Rocks and Structure of the Southern Sapphire Mountains, Granite and Ravalli Counties, Western Montana

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M. R. WATERS, and J. D. OBRADOVICH

A description and map of a thrust-sheet terrane dominated by the Middle Proterozoic Belt Supergroup and Cretaceous intrusive rocks

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[Plate in pocket]

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Rocks and Structure of the Southern Sapphire Mountains, Granite and Ravalli Counties, Western Montana

By C. A. Wallace, D. J. Lidke, M. R. Waters, *and* J. D. Obradovich

Abstract

Rocks in the southern part of the Sapphire Mountains are mainly units in the middle and upper parts of the Belt Supergroup (Middle Proterozoic), Late Cretaceous granitic plutons of the Sapphire and Idaho batholiths, and nonconsolidated gravels of Tertiary and Quaternary age. The Belt rocks in this area are allochthonous, part of the thrust-sheet terrane of the extensive Sapphire thrust plate.

The oldest sedimentary rock units are the Wallace Formation and the laterally equivalent Helena Formation; the Wallace is exposed over a large part of the map area, whereas the Helena comes to the surface only along the east edge of the map area. The Missoula Group, which overlies the Wallace and Helena Formations, includes, in ascending order, the Snowslip and Mount Shields Formations, the Bonner Quartzite, and the McNamara Formation. The Mount Shields Formation contains a carbonate-rich lithofacies in the uppermost part of member one; this unusual lithofacies has been mapped in the southern Sapphire Mountains and in the Flint Creek and Anaconda Ranges. The Missoula Group has an estimated aggregate thickness of about 6,600 m (21,650 ft) in the map area, although the thickness may be unreliable because of unidentified structural repetitions or deletions in the stratigraphic sequence. The Shepard Formation, which overlies the Snowslip Formation 35 km (22 mi) to the northeast, is absent in the map area probably because it thins to the south. The Garnet Range Formation overlies the McNamara Formation over most of the Sapphire thrust plate but was probably eliminated by thrust faulting in the map area. The Pilcher Formation, which forms the top of the Missoula Group in the north part of the Sapphire thrust plate, thins stratigraphically to the south and is absent 50 km (30 mi) northeast of the map area.

Bouldery gravel deposits of probable late Tertiary age formed on pediment surfaces in several places along the eastern boundary of the map area. Quaternary glacial deposits occupy many valleys, which were formed during extensive Pleistocene alpine glaciation. Minor deposits of Holocene alluvium occur in channels incised into till and outwash.

The main plutonic bodies are the Sapphire batholith, which occupies the central part of the map area, the Idaho batholith, which occurs along the southwestern and southern borders of the map area, and the Daly Creek stock, a small part of which is exposed along the northwestern border of the map area. The Sapphire batholith has an outer zone of biotite-hornblende granodiorite and biotite granodiorite and has a core of muscovite-biotite monzogranite and granodiorite; the batholith was relatively dry at the time of intrusion. Metamorphic mineral assemblages in the aureole and the absence of extensive penetrative deformation suggest that epizonal metamorphic conditions accompanied emplacement of the Sapphire batholith. Late-stage leucomonzogranite and porphyritic leucomicromonzogranite intruded the batholith as dikes, sills, and pods. Isotopic ages of the Sapphire batholith cluster at 73 Ma, and the batholith cuts thrust faults of the Sapphire thrust plate. In the map area, rocks of the Idaho batholith consist mainly of foliated tonalite and granodiorite that were intruded by irregular masses of monzogranite and by hypabyssal dikes and pods of rhyolite and dacite. The extensive migmatite border, complex deformation, and high-grade metamorphic minerals that formed in host rocks adjacent to the Idaho batholith suggest ductile deformation under mesozonal metamorphic conditions during intrusion. This ductile deformation may record continuation of compressional deformation at about 78 Ma. The Daly Creek stock is an epizonal, irregularly zoned body of granodiorite, quartz diorite, and tonalite. This stock was not studied in detail.

A geometric analysis and an interpretation of structural relations suggest the following sequence of deformation in this part of the Sapphire thrust plate: (1) Two flat thrust sheets were emplaced from the west. (2) The stacked thrust sheets were folded. (3) A younger imbricate thrust zone cut the folded thrust sheets. The oldest flat thrust cut the lower part of the Wallace and Helena Formations west of the map area as the Sapphire plate moved eastward, and at an unknown distance west of the map area a ramp formed that placed the Wallace and Helena Formations over most of the Missoula Group. A younger flat thrust undercut the ramp and formed another ramp a short distance west of the map area that cut the older thrust; this younger thrust carried a western

segment of the oldest thrust over an eastern segment of the older thrust. This sequence of deformation created a stack of thrust sheets that, in ascending order, consisted of the Wallace Formation, the Missoula Group, and the Wallace Formation. Thus, movement along only two thrusts created three thrust sheets and resulted in younger-on-older stratigraphic relations beneath the middle thrust sheet. Later deformation produced nearly isoclinal folds in the stacked thrust sheets in the western part of the map area and formed open folds in the central and eastern parts of the map area. Imbricate thrusts, which are younger than the stack of thrust sheets, form a zone along the eastern part of the map area.

The structural style of the thrust-sheet terrane of the Sapphire thrust plate implies that a large amount of crustal shortening could have occurred along master thrusts. Earlier estimates of the total shortening of the Sapphire thrust plate did not consider the effects of significant internal shortening within the plate.

Relations between isotopically dated rocks, thrust faults, and folds in the Sapphire thrust plate suggest that the thrust sheets were emplaced and folded before 81 or 82 Ma, the frontal imbricate terrane ceased movement before 82 Ma, and the younger zones of imbricate thrust faults predate 78 Ma and possibly 82 Ma. Geologic relations also suggest that the intrusion of plutonic bodies to epizonal levels in the stacked and folded thrust sheets followed the main event of compressional deformation in the Sapphire thrust plate.

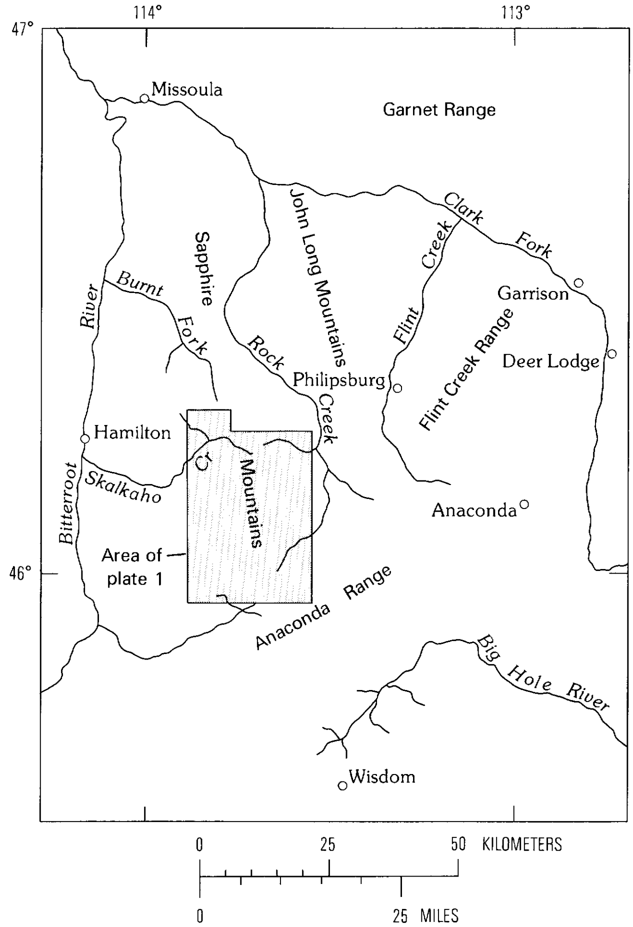

Figure 1. Location of map area and related geographic features in southwestern Montana.

INTRODUCTION

The south part of the Sapphire Mountains was mapped as part of a mineral resource potential evaluation conducted by the U.S. Geological Survey for proposed wilderness areas (Wallace and others, 1982; 1984). This area is about 33 km (21 mi) southeast of Hamilton, Mont., and about 39 km (24 mi) southwest of Philipsburg, Mont. (fig. 1). The map area straddles the crest of the south part of the Sapphire Mountains between Skalkaho Pass on the north and the East Fork of the Bitterroot River on the south. The southeastern part of the study area includes some of the northwest flank of the Anaconda Range.

Rocks in the map area are mainly thrust-faulted units of the Missoula Group and the Helena and Wallace Formations, which are all units of the Middle Proterozoic age Belt Supergroup, and these rocks have been intruded by the batholiths and smaller plutons, principally of granodiorite and monzogranite composition.[1] Metamorphosed Middle Proterozoic rocks in the central part of the map area range from hornblende-hornfels facies near intrusive contacts of the Sapphire batholith and plutons of Daly Creek to albite-epidote-hornfels facies away from these contacts. Rocks of the Idaho batholith are exposed in the south and southwest parts of the map area, and the metamorphosed rocks of the Belt Supergroup here exhibit polyphase deformation and high metamorphic grades. Felsic and mafic dikes and sills occur locally. Tertiary gravel deposits are sparse, whereas Quaternary glacial deposits are present in most valleys.

The first geologic map that showed stratigraphic and structural relations in the southern Sapphire Mountains was the 1:500,000-scale Geologic Map of Montana (Ross and others, 1955). Pederson (1976) produced the first detailed geologic map (1:24,000 scale) of part of the southern Sapphire Mountains as part of his study east of the topographic crest. Later work by Wallace and others (1982) produced a geologic map at a scale of 1:50,000 of most of the southern Sapphire Mountains. The geologic map included with this report is slightly modified from Wallace and others (1982).

Geologic mapping for this study was done by C. A. Wallace and D. J. Lidke in 1979, 1980, 1982, and 1983 and by M. R. Waters in 1983. Lidke examined about 100

[1]Intrusive rocks are classified according to the IUGS system (Streckeisen, 1973).

thin sections of igneous rocks in detail, and Wallace studied about 50 thin sections of metamorphic and sedimentary rocks. Feldspar composition was determined optically by standard flat-stage and Universal-stage methods. J. D. Obradovich determined isotopic ages of the Sapphire batholith using the potassium-argon method on mineral pairs of hornblende, biotite, and muscovite from five samples.

In this report we describe and interpret the sedimentary, igneous, and metamorphic rocks, describe the structural geology, and interpret the origin of thrust faults in the southern Sapphire Mountains. Proterozoic rocks are given the most emphasis in the section on sedimentary rocks and deposits; Tertiary and Quaternary deposits are described briefly. The discussion of the Middle Proterozoic succession presents only stratigraphic and sedimentary information; metamorphic characteristics of these rocks are treated in a separate section on metamorphosed Belt rocks. Intrusive rocks are discussed after the section on the stratigraphic sequence. Inasmuch as the intrusive bodies metamorphosed parts of the Belt sequence, metamorphic rocks are described and interpreted after the section on intrusive rocks. Concluding this report is a discussion of structural geology that includes the regional structural framework, structural elements in the southern Sapphire Mountains, and the sequential evolution of thrust faults. The geologic map (pl. 1, in pocket) provides field data upon which much of this report is based.

ACKNOWLEDGMENTS

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Don Winston (University of Montana) provided data about rock units in the Mount Emerine area, and D. P. Elston (U.S. Geological Survey) conducted investigations on the paleomagnetism of rocks of the Missoula Group near the map area, the results of which were made available to us. The text of this report was improved by reviews of P. D. Rowley, J. E. Elliott, J. M. O'Neill, and E. T. Ruppel (U.S. Geological Survey).

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SEDIMENTARY ROCKS AND DEPOSITS

Middle Proterozoic Rocks of the Belt Supergroup

Middle Proterozoic rocks of the Belt Supergroup exposed in the southern part of the Sapphire Mountains belong to the middle Belt Helena or Wallace Formations and to the overlying clastic Missoula Group, which includes, in ascending order, the Snowslip and Mount Shields Formations, the Bonner Quartzite, and the McNamara Formation. Rocks of the Ravalli Group, which elsewhere underlie the Helena and Wallace Formations, are absent from the stratigraphic succession.

Geologic studies in the southern Sapphire Mountains by Ross and others (1955), Pederson (1976), and Wallace and others (1982) have progressively refined understanding of the stratigraphic succession in the Belt Supergroup. Reconnaissance geologic mapping of Ross and others (1955) identified the main areas underlain by rocks of the Missoula Group and the "Newland limestone." Pederson (1976, p. 17–19) correctly determined that the "Newland limestone" of Ross and others (1955) is the Wallace Formation in most of the area Pederson studied. He divided the Missoula Group (Ross and others, 1955), into the Miller Peak Formation and Bonner Quartzite (Pederson, 1976, p. 26–30). The stratigraphic sequence determined by Pederson (1976) was modified by Wallace and others (1982): (1) Rocks of the Helena Formation were separated from the Wallace Formation. (2) Use of "Miller Peak Formation" was abandoned, as recommended by Harrison (1972), and the succession of Snowslip, Shepard, and Mount Shields Formations was used for rocks that overlie the Wallace or Helena Formation, (3) The McNamara Formation, which overlies the Bonner Quartzite, was separated from the Bonner Quartzite. Some rocks assigned to the Bonner Quartzite by Pederson (1976, p. 30–33) properly belong to member 2 of the Mount Shields Formation (Wallace and others, 1982). Only the lowermost part of the Snowslip Formation is exposed in the study area, and the Shepard Formation is absent.

Helena and Wallace Formations

The Helena Formation was deposited in the eastern part of the Proterozoic Belt basin, and the Wallace Formation was deposited in the western part of the basin. These two formations are considered to be lateral equivalents (Smith and Barnes, 1966; and Harrison, 1972), and each unit is probably more than 3,000 m (10,000 ft) thick in the central part of the Belt basin. The Wallace and Helena Formations form a lithologically distinct interval in the middle of the Belt Supergroup because they contain relatively high amounts of primary calcite and dolomite in beds and as cement in clastic rocks. Harrison (1972) used the informal term "middle Belt carbonate" for this interval. These formations are the oldest rocks exposed in the map area.

The Wallace and Helena Formations are considered to be intertonguing units in northwestern Montana (McKelvey, 1968; Harrison, 1972; and J. E. Harrison and J. W. Whipple, oral commun., 1984), but in the Sapphire Mountains of west-central Montana intertonguing relations are obscured by thrust faulting. In the southern Sapphire Mountains, intertonguing relations can only be inferred from interlayering of the different lithologies of these formations; the contact between the Wallace and Helena Formations is a tectonic contact throughout the Sapphire Mountains (Wallace and others, 1986). The Wallace Formation is the more widely exposed unit of the middle Belt carbonate in the map area. Along the eastern edge of the map area, rocks exposed in thrust slices below the Mount Shields Formation were originally identified (Pederson, 1976) as the Wallace Formation, but based on lithologic characteristics these rocks are here assigned to the western limy lithofacies of the Helena Formation (pl. 1).

Wallace Formation

The Wallace Formation is primarily a silty and argillaceous dolomite-bearing unit, in contrast to the clastic-poor, limestone-rich Helena Formation. In the map area a sequence of about 1,050 m (3,500 ft) of the middle Belt carbonate is assigned to the middle member of the Wallace Formation on the basis of bedding characteristics, dolomite content, and the occurrence of several zones of syndepositional breccia. The argillaceous upper member and the carbonate-rich, argillaceous lower member of the Wallace, which were mapped in the southern part of the Wallace quadrangle (Harrison and others, 1986), are not present in the map area. Neither the upper nor the lower contact of the Wallace Formation is exposed in the map area.

The middle member of the Wallace Formation is characterized by two intercalated lithofacies: (1) internally laminated and ripple cross-laminated, uneven-bedded, tan-weathering dolomitic siltstone interlayered with black-weathering argillite or dolomitic argillite, and (2) tan-weathering silty and sandy dolomite interbedded with whitish-weathering, unevenly bedded dolomitic siltite and quartzite. Some beds of limy siltite and impure limestone occur within the dominantly dolomitic rocks. Siltite and quartzite beds are uneven and laterally discontinuous and have scoured basal contacts, small-scale crossbedding, ripple cross-lamination, and sparse load casts. Carbonate-rich zones contain calcite pod and ribbon structures.

Syndepositional breccias (Wallace and others, 1976; Harrison and others, 1986) are especially characteristic of the Wallace Formation in the western part of the map area. The breccias probably occur at several levels in the middle member of the Wallace Formation, but the absence of stratigraphic control makes it impossible to determine the number and thickness of the breccia zones. Syndepositional breccias are composed entirely of angular and subangular blocks that clearly display composition and bedding characteristics typical of the Wallace Formation, and large clasts are enclosed in a matrix of smaller clasts and finely comminuted material that commonly has been dolomitized and silicified. Typically, the maximum diameter of clasts is about 4 m (12 ft), but some clasts in the Daly Creek area may be as much as 15–30 m (50–100 ft) in diameter, because erratic variations in attitudes suggest the presence of large blocks of bedded Wallace Formation enclosed in thick zones of breccia.

In the map area, the middle member of the Wallace Formation is bounded by thrust faults, and its true thickness cannot be estimated accurately. The maximum thickness measured from the geologic map (pl. 1) is about 1,050 m (3,500 ft), but the member may contain thrust faults that were not recognized. Elsewhere in the region, generalized stratigraphic reconstructions suggest that the Wallace Formation is about 3,000 m (10,000 ft) thick.

Helena Formation

Rocks of the Helena Formation are primarily limy argillite, limy siltstone, and impure limestone. No reliable estimate of thickness can be made from exposures in the Middle Fork of Rock Creek near Senate Mountain because of the tectonic complexity. Moreover, rocks of the Helena Formation exhibit crenulation cleavage and shear cleavage in these exposures, and details of bedding features are commonly obscured by this deformation. The base of the Helena Formation is not exposed and the Helena, like the Wallace Formation, is overlain by the Snowslip Formation.

In the map area, the Helena Formation consists of interbedded dark-gray limy argillite, argillaceous limestone and dolomite, and tan-weathering limy and dolomitic siltite. Laminated silty and argillaceous limestone dominate the sequence. Bedding is uneven and laterally discontinuous, and beds are internally laminated. Calcite-ribbon ("molar-tooth") structures and ripple cross-laminae are common. The abundance of calcite, the rare occurrence of siliceous quartzite, the absence of thickly bedded dolomitic siltstone and impure dolomite, and the absence of interbedded black-weathering argillite and tan-weathering dolomitic siltstone all suggest that these rocks properly belong to the western limy lithofacies of the Helena Formation.

The upper contact of the Helena Formation is exposed about 15 km (9 mi) north of the Senate Mountain area, where it appears to grade conformably into the overlying Snowslip Formation through an interval of about 60 m (200 ft). There, transitional beds of the uppermost Helena Formation are composed of thinly laminated, green and greenish-tan beds of argillite and dolomitic argillaceous siltstone; the upper contact of the Helena Formation is placed at the base of the lowest red argillite and siltite beds of the Snowslip Formation.

Missoula Group

The Missoula Group is the uppermost sequence of the Middle Proterozoic Belt Supergroup and is mainly composed of red and green argillite and siltite, quartzite, and minor conglomerate. The formations exposed in the map area are, in ascending order, the Snowslip and Mount Shields Formations, the Bonner Quartzite, and the McNamara Formation. These formations are about 5,550 m (18,200 ft) thick in the map area. The Shepard Formation, which occurs between the Snowslip and Mount Shields Formations 42 km (26 mi) northeast of the map area, apparently was not deposited in the southern Sapphire Mountains. The Garnet Range Formation and the Pilcher Quartzite overlie the McNamara Formation in the northern Sapphire Mountains near Missoula, Mont., but are absent from the map area. The Garnet Range Formation apparently has been eliminated from the map area by thrust faulting, and the Pilcher simply does not extend far south of the Clark Fork (Wallace and others, 1986).

Snowslip Formation

The Snowslip Formation is an interbedded argillite, siltite, and quartzite unit that is exposed about 2 km (1.3 mi) northwest of Kaiser Lake in the east part of the map and about 0.8 km (0.5 mi) southeast of the Senate Mine area. At these places the Snowslip lies with apparent conformity on the Helena Formation. Only the lower part of the Snowslip Formation is exposed in the map area; this rock unit is dominantly red but contains minor interbedded green zones. The lower 30 m (100 ft) of the formation contains coarse-grained, lenticular beds of muddy quartzite, oolitic and glauconitic quartzite, and abundant mud-chip conglomerate layers that are interbedded with unevenly laminated argillite and siltite beds. These lower beds are overlain by a zone of irregularly interbedded red and green argillite and siltite that contains randomly distributed, lenticular, argillaceous, fine-grained quartzite beds that typically are 2.5–15 cm (1–6 in.) thick. Very well-sorted, well-rounded, medium- to coarse-grained, white orthoquartzite beds are sparsely distributed in the dominant argillite and siltite unit; these distinctive beds are key features to identify the Snowslip Formation. Common sedimentary structures in the Snowslip are mud cracks, ripple marks, flaser bedding, small-scale cross-bedding, small channels, and water-expulsion structures.

The total thickness of the Snowslip in the mapped area is not known because most of the formation is eliminated by thrust faults. At least 460 m (1,500 ft) of the formation is present northwest of Kaiser Lake.

Mount Shields Formation

The Mount Shields Formation in the southern Sapphire Mountains contains three units, which correspond to the lower three members recognized regionally in the Belt basin (Schmidt and others, 1983). The Mount Shields Formation is overlain by the Bonner Quartzite in normal succession in the map area, but its base is not exposed. In ascending order, member one of the Mount Shields Formation is an argillite and quartzite unit (which also contains a carbonate-bearing interval at its top in the southeastern part of the map area), member two is a thickly bedded quartzite unit, and member three is an argillite-bearing quartzitic unit. A fourth member, a green argillite and siltite member, is recognized at the top of the formation in northern Montana by J. E. Harrison and J. W. Whipple (oral commun., 1983), but that member is absent here. The formation is estimated to be about 3,720 m (12,200 ft) thick in the southern Sapphire Mountains. Regional stratigraphic control, established in this study and in regional mapping of the Butte 1° by 2° quadrangle (Wallace and others, 1986), shows that member two of the Mount Shields Formation thickens and becomes coarser grained to the south in the Butte quadrangle. In the map area it has many lithologic characteristics similar to those of the overlying Bonner Quartzite.

Member one of the Mount Shields Formation is exposed in the core of the Meyers Creek syncline and exposed about 2 km (1.2 mi) west of Fox Peak; the basal contact is not exposed at either place. At both of these localities and farther north in the Sapphire Mountains, the upper contact with member two appears to be transitional. This contact is drawn at the base of prominent cliff-forming quartzite sequences. About 915 m (3,000 ft) of member one is exposed in the area of the Meyers Creek syncline, where a thrust fault bounds the base of the member.

In general, member one of the Mount Shields Formation is an argillite-quartzite unit that consists of argillaceous zones interbedded with feldspathic quartzite zones. Argillaceous rocks dominate in the lower part of the unit. Quartzite zones are thin in the lower part of member one but become progressively thicker and more abundant upward; argillaceous zones are progressively less abundant and thinner upward. Within the argillaceous zones, silty red argillite beds alternate with tan-weathering siltstone and fine- to medium-grained feldspathic quartzite beds, forming a red- and tan-striped sequence of fining-upward beds. Some argillaceous zones contain dolomitic and limy fine-grained quartzite and argillite. Quartzite zones contain thick beds and tan- and pink-weathering feldspathic quartzite that is moderately to well sorted and fine to medium grained; quartzite zones may contain some interbedded dispersed-framework pebble conglomerate. Individual bedding units in quartzite zones become finer grained upward, and their tops are generally defined by red silty or argillaceous layers.

A distinctive carbonate-rich lithofacies occurs in the uppermost part of member one on the ridge north of the Senate Mine. Although member one is metamorphosed near the Senate Mine, this distinctive lithofacies includes alternating zones of limestone, limy argillite, dolomite, sandy dolomite and limestone, dolomitic argillite, siltite, and silica- or carbonate-cemented quartzite. Zones of carbonate-bearing rock range from 10 cm to 3 m (4 in. to 10 ft) thick and are thinly bedded. Individual beds contain wavy thin laminae, ripple cross-laminae, and small-scale crossbeds. Edgewise conglomerates of dolomite and limestone clasts occur in some beds, and some of these contain oncolites and poorly developed stromatolites. Quartzite zones range between 1 and 100 m (3 and 330 ft) thick and resemble those in the carbonate-poor parts of the member. These carbonate-rich zones in the upper part of member one are interbedded with the alternating argillaceous and quartzite zones that typify the lower part of the member. At Senate Mountain, carbonate-rich rocks of member one are overlain by thick quartzite beds of member two, but the contact may be a fault, based on discordant bedding orientation. The carbonate-rich lithofacies has also been identified about 40 km (25 mi) to the northwest on the west side of the Sapphire Mountains and about 40 km (25 mi) to the northeast in the southern part of the Flint Creek Range. Bedding structures within the argillaceous zones of member one consist mainly of (1) thin planar laminae, mud cracks, and water-expulsion structures in argillite beds and (2) ripple cross-laminae, small-scale planar crossbeds, argillite-chip conglomerate, and channeled basal contacts in silty and sandy beds. In the carbonate-rich lithofacies edgewise conglomerate composed of rounded dolomite clasts, wavy laminae, ripple cross-laminae, argillite-chip conglomerate, and water-expulsion structures form the dominant sedimentary structures. Bedding structures in quartzite zones consist mainly of channeled contacts at the base of some quartzite beds overlain in turn by medium-scale crossbeds, ripple cross-laminae, and planar laminae at the top.

Member two of the Mount Shields Formation is exposed in the east and southwest parts of the study area; this unit forms the rugged topography along the crest of the Sapphire Mountains. Nowhere in the map area is a complete sequence exposed, because member two is bounded by thrust faults above or below. This member is estimated to be about 2,290 m (7,500 ft) thick, but it may contain faults that were not detected.

Member two consists of thick, evenly bedded, fine-, medium-, and coarse-grained feldspathic quartzite beds that locally contain lenticular beds of dispersed-framework pebble conglomerate in a sandy matrix. Composite bedding units generally range from 0.3–1.5 m (1–5 ft) thick. Bedding units that contain coarse sand or pebbles generally are progressively finer grained upward. Thin, lenticular red siltite and argillite beds occur locally in member two at the top of graded beds. Fine- and medium-grained quartzite beds are moderately to well sorted, whereas coarse-grained and pebbly rocks are generally poorly sorted. Most of these rocks are subarkose (Folk, 1968, p. 124), with feldspar forming 10 to 20 percent of the rock and lithic fragments present in trace amounts. Some medium-grained rocks contain less than 5 percent feldspar and are quartzarenite (Folk, 1968, p. 124). Microcline is the dominant feldspar; orthoclase and plagioclase are subordinate. Pebbly rocks contain more feldspar and rock fragments than do better sorted, finer grained rocks. Clasts in pebble conglomerates are primarily quartzite, red chert, and leucocratic fine-grained intrusive rocks. Sedimentary structures in coarse-grained rocks include graded bedding, planar and festoon crossbeds, channeled basal contacts, and argillite-chip conglomerates. Sedimentary structures in finer grained rocks are characterized by small-scale planar and festoon crossbeds, ripple cross-lamination, and planar lamination.

The upper contact of member two of the Mount Shields is gradational. Along the ridge southwest of Congdon Peak the contact is gradational across an interval of about 100 m (300 ft), in which thin interbeds of argillite become progressively more abundant between quartzites of the upper part of member two. The upper contact of member two is drawn where quartzite is replaced by argillite and thin, flaggy, fine-grained quartzite interbeds, the characteristic bedding style of member three.

Member three of the Mount Shields Formation is best exposed near Congdon Peak and on the ridge east of Lake Abundance. Only the lower part of this member is exposed, and the minimum thickness is 520 m (1,700 ft).

Member three consists of grayish-green feldspathic siltite and quartzite beds 2.5–20 cm (1–8 in.) thick that grade upward into purple or dark-gray argillite beds 0.3–3.8 cm (0.1–1.5 in.) thick. The proportion of argillite interbeds increases upward. Typical sedimentary structures are small-scale planar and festoon crossbeds, ripple cross-lamination, planar lamination, mud cracks, and water-expulsion structures. The dark-gray, purple, and grayish-green colors result from metamorphism of rocks that are normally buff, tan, pink, or red. The contact between the Mount Shields Formation and the Bonner Quartzite, which normally overlies it, is not exposed in the study area.

Bonner Quartzite

The Bonner Quartzite (Nelson and Dobell, 1961, p. 199) is exposed north of Skalkaho Pass in the Crystal Creek drainage, and on Mount Emerine. The formation is about 610 m (2,000 ft) thick in the area of Mount Emerine, where the middle and upper parts are best exposed, but it is about 90 m (300 ft) thick northeast of Skalkaho Pass, where only the lower part is exposed.

Most of the Bonner Quartzite consists of unevenly bedded fine-, medium-, and coarse-grained, granular and pebbly, feldspathic quartzite in which the grains are poorly to moderately sorted and subrounded to rounded. Bedding units are lenticular and generally are not separated by siltite or argillite beds as is common in the Mount Shields Formation. Composite bedding units range from 2.5 to 60 cm (1 to 24 in.) and many beds are normally graded. In the Skalkaho Pass region, where the lowest part of the Bonner is well exposed, conglomeratic beds are rare, although some thin, discontinuous beds of fine-pebble- and granule-bearing quartzite are interbedded with finer grained rocks. In the Mount Emerine area, the upper 60 m (200 ft) of the Bonner is finer grained than the main part of the formation. Fine-grained quartzite, siltite, dark-purple argillite, and argillaceous siltite mark the transition into the overlying McNamara Formation; the contact is apparently conformable.

McNamara Formation

In the southern Sapphire Mountains, the McNamara Formation (Nelson and Dobell, 1961, p. 201) is dominated by beds of fine-grained quartzite and contains subordinate zones of interbedded argillite, siltite, and fine-grained quartzite. About 760 m (2,500 ft) of the formation is exposed in the north part of the map area. The contact with the underlying Bonner Quartzite appears to be gradational where it is exposed near Fuse Lake and on Mount Emerine. The uppermost part of the McNamara is not present in the southern Sapphire Mountains.

Near Fuse Lake, north of the mapped area, and on the west flank of Mount Emerine, the lower 245 m (800 ft) is dominated by massive-weathering composite beds of fine-grained feldspathic quartzite; rare argillite beds are present as bedding-plane mud-drapes or as discontinuous layers 1.3–15 cm (0.5–6 in.) thick. Massive-weathering composite quartzite beds range from 1 to 2 m (3 to 6 ft) thick and are separated by thin argillite beds or by muddy siltite beds. Basal parts of composite bedding units commonly contain intraformational conglomerate of red chert and clay chips. Diagenetic chert clasts are common in the McNamara Formation, here and in other regions. However, beds of laminated chert, a second diagnostic feature of the McNamara in other regions, apparently are absent from these quartzites. The McNamara Formation in the map area is a coarser clastic lithofacies than equivalent rocks in the Missoula area or near Philipsburg. Zones of interbedded argillite, siltite, and feldspathic quartzite occur above the lower quartzite of the McNamara, but the stratigraphic position of these argillaceous zones is uncertain. Argillaceous zones are lithologically more typical of the McNamara to the north and east than is the basal quartzite, but a strict lithologic comparison of argillaceous rocks is not possible because outcrops south of Skalkaho Pass have been metamorphosed to muscovite-biotite schist.

Sedimentary structures common in basal quartzitic beds of the McNamara are small-scale planar and festoon crossbeds, ripple cross-lamination, planar lamination, channels, rib-and-furrow structures, and intraformational chert-bearing conglomerate. Although the basal part of the McNamara appears to resemble the quartzite member of the Mount Shields Formation, the basal quartzite of the McNamara is finer grained, contains smaller crossbed sets, and contains chert clasts.

Tertiary Deposits

Bouldery gravel deposits of probable Tertiary age form small discontinuous patches in the north and northeast part of the mapped area. Typically, these deposits are nonconsolidated, poorly sorted, and poorly stratified and contain angular to rounded boulders and cobbles in a pebbly, sandy, silty, and clayey matrix. Most of the large clasts are of local origin and can be traced to outcrops upslope from the deposits. Clasts in these deposits are commonly intensely weathered. Topographic surfaces developed on these deposits are smooth and slope gently upward to a sharp change in gradient at bedrock hillsides and talus slopes. These bouldery gravels probably represent deposits on pediments and are similar in origin to extensive deposits on pediments mapped to the northeast (Wallace and others, 1986). The bouldery gravel deposits are considered to be of Tertiary age because they locally contain clasts of Tertiary volcanic rocks (as in Anaconda Gulch, 5 mi (8 km) northeast of the map area) and because they are truncated by glacial deposits of Pleistocene age.

Quaternary Deposits

Quaternary deposits in the map area include Pleistocene glacial deposits of till and outwash and Holocene alluvial deposits. Holocene stream deposits (Quaternary alluvium) were mapped with glacial deposits in this area, except in the lower reaches of major drainages.

Most of the valleys in the study area were glaciated during the Pleistocene Epoch. The rugged topography along the crest of the south part of the Sapphire Mountains is a direct result of glacial erosion. Till is generally composed of poorly stratified, poorly sorted material in which angular to rounded boulders are dispersed in a matrix of cobbles, pebbles, sand, silt, and clay. Some larger clasts show faceted and striated surfaces. Extensive glaciers occupied the Ross Fork of Rock Creek and Copper Creek drainages in the east part of the study area, and till is plastered high on the slopes of U-shaped valleys at many locations. Well-preserved lateral moraines and hummocky surfaces characterize most till. Cirque basins in the southwest part of the study area contain glaciated bedrock surfaces that are commonly striated or polished. Large erratic boulders, small patches of till, and roche moutonnée surfaces are common in cirque basins. In the north part of the study area, glaciers were less extensive; till deposits are restricted to upper parts of drainages, and glacial erosion is absent in the lower parts of valleys.

Small areas of outwash deposits occur locally in places where stream gradients were relatively flat during Pleistocene time. These deposits consist mainly of nonlithified sand, sandy conglomerate, and minor interbedded pebbly zones. The outwash appears to have been deposited during the waning stages of glaciation.

Nearby ranges, such as the Anaconda and Flint Creek Ranges, preserve till from four glacial events (M. R. Waters, oral commun., 1985), but till and associated outwash in the southern Sapphire Mountains probably were formed during the youngest Pleistocene glaciation. The excellent preservation of hummocky topography and the immaturity of drainages developed on till and outwash suggest a late Pleistocene age for this glacial event.

Although nearly all streams contain some Holocene alluvium, these deposits were mapped separately in only a few places. Alluvium is composed of nonconsolidated bouldery and cobbly gravel in a sandy matrix, well-sorted cobble beds, and moderately to poorly sorted sand beds. Alluvial channels form a meandering pattern over till deposits, and in places channels are incised 3-15 m (10–50 ft) into the till.

PHANEROZOIC INTRUSIVE ROCKS

Intrusive rocks in the southern part of the Sapphire Mountains form three compositionally distinct and spatially separate plutonic masses: the Sapphire batholith is a zoned intrusive body that occupies the central part of the map area, plutonic rocks of the south and southwest border of the map area are part of the Idaho batholith, and intrusive rocks exposed in the Daly Creek area are the easternmost exposures of an east-trending, narrow pluton located northwest of the Sapphire batholith. The Sapphire batholith is the main intrusive body in the map area, and this plutonic complex is described in more detail than rocks of the Idaho batholith, which were discussed by Desmarais (1983), and plutonic rocks of the Daly Creek area, which have not been studied in detail.

The Sapphire batholith is a complex of six monzogranite and granodiorite bodies that have been intruded by late-stage leucomonzogranite and porphyritic leucomicromonzogranite dikes and sills. The batholith underlies about 235 km^2 (90 mi^2) of the central and northeastern part of the map area. Biotite-hornblende and biotite granodiorite form an outer zone of the batholith, which surrounds a core of muscovite-biotite monzogranite and granodiorite. Plutonic rocks of the Idaho batholith, south and southwest of the Sapphire batholith, include foliated monzogranite and granodiorite with tonalite borders; the contact of these plutonic rocks with rocks of the Belt Supergroup is marked by a high-grade metamorphic migmatitic aureole that records two deformation events (Desmarais, 1983). Intrusive rocks of Daly Creek are dominantly biotite-hornblende granodiorite and have a prominent hornblende-biotite quartz diorite border.

Sapphire Batholith

The Sapphire batholith is an epizonal, compositionally zoned siliceous and peraluminous complex that has biotite-hornblende- and biotite-bearing granodiorite in the outer zone and a two-mica granodiorite and monzogranite core. Compositional similarity and gradational contact relations of the outer zone and core rocks and isotopic dating suggest that the batholith was intruded in one episode, followed by intrusion of late-stage leucomonzogranite and porphyritic leucomicromonzogranite dikes, sills, and pods. Contacts of the batholith with Middle Proterozoic host rocks are generally sharp and discordant to bedding and to structures, although the northerly elongation of the batholith appears concordant with the regional northerly trend of thrust faults and some folds in Middle Proterozoic rocks of this region. Pederson (1976) mapped the east side of the Sapphire batholith, but he did not subdivide monzogranite and granodiorite bodies within the batholith.

Rocks of the Sapphire batholith range in composition from leucomonzogranite to granodiorite. Average modal analyses are given in table 1 and on figure 2; major-element chemical analyses for five samples are presented in table 2.

Outer Granodiorite and Leucomonzogranite Zone

Most of the outer zone of the Sapphire batholith is composed of four similar granodiorite bodies (Kg1, Kg2, Kg3, and Kbg); a single leucomonzogranite pluton (Klm) in the outer zone is small and restricted to the western side of the batholith. The granodiorites are texturally similar, but subtle differences in composition permit separation of these rocks by field observations and by petrographic data (table 1). The biotite granodiorite (Kbg) is distinguished from other plutons in the outer zone by characteristic light-gray plagioclase phenocrysts and by the rare occurrence of hornblende (table 1). The three biotite-hornblende granodiorite plutons (Kg1, Kg2, and Kg3), are separated by the following criteria: (1) Kg1 is the only biotite-hornblende granodiorite pluton that contains prominent pink alkali-feldspar phenocrysts (1–2 cm long); (2) Kg2 contains a larger percentage of biotite and hornblende than Kg3, and although the difference in percentage is small it is consistently recognizable. Granodiorite bodies show well-developed jointing, and the orientation of joints is different among the bodies. Foliation is rare and poorly developed in these rocks.

Contacts between granodiorites of the outer zone and Middle Proterozoic country rocks are sharp and discordant. Evidence of granitization or metasomatism of country rock is generally absent. Each of the biotite-hornblende granodiorite plutons has gradational porphyritic borders near contacts with Middle Proterozoic rocks and near contacts with other plutons. The most prominent porphyritic borders are shown on the geologic map (pl. 1) by a stippled pattern. Although porphyritic borders are present locally on the east side of the batholith, they have not been mapped there because they are not as continuous or as coarse grained as on the west side of the batholith.

Rocks from porphyritic border zones tend to be more siliceous than associated granodiorite more distant from contacts, and some porphyritic samples of the outer zone have modal compositions of monzogranite (fig. 2). Porphyritic rocks of the outer zone commonly contain biotite and a trace of muscovite; they lack hornblende. Phenocrysts are dominantly subhedral microcline and plagioclase.

The evidence suggests that porphyritic borders may have formed from interstitial enrichment of volatile components near the edges of the batholith during late-stage crystallization. This interpretation is supported by (1) the gradational contact between porphyritic zones and the main granodiorite plutons, (2) the relative increase in silica, potash, and soda with a concomitant decrease in calcium and iron in the porphyritic border, and (3) the gradational increase in the size of phenocrysts toward the country rock.

Contacts between granodiorite bodies of the outer zone are gradational; gradual changes in relative percentages of varietal minerals and subtle changes in grain sizes and color of phenocrysts occur over distances of 6–90 m (20–300 ft). The contacts are probably more uneven in detail than those shown on the map. Foliation, veins, xenoliths, and selvage zones are absent at contacts between granodiorite bodies in the outer zone. This suggests that the granodiorite bodies of the outer zone were intruded in one stage, cooled together, and represent slight chemical differences in the batholith.

A distinctive leucomonzogranite (Klm) separates porphyritic granodiorite of the outer zone from the country rock on the northwest side of the batholith (table 1). The leucomonzogranite has a sharp contact with porphyry border zones of the granodiorite bodies, but the absence of protoclasis in the leucomonzogranite suggests that this body was not forcefully intruded. At some places the leucomonzogranite (Klm) appears to be gradational with the porphyritic leucomicromonzogranite (Klmp), which suggests that these two bodies may be comagmatic. The leucomonzogranite occurs primarily between the porphyritic border of granodiorite plutons and the Wallace Formation. The leucomonzogranite is probably not a metasomatite or a reaction product between magma and the Wallace Formation, because calc-silicate and magnesium-rich minerals are absent. The more felsic composition of the leucomonzogranite and its sharp contact with granodiorite of the outer zone suggest that the leucomonzogranite crystallized somewhat later than the main batholithic mass from a residual liquid that was derived from the main part of the batholith.

Inner Two-Mica Monzogranite and Granodiorite Zone

The two-mica core of the batholith, located near Sand Basin, underlies an area of approximately 36 km^2 (14 mi^2). Core rocks are composed of biotite-muscovite monzogranite (Kbmm) and of biotite-muscovite granodiorite (Kbmg) (table 1). The occurrence of muscovite

Table 1. Average modal compositions (in percent) for plutonic rocks of the southern part of the Sapphire Mountains, Montana

[1,000 points per thin section; values less than 0.5 percent reported as a trace (tr). Dashes (---) indicate mineral not present]

Intrusive rock units	Number of samples	Essential minerals				Varietal minerals			Accessory minerals				Total
		Quartz	Ortho-clase	Micro-cline	Plagio-clase	Bio-tite	Horn-blende	Musco-vite	Epi-dote	Allan-ite	Opaque minerals	Sphene etc.[1]	
Plutons of the Sapphire batholith													
Leucomonzogranite (Klm)-----	4	29.7	6.2	30.7	32.9	tr	tr	---	tr	---	tr	tr	99.5
Core:													
Biotite-muscovite monzogranite (Kbmm)---	5	36.3	10.4	12.0	35.4	4.7	---	1.0	tr	---	tr	tr	99.8
Biotite-muscovite granodiorite (Kbmg)---	8	35.2	6.7	9.8	42.7	4.4	---	0.8	tr	---	tr	tr	99.6
Outer zone:													
Biotite granodiorite (Kbg)	6	34.5	14.1	4.7	39.9	5.4	tr	tr	tr	---	tr	tr	98.6
Biotite-hornblende granodiorite:													
Kg1---------------------	20	28.5	7.4	8.4	44.5	8.5	1.9	---	tr	tr	tr	tr	99.2
Kg2---------------------	10	30.9	3.6	12.5	43.3	7.4	2.0	---	tr	tr	tr	tr	99.7
Kg3---------------------	12	27.4	4.7	17.9	41.9	6.4	1.0	tr	tr	tr	tr	tr	99.3
Plutons of the Idaho batholith													
Biotite-hornblende granodiorite (Kgi):													
Tonalite border-----------	4	21.1	---	---	48.0	16.2	12.7	---	1.2	---	0.6	tr	99.8
Main body-----------------	3	31.3	6.1	8.1	43.0	8.5	2.1	---	0.6	---	tr	tr	99.7
Biotite granodiorite (Kbgi)	4	27.4	8.7	7.5	47.3	8.6	---	---	tr	tr	tr	tr	99.5
Tonalite (Kti)-------------	2	19.2	1.7	1.5	56.8	17.0	2.3	---	tr	tr	0.9	0.6	100.0
Plutons of Daly Creek													
Quartz diorite border (TKqd)	3	6.7	---	---	44.4	6.3	41.2	---	tr	---	1.1	tr	99.7
Biotite-hornblende granodiorite (TKb)------	2	23.5	1.3	13.6	51.3	7.5	2.3	---	tr	---	tr	tr	99.5

[1]Sphene, apatite, zircon, and calcite.

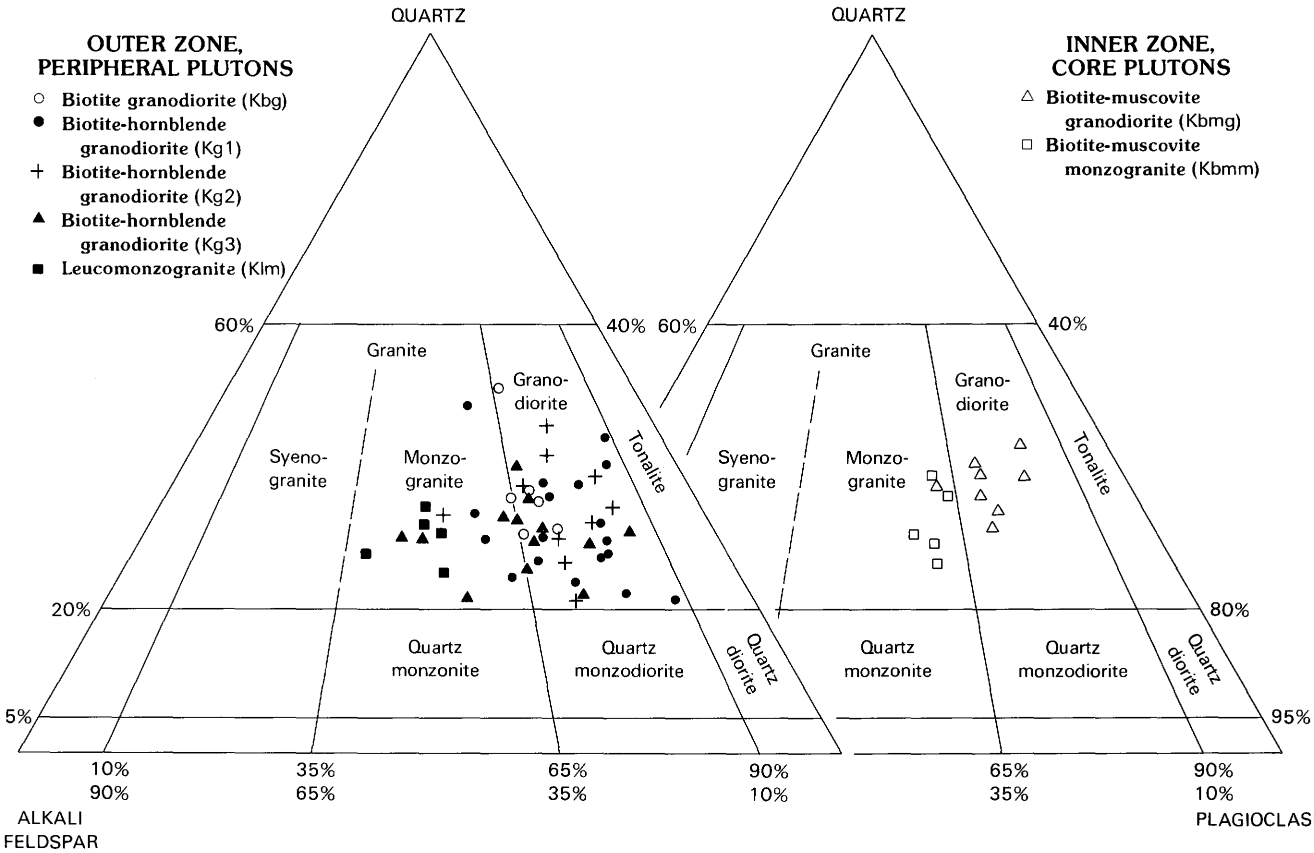

Figure 2. Modal compositions of plutons of the Sapphire batholith.

and the absence of hornblende are characteristic of these rocks and distinguish them from peripheral granodiorite bodies of the outer zone. Muscovite is present as individual grains (0.5 to 1.8 mm) that are commonly intergrown with late-stage alkali feldspar and biotite; most muscovite does not appear to be the result of deuteric alteration. The biotite-muscovite granodiorite (Kbmg) is the largest of the two intrusive bodies in the core; contacts are gradational between the two parts of the core. The biotite-muscovite monzogranite (Kbmm) is finer grained, slightly more siliceous, and contains more muscovite than the two-mica granodiorite (Kbmg). Contacts between rocks of the core and those of the peripheral zone are gradational.

Field and laboratory data suggest that the inner core of granodiorite and monzogranite was derived from the same melt as the outer zone of granodiorite. The presence of two late-crystallizing micas suggests that the core zone formed at a lower temperature and from a later, more hydrous phase of the parent magma than did the biotite- and hornblende-bearing granodiorite of the outer zone. Core rocks show relative enrichment in silica, potash, and soda, compared to rocks of the outer zone (table 2). This enrichment and the gradational nature of the contacts between the plutons of the core and those of the outer zone suggest that both zones formed from the same melt, but that the core solidified later, at a lower temperature, from a more hydrous phase.

Table 2. Major-element analyses of plutons of the Sapphire batholith by X-ray spectroscopy (in percent)

[Analyses by J. S. Wahlberg, J. Baker, and J. Taggart]

Major oxides	Map symbol and sample number				
	Kbmg 79-CW-34	Kbmm 79-CW-55	Kg1 79-CW-33	Kg3 79-CW-40	Kg3 79-LH-1
SiO_2	72.8	73.4	67.5	68.5	69.4
Al_2O_3	14.9	14.8	15.8	15.2	14.8
Fe_2O_3	1.19	.83	3.32	2.95	2.96
MgO	.55	.3	1.5	1.4	1.4
CaO	1.58	.87	3.54	3.35	2.96
Na_2O	3.9	4.2	3.8	3.6	3.3
K_2O	3.94	4.20	3.35	3.24	3.57
TiO_2	.12	.06	.37	.34	.35
P_2O_5	<.1	<.1	.1	<.1	<.1
MnO	.03	<.02	.051	.03	.05
LOI[1]	.640	.750	.580	.600	.880
Total	99.75	99.53	99.91	99.31	99.77

[1]Loss on ignition at 900 °C.

Dikes, Sills, Pods, and Veins

Dikes, sills, pods, and veins cut the main granodiorite and monzogranite bodies of the batholith; these represent the latest intrusive phases. The most common of these late-phase rocks is porphyritic leucomicromonzogranite, the largest masses of which form pod-shaped bodies near the center of the two-mica granitoid core (inner zone). The porphyritic leucomicromonzogranite is also present as small dikes and sills in the Wallace Formation west of the batholith.

In hand specimen and thin section, the leucomicromonzogranite is a leucocratic, fine-grained, porphyritic monzogranite that contains biotite, muscovite, and garnet; mineralogically the leucomicromonzogranite is closely related to rocks of the inner zone. The occurrence of the largest mass of leucomicromonzogranite in the inner zone also suggests a closer genetic relation to rocks of the two-mica core than to the granodiorites of the outer zone. However, sharp and discordant contacts between leucomicromonzogranite and its host rocks suggest that the host rocks were solid enough to fracture during concentration of late-stage melts.

The rare, discontinuous pegmatites and quartz veins in the batholith intrude granodiorite, monzogranite, and leucomicromonzogranite and represent the final stages of crystallization of the batholith. Intrusive relations of these late phases of crystallization and the rarity of pegmatites and quartz veins suggest that little residual melt remained following crystallization of the porphyritic leucomicromonzogranite and that the batholith crystallized from a relatively dry magma.

Alteration within monzogranite and granodiorite bodies is primarily weak propylitic and sericitic alteration. Plagioclase commonly shows minor alteration to sericite and, more rarely, to epidote. Biotite and hornblende are commonly slightly altered to chlorite. The only mappable alteration zone in the map area is northwest of Medicine Lake in the muscovite-biotite granodiorite (Kbmg), and this sheared and altered zone consists primarily of sulfide-bearing quartz veins that have sericitized borders.

Isotopic Ages

Nine potassium-argon age determinations were made on five rock samples from the Sapphire batholith by J. D. Obradovich. These ages are shown in table 3, and sample locations are shown on the plate 1. Age determinations of the five samples are very similar and average approximately 73 Ma. The concordance of age determinations for rocks of the two-mica granitoid core and those of the peripheral granodiorites indicates that rocks of both zones crystallized contemporaneously, a conclusion that is supported by field and petrographic data.

Geologic and isotopic evidence suggest that the Sapphire batholith is a small, siliceous, peraluminous, epizonal batholith that was intruded and cooled in a single episode. The more silica- and potassium-rich rocks in the core probably represent an in situ differentiate of the peripheral granodiorites. Both the outer and inner zones are intruded by porphyritic leucomicromonzogranite, which may represent intrusion and crystallization of late-stage residual liquids.

Table 3. Analytical data for potassium-argon isotopic age determinations on samples from the Sapphire batholith, Montana

[Determinations by J. D. Obradovich. Decay constants: ^{40}K $\lambda_\epsilon+\lambda_{\epsilon'}=0.581\times10^{-10}yr^{-1}$, $\lambda_\beta=4.962\times10^{-10}yr^{-1}$. Atomic abundance: $^{40}K/K=1.167\times10^{-4}$ atom/atom (Steiger and Jaeger, 1977). See plate 1 for sample localities]

Sample No.	Rock name and map symbol	Mineral dated	K (pct)	Moles ^{40}Ar* per gram of sample ($\times10^{-10}$)	^{40}Ar* as percent of total ^{40}Ar	Age (Ma ±1σ)
79-CW-33	Biotite-hornblende granodiorite (Kg1)	Biotite---	7.61	9.83	86.5	73.0±1.2
		Hornblende	.809	1.008	72.2	70.4±1.5
79-CW-34	Biotite-muscovite granodiorite (Kbmg)	Muscovite	8.68	11.32	86.9	73.6±1.2
		Biotite---	6.72	8.60	88.2	72.4±1.2
79-CW-40	Biotite-hornblende granodiorite (Kg3)	Biotite---	6.96	9.00	70.3	73.1±1.2
		Hornblende	0.656	0.861	81.4	74.1±1.5
79-CW-46	Biotite-muscovite monzogranite (Kbmm)	Muscovite	8.51	9.79	87.4	73.4±1.2
79-CW-55	Biotite-muscovite monzogranite (Kbmm)	Biotite---	6.02	7.78	85.7	73.1±1.2
		Muscovite	8.62	11.23	84.0	73.7±1.2

*Radiogenic argon.

Idaho Batholith

Rocks assigned to the Idaho batholith occur along the southern fringe of the mapped area in the lower part of the Moose Creek drainage, along the southwest border of the mapped area in the upper drainage of Sleeping Child Creek, and near Coyote Meadows. These plutons consist mainly of foliated granodiorite and tonalite and, according to interpretation of U/Pb concordia plots by Desmarais (1983), have a crystallization age of about 78 Ma and are slightly older than the Sapphire batholith.

The principal plutonic unit of the Moose Creek drainage (Kgi) is a foliated granodiorite with a foliated tonalite border (table 1 and fig. 3). This unit is intruded by irregular masses of monzogranite (not shown on map) and by hypabyssal dikes and irregular masses of rhyolite (Tr) and dacite (Tda). Only the northeast part of the pluton is exposed within the map area, and at the surface this plutonic mass is separated from the Sapphire batholith, located to the north and northeast, by about 2.5 km (1.5 mi) of metamorphosed rocks of the Belt Supergroup.

Tonalite of the border zone is apparently continuous along the north and northeast border of the granodiorite, and contacts between tonalite and granodiorite appear gradational. Intrusive contacts between the tonalite and Middle Proterozoic rocks are sharp and discordant along Moose Creek, but to the northwest the contact has a prominent migmatitic high-grade aureole. The tonalite border rocks and the granodiorite show a discontinuous northwest-trending foliation that is defined by biotite- and hornblende-rich bands.

Younger intrusive bodies occur within the granodiorite of Moose Creek. Monzogranite and leucomonzogranite bodies appear to intrude the granodiorite of Moose Creek, but details of relative ages among these rocks are not known because poor exposures obscure contact relations. Hypabyssal rhyolite and dacite bodies cut foliation of the crystalline rocks and are clearly younger than the granodiorite and tonalite.

Alteration of crystalline rocks of Moose Creek is dominantly propylitic; it consists of moderate sericite and epidote alteration of feldspar and chlorite alteration of biotite and hornblende. Hypabyssal rocks commonly contain oxidized biotite and hornblende, which are partially or totally altered to granular magnetite.

Biotite granodiorite (Kbgi) of Sleeping Child Creek and tonalite (Kti) of Coyote Meadows represent only the eastern parts of larger plutons that extend 16 km (10 mi) to the west and to the south (Desmarais, 1983). These two intrusive bodies have a distinctive migmatitic

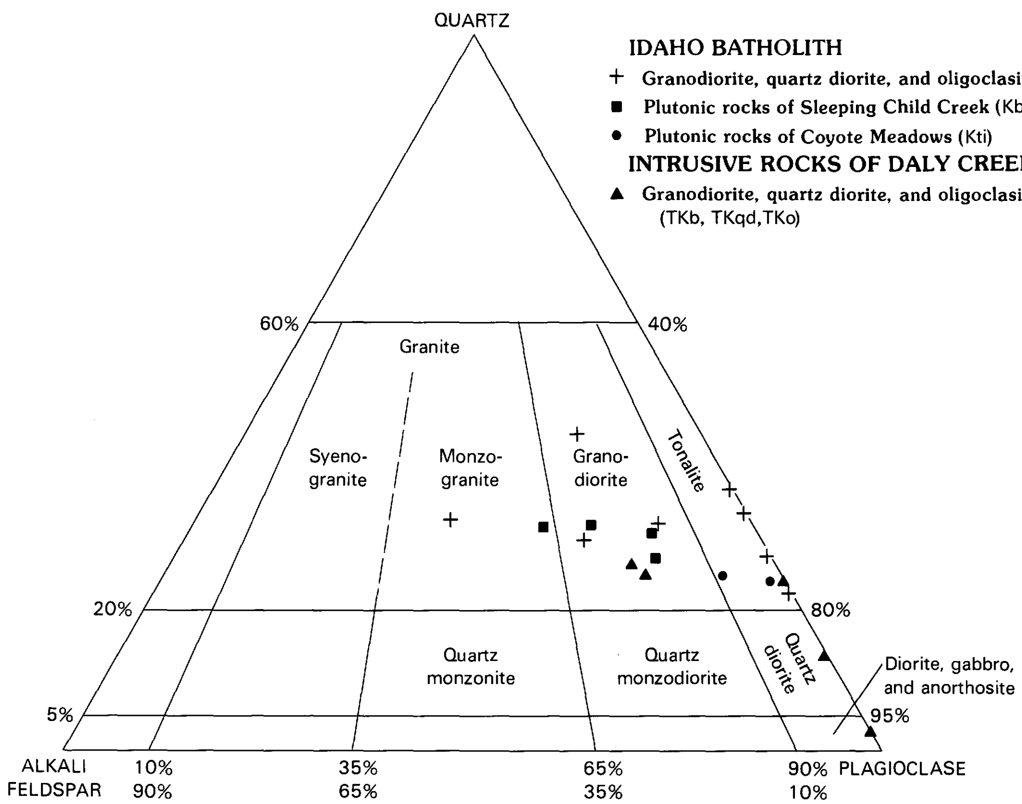

Figure 3. Modal compositions of plutonic rocks of the Idaho batholith and of plutonic rocks of Daly Creek.

border, unlike rocks at the contact of the Sapphire batholith. Locally, where the contact relations are well exposed, the tonalite and biotite granodiorite grade into strongly banded, intricately folded migmatite. The migmatite zone is variable in thickness but generally extends 3–300 m (10–1,000 ft) from the diffuse intrusive contact. The migmatite grades into metamorphosed rocks of the Belt Supergroup away from the intrusive contact. The band of migmatite extends to the northwest into Sleeping Child Creek beyond the map area. The presence of migmatite borders seems to have regional significance and may reflect different physical conditions of intrusion for the tonalite and biotite-granodiorite plutons than for the Sapphire batholith.

Pegmatite dikes, sills, and irregularly shaped masses are more common in the biotite granodiorite and tonalite plutons than in the Sapphire batholith. Many of the pegmatites are located near contacts between intrusive bodies and Middle Proterozoic rocks. However, in the Martin Creek drainage basin numerous small pegmatites, most of which are too small to map, have intruded the middle member of the Mount Shields Formation approximately 1.3 km (2 mi) from the contact of the plutons.

Isotopic age determinations were not obtained for these plutons (Kti and Kbgi) during these studies. However, Desmarais (1983) suggests that these rocks have an age of crystallization of about 78 Ma and that these plutons were contemporaneous with that of the Moose Creek area; therefore, these rocks of the Idaho batholith are probably slightly older than plutons of the Sapphire batholith.

Intrusive Rocks of the Daly Creek Area

In the northwest part of the map area, the Daly Creek drainage basin contains an epizonal, irregularly zoned granodiorite, quartz diorite, and tonalite body. At least one dike of oligoclasite occurs near this pluton.

Granodiorite forms the main part of this pluton and grades into a thin quartz diorite border zone. The border zone ranges in composition between tonalite and diorite; quartz diorite is an average composition (fig. 3). The presence of abundant hornblende phenocrysts and the absence of potassium feldspar are diagnostic of the quartz diorite border zone. Contacts of the quartz diorite with Middle Proterozoic rocks are discordant and sharp. The composition and the texture of the granodiorite of Daly Creek are similar to those of the biotite granodiorite of the Sapphire batholith. Granodiorite and quartz diorite in the Daly Creek area form the easternmost exposures of a narrow, east-west-trending stock about 10 km (6 mi) long. The prominent east-west orientation of this stock may be structurally controlled, but east-west structures are rare in the southern Sapphire Mountains. An oligoclasite dike that occurs in the Daly Creek area may be related to the granodiorite and quartz diorite body. This light-colored rock consists of feldspar that is moderately altered to saussurite and sericite; minor calcite, hematite, and quartz fill irregular voids. Potassium-argon ages were not obtained for the plutons of Daly Creek, and cross-cutting relations between the intrusive rocks of Daly Creek and those of the Sapphire batholith are not present. Consequently, age relations between the Sapphire batholith and the intrusive rocks of Daly Creek are not known.

Mafic Dikes and Sills

Mafic dikes and sills are scattered through Middle Proterozoic rocks in the map area. These dikes and sills are thin and discontinuous, and most were not mapped. Small discontinuous pods and sills of fine-grained augite-gabbro (TKga) are present south of Daly Creek and north of Hog Trough Creek. A dike of hornblende gabbro occurs in the Martin Creek drainage. None of these dikes show shear or retrograde metamorphism; hence, they not only postdate thrust faulting, but they probably postdate the main intrusive events in the area. A Tertiary-Cretaceous age has been tentatively assigned to the mafic dikes and sills.

Summary and Interpretation of Intrusive Rocks

Intrusive rocks of the Idaho and Sapphire batholiths and those of Daly Creek were emplaced during several magmatic events that occurred under different physical and tectonic conditions in Late Cretaceous time. Mesozonal rocks of the Idaho batholith in the south and southwest parts of the map area are syntectonic: they were intruded during thrust faulting at mesozonal depths according to Desmarais (1983). In contrast, the Sapphire batholith and the intrusive rocks of Daly Creek are not syntectonic, because they were intruded at epizonal depths after thrust faulting had ceased at those depths.

Geologic studies and interpretations by Desmarais (1983) of the plutonic and metamorphic complex of the Chief Joseph part of the Idaho batholith, which extends north to form the southern and southwestern plutonic bodies in the map area, suggest that foliation in granodiorite and tonalite plutons and in pendants of Middle Proterozoic host rocks was produced by ductile deformation during syntectonic intrusion at about 78 Ma. Contact relations with host rocks are generally concordant, and high-metamorphic-grade migmatite borders have developed at the contacts between the plutons and the host rocks. These circumstances suggest that mesozonal conditions prevailed during emplacement of this part of the Idaho batholith. The gradational contact in the Moose Creek pluton (Kgi) between tonalite at the border and granodiorite in the main body may indicate that in situ magmatic segregation preceded final crystallization of the magma. Pegmatite is commonly associated with the biotite-granodiorite of Sleeping Child Creek (Kbgi) and with the tonalite of Coyote Meadows (Kti), which we interpret to indicate that these plutons contained more volatiles in a residual or anatectic melt than did plutons of the Sapphire batholith and of Daly Creek.

After the syntectonic emplacement of the Idaho batholith, magma that later formed the Sapphire batholith intruded to a higher level in the crust. Epizonal conditions prevailed during emplacement of the Sapphire batholith, based on generally discordant contact relations between plutons and host rocks, the absence of migmatite borders, and the low grade of contact metamorphism. Rocks of the Sapphire batholith clearly postdate the thrust faulting: they terminate thrust faults, they are not foliated, and they lack low-angle shear zones. Moreover, the host rocks show no systematic deformation in contact zones. Age relations and contact relations indicate that the batholith had undergone in situ magmatic segregation to form a silica- and potassium-rich core prior to about 73 Ma. The Sapphire batholith was relatively dry at the time of intrusion, and most residual liquid formed leucomicromonzogranite dikes, sills, and pods; pegmatite dikes and sills are poorly developed in the Sapphire batholith.

The north-trending Sapphire batholith may be related to a series of plutons and stocks that trend northward from the batholith. The Big Spring Creek stock, 18 km (11 mi) to the north on the west side of Rock Creek, is similar to the Sapphire batholith in composition of intrusive phases (biotite granodiorite and muscovite-biotite granodiorite), external contact relations, internal zonation, and the presence of crosscutting, late-phase leucomicromonzogranite dikes, sills, and pods (Wallace, unpub. data, 1979). About 18 km (11 mi) north of the Big Spring Creek stock is the Welcome Creek stock, which is porphyritic biotite-hornblende monzogranite that is similar to the biotite-hornblende granodiorite (Kgl) and biotite granodiorite (Kbg) of the Sapphire batholith. Although similarity of compositions, zonation, and contact relations suggest a similar genesis for these plutonic bodies, evidence that might confirm a relation among them, such as detailed petrographic studies, geochemical data, and isotopic ages, is lacking.

The intrusive rocks of Daly Creek appear to have intruded at epizonal depths after thrust faulting had ceased. External contact relations are discordant, migmatitic borders are absent, and the metamorphic aureole is generally of low grade. Thrust faults terminate against this stock, and foliation tends to be concordant with external contacts between the stock and host rocks. The age of the intrusive rocks of Daly Creek and their genetic relations to the Sapphire batholith are not known.

METAMORPHOSED MIDDLE PROTEROZOIC ROCKS

Metamorphic rocks in the map area include low- and medium-grade contact hornfels and high-grade migmatitic gneiss. Pederson (1976, p. 38–40) briefly described contact metamorphic facies associated with the contact aureole on the east side of the Sapphire batholith and interpreted temperature and pressure conditions of metamorphism; our petrologic studies on the contact aureole are integrated with Pederson's results. Desmarais (1983) described the mineralogy, petrogenesis, and structures of migmatitic gneisses that border the Idaho batholith, and he interpreted the thermal and deformational history of those rocks; his conclusions are summarized in this report.

Metamorphic Aureole of the Sapphire Batholith

Emplacement of the Sapphire batholith metamorphosed rocks of the middle Belt carbonate and the Missoula Group to albite-epidote hornfels and hornblende hornfels facies. The Wallace and Mount Shields Formations show the greatest range of contact metamorphic facies, and these units were studied in the most detail. Metamorphism of the Bonner Quartzite and the McNamara Formation was not studied in much detail because these rocks are poorly exposed and occur only in a small area at the north end of the batholith; metamorphism of these units is not discussed in this report. Over most of the map area, identification of protolith units presented little difficulty because metamorphism preserved distinctive bedding features and rock compositions are distinctively different. However, one rock unit, the muscovite biotite schist, can be related to its protolith only tentatively.

Wallace Formation

Metamorphism of the carbonate-bearing Wallace Formation formed calc-silicate hornfels of the albite-epidote facies and the hornblende facies, as defined by Turner and Verhoogen (1960, p. 510–514). Two mineral assemblages are typical of the albite-epidote hornfels facies in the metamorphosed Wallace Formation:

1. Calcite-dolomite-quartz (±talc or kaolin).
2. Calcite-dolomite-quartz-biotite-actinolite (±muscovite ±tremolite ±plagioclase ±chlorite ±diopside ±epidote).

The first mineral assemblage is the lowest rank assemblage present, whereas the second represents the most common components of the higher grade albite-epidote hornfels facies. X-ray diffraction data indicate the presence of both calcite and dolomite in most rocks, and either mineral may dominate. Rocks transitional from the albite-epidote hornfels facies into the hornblende hornfels facies contain granules of diopside as a matrix component.

Hornblende hornfels facies of the Wallace Formation are typically represented by some or all of the following minerals: quartz-actinolite-scapolite-diopside-biotite-calcite-dolomite (±muscovite ±microcline ±plagioclase ±tremolite).

X-ray diffraction data show that calcite and dolomite are present in rocks of the hornblende hornfels facies, but are less common there than in rocks of the albite-epidote hornfels facies. Scapolite is a prominent component in rocks of the hornblende hornfels facies in the northwest part of the study area and is locally common in the Wallace Formation along the west side of the Sapphire batholith.

Lepidoblastic textures of the calc-silicate hornfels of the Wallace Formation appear to be controlled by bedding structures inherited from the sedimentary rocks. Most rocks of the albite-epidote hornfels facies have an equigranular groundmass. Porphyroblasts occur in more intensely metamorphosed rocks but are rare in lower grade rocks of the albite-epidote hornfels facies. In the hornblende hornfels facies of the Wallace Formation, prominent poikiloblasts of scapolite, diopside, or actinolite/tremolite are embedded in a finer grained granoblastic matrix. Primary bedding structures are usually obliterated by a well-defined schistosity or by incipient gneissic textures in rocks of the hornblende hornfels facies.

According to Pederson (1976, p. 39) the Wallace Formation was metamorphosed to the albite-epidote hornfels facies at about 400 °C and 2 kilobars pressure and to the hornblende hornfels facies at about 600 °C and about 2 kilobars pressure.

Mount Shields Formation

Around the Sapphire batholith it is difficult to consistently distinguish the albite-epidote hornfels facies from the hornblende hornfels facies in quartzofeldspathic rocks of the Mount Shields Formation on the basis of mineral assemblages alone. Therefore, textural criteria are used in conjunction with mineral assemblages to distinguish rocks of low metamorphic grade that may correspond to the albite-epidote hornfels facies from those of a higher metamorphic grade that correspond mineralogically to the hornblende hornfels facies.

A typical recrystallized mineral assemblage of the albite-epidote hornfels facies is quartz-muscovite-biotite (±chlorite ±magnetite).

In rocks of the albite-epidote hornfels facies, minerals of this assemblage have recrystallized among relics of detrital grains that were stable at relatively low pressure and temperature, so the texture of these rocks is in part detrital and in part metamorphic, and primary bedding structures are well preserved. Detrital plagioclase, microcline, and minor muscovite and biotite were unaffected by the thermal metamorphism, whereas quartz grains exhibit new growth and recrystallization that obliterated detrital boundaries. Most of the biotite, muscovite, and chlorite are metamorphic and formed as small grains from argillaceous matrix or detrital clay, and magnetite formed from detrital microgranular hematite.

The hornblende hornfels facies of the Mount Shields Formation is characterized by the mineral assemblage quartz-microcline-plagioclase-biotite-muscovite (±chlorite ±magnetite), which conforms to the hornblende hornfels facies of Turner and Verhoogen (1960, p. 511–575). Rocks of this facies are completely granoblastic, and all minerals have recrystallized to equilibrium assemblages. A trace of sillimanite was tentatively identified in one sample. Mineral banding appears to be related to original compositional variation of beds and laminae, which are partly preserved in rocks of the hornblende hornfels facies.

Metamorphic segregation of minerals has affected rocks of the hornblende hornfels facies south of the Sapphire batholith near the gneissic border of the Idaho batholith granodiorite. In these metamorphic rocks elongate erosion-resistant nodules are dispersed unevenly through a granoblastic matrix. The nodules are 1–2 cm in diameter and elongate parallel to local mineral banding in the rocks. Microscopic examination shows that the nodules are zoned and that cores of the nodules are composed of large crystals (1–3 mm) of quartz, muscovite, and biotite surrounded by a band of finer grained sericite and quartz. The outermost band is composed of fine-grained plagioclase, microcline, and quartz. The matrix surrounding the nodules is granoblastic medium-grained quartz, plagioclase, microcline, muscovite, and biotite. These nodules have the mineral assemblage of the hornblende hornfels facies. Field observations suggest that rocks showing this type of incipient metamorphic mineral segregation are present only near the tonalite (Kti) and biotite granodiorite (Kbgi) plutons of the Idaho batholith.

Muscovite-Biotite Schist

A poorly exposed schist of unknown thickness occurs about 2 km (1.5 mi) north of Fox Peak in the central part of the map area, and this unit cannot be assigned with confidence to any specific rock unit in the upper part of the Belt Supergroup. Metamorphism has obliterated key features used to identify argillaceous siltite and quartzite units in the Belt sequence. Fragments in soil suggest two distinct types of schistose rocks: (1) a schistose black- and greenish-black-weathering mica-rich rock that contains thin quartzofeldspathic laminations and zones, and (2) a gray- and buff-weathering quartzofeldspathic rock that contains interbedded thin, black-weathering mica-rich laminations and zones. Both rock types contain some thinly laminated zones, and the mica-rich rocks contain rare calc-silicate zones that appear to be laterally discontinuous. The relative amounts of these two rock types cannot be estimated from field observations.

The schist probably is part of the Missoula Group because (1) the siltite and quartzite beds within the schist are better sorted than similar beds of the Ravalli Group, (2) the percentage of argillite is lower in the schist than in rocks of the upper part of the Ravalli Group, (3) the rocks contain less carbonate than do argillaceous parts of the Ravalli Group, and (4) the thin interbeds of siltite-quartzite and argillite are not interlayered with thick quartzites, as is characteristic of lower parts of the Ravalli Group. This schist could be assigned to the Snowslip Formation or to member one or three of the Mount Shields Formation because only these units contain appreciable amounts of argillite in thin, distinct beds that are separated by moderately sorted thin siltite and quartzite beds. Because characteristic quartzite beds of the Snowslip Formation are apparently absent from the schist, we conclude that the schist is most likely part of member one or three of the Mount Shields Formation. Thrust faults may occur north and south of the schist, although stratigraphic evidence for these structures is tenuous.

No reliable thickness estimate can be made for the schist because it is intensely deformed on mesoscopic and megascopic scales and exposures are so poor that larger folds cannot be mapped.

The mineral assemblages in the muscovite-biotite schist were not studied in as much detail as those of the Wallace and Mount Shields Formations. Near the contact with the Sapphire batholith the mineral assemblage is quartz-plagioclase-microcline-biotite (±garnet). Mineralogically this assemblage represents a quartzofeldspathic hornblende hornfels facies (Turner and Verhoogen, 1960, p. 514). About 1 km (½ mi) west of the intrusive contact the typical mineral assemblage is quartz-muscovite-biotite (±chlorite). This assemblage is classed with the albite-epidote hornfels facies.

The schist is lepidoblastic, and porphyroblasts are absent. The prominent schistose texture results from preferred orientation of micas parallel to apparent bedding lamination. Beds that were originally quartzose contain more quartz and feldspar and less mica than beds that were originally clay-rich. Physical conditions of metamorphism were probably similar to those described for metamorphic facies of the Wallace Formation.

Metamorphic Aureole of the Idaho Batholith

Geologic mapping, structural analysis, and petrogenetic studies by Desmarais (1983) suggest that metamorphic rocks that border the Idaho batholith and roof pendants in the batholith record an event of synorogenic dynamothermal prograde metamorphism, an event of high-grade thermal metamorphism, and an event of low-temperature retrograde alteration. Desmarais mapped three zones of increasing metamorphic grade south of the Sapphire batholith and in roof pendants of the Idaho batholith.

Zone 1 and part of zone 1–2 of Desmarais (1983) include hornfels whose mineral assemblages and textures are like those described above for the aureole of the Sapphire batholith. The lowest grade of metamorphism, zone 1, mainly includes rocks of the albite-epidote hornfels facies. The next higher grade of metamorphism, zone 1–2, includes (1) gneissic and schistose quartzofeldspathic and calc-silicate rocks of the hornblende hornfels facies, (2) rocks that contain spherical mineral segregations, and (3) some higher grade sillimanite-bearing rocks that have a more prominent gneissic texture. These higher grade sillimanite-bearing quartzofeldspathic and calc-silicate rocks of zone 1–2 include folded and deformed mica minerals and show a secondary schistosity. This schistosity and the axial planes of folds trend northwest in zone 1–2.

Quartzofeldspathic and calc-silicate rocks of zone 2 are migmatitic and strongly gneissic. The quartzofeldspathic rocks are coarse grained and consist of layers of quartz and feldspar that alternate with layers of biotite, muscovite, and sillimanite (Desmarais, 1983). Microcline and orthoclase may be perthitic in these rocks, and muscovite and biotite occur as large poikiloblasts. Sillimanite occurs as mats and as prismatic crystals. Migmatitic veins contain plagioclase, orthoclase, biotite, muscovite, and sillimanite, and the veins have hypidiomorphic granular texture. Calc-silicate rocks exhibit a gneissic texture that consists of bands of diopside, plagioclase, and quartz that alternate with bands of hornblende, plagioclase, and some biotite. Porphyroblasts and poikiloblasts of hornblende, diopside, scapolite, and epidote occur in the medium- to coarse-grained idioblastic to subidioblastic matrix. Poikiloblasts were deformed after crystallization. Folds in zone 2 are generally upright, steeply plunging isoclinal structures (Desmarais, 1983).

Desmarais (1983) attributes the initial prograde metamorphism of zones 1, 1–2, and 2 to intrusion of this part of the Idaho batholith, and he attributes the attendant schistosity and foliation to ductile metamorphism during emplacement of the Sapphire thrust plate at about 78 Ma. Desmarais' (1983) interpretation of equilibrium relations suggests that the emplacement of plutons of this part of the Idaho batholith produced temperatures of 600° to 700 °C in nearby host rocks; pressures were in the range of 3.0 to 7.0 kilobars. A later, high-temperature metamorphic event formed non-oriented porphyroblasts of muscovite, biotite, scapolite, and tremolite that cut earlier formed schistose and gneissic textures. Finally, retrograde alteration is recorded by sericite alteration of sillimanite and feldspar, by chlorite alteration of biotite, hornblende, and diopside, and by alteration of scapolite to chlorite, epidote, and actinolite.

STRUCTURE

The main structural features in the map area are thrust faults and folds, cut locally by a few high-angle faults, which also shear rocks of the Sapphire batholith. The thrust faults and folds formed during Late Cretaceous time, when Proterozoic rocks in the map area were thrust eastward as part of the Sapphire thrust plate (fig. 4) (Ruppel and others, 1981), before intrusion of the Sapphire batholith. The structural pattern of this relatively small part of the Sapphire thrust plate is described and interpreted here, in an initial attempt to explain the geometry, distribution, and evolution of the complex structural relations in the map area. Although the structural features of the map area cannot all be fully integrated into the incompletely known structural framework of this region, this preliminary tectonic interpretation develops regionally consistent hypotheses for the origin of large-scale structures shown on plate 1.

Regional Tectonic Setting

The Sapphire thrust plate is the main tectonic terrane in the area between the Idaho and Boulder batholiths and south of the north boundary of the Lewis and Clark line; the southern Sapphire Mountains occupy the southwestern part of the Sapphire thrust plate (fig. 4). The full extent of the Sapphire thrust plate is not known because (1) north of the Idaho batholith thrust faults of the leading edge of the plate are truncated by faults of the Lewis and Clark line, (2) the eastern edge of the plate was intruded by the Boulder batholith, (3) the southwestern part of the plate was intruded by the Idaho batholith, and (4) relations to thrust plates south of the Sapphire plate are not known (Ruppel and others, 1981). Most structures of the Sapphire thrust plate were formed during Late Cretaceous compressional deformation. Plutonic masses that cut thrust faults, such as the Boulder and Sapphire batholiths, most of the northern part of the Idaho batholith, most of the Anaconda and Flint Creek Range plutonic suites, and the Garnet and Miners Gulch stocks postdate compressional deformation (Lidke and others, 1987). Some plutons of the northern Idaho batholith may have intruded during late stages of compressional deformation (Desmarais, 1983). Compressional structures were slightly modified during Tertiary extensional faulting. The interior part of the Sapphire thrust plate contains folded stacks of thrust sheets, which are broken by younger zones of imbricate thrust faults, whereas the border of the plate is characterized by anastomosing imbricate thrust faults that represent fragmented frontal zones of thrust sheets (fig. 4).

The boundaries of the Sapphire thrust plate are not precisely located in the far western part of the plate and in the eastern, southwestern, and southern parts of the plate. The northern edge of the Sapphire thrust plate trends generally eastward and southeastward between the vicinity of Missoula, Mont., and the Boulder batholith. West of Missoula, the leading edge of the Sapphire plate impinges on steep faults of the Lewis and Clark line (Harrison and others, 1986); because the steep faults cut the imbricate thrusts into many discontinuous segments, the leading edge of the plate cannot be accurately located west of Missoula. The leading edge of the Sapphire thrust plate turns south in the area of Elliston, Mont., and is terminated by the Boulder batholith about 20 km (12 mi) south of Elliston. Although the frontal faults of the plate probably continued south before the batholith was emplaced, they now cannot be traced beyond this point. The southern boundary of the Sapphire thrust plate is not known. Thrust faults and rocks of the Sapphire plate have been traced into the Anaconda Range (Lidke, 1985; Elliott and others, 1985), but about 70 km (40 mi) south of the Anaconda Range in the Pioneer Mountains, Ruppel (in Ruppel and others, 1981) identified the Grasshopper thrust plate as the main tectonic terrane. Relations between the Sapphire and Grasshopper thrust plates are not known, but the Grasshopper plate in the Pioneer Mountains may correspond to one or more of the thrust sheets that we have identified in the Sapphire thrust plate farther north (fig. 4). Alternatively, Desmarais (1983) suggested that the southern boundary of the Sapphire plate may be just south of the mapped area, and that the boundary may be defined by a northwest-trending zone of ductile shear, which is expressed as a prominent foliation in syntectonic Cretaceous plutons and in metamorphic pendants of Middle Proterozoic rocks.

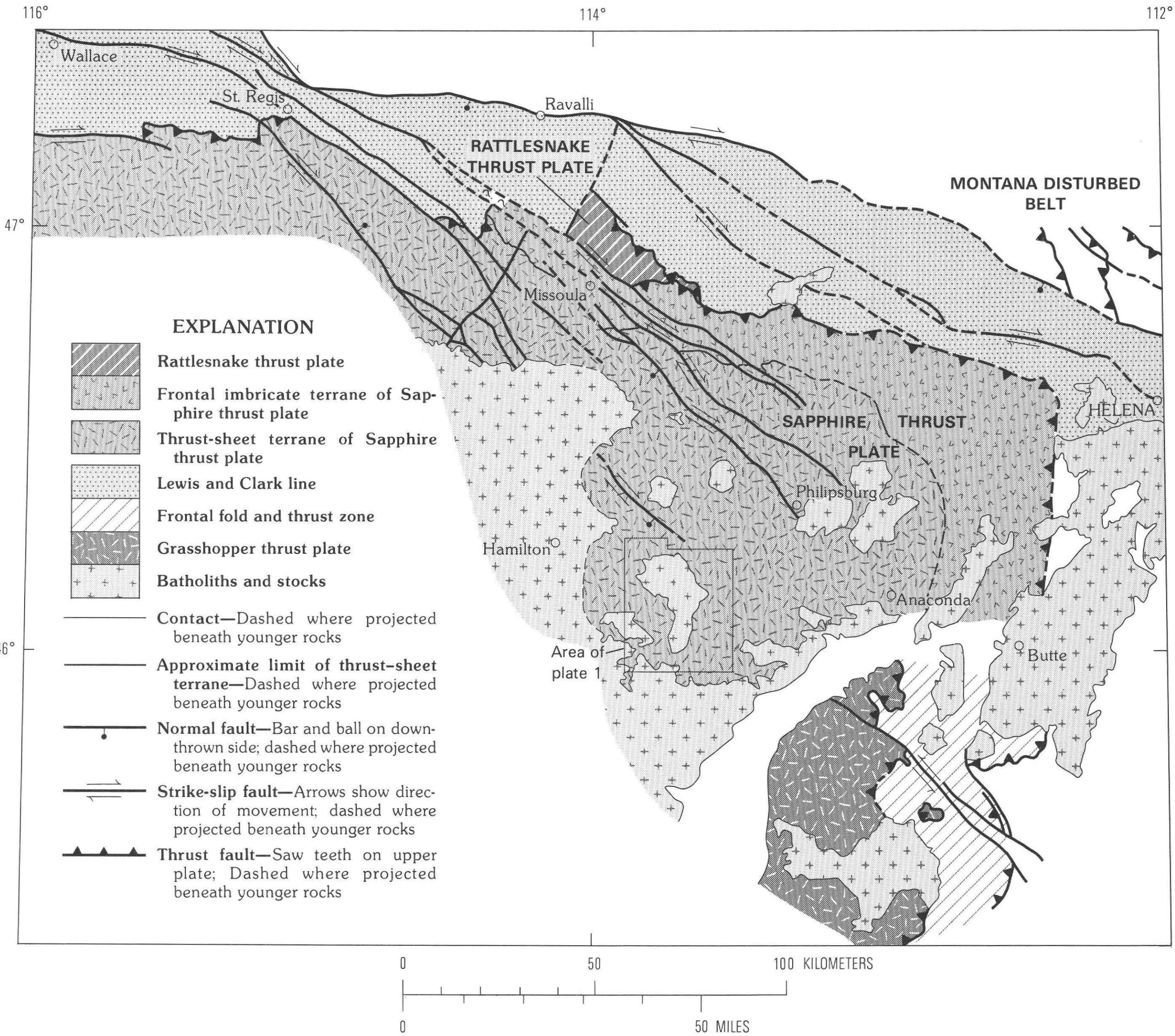

Figure 4. Tectonic features and principal plutons in the region of the Sapphire thrust plate, west-central Montana.

The two-fold subdivision of the Sapphire thrust plate used in this report identifies a terrane of stacked thrust sheets and a frontal zone of imbricate thrust faults (Lidke, 1985; Lidke and others, 1987); these terranes cross boundaries of earlier lithotectonic subdivisions proposed by Hyndman (1980) and by Wallace (in Ruppel and others, 1981). Hyndman (1980) defined two lithotectonic elements in the area of the Sapphire thrust plate as (1) a western part, the "Sapphire tectonic block," which consisted of allochthonous Middle Proterozoic rocks, and (2) an eastern part, the "bulldozed" terrane, which was composed mostly of parautochthonous Paleozoic and Mesozoic rocks. Wallace (in Ruppel and others, 1981) divided the Sapphire thrust plate into three allochthonous subplates: (1) the Rock Creek subplate, in the western part, consisting of Middle Proterozoic rocks; (2) the Garnet Range subplate, in the northern and eastern part, consisting mainly of imbricated Paleozoic and Mesozoic rocks; and (3) the Flint Creek subplate consisting of klippen of Middle Proterozoic rocks above the Garnet Range subplate. These subplates were differentiated by contrasting structural styles and unique sequences of rocks, and this subdivision implied that major flat thrust faults separated subplates. These early subdivisions of the Sapphire thrust plate did not coincide; Hyndman's "Sapphire tectonic block" generally corresponded to the Rock Creek subplate, but his "bulldozed" terrane included the Garnet Range and Flint Creek subplates, which Wallace (in Ruppel and others, 1981) considered to be separate terranes of different structural style and lithostratigraphy. Although these early interpretations of lithotectonic units were useful working hypotheses, modern geometric analysis of structures of the Sapphire thrust plate suggests that (1) the Rock Creek subplate is composed of at least three regionally extensive thrust sheets, (2) the Flint Creek subplate represents only one thrust sheet within the Rock Creek subplate, and (3) the Garnet Range subplate consists partly of the imbricate frontal zone and partly of thrust sheets. Because some of the thrust sheets and the imbricate frontal zone of thrust faults cross both the tectonic subdivisions proposed by Hyndman (1980) and those proposed by Wallace (in Ruppel and others, 1981), the previous terminology is not used in this report; the Sapphire thrust plate is here divided into a terrane of thrust sheets and a terrane of frontal imbricate thrusts (Lidke and others, 1987). The study area is in the southwestern part of the thrust sheet terrane (fig. 4).

On the Sapphire thrust plate, the terrane of thrust sheets and the terrane of frontal imbricate thrust faults differ in structural style. In the first of these, individual thrust sheets are composed of distinct lithologic sequences and are bounded by master thrust faults that generally parallel bedding except where they ramp through bedding. The thickness of thrust sheets appears to range between 1,500 and 4,500 m (5,000 and 15,000 ft), and thrust sheets commonly contain imbricate thrust slices. The stacked thrust sheets of the thrust-sheet terrane terminate in anastomosing, imbricate thrust faults of the frontal terrane, which forms the leading edge of the Sapphire plate. Thrust sheets cannot be identified in the frontal imbricate terrane. Thrust faults of the frontal terrane have moderate to gentle dips, cut bedding steeply or are parallel to bedding, and are commonly accompanied by drag structures. The stacked thrust sheets and their enclosing master faults in the thrust-sheet terrane are broadly to tightly folded and are cut by zones of imbricate thrust faults. Locally these younger faults form anastomosing zones similar in map pattern to those of the frontal imbricate terrane of the Sapphire thrust plate; where the younger zones extend into the frontal imbricate terrane, the two periods of thrust faulting are indistinguishable.

Emplacement of the Sapphire thrust plate consisted of three main phases: (1) thrust sheets were emplaced and restacked at the same time that their leading edges were fragmented to form the frontal imbricate terrane, (2) thrust sheets were folded, and (3) younger imbricate thrust faults cut thrust sheets and folds. During emplacement of the thrust sheets, episodic movement along different segments of the fault system stacked the thrust sheets in this sequence: (1) movement of thrust sheets along some master thrust faults formed a ramp-and-flat geometric profile, (2) continued movement along these thrusts formed new splays that undercut and piggybacked some abandoned ramps, and (3) new ramps formed along splays that cut through flats of overlying master thrusts. Nonsynchronous movement along master thrust fault segments and crosscutting at ramps produced unconventional thrust fault relations in which some younger rock sequences were moved above older rock sequences (Lidke, 1985; Lidke and others, 1987). After the thrust-sheet and frontal imbricate terranes were emplaced, the thrust sheets were folded and cut by zones of imbricate thrust faults during waning stages of emplacement of the Sapphire thrust plate (Lidke and others, 1987).

In this report, we apply geometric methods of analysis to structures of the southern Sapphire Mountains in a similar manner to that used by Boyer and Elliott (1982) to study duplex systems. Our geometric analysis shows that three thrust sheets underlie most of the southern Sapphire Mountains, and these thrust sheets were folded and later cut by a younger zone of imbricate thrust faults.

Description of Structures

Structures in the map area consist of thrust faults, high-angle faults, open folds, and local small-scale tight folds. The structures discussed below are shown on figure 5.

Thrust Faults

Thrust faults in the central and western part of the area have different orientations because they are folded, and many of these thrusts also are cut discordantly by the batholith and by plutons farther south. Most of the thrust faults in the eastern part of the area trend north and northeast and dip moderately to steeply westward; many of these show small apparent stratigraphic separation, but some thrusts in the imbricate zone have large stratigraphic separation. Younger-on-older stratigraphic relations are more common along thrusts in the east part of the map area. Thrust faults are discussed below from west to east.

Thrust faults A and B (fig. 5), in the northern part of the area, apparently merge to the south, near the Sapphire batholith, which discordantly cuts the combined thrust. Fault A has the Wallace Formation in both its footwall and its hanging wall and therefore shows little apparent stratigraphic displacement. Fault B, however, has the Wallace Formation in the hanging wall and younger rocks of the McNamara Formation in the footwall and thus shows rather large apparent stratigraphic offset. South of the place where faults A and B merge, the stratigraphic relations across the thrust are those that characterize thrust B. These relations suggest that fault A probably is a relatively minor subsidiary thrust to fault B in this area.

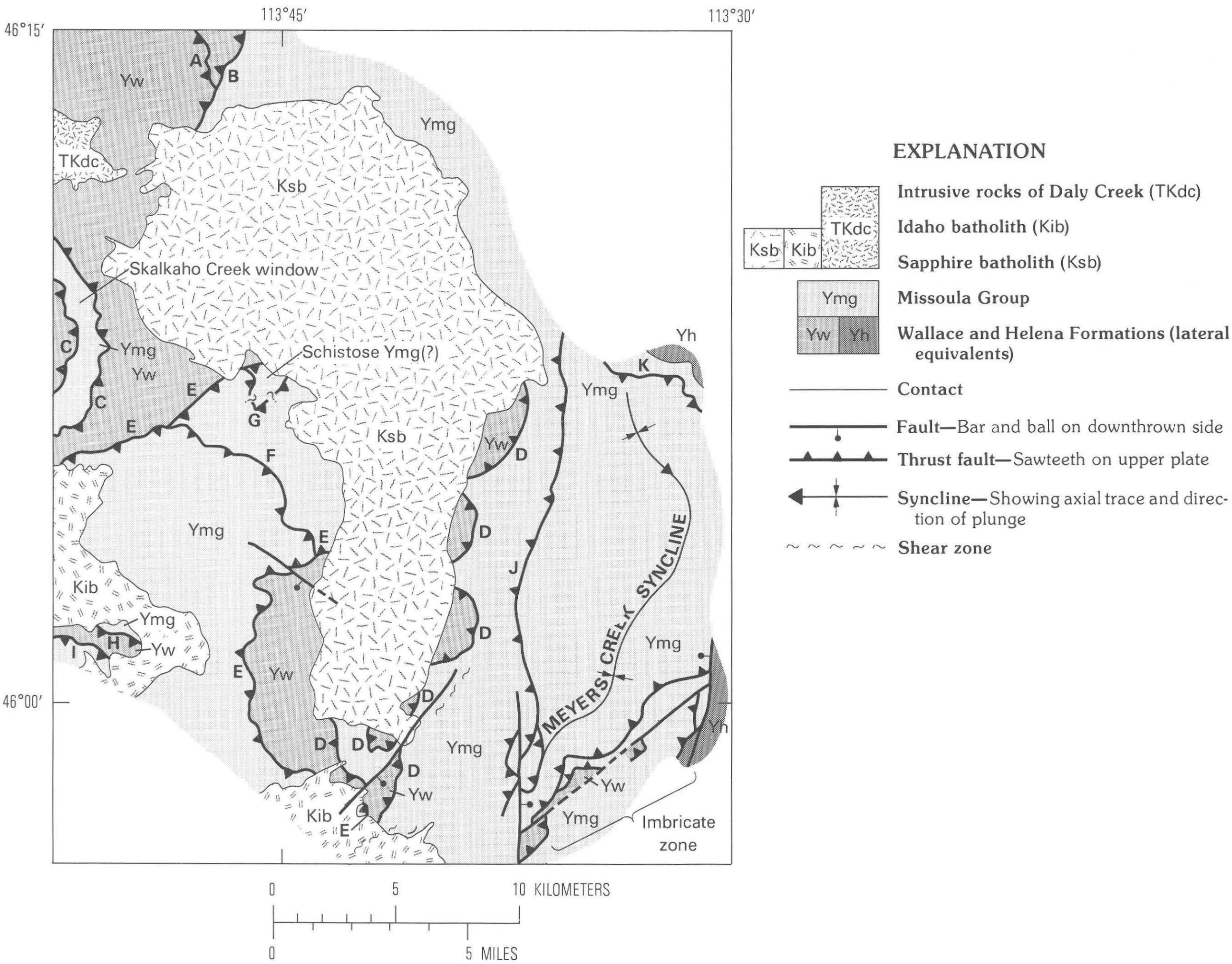

Figure 5. Major structures and generalized geology in the southern Sapphire Mountains area. See text for discussion of thrust faults A–K.

Thrust C (fig. 5), in the west-central part of the map, defines the Skalkaho Creek window in which the Wallace Formation forms the hanging wall and younger rocks of the middle member of the Mount Shields Formation form the footwall; thrust C shows significant stratigraphic displacement. In the Skalkaho Creek window, thrust C is anticlinally folded about a sinuous north- to northwest-trending axis, and younger rocks beneath this thrust are exposed in the core of the anticline. The Wallace Formation above the thrust and the Mount Shields Formation below the thrust are much more tightly folded than the thrust is, suggesting that some of this folding probably preceded or coincided with movement along this thrust.

Thrust D (fig. 5) is along the east side and south end of the Sapphire batholith; it has the Wallace Formation in the hanging wall and younger rocks of member two of the Mount Shields Formation in the footwall; hence the thrust has a large stratigraphic displacement. This thrust occurs as segments because it was stoped at several places by the Sapphire batholith. Along the east side of the Sapphire batholith thrust D is cut semiconcordantly by the batholithic rocks. At the south end of the batholith these cross-cutting relations are more markedly discordant, and the thrust is folded, apparently into a sinuous north- to northwest-trending anticline that also appears to be cut discordantly by the batholithic rocks. Most of the structural and stratigraphic relations that characterize fault D are very similar to those that were previously discussed for fault C, but thrust D is separated from thrust C by the Sapphire batholith.

Fault E (fig. 5) has the Wallace Formation in the footwall beneath member two of the Mount Shields Formation and thus has younger-on-older stratigraphic relations. Several thousand feet of the lower part of the Missoula Group section, which is present in areas nearby, are absent here. Fault E has two distinct segments that show opposing dip directions and that are referred to as the south and north segments of fault E in the following discussion. The south segment of this fault is arcuate and dips westerly. Bedding attitudes in the Mount Shields Formation above the south segment change from a west dip to an east dip near the fault. The north segment of the fault has a consistent northeast trend and dips to the southeast. The Wallace Formation is tightly folded beneath this segment of the fault, and the Mount Shields Formation in the hanging wall is intensely metamorphosed and poorly exposed. The opposing dip directions of these two segments suggest fault E is spoon shaped. Available data do not indicate if the shape of the fault plane is an original feature or if the fault was folded. If the thrust was not deformed, its shape suggests that movement was southwest to northeast. However, if movement was generally from the west to the east, which is the regional direction of transport for the Sapphire plate, then the thrust has been folded about a northeast-trending axis. The apparent overturning of strata in the hanging wall along the south segment of fault E may indicate that this segment is nearer to the leading edge of the fault than is the north segment and that movement, therefore, was primarily from west to east. Alternatively, the overturn could reflect a small northeast-trending anticline that formed over a lateral ramp, and that configuration would imply movement primarily from southwest to northeast. We suspect the fault is deformed because a southwest to northeast direction of thrust movement is atypical of the general west-to-east movement of the Sapphire plate (Hyndman and others, 1975; Hyndman, 1980; and Ruppel and others, 1981) and because other thrusts in this region are folded (Emmons and Calkins, 1913; Poulter, 1956; Lidke, 1985).

Fault F (fig. 5) is also a younger-on-older fault, and it shows little apparent stratigraphic offset. Members two and three of the Mount Shields Formation form the hanging wall and members one and two form the footwall. In the area between Congdon and Fox Peaks on plate 1, the nearly homoclinal attitudes of rocks in the upper and lower plates make it hard to explain how these younger-on-older structural relations could result from southwest-to-northeast movement. However, if this fault represents a lateral splay or ramp that merges with fault E, movement in a dominantly eastward direction could produce this structural pattern.

Structural relations of faults G, H, and I (fig. 5) are obscure because high-grade metamorphism makes identification of rock units uncertain. Fault G reflects an approximate contact between schistose rocks and the quartzite member of the Mount Shields Formation; its trace is only approximately located. Faults H and I are in a migmatitic roof pendant that is surrounded by granodiorite (Kib) of the Idaho batholith. Fault H is an older-on-younger fault that puts the Wallace Formation on member two of the Mount Shields Formation, as do faults C and D. Fault I has younger-on-older stratigraphic relations and has transported member two of the Mount Shields Formation over the Wallace Formation, as does fault E. Because the geologic relations of faults G, H, and I are obscure, they are not integrated into the structural framework of the map area.

The inferred north-trending thrust shown below till in Copper and Moose Meadow Creeks on plate 1 (fault J, fig. 5) has younger-on-older stratigraphic relations and shows little apparent stratigraphic offset. Along the north segment of the thrust, member two of the Mount Shields Formation overlies member one, whereas along the south part of the thrust, member two overlies itself. This thrust appears to join thrusts of the imbricate zone, which is described below, along its south extension. The younger-on-older stratigraphic relations apparently result from faulting of a north- to northeast-trending fold system; the Meyers Creek syncline is the only large-scale fold of that system that can be mapped with certainty.

A small segment of a thrust, which crosses Lone Pine Ridge on plate 1 (fault K, fig. 5), east of thrust J, also has younger-on-older stratigraphic relations and shows little apparent stratigraphic offset. This fault puts member one of the Mount Shields Formation over the lower part of the Snowslip Formation. The younger-on-older stratigraphic relations apparently result from truncation by the thrust of inclined strata of the east limb of the Meyers Creek syncline; bedding above and below the thrust dips more steeply west than does the thrust.

Thrust faults in the imbricate zone merge laterally to produce a braided map pattern (fig. 5). These faults appear to be listric, and they probably merge at depth to form a sole thrust that is not exposed in this area. Like faults J and K, faults in the imbricate zone cut folded strata but do not appear to be folded themselves, and some show younger-on-older stratigraphic relations that apparently result from truncation of inclined strata of the Meyers Creek syncline. The juxtaposition of slices of the laterally equivalent Wallace and Helena Formations by faults in this zone suggests large lateral translations along some of these faults, even though individual thrust slices are small. The imbricate zone and faults J and K (fig. 5) seem to be younger than the flat thrusts that bound the thrust sheets farther west, because faults of the imbricate zone cut folds that deform the thrust sheets. The juxtaposition of thin thrust slices of the Wallace Formation with the Helena Formation and with the Mount Shields Formation in this zone may result from faults in the imbricate zone cutting the older folded flat faults.

Folds

The geometric elements of large-scale folds are difficult to identify in the map area because (1) the folds are broad and sinuous, (2) the limbs of some folds are truncated by thrust and high-angle faults, (3) some folds appear to be confined to thrust sheets, and (4) some thrusts are folded and cut by faults. The largest fold shown on the map is the broad Meyers Creek syncline in the eastern part of the area; some smaller tight to isoclinal folds occur in the western part of the area.

Pederson (1976, p. 55–56) mapped two folds in the Proterozoic section in the eastern part of the study area, the Whetstone anticline in the area of Whetstone Ridge, and the Meyers Creek syncline in the area of Meyers Creek. Pederson's Whetstone anticline parallels a concealed thrust fault, as mapped during this study, that follows a tributary of Moose Meadow Creek on plate 1 (thrust J, fig. 5). The trace of the axial surface of the Meyers Creek syncline was revised during this study, although it generally follows the trend established by Pederson (1976). Our mapping extends the axial trace of the Meyers Creek syncline about 8 km (5 mi) to the north, into an area that was not included in Pederson's mapping. The sinuous trace of the Meyers Creek syncline may result from movement along faults J and K and from movement on faults of the imbricate zone following folding.

Tight and isoclinal folds occur locally along the west side of the batholith near thrust C (fig. 5). Several small-scale isoclinal folds were mapped in a small area north of Railroad Creek in the Wallace Formation. These folds trend north-northwest and have apparent plunges to both the north and south, and most are overturned to the west. The area in which these folds occur is probably larger than shown on the map, but poor exposures did not permit more detailed mapping. Directly to the southwest and structurally below the Wallace Formation and thrust C, in the Skalkaho Creek window, member two of the Mount Shields Formation is also tightly folded. These folds are shown diagrammatically in cross section *A–A′* of the geologic map. Mapping was not detailed enough to define the symmetry of these folds, but the attitudes of strata suggest the folds are tight and have north-northwest trends similar to those of the folds in the overlying Wallace Formation. The thrust that underlies the thrust sheet of the Wallace Formation and overlies member two of the Mount Shields Formation (thrust C) is folded, but this thrust does not appear to be as tightly folded as are the footwall and hanging-wall rocks above and below it. This thrust may truncate the small-scale folds above and below it, or it may have acted as a detachment for the tight folding. Approximately 1.6 km (1 mi) north of Fox Peak, near the queried fault G (fig. 5), poorly exposed tight folding apparently affects the schist, the Mount Shields Formation, and possibly the inferred thrust that separates them. The small segment of fault E that underlies these folded rocks does not appear to be folded, but this segment is small and poorly exposed. The attitude of bedding and the schistosity suggest these folds are also tight and northwest-trending.

Some thrust faults were folded after emplacement of the thrust sheets. The map pattern of thrust C (fig. 5) reflects that of a sinuous anticline that trends northeast in its south part, but northwest in its north part. The south part of fault D appears to be folded along a somewhat sinuous but generally northerly trend. Fault E probably is folded along a northeast-trending, southwest-plunging axis, similar to the trend and plunge of the Meyers Creek syncline.

High-Angle Faults

Pederson (1976) mapped high-angle, strike-slip, reverse, and normal faults in the map area, but only a few of these were located during our mapping. Pederson (1976, p. 57–60) indicated that some faults were marked by breccia zones, silicified breccia zones, and breccia associated with quartz veins, but most of these breccia zones are discontinuous. Relative offset directions and amounts of separation cannot be determined for most of these zones, and they are shown as shear zones on the geologic map (pl. 1). Pederson (1976, p. 56–57) used traces on aerial photographs and geomorphic interpretation to locate possible normal-fault trends on his map. Our examination of these possible faults shows that many of these high-angle faults cannot be demonstrated. One of Pederson's postulated normal faults, in the Moose Meadow Creek area, appears to be a thrust fault.

The northwest-trending fault south of Bare Hill on plate 1 may have as much as 30 m (100 ft) of stratigraphic separation. This high-angle fault offsets the Mount Shields and Wallace Formations and thrust fault E (fig. 5). This steep fault may offset rocks of the Sapphire batholith as well. A northeast-trending, high-angle fault in the south-central part of the area along Sign Creek (pl. 1) displaces both the Mount Shields and Wallace Formations and a thrust fault downward on the southeast block. This fault also cuts thrust D (fig. 5). To the northeast, this steep fault apparently is expressed as a wide zone of shear. Northwest of this shear zone, other northeast-trending shear zones occur in plutonic rocks of the batholith, mainly in the area of Frogpond Basin on plate 1. The north-trending high-angle fault in the southeast part of the area, about 1.6 km (1 mi) north of Clifford Point on plate 1, lowers thrusts in the imbricate zone (fig. 5) to the southeast about 15-30 m (50–100 ft).

Evolution of Structures

Geometric analysis of thrust faults using methods similar to those outlined by Boyer and Elliott (1982) suggests that at least two flat thrust sheets of the

Sapphire thrust plate were emplaced in the map area and that these thrust sheets were folded and broken by thrust faults of the imbricate zone prior to intrusion of the Sapphire batholith. Movement on high-angle faults and shear zones appears to postdate emplacement of the Sapphire batholith.

The geometric methods used to reconstruct the sequence of tectonic events in the southern Sapphire Mountains are partly predicated on our interpretation that emplacement of the Sapphire batholith did not cause thrust faulting and, therefore, that thrust faults can be joined across the exposed batholith. Some thrust faults obviously were not caused by emplacement of the Sapphire batholith because they are truncated by rocks of the batholith, and these faults cannot be traced into the batholithic rocks as zones of shear, brecciation, or foliation. The zone of imbricate thrusts east of Senate Mountain is probably unrelated to emplacement of the batholith, because this zone apparently continues 105 km (65 mi) northwest to near Missoula, Mont.; it is unlikely that movement of such regional extent was caused by emplacement of a local plutonic body. The pattern of axial trends of folds does not suggest annular folding around the elongate batholith. The Meyers Creek syncline appears to be part of a regional fold system that continues 34 km (21 mi) east of the batholith, so the syncline is not likely related to intrusion of the batholith. The anticlinal fold that defines the Skalkaho window appears to pre-date intrusion of the Sapphire batholith, because axial-plane cleavage does not cut metamorphic textures formed by the batholith. Although the individual pieces of evidence cited above do not provide conclusive evidence that the batholith played no active role in thrust faulting and large-scale folding, taken together, this evidence strongly supports our interpretation. This interpretation provides no solution to the long-standing problem of creating space in upper levels of the crust for batholiths, but it provides support for restoration of thrust faults across the batholith.

Figure 6 is an interpretive map that shows structures in the map area to consist mainly of two folded thrust faults that bound thrust sheets and their subsidiary thrust splays, an imbricate system of thrust faults that cuts the folds and probably the thrust sheets, and a few high-angle faults and shear zones that cut thrust faults and folds.

A geometric pattern of stacked and folded thrust sheets has recently been recognized as a regional structural characteristic of the Sapphire thrust plate. Two stacked and folded thrust sheets dominate the structural pattern over most of the map area. About 19 km (12 mi) northwest of the map area in the area of Burnt Fork, three stacked thrust sheets have been identified, two of which extend into the map area and are bounded by thrust faults 1 and 2 (fig. 6). Although not exposed in the map area, this third and structurally highest thrust sheet is shown in the cross section (fig. 6). The lateral continuity of these thrust sheets suggests that displacement along individual bounding thrusts might be on the order of tens of kilometers. The juxtaposition of different lithofacies of the Missoula Group across these bounding thrusts also supports the possibility of relatively large lateral translation along these faults.

Thrust faults 1 and 2 underlie two thrust sheets and have, respectively, older-on-younger and younger-on-older stratigraphic relations. Both faults have subsidiary thrust splays that may be similar to the subsidiary thrusts that bound horses as described by Boyer and Elliott (1982). Thrust 1, the lower thrust, juxtaposes a thrust sheet of the Wallace Formation over Missoula Group rocks. Thrust fault 1a, in the northern part of the area, probably represents a splay fault from thrust 1; the splay may be confined within the thrust sheet of Wallace Formation. Thrust fault 2 overlies the thrust sheet of Wallace Formation and underlies younger rocks of the Mount Shields Formation. Thrust faults 2a and 2b are interpreted to be splay faults from thrust 2 and similar in character to thrust 1a.

The imbricate zone and thrust faults 3 and 4 (fig. 6) seem to be younger than the flat thrusts that bound the thrust sheets, inasmuch as these imbricate faults cut folds that deform the thrust sheets. In the imbricate zone, the juxtaposition of the Mount Shields Formation with thin thrust slices of the Wallace Formation and the laterally equivalent Helena Formation may result from imbricate faults cutting the folded flat thrusts 1 and 2.

A pair of thrust faults along the west side of the study area (labeled 5 on fig. 6) are of uncertain relation to the regional pattern of thrust faults. These two faults have structural and stratigraphic relations similar to those of faults 1 and 2, but they are in a roof pendant within plutonic rocks of the Idaho batholith. Because structural relations of these faults are uncertain, they are not considered in the geometric restoration that follows.

The geometric analysis of fault systems (Boyer and Elliott, 1982), provides an approach that can be used to interpret the sequential evolution of structures in this map area. Figure 7 shows a simplified geometric solution for the development of the structures in the map area; a similar solution has been proposed for an area several kilometers to the east along the north flank of the Anaconda Range (Lidke, 1985). Both of these solutions depend on the premise that the system of master thrusts formed ramps and undercut ramps sequentially in relatively thick, competent rocks of the Belt Supergroup.

The first stage (fig. 7*A*) shows the sequence of rock units prior to thrust faulting. In this stage, an incipient flat thrust (fault 1) is shown as the dashed line; it formed in the lower part of the Wallace and Helena Formations on the west side of the diagram, but to the east it ramped

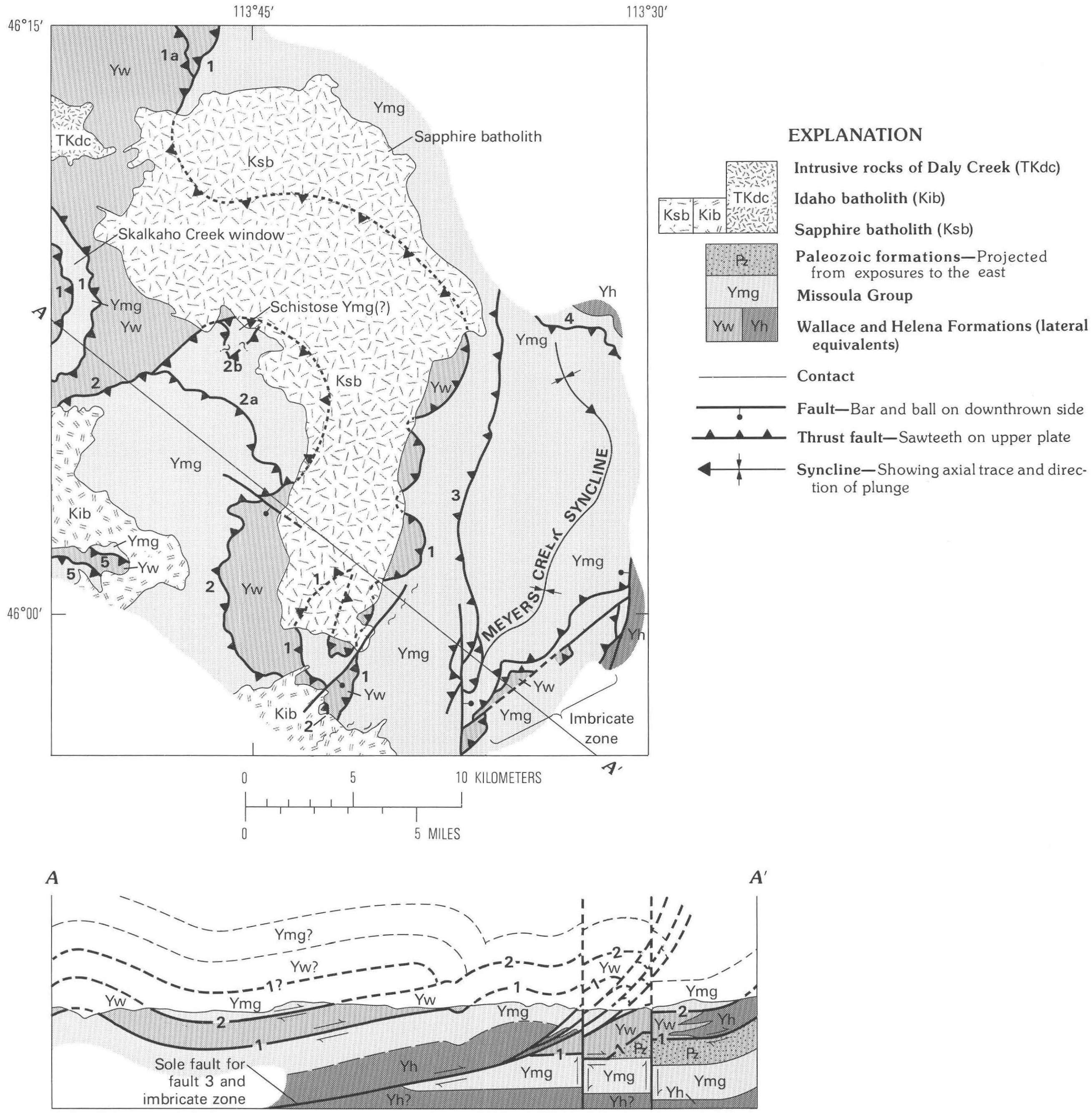

Figure 6. Interpretive sketch map and cross section of structures in the southern Sapphire Mountains. Compare with figure 5. See text for explanation of thrust faults 1–4.

through the Helena Formation and much of the Missoula Group and flattened in the upper part of the Missoula Group section. Argillaceous rocks in the upper part of the Missoula Group may have provided a preferred zone of weakness for thrust propagation.

The second stage (fig. 7*B*) shows the geometric configuration of rock units after movement on the incipient thrust (thrust 1) of stage 1; that movement put the Wallace Formation on younger rocks of the Missoula Group in the west and central part of the diagram along fault 1. The second stage also shows the position of a second incipient thrust (thrust 2), which, with movement, might have partly collapsed the westernmost ramp that formed during movement along fault 1 and formed another ramp farther east. The new ramp would have cut the Missoula Group, the earlier formed thrust (thrust 1), and the Wallace Formation that overlies thrust 1.

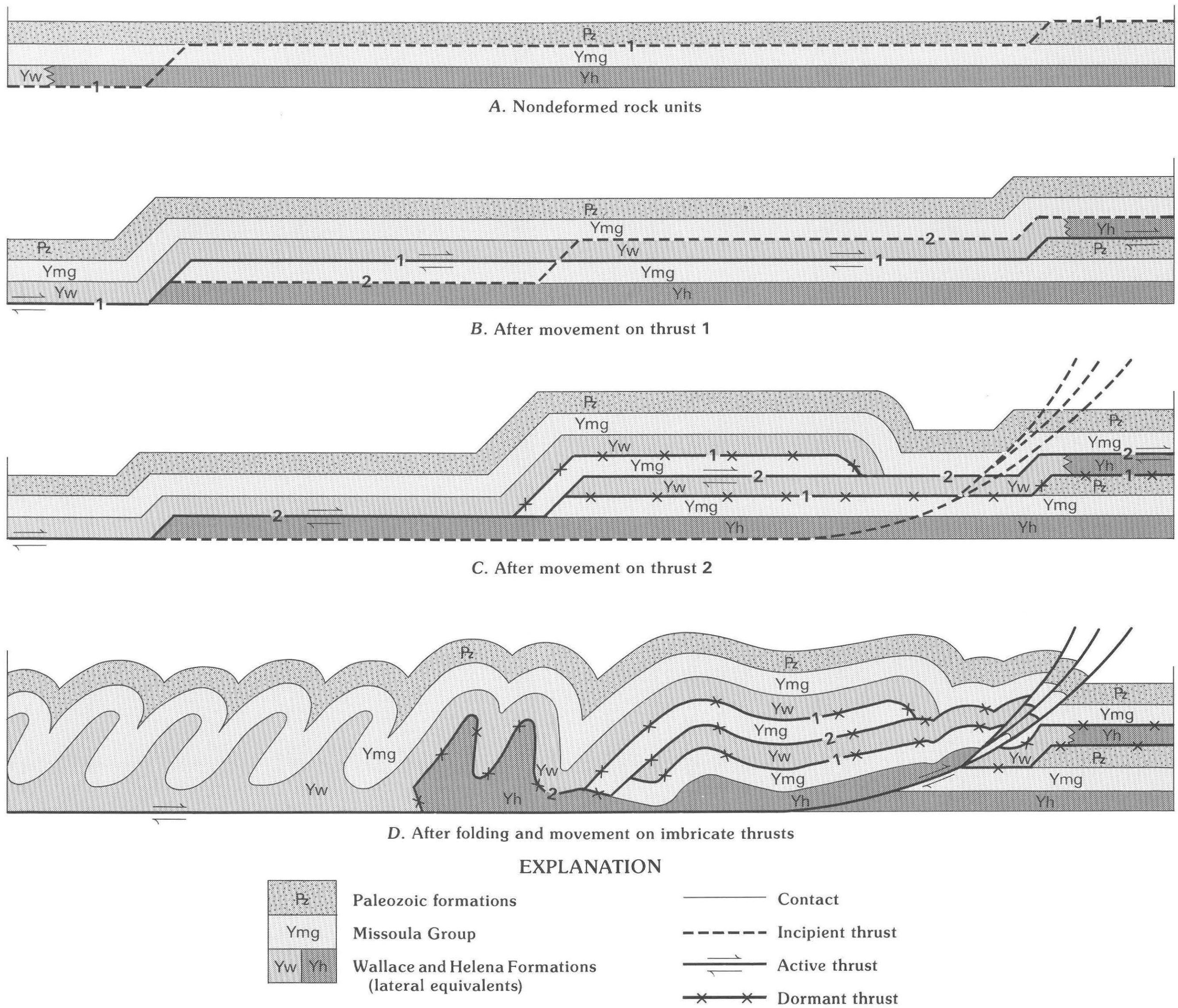

Figure 7. Simplified sequence of structural evolution in the map area. Each diagram shows active thrusts for the stage represented, dormant thrusts from the previous stage, and (or) incipient thrusts that became active in the following stage. Compare the right half of stage *D*, above, to cross section *A–A′* on figure 6.

The third stage (fig. 7*C*) shows the geometric configuration that would have resulted from movement along thrust 2, and it shows that the location of the incipient imbricate thrusts may have been controlled by the geometry of the thrust sheets that were stacked during stages 2 and 3. The third stage also shows that movement along thrust 2 has piggybacked a more western part of thrust 1 over a more eastern part, creating a stack of three thrust sheets from movement along only two thrusts, and creating younger-on-older stratigraphic relations across thrust 2.

A later folding event, which affected the stacked thrust sheets, probably preceded the movement of faults in the imbricate zone. The final geometric configuration of rock units, which reflects the late folding event and imbrication of the flat thrust and folds by the young faults of the imbricate zone is shown in stage 4 (fig. 7*D*). This configuration is nearly identical to the configuration shown as cross section *A–A′* on the sketch map (fig. 6).

Although other explanations of the geometric distribution of thrust faults and rock units might be used for this region, the solution illustrated in figure 7, which incorporates an approach similar to that used by Boyer and Elliott (1982) to explain the development of duplexes, may be the simplest method for restoration of rocks to the undeformed condition. This solution suggests that the sequential development of flat thrusts has produced thrust sheets of Belt rocks that show regional continuity, and that some of these developed as younger-on-older flat thrusts that also have regional continuity. This geometric solution and other evidence suggest that the regional occurrence of younger-on-older thrust faults is a normal part of thrust deformation on the Sapphire thrust plate.

Implications of the Style of Deformation and Timing of Plutonism

The folded and faulted stack of thrust sheets in the southern Sapphire Mountains represents a structural style that is typical of the thrust-sheet terrane of the Sapphire thrust plate (fig. 4). The prevalence of deformed stacks of thrust sheets, in which master thrusts are nearly parallel to bedding, implies large amounts of internal shortening along master thrusts between thrust sheets, which previous estimates of supracrustal shortening in the Sapphire thrust terrane did not consider. Relations between isotopically dated plutonic rocks and thrust faults and folds in the southern Sapphire Mountains suggest that plutonism occurred during the waning stages of compression or after compression ceased, but these relations do not provide absolute ages for relating different compressional events that occurred during emplacement of the Sapphire thrust plate.

The amount of tectonic shortening that accompanied emplacement of the Sapphire thrust plate may be much greater than earlier estimates by Hyndman (1980) and Wallace (in Ruppel and others, 1981), because these interpretations did not account for large amounts of shortening among stacked thrust sheets. Hyndman's hypothesis proposed that shortening occurred along the décollement that bounded the "Sapphire tectonic block" and that the "tectonic block" was shortened internally by listric thrusts of relatively small displacement that joined the décollement at depth (Hyndman, 1980, fig. 4). Hyndman (1980, p. 434) estimated that the "Sapphire tectonic block" moved eastward about 60 km (35 mi). Wallace (in Ruppel and others, 1981, p. 153–156) proposed that shortening occurred both on master thrusts between subplates and on listric thrusts within subplates, which joined the master thrusts at depth: he also suggested that the depositional axis of the Belt basin had been displaced 70 to 150 km (45 to 95 mi) to the east. These early views of thrust faulting in the Sapphire thrust plate do not account for large amounts of internal shortening implied by stacked and restacked thrust sheets. Moreover, different thrust sheets in the stack reflect different amounts of supracrustal shortening, depending on the sequence of stacking, the locations of ramps, and the distance that inactive thrust sheets were piggybacked above active thrust sheets. Although estimates of the amount of supracrustal shortening represented by the Sapphire thrust plate await regional structural and stratigraphic analysis, the structural style documented for the southern Sapphire Mountains implies that a previous estimate of 150 km (95 mi) by Wallace (in Ruppel and others, 1981) is probably a minimum distance required to restore the depositional axis of the Belt basin to its original site before thrust faulting.

Relations between isotopically dated plutonic rocks, thrust faults, and folds in the Sapphire thrust plate show that the intrusion of large batholiths to epizonal levels was mainly a postcompressional event. Regional isotopic data indicate that (1) thrust sheets were emplaced and folded before 81 or 82 Ma, (2) the frontal imbricate terrane formed before about 82 Ma, and (3) younger zones of imbricate thrust faults formed before about 78 Ma (fig. 8).[2] Although Desmarais (1983) cites geologic evidence for syntectonic plutonism at mesozonal depths for a pluton of the Idaho batholith in the southern Sapphire Mountains, the U/Pb age of 78 Ma attached to that event has error limits of ± 20 Ma. This large error limit provides little constraint on the actual timing of eastward-directed thrust faulting at epizonal levels. Potassium-argon isotopic data from the Sapphire batholith indicate that magma penetrated to epizonal levels and cut folded thrust sheets before 73 Ma. Because the batholith is not sheared by thrust faults, the thrust faulting in the southern Sapphire Mountains must have ceased before 73 Ma. Similar relations between plutons and thrust faults in other parts of the Sapphire thrust plate show that the thrust sheets were emplaced and the frontal imbricate terrane formed before 81 or 82 Ma (fig. 8). The Garnet stock has a potassium-argon age of about 82 Ma (82.4 ± 1.0 Ma from hornblende and 79.1 ± 0.7 Ma from biotite) and truncates thrust faults of the frontal imbricate terrane of the Sapphire plate. The Miners Gulch stock (potassium-argon age of about 81 Ma) truncates folded thrust faults of the thrust-sheet terrane. The Philipsburg batholith has potassium-argon ages that range between 78 and 74 Ma (Hyndman and others, 1972),[2] and it truncates zones of imbricate thrust faults that cut thrust sheets (Wallace and others, 1986). Although these ages do not establish the absolute timing of thrust sheet emplacement, formation of the imbricate frontal zone, and movement on the younger zones of imbricate thrust faults, the crosscutting relations imply that the plutonism followed compressional deformation and that the youngest compressional deformation ceased before about 78 Ma in the Sapphire thrust plate. However, 78 Ma is a minimum age for movement along the younger zones of imbricate thrust faults, and this movement could have ceased as early as 81 or 82 Ma.

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[2]The 78–Ma and 74–Ma isotopic ages mentioned here have been approximately corrected from the original ages given by Hyndman and others (1972), to be consistent with revised potassium-argon decay constants.

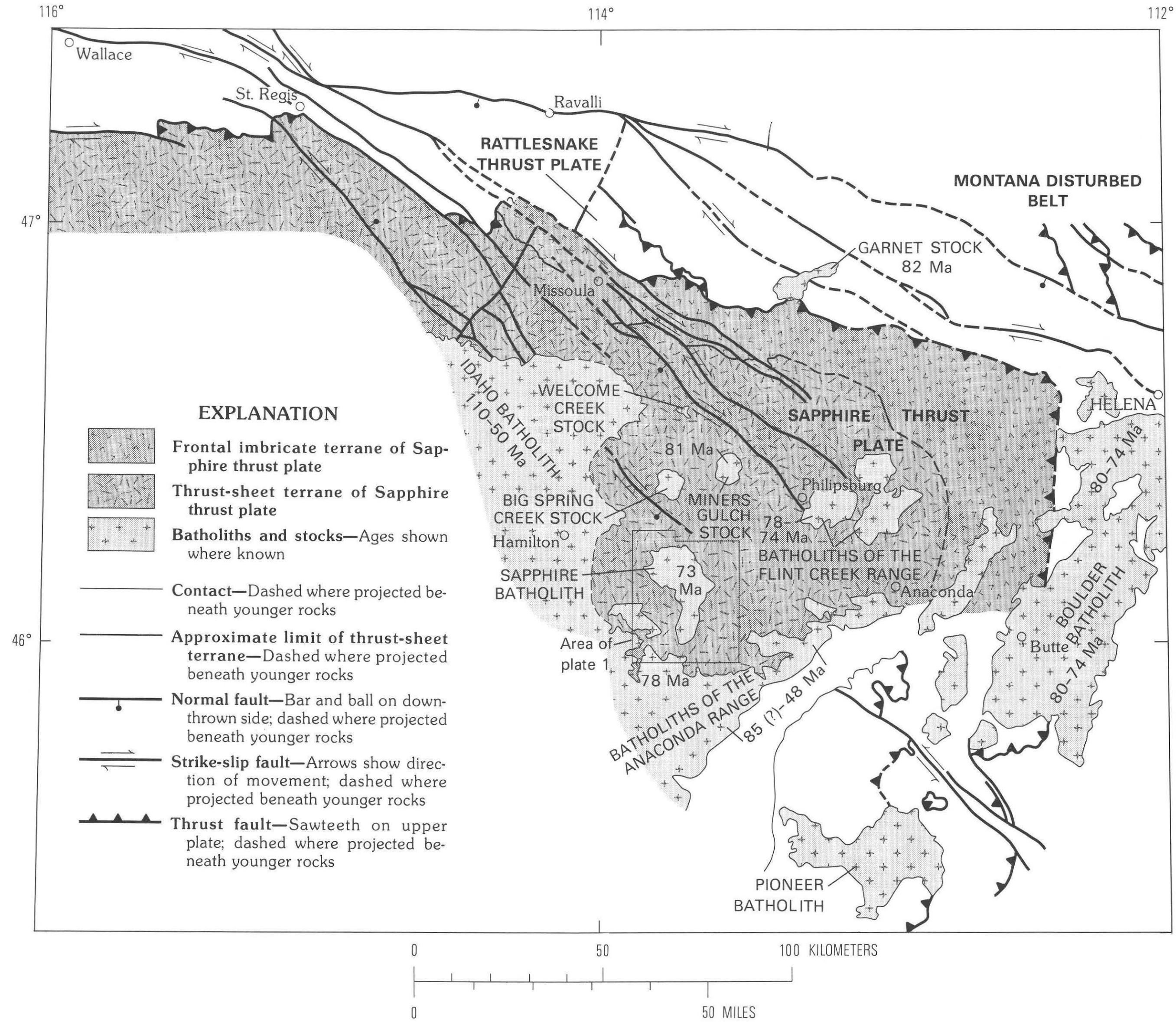

Figure 8. Major stocks and batholiths around the Sapphire thrust plate, west-central Montana.

REFERENCES CITED

Boyer, S. E., and Elliott, David, 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, no. 9, p. 1196–1230.

Desmarais, N. R., 1983, Geology and geochronology of the Chief Joseph plutonic-metamorphic complex, Idaho-Montana: Seattle, Wash., University of Washington, Ph. D. thesis, 150 p.

Elliott, J. E., Wallace, C. A., O'Neill, J. M., Hanna, W. F., Rowan, L. C., Segal, D. B., Zimbelman, D. R., Pearson, R. C., Close, T. J., Federspiel, F. E., Causey, J. D., Willett, S. L., Morris, R. W., and Huffsmith, J. R., 1985, Mineral resource potential map of the Anaconda–Pintlar Wilderness and contiguous roadless area, Granite, Deer Lodge, Beaverhead, and Ravalli Counties, Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF–1633-A, scale 1:50,000.

Emmons, W. H., and Calkins, E. C., 1913, Geology and ore deposits of the Philipsburg quadrangle, Montana: U.S. Geological Survey Professional Paper 78, 271 p.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Tex., Hemphill's, 170 p.

Harrison, J. E., 1972, Precambrian Belt basin of northwestern United States—Its geometry, sedimentation, and copper occurrence: Geological Society of America Bulletin, v. 83, p. 1215–1240.

Harrison, J. E., Griggs, A. B., and Wells, J. D., 1986, Geologic and structure maps of the Wallace 1°×2° quadrangle, Montana and Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map, I–1509–A, scale 1:250,000.

Hyndman, D. W., 1980, Bitterroot dome—Sapphire tectonic block, an example of a plutonic-core gneiss-dome complex with its detached suprastructure, *in* Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H., eds., Cordilleran metamorphic core complexes, Geological Society of America Memoir 153, p. 427–443.

Hyndman, D. W., Obradovich, J. D., and Ehinger, Robert, 1972, Potassium-argon age determinations of the Philipsburg batholith: Geological Society of America Bulletin, v. 83, p. 473–474.

Hyndman, D. W., Talbot, J. L., and Chase, R. B., 1975, Boulder batholith—A result of emplacement of a block detached from the Idaho batholith infrastructure(?): Geology, v. 3., p. 401–404.

Lidke, D. J., 1985, Geology, structure, and geometrical analysis of structural relations along the south part of the Georgetown thrust, southwest Montana: Boulder, Colo., University of Colorado M.S. thesis, 104 p.

Lidke, D. J., Wallace, C. A., and Obradovich, J. D., 1987, Structural features and constraints on age of emplacement of the Sapphire thrust plate, west-central Montana: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 314.

McKelvey, G. E., 1968, Depositional environment of middle carbonate units of Belt Supergroup, Montana and Idaho: American Association of Petroleum Geologists Bulletin, v. 52, p. 858–864.

Nelson, W. H., and Dobell, J. P., 1961, Geology of the Bonner quadrangle, Montana: U.S. Geological Survey Bulletin 1111–F, p. 189–235.

Pederson, R. J., 1976, Geology of the upper Rock Creek drainage, Granite County, Montana: Butte, Mont., Montana College of Mineral Science and Technology, M.S. thesis, 238 p.

Poulter, G. J., 1956, Geologic map of the Georgetown thrust area, Granite and Deer Lodge Counties, Montana: Montana Bureau of Mines and Geology Geological Investigations Map 1, 2 sheets with text.

Ross, C. P., Andrews, D. A., and Witkind, I. J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:500,000.

Ruppel, E. T., Wallace, C. A., Schmidt, R. G., and Lopez, D. A., 1981, Preliminary interpretation of the thrust belt in southwest and west-central Montana and east-central Idaho, *in* Guidebook to southwest Montana: Montana Geological Society Field Conference and Symposium, 1981, p. 139–159.

Schmidt, R. G., Wallace, C. A., Whipple, J. W., and Winston, Don, 1983, Stratigraphy of the eastern facies of the Ravalli Group, Helena Formation, and Missoula Group between Missoula and Helena, Montana, *in* Hobbs, S. W., ed., Guide to field trips, Belt Symposium II: Missoula, Mont., University of Montana, p. 5–34.

Smith, G. A., and Barnes, W. C., 1966, Correlation and facies changes in the carbonaceous, calcareous, and dolomitic formations of the Precambrian Belt-Purcell Supergroup: Geological Society of America Bulletin, v. 77, p. 1399–1426.

Steiger, R. H., and Jaeger, E., 1977, Subcommission on geochronology—Convention and use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Streckeisen, A. L., 1973, Classification and nomenclature recommended by the IUGS Subcommission on the Systematics of Igneous Rocks: Geotimes, v. 18, no. 10, p. 26–30.

Turner, F. J., and Verhoogen, John, 1960, Igneous and metamorphic petrology: New York, McGraw-Hill Book Company, Inc., 694 p.

Wallace, C. A., Harrison, J. E., Klepper, M. R., and Wells, J. D., 1976, Carbonate sedimentary breccias in the Wallace Formation (Belt Supergroup), Idaho and Montana, and their paleogeographic significance: Geological Society of America Abstracts with Programs, v. 8, p. 1159.

Wallace, C. A., Lidke, D. J., Elliott, J. E., Antweiler, J. C., Campbell, W. L., Hassemer, J. H., Hanna, W. F., Banister, D. P., and Close, T. J., 1984, Mineral resource potential of the Sapphire Wilderness Study Area and contiguous roadless areas, Granite and Ravalli Counties, Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF–1469–B, scale 1:50,000.

Wallace, C. A., Lidke, D. J., and Obradovich, J. D., 1982, Geologic map of the Sapphire Wilderness and contiguous roadless areas, Granite and Ravalli Counties, Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF–1469–A, scale 1:50,000.

Wallace, C. A., Schmidt, R. G., Lidke, D. J., Waters, M. R., Elliott, J. E., French, A. B., Whipple, J. W., Zarske, S. E., Blaskowski, M. J., Heise, B. A., Yeoman, R. A., O'Neill, J. M., Lopez, D. A., Robinson, G. D., and Klepper, M. R., 1986, Preliminary geologic map of the Butte 1° × 2° quadrangle, western Montana: U.S. Geological Survey Open-File Report 86–292, scale 1:250,000.

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