIMING OF MIGRATION

Paleozoic rocks in the Montana thrust belt are supermature with respect to oil generation except for those on the hanging wall of the Lewis thrust (subprovince 1), the Tendoy thrust (subprovince 3), and the eastern part of the Blacktail Mountains salient, discussed below, which have not been deeply buried by overriding thrust sheets (Clayton and others, 1983; Perry and others, 1983a and unpublished data). In the eastern part of the disturbed belt (subprovince 1), Upper Cretaceous (Marias River) shales are immature with respect to liquid hydrocarbon generation (Clayton and others, 1983) and may be in the oil window beneath the Eldorado and Lewis thrust plates. To the south of the structural depression in the Lewis plate beneath Glacier Park (Gordy and others, 1977), subthrust Paleozoic rocks rise into the complex structural high represented by the Sawtooth Range (Fig. 2) where the entire section down into the Cambrian is exposed. Examples of exhumed oil deposits within the Madison Group are present in this area (R. B. Halley, oral communication, 1985). Updip to the east, major oil and gas accumulations are present on the Sweetgrass arch. The largest of these, the giant Cutbank field, lies in rocks submature with respect to oil generation (D. D. Rice, oral communication, 1987). Much of this oil and gas is believed to have been derived from updip migration from the disturbed belt to the west. The Sweetgrass arch is a forebulge in front of (east of) the thrust belt, which was a positive area before, during, and subsequent to thrusting (Lorenz, 1983). The tectonic model of thrust emplacement presented by Fritts and Klipping (1987a, Fig. 7) indicates that the Lewis thrust developed prior to the footwall imbrication beneath the Lewis plate. These factors when considered together suggest that hydrocarbon generation and migration from beneath the present disturbed belt occurred chiefly before subthrust traps were formed in subprovince 1. Unfavorable timing, elevated temperature history in the southern and western part of the subprovince, and the present depth of erosion appear to have all negatively impacted the hydrocarbon potential of subprovince 1. It would now appear that the earlier optimism concerning the petroleum potential of the disturbed belt (for example, Mudge and others, 1977, 1978, Perry and others, 1983b) was misplaced. Alternatively, subtle traps could be present, and since vast areas such as Glacier National Park and nearby wilderness areas have been withdrawn from hydrocarbon exploration, the case could be and has been made that large amounts of hydrocarbons remain to be discovered. However, the tectonic and erosional history of the region do not support such a contention.

Paleozoic rocks throughout the Montana thrust belt have generally very low porosity where encountered in the subsurface and thus appear to have limited reservoir potential. The history of volcanism and batholithic intrusions during and subsequent to Cretaceous thrusting, followed by Tertiary extension faulting with continued volcanism and extensive hydrothermal activity, appears to have had a severe negative impact on hydrocarbon potential for Paleozoic and younger reservoirs and traps, particularly in subprovince 2. The timing and temperature history of subprovince 2 is such that the only rocks considered prospective for hydrocarbons in this subprovince are those of the Tertiary basins. Several areas within subprovince 3 were considered to have moderate oil and gas potential (Perry and others, 1983b) based on the presence of submature source rock at the surface and inferred mature source rock at depth plus the presence of thick Mississippian and Pennsylvanian potential reservoir rocks and inferred structural traps (Perry and others, 1983a, 1983b). Subsequent drilling in critical parts of this subprovince has not revealed any hydrocarbon accumulations (Amoco - 1 Snowline Grazing-Federal, Fig. 7 and Perry, 1986; Amoco - 1 McKnight Canyon unit, Figs. 1b and 5, see Appendix). In each case, very low porosity and permeability was found in the subthrust sequence, and Paleozoic rocks encountered in the subthrust sequence were supermature with respect to liquid hydrocarbon generation. Many of the wells in this sub-province show evidence of fresh water flushing of hydrocarbons; i. e., low-salinity formation waters which appear to represent deep circulation of meteoric waters along Tertiary and Quaternary extension faults (data provided by industry). The thick upper Paleozoic sequence of the Snowcrest trough (Fig. 7) was structurally inverted during the Santonian to Campanian (Cretaceous) development of the Blacktail-Snowcrest uplift and the bulk of this sequence was eroded by mid-Campanian time (Perry and others, 1983a;

Nichols and others, 1985; Perry, 1986, and Perry and others, 1988), destroying any significant hydrocarbon potential within the former trough area. One possible exception is the Blacktail Mountains salient (Fig. 1b) on the northern margin of the trough. The abrupt southern margin of the trough produced rapid thinning of upper Paleozoic potential source and reservoir rocks southeastward onto the Wyoming shelf, possibly due to a system of upper Paleozoic down-to-north normal faults (Perry, 1986) along the Greenhorn lineament of Maughan (1983). The entire rock sequence in the southern part of subprovince 3 has been affected by late Tertiary to Quaternary high heat flow and extension faulting associated with development of the adjacent Snake River volcanic field to the south.

HYDROCARBON OCCURRENCES

Unlike the adjacent and contiguous Alberta foothills belt to the north, the Montana thrust belt has failed to yield appreciable hydrocarbons in spite of more than 80 years of exploration and approximately 110 wildcat wells, favorable source rocks in the eastern part of the province, and seeps in the northern part of subprovince 1. Oil and gas seeps were located along both the east and west sides of what is now Glacier Park as early as 1901 (Boberg, 1984). The first oil discovery well in Montana was completed in the Swiftcurrent oil field during the summer of 1905 at a total depth of about 550 ft in the eastern part of Glacier Park (Fig. 1b). The well only produced enough oil to display at the State Fair in 1905; operations were terminated in 1907. Based on the geologic setting and available records, the oil was probably from fractures in the Cone Member of the Upper Cretaceous Marias River Shale (Fig. 6). Between 1905 and 1907 one other oil well, with initial capacity of 20 bbl/day and two dry holes were completed in this area. Even in the economic climate of the times the Swiftcurrent oil field was not profitable, although it "has the nominal distinction of being the first oil and gas field in Montana" (Boberg, 1984). A similar oil discovery near East Glacier in the early 1980's proved subeconomic although oil at the time was bringing more than $30/bbl. A second exploration well was drilled about 1 mile to the east from 1907 to 1909, reaching a total depth of 2,800 ft and completed as a gas well in the Marias River Shale; the developer piped gas into his house until 1914 when the well was abandoned. This is credited as the first producing well in the State of Montana (above historical summary condensed from Boberg, 1984, p. 10-11).

Only one productive gas field is present in the Montana thrust belt, the two-well Knowlton field in subprovince 1 (Fig. 1b; officially the Blackleaf Unit field (Knowlton area), W. B. Hansen, written communication, 1988). This field has limited potential, 26 bcf in place, of which 19.5 bcf is recoverable (Napier, 1983). The two wells now producing in this field have yielded more than 3 bcf natural gas each and a total of more than 33,000 bbl. condensate, although the field has been shut in periodically due to contract problems and demand fluctuations (E. Neibauer, oral communication, 1988). The Blackleaf Canyon 1958 gas discovery just to the west has never been produced although 20 bcf gas in place is estimated (Johnson, 1984). Development of the Blackleaf Canyon gas reservoir has been delayed by environmental considerations. Such concerns and resulting litigation have delayed or curtailed oil and gas exploration throughout much of subprovince 1. The presence of the giant Waterton gas field (Fig. 1b) north of Glacier Park in southern Alberta, Canada (Gordy and Frey, 1977, p. 87-89), continues to spur interest in the hydrocarbon potential of subprovince 1. However, the Waterton field lies north of a major structural depression beneath the Lewis thrust sheet centered beneath Glacier Park (Gordy and Frey, 1977; Kulik, 1983) and west of the northern terminus of the Sweetgrass arch, such that the Waterton field lies in an optimal area for hydrocarbon accumulation. The smaller Lookout Butte gas field (Fig. 1b) southeast of the Waterton field lies on the southern flank of this area. More than a dozen exploratory wells have been drilled in the eastern part of subprovince 1 and one very deep test in the western part of subprovince 1 during the 1980's (source of data, various articles in Montana Oil Journal). None were productive; few had significant hydrocarbon shows.

More than 60 years of exploration in subprovinces 2 and 3, including at least 46 wildcat wells, have failed to discover commercial quantities of hydrocarbons. Much of this exploration investigated closures defined by seismic reflection methods in areas considered by industry to have the best oil and gas potential based on potential source rock and reservoir studies.

DISCUSSION OF PLAYS

Because of continuing interest in subprovince 1, two possible plays are considered below: the Eldorado-Lewis subthrust play and the Frontal imbricate play. No viable hydrocarbon plays have been identified in subprovince 2, based on the many negative factors discussed above. The Blacktail Mountains salient play in subprovince 3 is discussed below.

BLACKTAIL SALIENT PLAY

The play area is shown on the attached map (Fig. 1B). The convex-eastward curvature of the thrust belt in this area, including the McKenzie thrust system, is designated the Blacktail Mountains salient. The play is chiefly structural and is based on the supposition that subsurface structural traps are present within the play area. The play area is ovate, extending approximately 26 miles north-south and 19 miles east-west.

Geologic characterization

The play is bounded on the east by the front of the Montana thrust belt and on the west by a complex of down-to-the-west normal faults. Complexly imbricated Upper Devonian and Mississippian rocks occur in the eastern part of the McKenzie thrust system (Fig. 5 and Perry and others, 1988). This system was formerly included in the northern Tendoy, Limekiln, and Johnson thrust sheets (Scholten and others, 1955; Ryder and Scholten, 1973). From the southern edge of the play area, the front of the thrust belt extends northeastward to the eastern Blacktail Mountains (at 45^{o} N, 113^{o} 36′ W) chiefly under younger cover, on the basis of mapping by Pecora (1987) and unpublished mapping by J. C. Haley.

Imbricate slices within the McKenzie thrust system comprise at least two duplexes, i. e., stacked thrust slices bounded by roof and floor detachments: The lower duplex involves a unique suite of platform to basin Kinderhookian to Meramecian (chiefly Lower Mississippian) carbonate rocks of the newly defined Tendoy Group (Sando and others, 1985), very different from the Madison Group to the north. This imbricate stack appears to floor within the Upper Devonian and Lower Mississippian Three Forks Formation and roof within the Upper Mississippian Kibbey Sandstone. The upper duplex involves Upper Mississippian rocks above the Kibbey Sandstone. A minimum of four miles of eastward displacement of the McKenzie plate can be demonstrated along the bounding thrust at the northern margin of the plate.

Sapropelic source rocks in the play area include the Retort Phosphatic Shale Member of the Permian Phosphoria Formation and Bakken equivalents within the Three Forks Formation, namely the basal Sappington Member (Johnson and others, 1985, Fig. 3). Clinker beds within the Sappington exposed in the McKenzie thrust system suggest a high original total organic carbon (TOC), in excess of the 7.5% TOC previously reported (Perry and others, 1983a). The type area of the Permian Retort Member lies within the Blacktail Mountains salient. It is a demonstrated oil shale where it was retorted at Retort Mountain in the northeastern part of the play area. Source rocks in the Lombard Limestone (source rocks equivalent to the Heath Formation of the Big Snowy Group) may also contain sapropelic kerogen, although analyses in Perry and others (1983) show mainly woody to herbaceous kerogen in the Lombard where sampled farther south, in the Lima, Montana area.

Potential reservoir rocks include the Pennsylvanian Quadrant Sandstone, which thickens southward into the keel of the upper Paleozoic Snowcrest trough (Perry, 1986; Saperstone, 1986), underlying sandstones and carbonate rocks of the Mississippian and Pennsylvanian Conover Ranch Formation (rocks formerly assigned to the Amsden Formation), and limestones of the Mississippian Madison Group with possible karstic porosity and secondary dolomitization near the top of the Mission Canyon Limestone.

Rocks at the surface in the northeastern part of the play area are submature with respect to oil generation. Those of the McKenzie thrust system are late mature to supermature. Possible structural traps in rocks of favorable thermal maturity are anticipated to underlie the frontal part of the McKenzie thrust system, the northern Red Rock Valley to the east and the western Blacktail Mountains (beneath Cretaceous through Quaternary cover). The recognition of the Blacktail Mountains salient in the southwestern part of the Montana thrust belt with its complex structural patterns and platform-to-basin carbonate sequence provides new exploration targets in southwest Montana. The play is mainly structural and will be chiefly developed on the basis of seismic data. The distribution of possible structural traps is not publicly available.

Status of exploration

Only one well has been drilled within the area of this play, a 4,351 ft test drilled 7 years ago by American Quasar (A on Fig. 1B) in the northeastern part of the play area. The completion report of this well listed shows of gas in the Madison and total depth in Devonian rocks. Recent examination of the cuttings from this well by American Stratigraphic Company (AMSTRAT log no. M-3313) revealed that the shows actually occurred in rocks of the Conover Ranch Formation and the test bottomed in Upper Mississippian Lombard Limestone. Numerous black shale stringers were encountered in both the Conover Ranch and Lombard as well as slight oil cuts in the deeper section. The apparent dip of the section drilled is very steep as indicated by "stretched" section, and the well appears to lie near the leading edge of a nonsurfacing thrust.

A 16,000 ft Quadrant test, the Amoco No. 1 McKnight Canyon Unit (Fig. 1B), drilled in section 21, T.12 S., R 10 W., just south of the play area, encountered complexly faulted rocks of the Beaverhead Group (Cretaceous synorogenic deposits; see summary log in Appendix). The test was located in part on the basis of partial oil saturation of Upper Cretaceous rocks of the Beaverhead Group at the surface, oil possibly generated beneath the salient. Triassic and older rocks encountered below 7495 ft in this drill-hole contained dead oil. Abundant Cretaceous(?) intrusive rocks were encountered between 11,570 and 12,230 ft in this drill-hole (see Appendix).

ELDORADO-LEWIS SUBTHRUST PLAY

This structural play extends southward from the International Boundary with Canada to the south side of the extension of the Scapegoat-Bannatyne trend (Fig. 1B; Mudge, 1983). The play is based on the probability of Waterton-type imbricate stacks of thrust sheets beneath and just forward of the ramp(s) of the Lewis and Eldorado thrust sheets (Fig. 2)(Gordy and others, 1977; Kulik, 1983, Fritts and Klipping, 1987a, 1987b). The western boundary of this play is the Rocky Mountain trench. The eastern edge is the leading edge of the Eldorado-Lewis thrust complex south of Glacier Park and the front of the Lewis thrust in Glacier Park.

Geologic characterization

This is primarily a geophysical play for which we only have indirect data south of the International Boundary, (1) gravity modeling by Kulik (1983) and inferences based on reflection seismic data by Fritts and Klipping (1987a, 1987b), (2) the known position of certain major Tertiary normal faults which are widely suspected to have developed over ramps in the Lewis and Eldorado thrust systems (Gordy and others, 1977; Price, 1981), and (3) the positions of major synclines and culminations in the disturbed belt (Mudge and Earhart, 1983) which provide important clues to the thrust stacking at depth. This play differs from the Frontal imbricate play, described below, in that it includes the rocks beneath the Lewis thrust sheet under Glacier Park as well as beneath the Lewis and Eldorado thrust sheets farther south. Only in the vicinity of Glacier Park does it extend to the mountain front. Reservoir rocks are considered to be primarily those of the Frontal imbricate play: dolostones of the upper part of the Madison Group (see discussion by K. M. Nichols, below). Source rocks are anticipated to include the Cretaceous Marias River Shale in the Glacier Park area and Cretaceous Flood Member of the Blackleaf Formation, dark shales and mudrocks of the Jurassic Sawtooth and Rierdon Formations, and Devonian and Mississippian Exshaw Formation, throughout the play area. Of these units, only the Flood Member of the Blackleaf Formation is well developed in the southern part of the play area. South of the Scapegoat-Bannatyne trend and its southwestern extension under the disturbed belt, syntectonic and post-tectonic igneous activity indicates regionally high heat-flow conditions during the Late Cretaceous and early Tertiary (M.R. Reynolds, oral commun., 1985). No deep wells have been drilled within the area of this play.

Nature of expected hydrocarbons and traps

Gas analyses from the Knowlton field (Fig. 1B) and Blackleaf Canyon area show more than 11.4% CO_2 (Johnson, 1984). Potential Madison reservoirs beneath the Lewis and Eldorado thrusts should be even higher in CO_2, based on the results of recent wells drilled by Shell Canada northwest of Glacier Park, which "encountered CO_2 in porous zones in subthrust Paleozoic rocks" beneath the Lewis thrust (Fritts and Klipping, 1987b). A discussion of the ARCO 1 Paul Gibbs deep test (Fig. 1B) (TD 17,774 ft) drilled west of the Rocky Mountain trench (Boberg, 1985) indicates that gas shows encountered in the Prichard Formation of the Belt Supergroup are probably indigenous to the Prichard, which "contains intervals with sufficient organic carbon to have acted as a hydrocarbon source rock for much of its greater than 1,300 m.y. existence". However, these rocks underwent low-grade metamorphism in Precambrian time (E. R. Cressman, oral communication, 1988). Therefore the Prichard could have been the source of dry gas and possibly the CO_2 encountered farther east. Structures, primarily inferred imbricate stacks of Madison and older rocks (Fritts and Klipping, 1987a, 1987b), are larger than those in the Frontal Imbricate play.

FRONTAL IMBRICATE PLAY

The Frontal imbricate play is a hydrocarbon play primarily in Mississippian carbonate rocks involved in small imbricate or pop-up structures (Fig. 9) in front of the Eldorado and Lewis thrusts in the eastern part of and east of the Bob Marshall Wilderness and east and south of Glacier Park in the Montana disturbed belt, subprovince 1 of the Montana thrust belt. Following Harrison (1974), the disturbed belt is restricted to the eastern part of subprovince 1 (Figs. 1 and 4). The play area is shown in Figure 1B.

Geologic characterization

This play is broken into two parts based on geology: (1) the eastern part of the disturbed belt characterized by numerous closely spaced thrust faults involving chiefly Upper Cretaceous rocks (subbelt I of Mudge, 1983, Fig. 2); (2) the western part of the disturbed belt, near and west of the mountain front, but east of the Lewis and Eldorado thrusts, in which Devonian and Mississippian rocks are imbricately thrusted (subbelts II and III of Mudge, 1983, Fig. 2). The disturbed belt sector of the Montana thrust belt has undergone a structural and stratigraphic history similar to the Alberta foothills thrust belt which contains major reserves of gas from Mississippian carbonate rocks (Gordy and Frey, 1977). Numerous maps and reports by M. R. Mudge and others, have described the geology of the play area; much of this work is summarized by Mudge (1983). Perry and others (1983b) assigned the western part of this play area a relatively high resource potential based in large part on identified source rock: Marine shale of Jurassic and Cretaceous age contain abundant organic material, much of which is demonstrated oil-prone source rock (Clayton and others, 1983). The Cone Member of the Upper Cretaceous Marias River Shale contains the greatest amount of hydrogen-rich kerogen (greatest oil-generating capacity) with an average TOC of 2.4 wt. % organic carbon (Clayton and others, 1983). Anticipated and demonstrated reservoir rocks in the play area are chiefly dolomitized limestones of the upper part of the Madison group, described by K. M. Nichols, below. Traps are structural, the faulted leading edge of reservoir rocks in the upper plates of imbricate thrusts and associated pop-up structures (Figure 9). Folding is secondary.

Exploration status

Drilling operations have been curtailed during the past decade in much of the western part of this play by environmental considerations and litigation. Oil and gas exploration has been conducted in the eastern disturbed belt, chiefly on private lands east of the mountain front for many years, which has been almost uniformly unsuccessful. One two well field (the Knowlton gas field) has been developed in the Madison Group on a cross-structure in which the basement is higher than in other parts of the disturbed belt (Mudge, 1983, Fig. 4). Oil and gas fields on the Sweetgrass arch to the east (Dyman, 1987), the larger of which were discovered in the 1920's, are now depleted or undergoing secondary or tertiary recovery. The significance of these fields on the Sweetgrass arch is discussed above under hydrocarbon occurrences and by Dyman (1987). Production there has been chiefly from stratigraphic traps in Cretaceous as well as Mississippian rocks.

Anticipated hydrocarbons and traps

No oil has been discovered in Mississippian rocks in the southern part of the Alberta thrust belt near the United States, nor have commercial quantities of oil been discovered in Mississippian rocks in the Montana thrust belt. The Cone Member of the Marias River Shale has probably generated the subcommercial quantities of oil discovered to date in Upper Cretaceous rocks east of the Mountain Front. Gas and gas condensate are the principal hydrocarbon resources expected. More than 11% CO_2 is anticipated in Paleozoic reservoirs as discussed above in the Eldorado-Lewis subthrust play. Reservoirs discovered to date east of and near the mountain front in the disturbed belt have been disappointingly small (Figure 9; Johnson, 1984). However, the gas fields in the southern Alberta foothills belt of Canada (Boberg, 1984, Fig. 1), near the International Boundary, continue to attract exploration interest in the two plays discussed above.

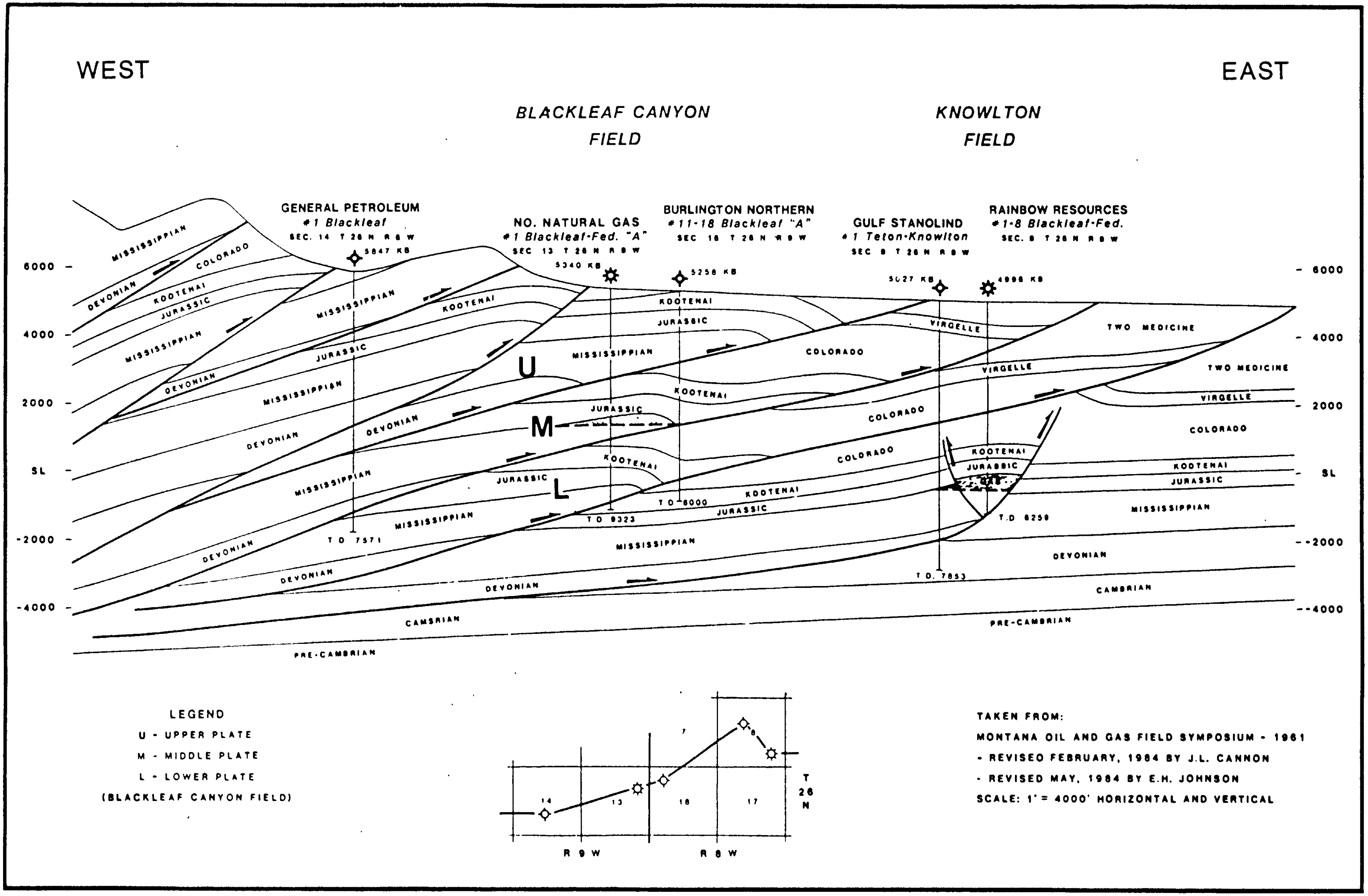


Figure 9. Cross section through Blackleaf Canyon gas reservoir and Knowlton gas field, Montana disturbed belt, from Johnson (1984, Fig. 1).

GEOLOGY OF POTENTIAL MISSISSIPPIAN RESERVOIR ROCKS, MONTANA DISTURBED BELT SECTOR OF THE MONTANA THRUST BELT

By Kathryn M. Nichols

Mississippian carbonate rocks are proven oil and gas reservoir rocks in parts of the northern Rocky Mountains. The upper part of the Mississippian sequence is the main reservoir in several fields on the Sweetgrass arch (Chamberlain, 1955), where these rocks were never deeply buried. These rocks in the foothills of Alberta have yielded abundant gas and gas condensate, particularly in the giant Waterton gas field just north of the International Boundary (Gordy and Frey, 1977). Cambrian and Devonian rocks in the Montana disturbed belt area have minimal reservoir potential.

Mississippian rocks in this area have been assigned to the Madison Group and range in thickness from about 900 to 1,200 ft. The Madison Group is divided into two formations, the Allan Mountain Formation below and the Castle Reef Formation above (Figs. 10 and 11; Nichols, 1984, Figs. 2 and 3). The Allan Mountain is mainly medium- to dark-gray limestone with some dolomitic limestone, whereas the Castle Reef is mostly light-gray dolomite and dolomitic limestone.

The most significant Mississippian potential hydrocarbon reservoir in the disturbed belt is the dolomitized crinoidal grainstone unit that forms the informal Gateway Pass unit of the Castle Reef Formation (Figs. 10 and 11). The Gateway Pass was originally included by Mudge and others (1962) in the Sun River Member of the Castle Reef Formation (Fig. 10). The Gateway Pass exhibits both vuggy and intercrystalline porosity (4-12%) and a permeability of 6-12 md. on surface exposures. Many of the pores are filled with dead oil in the Hannah Gulch section. The Gateway Pass has undergone eogenetic secondary dolomitization, probably in Late Mississippian time, and hence prior to any significant erosional events (Nichols, 1980). Porosity most likely resulted from solution effects during pre-Jurassic erosion, and was fully developed prior to deposition of the overlying Jurassic strata. Phreatic calcite cement partially occludes some of the pore space; the cement developed after migration of liquid hydrocarbons into the Gateway Pass. The Gateway Pass is the reservoir in the small Blackleaf Canyon gas discovery in the disturbed belt northwest of Choteau. Here porosity has been locally enhanced by extensive fracturing in the subsurface. Core analysis from the Northern Natural Gas No. 1 Blackleaf-Federal A well (Fig. 9), which tested 6.3 MMCF gas per day, indicates a net productive interval of 135 ft in the Gateway Pass, with porosity ranging from 8 to 11% and permeability from 10 to 15 md.

Crinoidal grainstone beds in the upper part of the Allan Mountain Formation have minor potential as a hydrocarbon reservoir. These beds exhibit moldic porosity after dissolution of bioclasts and show a surface porosity of 2 to 5% and are relatively impermeable (0.01 to 0.03 md).

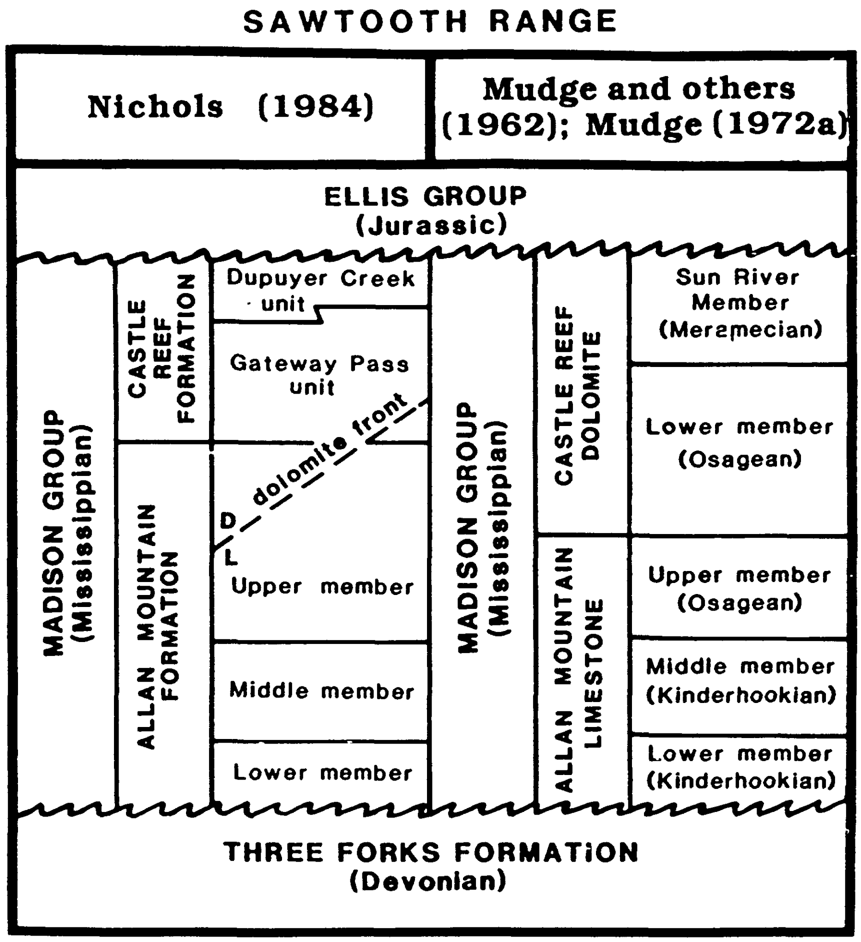


Figure 10. Comparison of rock-stratigraphic nomenclature of Mississippian carbonate rocks in the Sawtooth Range, Montana disturbed belt (eastern part of subprovince 2) from Nichols (1984, Fig. 2).

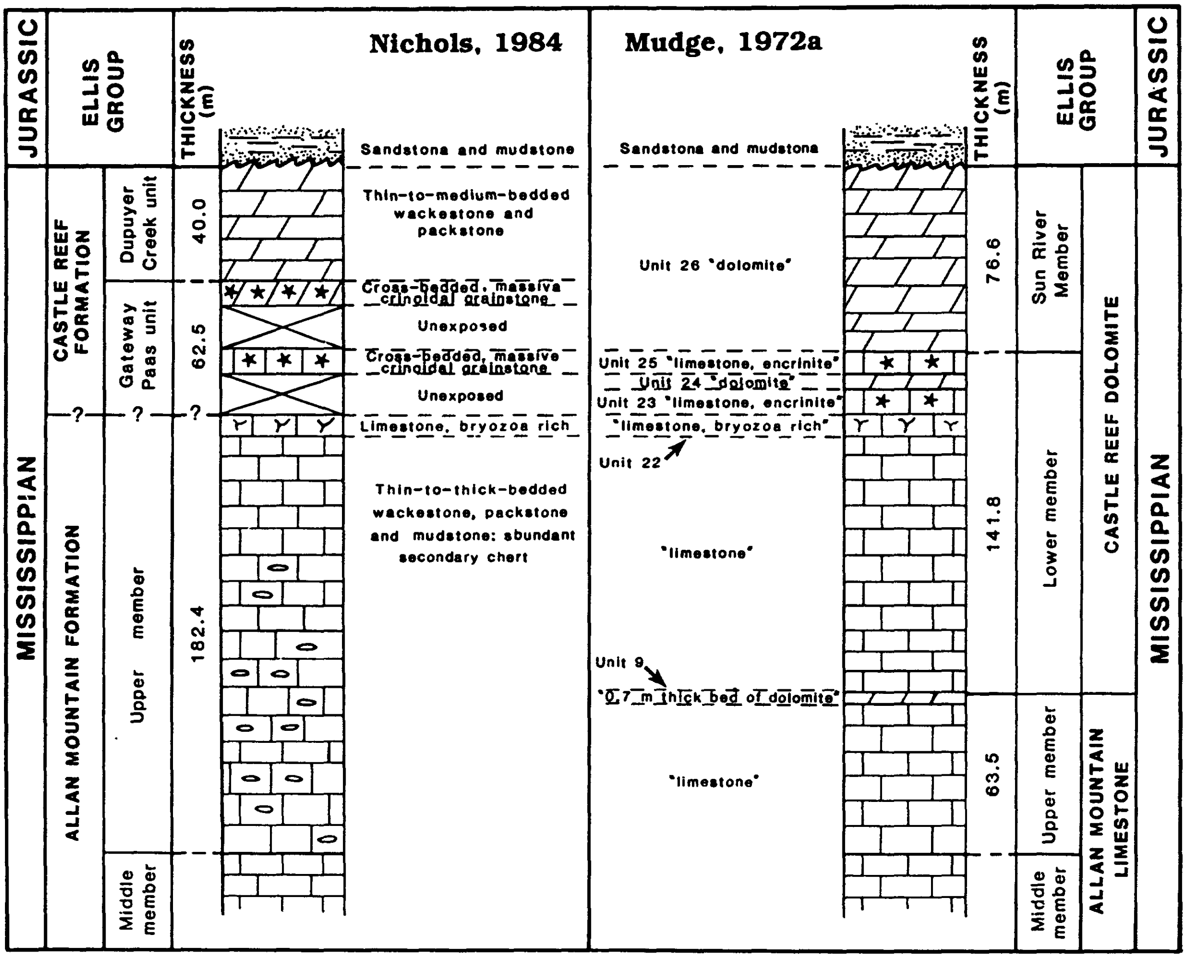


Figure 11. Stratigraphic columnar section of the upper part of the Mississippian Madison Group at Hannah Gulch, east-central Sawtooth Range of Montana disturbed belt, showing the redefined boundary between the Allan Mountain and Castle Reef Formations (from Nichols, 1984, Fig. 3). The stratigraphic position of the Gateway Pass and Dupuyer Creek units of the Castle Reef Formation is shown on the left. The equivalent measured section by Mudge (1972a) is shown on the right for comparison. Hannah Gulch is locality 'HG', Figure 2.

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APPENDIX

Amoco Production Company no. 1 McKnight Canyon Unit
T. 12 S., R. 10 W., 1187′ FSL, 1804′ FWL, (se sw) Sec. 21
Kidd MT 7 1/2′ Quadrangle
Beaverhead County, Montana

Drilling began 1-02-86; completed 6-21-86
Elevation 6911 ft GL; 6934.5 ft KB.
Total Depth 16,000 ft driller, 15,966 ft on density and sonic logs.

Tops inferred from gamma ray, density, sonic, drilling time, and sample logs. Some information provided anonymously by petroleum geologists from industry. Contacts above 4,000 ft are approximated from sample logs.

Samples begin @ 367 ft in Cretaceous rocks: member c of Beaverhead Formation of Lowell and Klepper (1953), now Beaverhead Group; base of unit at about 2660 ft. All rocks encountered from the surface to a depth of 7,453 ft are herein interpreted as Beaverhead Group (Cretaceous).

	Top	Base (feet)
McKnight limestone unit[1], member b as above	2,660	2,800
sandstone and claystone, with some volcanic ash? and a variety of clasts (steep dip suspected)	2,800	2,940
sandstone and shale with some limestone conglomerate; basalt? clasts probably from near top of interval; interval may be very steeply dipping and likely represents little true thickness	2,940	4,000
limestone conglomerate (possibly Lima Conglomerate, if so, base of interval is overturned)	4,000	4,150
sandstone and shale (equivalent to beds above 2,940 ft?)	4,150	4,475
reverse fault (or overturned section) @ about 4,475 ft		
Kidd quartzite and argillite conglomerate unit[1]	4,475	5,392
sandstone and shale (equivalent to beds above 2,940 ft?) (volcanic ash reported in interval 5,520-5,640; dark gray to gray blocky shale in interval 5,640-5,780 appears similar to that of Alder Creek pollen locality)	5,392	5,797
Kidd quartzite and argillite conglomerate unit[1] (top overturned or beneath reverse fault?)	5,797	6,605
sandstone and shale (equivalent to beds above 2,940 ft?, interval below 6,500 ft appears normal)	6,605	6,738
limestone conglomerate (probably Lima Conglomerate)	6,738	7,300
siliciclastic rocks (reported quartzite and argillite conglomerate may be chiefly cavings; interval may be similar to basal Beaverhead on Tendoy plate)	7,300	7,453
UNCONFORMITY		
Woodside Formation (Triassic)	7,495	7,788
Dinwoody Formation (Triassic)	7,788	8,524
Phosphoria Formation (Permian)	8,524	8,850
Quadrant Sandstone (Pennsylvanian)	8,850	9,285
KIDD THRUST (of Perry and others, 1988) @ 9,285 ft		

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[1]Various informal stratigraphic units of Beaverhead Group are from Ryder and Scholten (1973) as modified by Perry and others (1988), except as noted.

Kidd quartzite and argillite conglomerate unit[1]	9,285	11,410
sandstone and shale (equivalent to beds above 4,000 ft?, contains weathered basalt? clasts)	11,410	11,570
Cretaceous(?) igneous rocks	11,570	11,705
UNCONFORMITY (obscured by igneous intrusives)		
Intercalated Mississippian limestone and Cretaceous(?) igneous rocks	11,705	12,230
Mississippian rocks:		
Lombard Limestone	11,705	14,300
Kibbey Formation	14,300	14,428
Mission Canyon Limestone	14,428	15,695
Lodgepole Limestone	15,695	TD 16,000