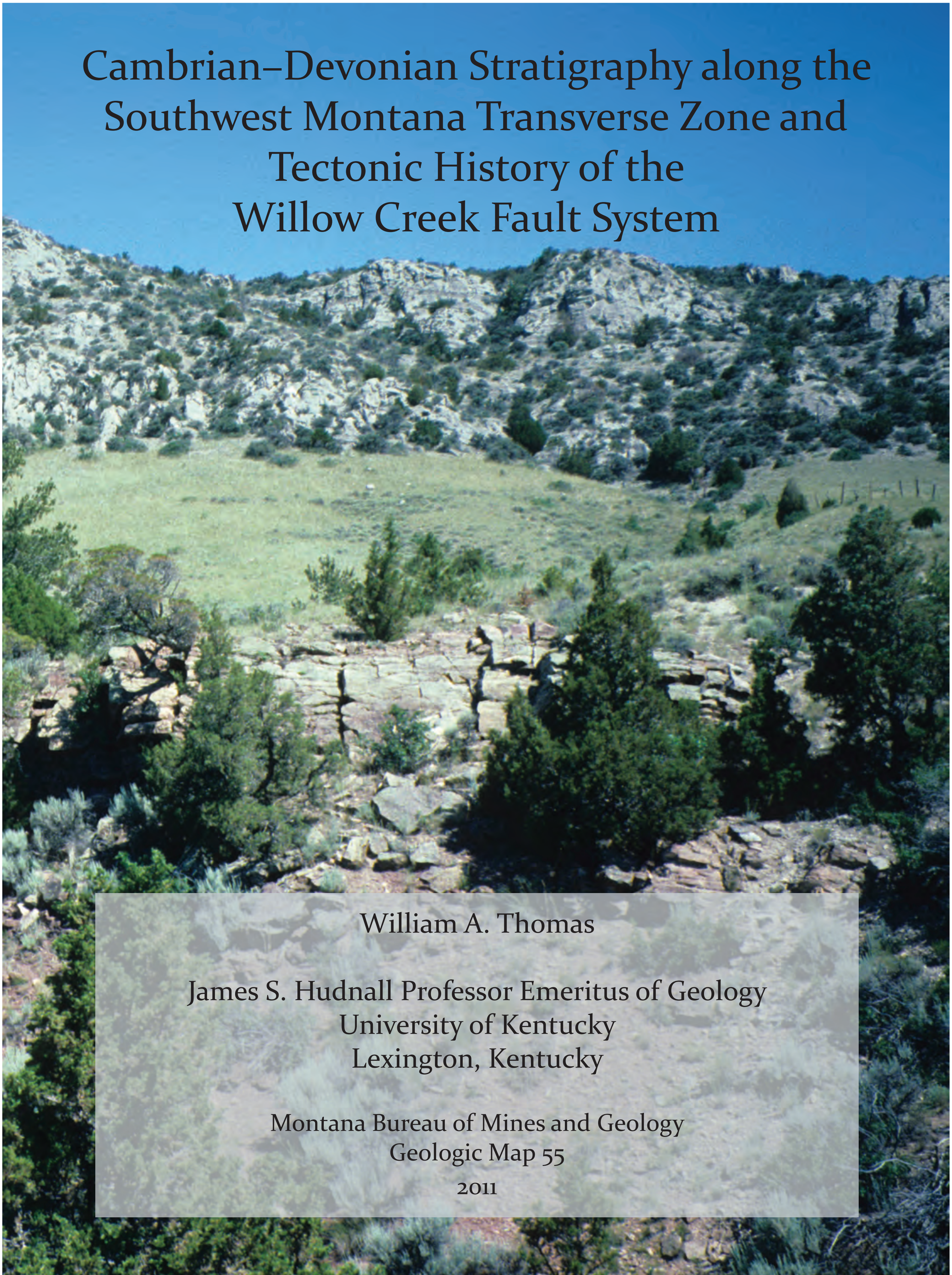
Cambrian–Devonian Stratigraphy along the Southwest Montana Transverse Zone and Tectonic History of the Willow Creek Fault System



William A. Thomas

James S. Hudnall Professor Emeritus of Geology
University of Kentucky
Lexington, Kentucky

Montana Bureau of Mines and Geology
Geologic Map 55
2011

Cover Photo: Meagher Limestone, Wolsey Shale, Flathead Sandstone, and Belt Supergroup in the lower part of the Milligan Canyon section (see fig. 3B for details). Photo by W.A. Thomas.

Geologic Map 55

CAMBRIAN–DEVONIAN STRATIGRAPHY ALONG THE SOUTHWEST MONTANA TRANSVERSE ZONE AND TECTONIC HISTORY OF THE WILLOW CREEK FAULT SYSTEM

William A. Thomas
James S. Hudnall Professor Emeritus of Geology
University of Kentucky
Lexington, Kentucky

Montana Bureau of Mines and Geology
2011

Table of Contents

Figures

PREFACE

Transverse zones, cross-strike alignments of points of along-strike structural change, are common features of thrust belts worldwide. My research on transverse zones in the southern Appalachian thrust belt provided the impetus to study examples of transverse zones in other thrust belts. A primary focus of this work is on the control(s) on location and geometry of transverse zones. The Southwest Montana transverse zone in the Cordilleran thrust belt offers a view of structures at the top of crystalline basement rocks, a structural level that is deep in the subsurface in the southern Appalachians. My introduction to the structure of the Southwest Montana transverse zone came through the writings of Christopher J. Schmidt and his colleagues, J. Michael O'Neill, John M. Garihan, and William C. Brandon. A field trip with Chris Schmidt in 1985 completed my introduction. The Southwest Montana transverse zone is positioned along the Perry line, an alignment of basement faults that define the southern limit of thick sedimentary rocks of the Belt Supergroup. The basement faults and the southward termination of the Belt strata are the primary controls on location and geometry of the transverse zone. Possible additional controls are stratigraphic variations in lower Paleozoic strata that might have resulted from synsedimentary reactivation of the basement faults. The opportunity to test possible stratigraphic controls on location of the transverse zone gave rise to the research reported here. This work addresses the Cambrian and Devonian units that may be décollement-host strata for thin-skinned thrust faults south of the Southwest Montana transverse zone.

Fieldwork was conducted during the summers of 1990 and 1991 with support from the National Science Foundation (EAR-8905229). My field assistants were James M. Montgomery, Jr., Brenda J. Buck, and Rachel L. Thomas. The Indiana University Geologic Field Station on the South Boulder River provided a base for field operations, and Lee J. Suttner provided both geological and logistical assistance. Mervin J. Bartholomew guided my search for base maps, aerial photographs, and references; and the Montana Bureau of Mines and Geology (MBMG), through the support of State Geologist Edward T. Ruppel, provided various field materials. An Indiana University field seminar, conducted by J. Robert Dodd and myself, directed the efforts of Joseph L. Allen, Paul A. Azevedo, Brenda J. Buck, Holly J. Corner, John C. Mars, and Robin J. McDowell in specific studies of parts of the section. Joseph L. Allen computed stratigraphic thickness from traverse data, using a program provided by Richard W. Allmendinger. During the preparation of this report, Christopher J. Schmidt provided especially helpful suggestions concerning the discussion of structural setting. Harold L. James (MBMG) accompanied me in the field to obtain photographs for the report. Completion of the report has been strongly supported by State Geologist Edmond G. Deal, Publications Editor Susan Barth, Geologic Cartographer Susan Smith, and Geologist Susan Vuke.

The details of stratigraphy are illustrated graphically in plate 1, which is designed for efficient tracing of the units in the field. The plotted stratigraphic columns show locations of ridges, ledges, valleys, and benches, as well as the positions of sills, to aid in determining locations in the field. In addition, the Appendix includes a map of the traverse of each measured section. The intent is that the plate can be used in the field to follow the stratigraphy at whatever level of detail is desired.

William A. Thomas
James S. Hudnall Professor Emeritus of Geology
University of Kentucky
Lexington, Kentucky

INTRODUCTION

The Southwest Montana transverse zone is expressed as a large-scale dextral offset of the Cordilleran thrust front (Schmidt and O'Neill, 1983; Schmidt and others, 1988), defining the southern boundary of the Helena salient (fig. 1). The leading frontal ramps (e.g., Battle Ridge monocline) in the Helena salient north of the transverse zone protrude >75 miles (>120 km) farther east onto the North American craton than the leading frontal ramps south of the transverse zone (fig. 1). The east-striking, south-directed Jefferson Canyon thrust fault forms a distinctive segment in the middle part of the trace of the transverse zone along the Jefferson River canyon between the communities of Three Forks and Whitehall. The Jefferson Canyon fault constitutes a lateral ramp that accommodates ~12 miles (~20 km) of dextral offset between the east-directed Lombard thrust fault within the Helena salient on the north and the Tobacco Root and Mayflower Mine faults (oblique ramps) on the south (fig. 1).

The primary structure of the Southwest Montana transverse zone is a large-scale, east-striking, up-to-south lateral ramp. North of the transverse zone, the basal décollement is in Precambrian sedimentary strata of the Proterozoic Belt Supergroup, and the Belt rocks are overlain by a succession of Cambrian and younger strata. South of the transverse zone, where the Belt Supergroup is unconformably absent and Cambrian strata rest on Archean metamorphic basement rocks, the basal décollement of the thrust belt is in lower Paleozoic strata.

The distribution of Proterozoic Belt sedimentary rocks and Archean basement rocks beneath the

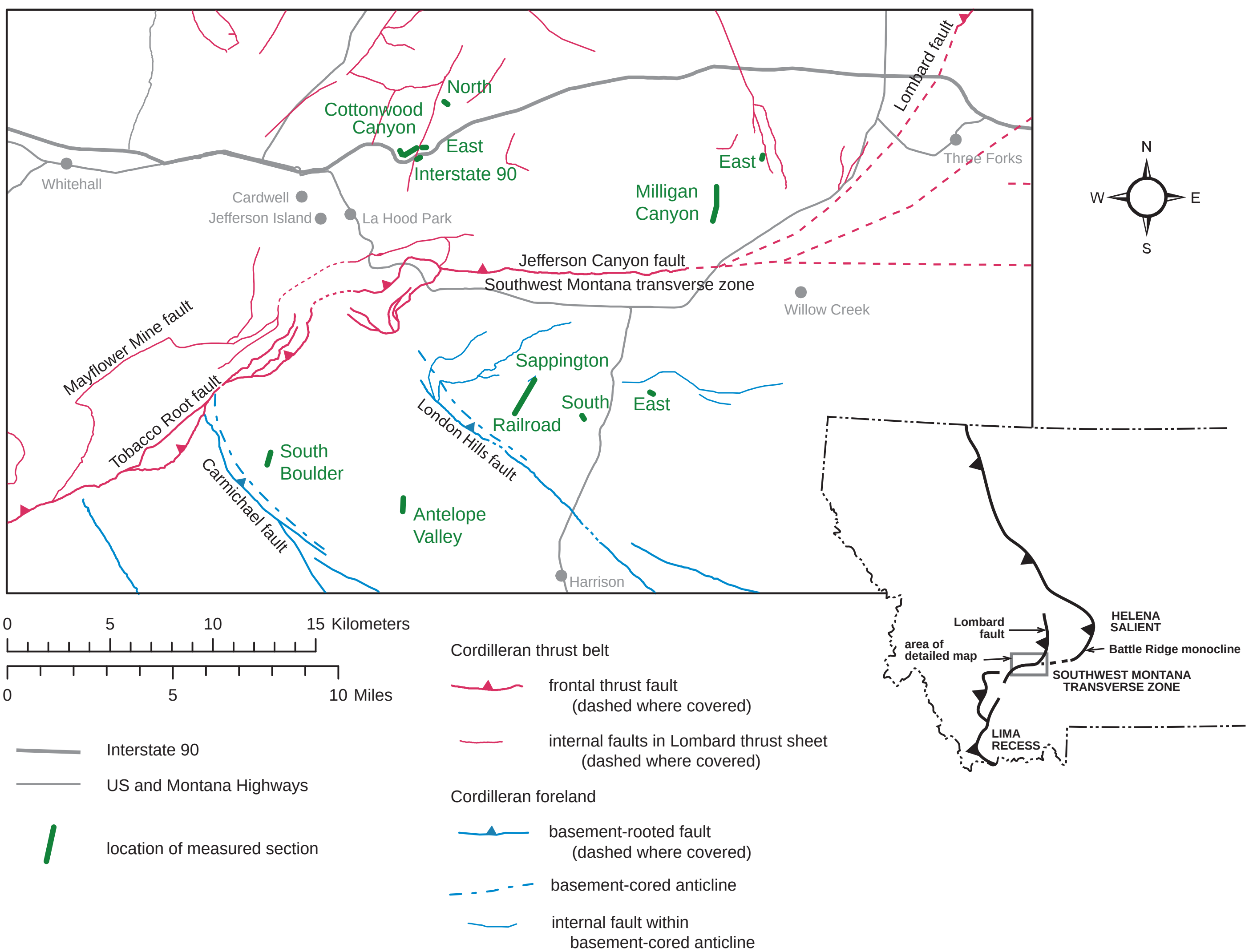


Figure 1. Outline map of structural geology along the Southwest Montana transverse zone and locations of measured sections. Structure map compiled from Robinson (1963), Schmidt (1975), Woodward (1982), Schmidt and O'Neill (1983), and O'Neill and others (1990).

sub-Cambrian unconformity documents the southern boundary of a sedimentary basin, where a thick succession of Belt strata was deposited (McMannis, 1963; Robinson, 1963). The abruptness of the southward termination of the Belt rocks indicates that the basin boundary was defined by a down-to-north fault system. (For a summary of evolution of thought, see Schmidt and others, 1988.) Belt rocks near the boundary are coarse, proximal-fan facies; a northward gradation to finer, more distal facies confirms the steep, fault-defined southern boundary of the Belt sedimentary basin (McMannis, 1963). The regional southern boundary of the Belt basin is named the Perry line (Harris, 1957); the part of the Perry line along the Jefferson Canyon segment of the Southwest Montana transverse zone is called the Willow Creek fault (Robinson, 1963). Local lateral facies variations within the Belt Supergroup, as well as intersections or offsets at northwest-striking basement faults, suggest a set of multiple west-striking faults (Schmidt and others, 1988), here named the Willow Creek fault system.

The location of the Southwest Montana transverse zone coincides spatially with the Perry line, and the basal décollement of the thrust belt rises stratigraphically from within the Belt Supergroup southward across the transverse zone into the lower Paleozoic succession, indicating that the basement fault system at the southern boundary of the Belt sedimentary basin controlled the subsequent location of the transverse zone in the Cordilleran thrust belt (Schmidt and others, 1988). More specifically, the location of the Willow Creek fault system and the distribution of the Belt strata controlled the location of the east-striking lateral ramp that is expressed as the Jefferson Canyon fault (Schmidt, 1975; Schmidt and O'Neill, 1983; Schmidt and others, 1988).

Although Proterozoic movement along the Willow Creek fault system is well documented, later reactivation of the basement faults prior to Cordilleran thrusting is problematic. Synsedimentary reactivation of the Willow Creek basement fault system might have resulted in stratigraphic variations in the lower Paleozoic strata through which the décollement subsequently propagated south of the Southwest Montana transverse zone, and any such stratigraphic variations may have exerted additional controls on location and geometry of the transverse zone. The shallow-marine depositional systems represented in the Cambrian and Devonian succession (Sloss, 1950) would have been especially sensitive to minor synsedimentary fault reactivation. In order to test the possibility of synsedimentary fault-controlled lateral variations in the lower Paleozoic stratigraphy and to evaluate the magnitude of possible Cambrian–Devonian movement along the Willow Creek fault system, a detailed study of Cambrian through Devonian strata has been conducted on both sides of the Jefferson Canyon fault along the Southwest Montana transverse zone. The results of the study are presented in four composite stratigraphic sections (plate 1). The measured sections are identified by names (Appendix) throughout the text and illustrations (plate 1; fig. 1).

STRUCTURAL SETTING

The Jefferson Canyon fault is a distinct segment of the Southwest Montana transverse zone, and the Willow Creek fault system constitutes a spatially comparable segment of the Perry line (the south boundary fault system of the Belt sedimentary basin). The Jefferson Canyon fault and the Willow Creek fault system form significant boundaries in the Cordilleran thrust belt and in the sub-thrust structures, respectively.

North of the Southwest Montana transverse zone, the basal décollement flat is within the Proterozoic Belt sedimentary succession, and frontal ramps cut stratigraphically upward through the overlying Paleozoic strata (Schmidt and O'Neill, 1983; Burton and others, 1993). The Lombard thrust fault (fig. 1), a frontal ramp within the Helena salient, evidently is continuous with the east-striking Jefferson Canyon fault (lateral ramp), marking the eastern and southern boundaries of the Lombard thrust sheet (Robinson, 1963; Schmidt and O'Neill, 1983; Schmidt and others, 1988). Previously, the Lombard fault has been interpreted to be a frontal ramp from the basal décollement to the present surface, and translation of the Lombard thrust sheet relative to the foreland south of the Jefferson Canyon fault was estimated to be ~7 to 10 miles (~11 to 16 km) (Schmidt and O'Neill, 1983). More recently obtained seismic reflection profiles and well data, however, indicate that the Lombard fault is the roof thrust of a duplex of Belt Supergroup and Phanerozoic strata as young as Cretaceous (Schmidt and others, 1990; Burton and others, 1993). The floor thrust of the duplex (in Belt strata) is the basal décollement of the Cordilleran thrust belt, and the Jefferson Canyon fault evidently is an up-to-south lateral ramp of both the basal décollement and the Lombard fault. The Lombard thrust sheet extends above the duplex at least 23 miles (37 km) west from the exposed fault trace. Translation of the Lombard thrust sheet relative to the foreland south of the Jefferson Canyon fault is estimated to be as much as 50 miles (80 km) (Burton and others, 1993). The Lombard fault truncates structures in the footwall and is folded by younger footwall structures, indicating a complex sequence of thrusting (Burton and others, 1993). Within the southern part of the Lombard thrust sheet, adjacent to the Jefferson Canyon fault, imbricate frontal thrust splays and fault-related folds deform the Paleozoic rocks, which are exposed in several outcrop belts (Robinson, 1963; Schmidt, 1975, 1976; Woodward, 1982).

South of the Southwest Montana transverse zone, the basal décollement is within the Paleozoic strata above Archean crystalline basement rocks. Thrust flats at several different stratigraphic levels in the Paleozoic succession are connected by frontal and lateral ramps. Parts of the Paleozoic stratigraphy are exposed along the leading edges of several imbricate thrust sheets (Schmidt, 1975). In the foreland east of the Cordilleran thrust front and south of the transverse zone, northwest-striking, basement-cored, asymmetric anticlines are bounded on the steep southwest limbs by steep reverse faults (fig. 1). Cordilleran thin-skinned thrust faults impinge on the basement-cored uplifts, and small-scale lateral ramps formed where thin-skinned thrust faults propagated through the folded strata on the basement-cored anticlines (Schmidt and Garihan, 1983; Schmidt and others, 1988). Paleozoic and younger strata are exposed on the northeast limbs of the asymmetric basement-cored anticlines.

The basal décollement of the thrust belt rises both structurally and stratigraphically southward across the Southwest Montana transverse zone, defining an up-to-south lateral ramp (Jefferson Canyon fault) expressed in both the hanging wall and footwall (Schmidt and O'Neill, 1983; Schmidt and others, 1988). The hanging-wall cutoff of the basal décollement rises stratigraphically southward >3000 m from Proterozoic Belt to lower Paleozoic strata, and the elevation of the footwall rises southward from deep in the subsurface to the present outcrop level. The lateral ramp (Jefferson Canyon fault) evidently originated over the Willow Creek fault system at the south boundary of the Belt sedimentary basin, primarily because of the lateral termination of the Belt décollement-host stratigraphy. South of the Willow Creek fault system, where the Belt Supergroup is unconformably absent, the stratigraphically lowest décollement-host horizons are in the lower part of the Cambrian–Devonian succession.

SUMMARY OF STRATIGRAPHIC SECTIONS

Four composite stratigraphic sections (plate 1; Appendix) of Cambrian–Devonian rocks were measured along traverses selected for completeness of exposure. Two of the composite sections are in the Cordilleran thrust belt north of the Southwest Montana transverse zone (north of the Jefferson Canyon fault within the southern part of the Lombard thrust sheet), and two are on basement-cored uplifts in the foreland south of the transverse zone (fig. 1). The sections in the thrust belt are 2 to 4 miles (3 to 6 km) north of the Jefferson Canyon fault and are ~10 miles (~16 km) apart in a direction nearly parallel to the transverse zone. Thrust faults and folds between the two sections are estimated to have shortened the original distance by ~7.5 miles (~12 km) (measured from cross sections in Schmidt, 1976). The sections in the foreland south of the transverse zone are ~9 miles (~14 km) apart in a direction approximately parallel to the transverse zone; the most westerly section is ~2.5 miles (~4 km) east of the Cordilleran thrust front. The original distance between the sections in the foreland was shortened by a mile or more across a basement-cored anticline (London Hills anticline) and a steep reverse fault (fig. 1). The sections north and south of the transverse zone are ~8 miles (~13 km) apart in a direction approximately perpendicular to the transverse zone; however, the original distance has been shortened by a few miles by a southward-thrusting component in oblique slip on the Jefferson Canyon fault (Schmidt and others, 1988). In addition, the sections in the thrust belt north of the Jefferson Canyon fault have been translated eastward as much as 50 miles (80 km) relative to the foreland (Burton and others, 1993). As part of the measurement of stratigraphic sections, geologic structure was mapped locally, and traverses were routed through continuous stratigraphic successions. Sills are common throughout the region; the thickness of sills was omitted from the measured stratigraphic sections.

DESCRIPTION OF STRATIGRAPHIC UNITS

Precambrian Rocks

North of the Willow Creek fault system, Cambrian strata rest on Proterozoic sedimentary rocks of the Belt Supergroup. South of the fault system, the Cambrian Flathead Sandstone rests on Archean metamorphic and plutonic rocks.

Archean crystalline basement rocks on the upthrown block south of the Willow Creek basement fault system are predominantly quartz–feldspar–biotite gneiss. Coarse granites and pegmatites cut the gneisses locally. The basement rocks also include quartz–feldspar–hornblende gneiss and amphibolite (Robinson, 1963).

Rocks of the Proterozoic Belt Supergroup are limited to the north, downthrown side of the Willow Creek basement fault system. Adjacent to the Willow Creek fault system, the Belt Supergroup includes a very coarse facies, the LaHood Formation, which contains coarse boulder conglomerates, rubble beds, arkosic conglomerates, and arkoses (McMannis, 1963; Hawley and Schmidt, 1976). The coarse facies is in a relatively narrow band on the downthrown block of the Willow Creek fault system, indicating proximal deposition adjacent to upthrown metamorphic rocks south of the fault. Grain size decreases northward away from the Willow Creek fault system, representing gradation from proximal to distal depositional settings. The most distal facies are mudstones, and an intermediate facies includes interbedded sandstones and mudstones (McMannis, 1963).

The Belt strata at the Milligan Canyon section (plate 1) are red to brown arkose to arkosic sandstone. The rocks are very poorly sorted and include fine- to very coarse-grained quartz and fine- to coarse-grained feldspar. Part of the sandstone contains mica. Clay matrix is common. Part of the sandstone has calcite cement. The red color reflects secondary hematite (McMannis, 1963). The sandstones are thin bedded.

The Belt strata at the Cottonwood Canyon section (plate 1) represent a more distal facies than that at the Milligan Canyon section. Sandstone units, ~30 cm thick, alternate with clay shale in units ~1 m thick. The shales are dark gray, and the sandstones are brownish red. The sandstone beds are graded, ranging from very fine to very coarse grained at the base to fine grained at the top. The sandstones are dominantly quartz but include some feldspar and rare mica. Clay matrix is abundant, and calcareous cement is common. The lower, fining-upward part of each bed is massive, and the uppermost 3 cm is thinly laminated, fine-grained sandstone. Some thin sandstone beds are laminated throughout.

Flathead Sandstone

The Middle Cambrian Flathead Sandstone, the basal unit of the Paleozoic succession, is a light-colored quartzose sandstone that generally forms a prominent ridge (fig. 2). Regionally, the formation ranges in thickness to somewhat more than 45 m; however, it is absent locally because of onlap onto paleotopographic highs on the Belt strata (Robinson, 1963; Graham and Suttner, 1974; Thomas and others, 1996). The base of the Flathead is a prominent unconformity, corresponding to the base of the craton-wide transgressive Sauk sequence (Sloss, 1963). The Flathead grades upward into shaly beds that characterize the Wolsey Shale.

Characteristic rocks of the Flathead Sandstone are light gray to white, fine- to very coarse-grained quartzose sandstone; part of the sandstone contains quartz pebbles as much as 2.5 cm in diameter.

Figure 2. Steep ridges on nearly vertical Flathead Sandstone at the Cottonwood Canyon section (plate 1). Photo by H.L. James, MBMG.

Very fine-grained sandstone is rare. Despite the wide range of grain sizes in the formation, most beds contain moderately well-sorted sand. In parts of the formation, thin beds and laminae of very fine- to fine-grained sandstone alternate with thin beds and laminae of fine- to medium-grained sandstone, and in a medium- to coarse-grained sandstone, medium-dominated laminae alternate with coarse-dominated laminae. The sandstones are dominantly quartz. The quartz grains are subround to round, but the shapes are modified commonly by overgrowths and less commonly by grain-boundary solution. Glauconite pellets are common in parts of the formation. Although light colors dominate, shades of light brown and pink are common, and parts of the sandstone weather to a distinctive brown-spotted pattern. Beds range from thin laminae to thick (1 m) massive beds. Sedimentary structures include crossbeds in sets as much as 30 cm thick, low-angle cross laminae, horizontal laminae, and ripple laminae. Horizontal burrows are rare. Thin interbeds and lenses of medium gray clay shale are scattered through the succession at the Cottonwood Canyon section (plate 1), and some shale units encompass thin interbeds and lenses of sandstone. The South Boulder section (plate 1) contains thin interbeds and lenses of green clay shale, and part of the sandstone contains flat clay chips as much as 3 cm across.

The Flathead Sandstone at the Milligan Canyon section (plate 1) exhibits several exceptions to the general description, primarily because of incorporation of reworked detritus from the underlying red, arkosic sandstones of the Belt Supergroup. The sandstone is less well sorted than elsewhere. For example, the section includes very poorly sorted, fine- to very coarse-grained sandstone, as well as bimodal, fine-grained and coarse- to very coarse-grained sandstone. The sandstone includes detrital feldspar, and a small part is arkosic. Quartz pebbles are scattered through part of the section, and part of the sandstone contains flat chips of green shale. Glauconite pellets are similar to those in the more quartzose sandstones that characterize the Flathead elsewhere. Calcareous cement is common. Part of the sandstone is argillaceous, and part of the rock ranges from very argillaceous sandstone to very sandy mudstone. The feldspathic sandstones range from dark maroon to dull red in color. Interbeds of dark maroon silty shale, containing mica flakes, are scattered through the upper part of the formation. Horizontal burrows are common in the silty shales. The Milligan Canyon section includes beds of light-colored (yellowish gray to brownish gray) quartzose sandstones similar to those that characterize the Flathead elsewhere.

Two distinct suites of Precambrian rocks underlie the sub-Flathead unconformity and attest to pre-Flathead deformation and erosion. South of the Southwest Montana transverse zone (south of the Willow Creek basement fault system) in the South Boulder and Sappington Railroad sections (plate 1), the Flathead Sandstone rests on an Archean crystalline basement complex of gneisses and granites (Robinson, 1963). In contrast, north of the transverse zone, the Flathead overlies Proterozoic sedimentary rocks of the Belt Supergroup (Cottonwood Canyon and Milligan Canyon sections, plate 1), and the beds commonly show angular discordance at the unconformity. Local detailed measurements in the vicinity of Cottonwood Canyon indicate angular discordance of 17° to 51° between horizontally restored Flathead beds and south-dipping strata of the LaHood Formation of the Belt Supergroup (Hawley and Schmidt, 1976); most LaHood dips are in the lower part (generally <25°) of the range of angular discordance (C.J. Schmidt, personal communication, 1995).

Thickness variations of the Flathead Sandstone document onlap of the Flathead onto a surface of paleotopographic relief on the Belt strata north of the Willow Creek fault system (Graham and Suttner, 1974), as well as on Archean crystalline rocks south of the fault system. Incorporation of reworked detritus from the Belt sandstones to generate the distinctive composition of the Flathead at the Milligan Canyon section (fig. 3) reflects onlap onto a paleotopographic high, which is further indicated by the local distribution of the Flathead. The Flathead at the Milligan Canyon section is relatively thin (~12 m, plate 1). A short distance west of the Milligan Canyon section, the Flathead pinches out westward (fig. 3; Appendix), and the overlying Wolsey Shale onlaps the erosion surface on the Belt rocks (Robinson, 1963; Graham and Suttner, 1974). The Milligan Canyon section documents one of three "islands" (defined by Graham and Suttner, 1974) where the Flathead Sandstone pinches out by onlap onto paleotopographically high coarse strata of the Belt Supergroup. In contrast, at the Cottonwood Canyon section (fig. 2), a relatively thick (42 m) Flathead and no clear indication of local reworking of the Belt rocks combine to indicate a paleotopographic low on the sub-Flathead surface. Similarly, a relatively thick (~47 m) Flathead Sandstone overlies Archean crystalline rocks south of the Willow Creek fault system (South Boulder and Sappington Railroad sections, plate 1). The three "islands" where Flathead pinches out and Wolsey Shale onlaps Belt strata are aligned along the coarse facies of the Belt Supergroup on the downthrown side of the Willow Creek fault system.

Paleotopographic relief on the sub-Flathead surface closely reflects the sedimentary facies distribution in the Belt strata (Thomas and others, 1996). Stratigraphic onlap relationships indicate paleotopographic highs on the coarse proximal facies of the Belt Supergroup; in contrast, fine-grained distal facies of the Belt, as well as Archean crystalline rocks south of the Willow Creek fault system, evidently formed paleotopographic lows. Because the coarse proximal facies of the Belt is closely associated with the Willow Creek fault system, the distribution of sub-Flathead paleotopographic highs is aligned with the basement fault system (Thomas and others, 1996). The alignment of paleotopographic highs with the Willow Creek fault system might have been a result of pre-Flathead fault inversion (north-side-up displacement, in contrast to north-side-down displacement during Belt deposition). The close correspondence of paleotopography to distribution of rock types below the erosion surface, however, indicates that differential erosion produced the relief and that the alignment of paleotopographic highs along the north side of the Willow Creek fault system is an artifact of the association of the Belt coarse facies with the fault. No post-Belt inversion of the fault system is required to explain the paleotopographic relief on the sub-Flathead surface.

Wolsey Shale

The Middle Cambrian Wolsey Shale is characteristically a clay shale succession that represents

Figure 3. (A) Lower part of the Milligan Canyon section (plate 1). The ridge on the skyline is formed on the upper part of the Pilgrim Limestone; the smaller ledge on the slope is on lower Pilgrim. The high, light-colored, lower ridge is formed on the Meagher Limestone; the covered slope below the Meagher cliff conceals the Wolsey Shale. The brushy ridge on the left, below the Wolsey slope, is formed on arkosic sandstones of the Belt Supergroup; the Flathead Sandstone is unconformably absent. In contrast, in the canyon partially concealed behind the low hill on the right, the Flathead Sandstone intervenes between the Wolsey Shale and Belt Supergroup. Photo by H.L. James, MBMG.

Figure 3. (B) View from the canyon on the right side of photograph in fig. 3A. On the skyline is the ridge on the Meagher Limestone, and the covered slope below is on the Wolsey Shale. Part of the Wolsey Shale is exposed on the bare slope on the left. Ledges in the foreground are Flathead Sandstone, resting unconformably on arkosic sandstones of the Belt Supergroup at the Milligan Canyon section (plate 1). Photo by W.A. Thomas.

a sedimentological transition from the Flathead Sandstone to the overlying dominantly carbonate succession. The shale succession contains thin interbeds of a wide variety of rock types, and the middle part of the Wolsey is a distinctive limestone member, the Silver Hill Member.

Clay shales that typify the Wolsey range in color from medium gray to greenish gray and gray-green. The shale is thinly fissile. Very fine mica is common on bed surfaces. Part of the shale is silty; part is calcareous. At contacts with sills, the clay shale is altered to black argillite.

The shale in the lower part of the Wolsey (below the Silver Hill Member) contains a variety of thin interbeds. Rock types in the interbeds include light gray to brown and yellow, very fine-grained sandstone to siltstone, and medium to light gray limestone (micrite, bioclastic wackestone, and bioclastic packstone). The largest and most common bioclasts are trilobite fragments. Part of the sandstone and siltstone is calcareous, and some of the limestone contains quartz sand and silt. Some of these beds are gradational from very sandy (silty) limestone to very calcareous sandstone (siltstone). In one bed at the Sappington Railroad section (plate 1), that gradation is expressed as alternate laminae of silty bioclastic limestone (packstone) and siltstone that contains bioclasts. Other limestone beds contain very silty to sandy laminae. Parts of the sandstone and siltstone contain scattered bioclasts; in some beds, bioclasts are distributed in indistinct laminae. At the Milligan Canyon section, some limestone beds are capped by thin layers of sandstone. Many beds of both the clastic and carbonate rocks contain glauconite pellets. The sandstones and siltstones are in part argillaceous, and some beds contain discontinuous clay laminae. Very fine mica is common. All of the interbeds in the shale are thin (<30 cm), mostly no more than 5 cm thick; some beds are thinly laminated. Ripple lamination is rare. Horizontal burrows are common on bed surfaces. At the Sappington Railroad section and in the surrounding area, the lower part of the Wolsey contains a distinctive dark red, medium- to coarse-grained, calcareous, glauconitic, hematitic sandstone in slabby beds no more than 15 cm thick; the sandstone unit contains interbeds of sandy, glauconitic, bioclastic grainstone and glauconitic siltstone. At the Milligan Canyon section (plate 1), the lower Wolsey contains a unit of limestone 3.4 m thick. The lower part of the limestone consists of glauconitic, bioclastic grainstone to packstone with interbeds of bioclastic wackestone; the upper part is bioclastic wackestone.

The Silver Hill Member of the Wolsey Shale is dominated by light gray to dark gray micritic limestone. The limestone member also includes beds of medium light gray to dark gray bioclastic wackestone, bioclastic packstone, bioclastic grainstone, intraclastic wackestone, intraclastic packstone, and peloidal wackestone to packstone. Identifiable bioclasts are mainly trilobite fragments. Part of the limestone is slightly dolomitic. Silty to slightly sandy limestone is rare. The limestones generally are thin bedded. A few limestone beds contain anastomosing clay partings, and some beds have anastomosing laminae and burrow mottles like those that characterize the Cambrian limestones above the Wolsey. Part of the member includes thin interbeds of medium gray to greenish gray clay shale. The Silver Hill Member is well exposed in the most westerly measured sections (Cottonwood Canyon and South Boulder); it is thickest at the Cottonwood Canyon section (plate 1). The member is not exposed and may be absent in the more easterly measured sections (Milligan Canyon and Sappington Railroad, plate 1); however, it may be concealed beneath a grassy slope at the Milligan Canyon section (fig. 3) and beneath stream alluvium at the Sappington Railroad section.

The upper part of the Wolsey Shale contains more numerous and thicker carbonate interbeds than the shale succession below the Silver Hill Member, and the upward increase in carbonate rocks constitutes an irregular gradation to the overlying carbonate-dominated succession (fig. 4). In part of the succession, thin-bedded limestones in intervals as much as 1 m thick alternate with calcareous mudstones. In the upper part of the Wolsey at the Sappington Railroad section (plate 1), thin-bedded limestone with clay partings constitutes a unit nearly 9 m thick. In addition to the relatively thick limestone units, thin limestone beds are scattered in other parts of the shale succession. The limestones are thin bedded, and some are nodular.

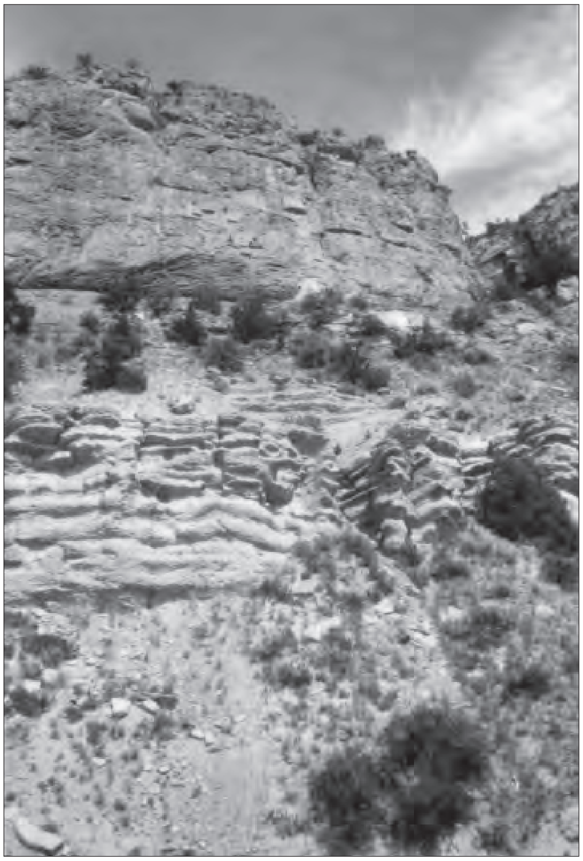


Figure 4. Upward gradation from Wolsey Shale (shale-dominated succession on lower slope, and overlying interbedded shales and limestones, including limestone unit with thin clay partings) to Meagher Limestone (limestone cliff) at the Sappington Railroad section (plate 1). Photo by W.A. Thomas.

Limestones include medium to light gray micrite and bioclastic wackestone; bioclastic packstone is rare. Part of the limestone contains glauconite pellets. Some of the limestone is silty to sandy, and part is argillaceous. Some thin interbeds grade from silty limestone to calcareous siltstone. Dolomitic limestone is rare. The upper Wolsey also includes thin (<5 cm thick) interbeds of light to medium gray, partly calcareous, very fine-grained sandstone to siltstone, part of which contains glauconite. Horizontal burrows are common in the sandstones and siltstones. Siltstone beds at the Sappington Railroad section are marked by adhesion ripples. A sandstone bed at the South Boulder section contains flat mudstone chips <1 cm across. Some of the sandstone and siltstone beds contain argillaceous laminae. The contact with the overlying Meagher Limestone is placed at the top of the limestone succession that contains abundant shale interbeds (shale constitutes ~50% of the succession).

The Wolsey Shale ranges in thickness from ~68 to ~125 m (plate 1); however, thickness distribution is not systematically related to the location of the Willow Creek fault system. The Wolsey Shale overlies the Flathead Sandstone, except where the Flathead pinches out and the Wolsey (locally upper Wolsey) onlaps coarse facies of the Belt Supergroup along an alignment of "islands" (Graham and Suttner, 1974) along the north side of the Willow Creek fault system. Locally, limestone in the upper Wolsey contains detrital feldspar and quartz reworked from arkosic Belt sandstones. The paleotopography is interpreted to be a result of differential erosion on contrasting rock types below the unconformity (Thomas and others, 1996).

Meagher Limestone

The Middle Cambrian Meagher Limestone is remarkably uniform in thickness and lithology throughout the area of the Southwest Montana transverse zone (plate 1). Local faults obscure the thickness at the Sappington Railroad section; at the other three measured sections, thickness of the Meagher is identical. The base of the formation is gradational with the Wolsey Shale, and the contact is placed at the base of the lowest thick limestone unit that lacks a substantial thickness of shale interbeds. The upper contact is gradational to the overlying Park Shale; however, the gradation is contained within a few meters of limestone and shale interbeds.

Typical limestones of the Meagher are medium gray to dark gray micrite; some interbeds are light gray. The limestones are characterized by anastomosing laminae and burrow mottles (fig. 5). The laminae and mottles consist of microcrystalline limestone, part of which is dolomitic. A rough weathering surface suggests that the laminae yield some insoluble residue, and the laminae appear to be partly argillaceous to silty. Although the limestones are generally medium to dark gray, the anastomosing laminae and burrow mottles are a lighter shade of gray to brownish gray and weather to buff, rust, and yellow. The color pattern of these rocks has been called mottled "black and gold," "blue and gold," or "black and tan" (Hanson, 1952; Robinson, 1963). The mottled beds are generally <10 cm thick. Even though the burrow-mottled, laminated

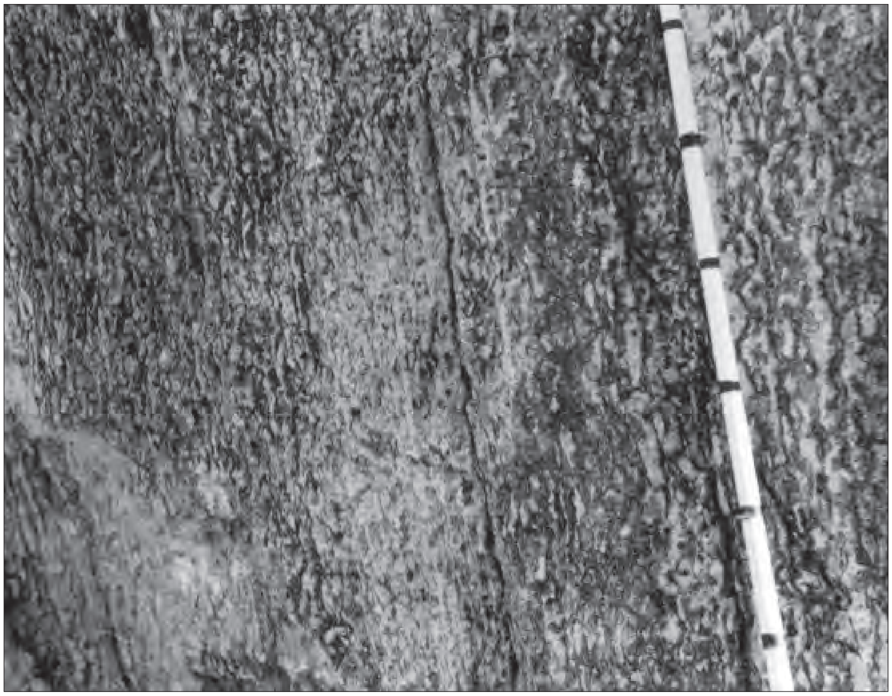


Figure 5. Steeply dipping Meagher Limestone at the Cottonwood Canyon section, showing characteristic anastomosing laminae and burrow mottles. Increments on rod are 10 cm. Photo by H.L. James, MBMG.

limestones are thin bedded, parts of the succession appear thick bedded to massive with internal mottling and lamination. Some limestone units within the formation are thick bedded and apparently lack the distinctive anastomosing laminae. Locally, the limestone contains a few scattered “chert-rim nodules,” consisting of a thin rim of chert around a limestone core. The nodules are generally <10 cm across. At sill contacts in the Cottonwood Canyon section, the limestone is altered to white calcite marble in thin irregular bands.

The lower part of the formation is dominated by micrite with anastomosing laminae and burrow mottles. Scattered, thin interbeds within the micrite succession include intraclastic packstone in which the intraclasts are flat chips of micrite <4 cm in diameter, intraclastic wackestone, and oolitic packstone to grainstone. Parts of the micritic limestones contain scattered bioclasts. In the lowermost part of the formation at the Cottonwood Canyon section, the anastomosing laminae include argillaceous limestone and irregular layers of green clay and medium gray calcareous clay. The lowermost part of the Meagher Limestone at the Milligan Canyon section contains a distinctive gray-black micrite in thin planar beds, and the lower part of the formation at the South Boulder section also contains gray-black micrite in thin beds (plate 1). The lowermost part of the Meagher at the Sappington Railroad section (plate 1) consists of gray-black, partly argillaceous, micritic limestone with scattered bioclasts (trilobite fragments); the thin-bedded limestone contains partings and interbeds of gray-black calcareous shale <10 cm thick.

The middle part of the Meagher Limestone is marked by a distinctive medium light gray to medium dark gray oolitic packstone to grainstone, part of which includes oolitic wackestone (plate 1). The ooids are <0.8 mm in diameter and generally are darker than the limestone matrix. The oolitic packstone to grainstone at the Milligan Canyon section contains scattered bioclasts (trilobite fragments). The oolitic packstone to grainstone is crossbedded in tangential sets as much as 30 cm thick, and at the South Boulder section, crossbed dips are bipolar. Parts of the succession include interbeds of micrite and intraclastic limestone. In part of the South Boulder section, alternate zones of oolitic limestones and micritic limestones are each no more than 1 m thick. The distribution of oolitic limestones within the succession shows no discernible difference on opposite sides of the Southwest Montana transverse zone.

The upper part of the Meagher Limestone, like the lower part, is characterized by mottled micrite, and includes interbeds of other types of limestones. The upper part of the formation at the Cottonwood Canyon section contains thick units of interbedded limestones of three types: micrite, medium to coarse bioclastic packstone and wackestone, and intraclastic wackestone. Trilobite fragments are common in the bioclastic packstone and wackestone. The intraclasts are flat chips of micrite as much as 1 cm thick and 4 cm across. All three types of limestone generally range in color from light medium gray to dark gray, and some bed surfaces weather to a rusty buff. The limestones are in thin beds (<15 cm; most <5 cm), and bedding generally is expressed as anastomosing laminae, burrow mottles, and slightly irregular bed surfaces.

The upper part of the Meagher Limestone at the Milligan Canyon section contains thin interbeds of bioclastic wackestone, bioclastic packstone, intraclastic packstone, and oolitic packstone that contains scattered bioclasts; the micrite that dominates the succession also contains scattered bioclasts. At the Sappington South section, the upper part of the Meagher Limestone includes bioclastic and intraclastic limestone, in addition to micrite. At the Sappington Railroad section, the micrite succession contains beds of intraclastic wackestone, in which the intraclasts are flat chips as much as 1 cm thick and 3 cm across. Locally, a small part of the limestone is slightly dolomitic and has a microcrystalline to fine-crystalline texture.

Limestone in the uppermost part of the formation contains interbeds and thin partings of dark gray to medium gray clay shale (plate 1). At the Cottonwood Canyon section, dark medium gray micrite in thin beds and lenses is interbedded with shale. At the Milligan Canyon section, the upper 5 m of the formation consists of medium gray, coarse bioclastic packstone to grainstone and interbedded medium dark gray micrite with scattered bioclasts. The limestone is thin bedded, and the unit contains thin shaly partings. At the Sappington Railroad section, the upper 1.2 m of the Meagher Limestone consists of light gray, thin-bedded micrite and intraclastic wackestone, in which the intraclasts are flat chips as much as 1 cm thick and 8 cm across; the limestone unit includes thin shaly partings and thin laminae of medium gray clay shale. The Sappington South section includes very argillaceous limestone to very calcareous mudstone in thin shaly beds, and the uppermost beds are thinly interbedded micrite, intraclastic packstone, and bioclastic packstone to grainstone. The highest exposed Meagher Limestone at the South Boulder section lacks shaly partings, and the thin-bedded limestone is coarse to very coarse bioclastic packstone to wackestone that contains trilobite fragments and limestone flat-chip intraclasts as much as 4 cm across. Oncolites are abundant in part of the bioclastic limestone at the Milligan Canyon, South Boulder, and Sappington South sections.

The uniform thickness (149 to 152 m) of the Meagher Limestone among the measured sections (plate 1) is consistent with the broader regional distribution (Thomas and others, 1996). The lateral consistency of carbonate facies indicates deposition on an extensive shallow-marine shelf with no abrupt variations in paleobathymetry. These characteristics document no movement on the Willow Creek fault system during Meagher deposition.

Park Shale

The Middle Cambrian Park Shale is generally not well exposed. It forms a valley or bench between ridges or ledges of the Meagher and Pilgrim Limestones. Thickness variations in the interval between the Meagher and Pilgrim Limestones are substantial but are not systematically distributed (plate 1). Disharmonic small folds exposed in some outcrops suggest that variations in thickness of the Park interval are caused by deformation of the shale between the more competent carbonate units above and below.

The Park Shale is dominated by thinly fissile clay shale which ranges in color through medium to dark gray, olive-gray to green-gray, tan to brown-gray, and dull maroon to red-buff to purple. Part of the color variation is expressed as beds and part as mottles. Very fine mica lies on some bed surfaces. A small part of the shale is calcareous. Fossils (pelecypods, trilobites) are rare. Part of the shale is marked by horizontal burrows.

The lower part of the clay shale succession includes thin limestone interbeds. The limestones are generally light medium gray to dark gray and include micrite, bioclastic packstone and wackestone, and intraclastic wackestone. The intraclasts are flat chips <10 cm across. Trilobite fragments are common in the bioclastic limestones. The limestones are thin bedded, and some include thin partings and interbeds of clay shale.

The upper part of the Park Shale is well exposed at the Cottonwood Canyon section and at the Sappington Railroad section on opposite sides of the Southwest Montana transverse zone (plate 1). At both places, the shale succession contains distinctive thin interbeds, including siltstone, dolostone, limestone, and conglomerate.

The upper part of the shale succession at the Cottonwood Canyon section (plate 1) includes lenses or concretions of rusty-weathering, silty-appearing, limonitic micrite; and the same succession includes one bed of rusty-weathering, slightly silty, microcrystalline dolostone. A limestone interbed near the top of the formation at the Cottonwood Canyon section contains oncolites. The section also contains discontinuous lenses and thin beds of micrite and slightly argillaceous micrite. The most distinctive interbeds in the upper part of the Park Shale are discontinuous lenses (<10 cm thick) of limestone-clast conglomerate (fig. 6). The clasts are light gray micrite, a minor part of which is slightly argillaceous. In addition to the micrite clasts, the conglomerates contain rare clasts of fine bioclastic wackestone and of laminated siliciclastic mudstone. The clasts are round, oblate, and as large as 10 by 1 cm. The matrix consists of micrite, part of which is argillaceous, and sand-sized micritic limestone clasts. The matrix contains a few scattered fine grains of quartz sand. At the top of the Park Shale, a single bed of conglomerate (~10 cm thick) is "welded" onto the basal dolostone bed of the overlying Pilgrim Limestone. The clasts are mostly micrite, but the conglomerate contains a few clasts of silty micrite, interlaminated silty and

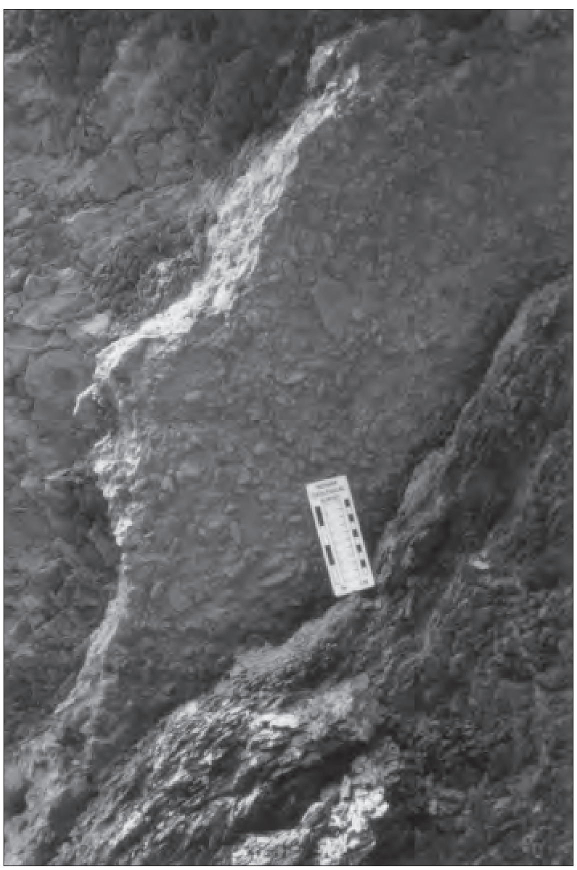


Figure 6. Limestone-clast conglomerate in the upper part of the Park Shale at the Cottonwood Canyon section. Photo by W.A. Thomas.

non-silty micrite, and very calcareous argillaceous siltstone. The clasts are round, oblate, and as large as 40 by 20 by 5 cm. The flat clasts are parallel with the bed surface. Part of the conglomerate is matrix supported; part is clast supported. The matrix is a rusty-weathering micrite, part of which appears silty.

The Park Shale at the Sappington Railroad section contains thin interbeds of siltstone, dolostone, and conglomerate (plate 1). The siltstones are brownish gray to medium gray, argillaceous, and partly dolomitic to calcareous. The siltstones are thin bedded (<10 cm) and are characterized by thin wavy laminae. Alternate argillaceous and non-argillaceous siltstone laminae are on a millimeter scale. Very fine mica lies on some bed surfaces. Siltstone units have gradational contacts with clay shale and with dolostone. Distinct coarsening-upward cycles encompass greenish gray clay shale; thinly laminated, silty to non-silty, very fine-crystalline dolostone; and thinly laminated (2 mm), dolomitic siltstone. The formation includes two beds of conglomerate within the shale succession and another bed at the top. The clasts are very fine-crystalline dolostone, part of which is silty to sandy; siltstone; and interlaminated siltstone and dolostone. The matrix is very fine-crystalline to dense dolostone, part of which is silty to sandy. Part of the conglomerate has a minor amount of calcite cement. The clasts are flat and ovoid to round. They range in size to a maximum of 11 by 5 by 2 cm. In the lower conglomerate bed (7.5 to 15 cm thick), the clasts lie flat on the top surface of the bed, and the base of the bed has a shallow scour-fill shape. The upper 2.5 cm of the middle conglomerate bed is a layer one clast thick. Beneath the layer of clasts, the lower 10 cm of the bed consists of silty dolostone lenses and nodules in clay shale matrix. Part of the matrix in the middle conglomerate bed is argillaceous. The top bed of the Park Shale at the Sappington Railroad section, which is positioned stratigraphically like that at the Cottonwood Canyon section, is 20 cm thick and contains clasts of microcrystalline, partly silty dolostone and laminated dolostone–siltstone. Clast shape ranges from flat (as large as 8 by 1 cm) to subround blocky (as large as 4 by 5 cm). The matrix is silty to sandy, fine-crystalline dolostone. The composition of the clasts suggests reworking from dolomitic siltstone and silty to non-silty dolostone interbeds and lenses in the Park Shale succession. The shapes of some clasts suggest that they may be reworked concretions; they are similar in scale to the rusty-weathering, silty-appearing micrite concretions in the shale at the Cottonwood Canyon section.

Variations in apparent thickness (35 to 81 m) of the Park Shale (plate 1) are not significant because they result from post-depositional structural thickening and thinning of the formation. The lateral consistency of distinctive facies, such as the thin conglomerate beds, indicates no variation in depositional settings across the location of the Willow Creek fault system.

Pilgrim Limestone

The Upper Cambrian Pilgrim Limestone includes three distinct subdivisions, although the characteristics of the lower and upper subdivisions vary at different locations (plate 1). Generally the upper and lower parts are massive dolostone cliff formers (fig. 7), and the middle part is a distinctive laminated "blue and gold" limestone. Contacts between the subdivisions are somewhat gradational, and preserved textures suggest various original limestone types. Dolomitization has affected various amounts of the upper and lower Pilgrim, and

Figure 7. Pilgrim Limestone at the Cottonwood Canyon section (plate 1), showing topographic expression of the upper (right) and lower (left) cliff-forming dolostone units of the formation. The Park Shale, including the limestone-clast conglomerate shown in fig. 6, is exposed in the drainage ditch (below a tunnel through the lower Pilgrim ridge) on the left. The unconformable contact between the Cambrian Pilgrim Limestone and Devonian Maywood Formation is exposed in the canyon (concealed from view on the right of the upper Pilgrim ridge), and a local dolostone-clast conglomerate marks the base of the Maywood Formation. Photo by H.L. James, MBMG.

degree of destruction of the original texture varies from limited to complete. The uppermost part of the Pilgrim locally contains distinctive interbeds.

The lower subdivision of the Pilgrim is a distinctive cliff-forming dolostone (plate 1). At the Cottonwood Canyon, Sappington Railroad, and South Boulder sections, the dolostone ranges from microcrystalline to very fine crystalline and fine crystalline. Colors range from blue-gray and medium gray to light gray, and part is mottled buff-gray to yellow-brown. Part of the mottled dolostone weathers pitted. Most of the dolostone is thick bedded to massive, but part of the unit is thinly laminated. A small part of the dolostone contains intraclasts, which are flat dolostone chips as much as 3 cm across. The upper 1.4 m of the lower Pilgrim dolostone at the Cottonwood Canyon section contains interbeds of dark gray limestone (micrite). At the South Boulder section, part of the dolostone is calcareous. At the Sappington South section (plate 1), the partly calcareous dolostone contains ooid ghosts, suggesting dolomitized ooid grainstone; intraclastic dolostone at the same location suggests dolomitized intraclastic packstone. The remnants of ooids are ~0.5 mm in diameter, similar to the ooids in limestones elsewhere in the formation. The preservation of textures at the Sappington South section, also including horizontal burrows, is consistent with a regional pattern of decreasing dolomitization of Pilgrim limestones toward the east (Hanson, 1952). Another indicator of the eastward decrease in dolomitization is that the lower part of the Pilgrim at the Milligan Canyon section is mostly limestone (plate 1), characteristically medium gray, mottled light gray, oolitic grainstone to packstone in thick beds; part of the oolitic limestone contains scattered bioclasts. The ooids have dark centers and are ~0.5 mm in diameter. Part of the oolitic limestone is slightly dolomitic and appears recrystallized. A thin interbed of dolostone at the Milligan Canyon section is similar to the dolostones in the other sections. A unique aspect of the lower Pilgrim dolostone at the Sappington South section is the inclusion of a few scattered chips of light green clay as much as 2 mm across.

The middle part of the Pilgrim is characterized by thin-bedded (most <10 cm) limestone, in which the beds are marked by discontinuous to continuous anastomosing laminae and burrow mottles. Thin irregular laminae part the thin limestone beds and drape around lenses of limestone. The parting laminae weather silty to argillaceous; some are dolomitic. The parting laminae weather in relief, giving the outcrops a distinct "ribboned" appearance. Detailed microscopic analysis shows the partings to be dolomitic argillaceous siltstone (Sepkoski, 1977). Although individual limestone beds are dominantly thin, parts of the succession form thick-bedded to massive appearing outcrops. Distinct horizontal burrows are rare. Shallow scour fills are rare. The limestones range from dark gray to medium light gray; the anastomosing partings range from buff to orange and yellow. The color pattern gives rise to the description "black and gold" or "blue and gold."

The middle Pilgrim limestones are of three dominant types: micrite, fine to coarse bioclastic wackestone to packstone and grainstone, and intraclastic wackestone to packstone. The bioclastic rocks commonly contain scattered intraclasts, and part of the intraclastic rock has a bioclastic matrix. Distinctive bioclasts throughout the succession are trilobite fragments. Intraclasts are micrite and are flat chips as much as 15 cm across. Intraclast orientations range from horizontal to vertical. At the Cottonwood Canyon and Milligan Canyon sections, tepee-shaped mounds of flat-chip intraclasts are stacked as much as 15 cm high and 40 cm across. In thin section, the matrix of an intraclastic wackestone can be seen to be a peloidal packstone; however, in the field, the rock appears as micrite. The succession includes a few beds of oolitic packstone to grainstone, part of which also contains bioclasts. The ooids are ~0.5 mm in diameter and are generally darker than the limestone matrix. A small part of the micrite is argillaceous. A small part of the limestone contains glauconite pellets. Substantial parts of the limestone succession are dominantly micrite and include only scattered bioclastic and intraclastic beds. In some parts of the succession, the three limestone types are interbedded in approximately equal proportions.

Although the middle Pilgrim is dominated by limestones, the sections on the west contain some dolostone. The top of the middle Pilgrim at the

Cottonwood Canyon section is a fine-crystalline, calcareous dolostone containing intraclasts as much as 8 cm across oriented at a high angle to bedding. At the South Boulder section, the middle Pilgrim contains dolostone interbeds. Near the base, a bioclastic limestone contains lenses of medium light gray, microcrystalline, partly calcareous dolostone and dolostone-clast conglomerate; dolostone clasts are ovoid, <8 cm across, and in a bioclastic limestone matrix. In the lower part of the section, micrite-dominated limestones contain rare thin interbeds of light gray, microcrystalline, calcareous dolostone. Near the top of the middle Pilgrim, part of the bioclastic limestone is dolomitic, and the section includes medium gray, very fine-crystalline, calcareous dolostone.

The upper part of the Pilgrim Limestone forms one of the most prominent cliffs in the lower Paleozoic outcrops (figs. 3, 7). The cliff-forming rock is a thick-bedded to massive dolostone, but parts of the succession are thin bedded to thinly laminated. Part of the lamination is wavy and discontinuous, and part appears burrow mottled like the bedding in the limestones of the middle Pilgrim. Discontinuous argillaceous laminae are very rare. The dolostone ranges from medium gray to very light gray in color. Part of the dolostone is mottled in a wide range of colors, mostly light gray to buff and including brownish gray, yellowish gray, and rare pink. Part of the color mottling is patterned like the burrow-mottled bedding in the middle Pilgrim, and part of the mottling is irregular. At the Sappington Railroad section, beds near the top of the upper Pilgrim are mottled pale pink, possibly as a result of surficial staining from the red shale, siltstone, sandstone, and mudstone of the stratigraphically higher Red Lion and Maywood Formations. Nearly all of the dolostone is microcrystalline to fine crystalline; medium-crystalline dolostone is very rare. Part of the dolostone is intraclastic; most intraclasts are flat chips no more than 15 cm across. An exceptional intraclastic unit, at the South Boulder section, contains intraclasts nearly 100 cm long; both the matrix and some of the clasts are crossbedded. At the Sappington Railroad section, the uppermost dolostone bed of the Pilgrim contains flat-chip intraclasts <2 cm across. Part of the dolostone is slightly calcareous. The base of the upper Pilgrim at the Milligan Canyon section is marked by very calcareous dolostone to dolomitic limestone. The Milligan Canyon section includes a mottle-bedded, medium gray limestone (micrite), part of which is intraclastic, containing intraclasts as much as 8 cm across. Other distinctive rare interbeds include yellow, silty, microcrystalline dolostone and yellow-gray, fine- to medium-crystalline, slightly calcareous dolostone, containing abundant glauconite pellets.

At the Sappington Railroad section, bedding in the lower part of the upper dolostone part of the Pilgrim Limestone appears identical to that in the thin-bedded ribboned (anastomosing burrow-mottled partings) limestone that is typical of the middle Pilgrim, further suggesting variations in the amount of the total succession that has been dolomitized. In part of the thin-bedded dolostone at the Sappington Railroad section, bedding is disrupted and deformed. The deformation generally includes small folds and pull-apart faults that are restricted to stratigraphic intervals ~20 cm thick. One sedimentary clastic dike, consisting of broken and deformed bed segments, is as much as 1.3 m thick and cuts across ~5.5 m of strata. All of the deformation terminates stratigraphically upward and downward, indicating synsedimentary soft-sediment slumping; however, no consistent sense of slip is evident.

At the Cottonwood Canyon section, the Upper Cambrian Pilgrim Limestone is unconformably overlain by the Upper Devonian Maywood Formation (plate 1). The succession is incompletely exposed at the Milligan Canyon section, but a section measured 2.1 miles (3.4 km) to the east (in a west-draining tributary canyon of Milligan Canyon) shows that Maywood rests unconformably on Pilgrim (Meyers, 1971). The unconformable absence of the Upper Cambrian Red Lion Formation implies at least some truncation of the uppermost Pilgrim. The basal bed of the Maywood at the Cottonwood Canyon section contains clasts of Pilgrim dolostones.

At the South Boulder, Cottonwood Canyon Interstate 90, and Sappington Railroad sections, the Pilgrim Limestone is conformably overlain by the Upper Cambrian Red Lion Formation (plate 1). Where the Red Lion and, therefore, the uppermost

Pilgrim are preserved beneath the Maywood Formation, the upper Pilgrim contains rock types that are not seen elsewhere. The upper part of the upper Pilgrim at the South Boulder section contains abundant vertical twig-like stromatoporoids in one bed. The South Boulder section also includes very slightly sandy (very fine-grained quartz) dolostone, as well as a thin unit (1.1 m thick) of gray-white, very fine- to fine-grained, dolomite-cemented quartzose sandstone in thin planar beds and thin horizontal laminae. The laminae (<1.5 cm thick) are defined by variations in proportion of dolomite and quartz sand in alternate dolomitic sandstone and very sandy dolostone. The upper Pilgrim dolostone unit at the Sappington Railroad section is thicker than in the other sections, suggesting preservation of a complete succession below the Red Lion Formation.

Variations in thickness of the Pilgrim Limestone are not systematically related to the location of the Willow Creek fault system. Both the maximum (174 m at the Sappington Railroad section, plate 1) and minimum (105 m at the South Boulder section, plate 1) are south of the Willow Creek fault system, where the Upper Cambrian Red Lion Formation overlies the Pilgrim Limestone. Intermediate thicknesses (107 m at the Cottonwood Canyon section and 123 m at the Milligan Canyon section, plate 1) are both north of the Willow Creek fault system, and the Pilgrim is overlain unconformably at a regional unconformity by the Upper Devonian Maywood Formation. Disrupted, deformed bedding and an intraformational clastic dike in the upper Pilgrim at the Sappington Railroad section suggest contemporaneous seismicity, but no associated active fault can be identified.

Red Lion Formation

A lithologically diverse unit of Upper Cambrian strata overlies the Pilgrim Limestone in many places in southwestern Montana (Hanson, 1952). Fine clastic rocks characterize the unit, but because of the heterogeneity of the succession, it has been variously assigned to the Red Lion Formation or the Snowy Range Formation. The Upper Cambrian strata are overlain unconformably by the Upper Devonian Maywood Formation, expressing the craton-wide unconformity beneath the transgressive Kaskaskia sequence (Sloss, 1963). The beds preserved locally beneath the sub-Maywood unconformity near the Southwest Montana transverse zone seem to be intermediate in lithology between typical Red Lion and Snowy Range, but for simplicity the name Red Lion is used here. The South Boulder, Cottonwood Canyon Interstate 90, and Sappington Railroad sections have good exposures of the Red Lion Formation (plate 1). At the Cottonwood Canyon section, the Devonian Maywood Formation rests unconformably on the Pilgrim Limestone, and the Red Lion is absent. Similarly, the section measured 2.1 miles (3.4 km) east of the Milligan Canyon section shows that Maywood rests unconformably on Pilgrim (Meyers, 1971). At the Cottonwood Canyon East and Antelope Valley sections, a covered interval obscures any possible Red Lion, as well as upper Pilgrim and lower Maywood contacts.

At the Cottonwood Canyon Interstate 90 section (plate 1), the lower part of the Red Lion Formation consists of interbedded limestone and clay shale in intervals <70 cm thick. The limestone is light gray to light brown and green, argillaceous to very argillaceous micrite in thin platy beds. Flat mudstone chips <4 cm across lie on the surface of one limestone bed. The clay shale is light gray to medium gray and green, and weathers yellow. The shale is very calcareous, and part grades to argillaceous limestone. Some of the shale is silty. The lower Red Lion includes one bed of medium dark gray, microcrystalline dolostone.

The most distinctive rocks of the Red Lion Formation are hard, brittle, fissile clay shales that range in color from pale olive-gray and light medium gray to gray-black; part of the shale is purple to reddish purple. Part of the shale is siliceous, and part is dolomitic to slightly calcareous. The shale includes some silty beds.

The South Boulder section (plate 1) includes olive-gray, argillaceous, slightly calcareous siltstone in thin platy beds and interbeds of olive-gray, slightly calcareous, silty mudstone. Alternate laminae no more than 1 cm thick consist of slightly sandy siltstone and very argillaceous siltstone to silty mudstone. The siltstones include thin clay laminae.

At the Sappington Railroad section, the Red

Lion consists of clay shale, mudstone, siltstone, and sandstone. Dull red and pale olive, fissile clay shale is interbedded with light medium gray and pale red, partly dolomitic to calcareous, very fine-grained sandstone and siltstone. Sandstone beds are thin and thinly laminated; very fine mica lies on laminae. The siltstone beds include alternate laminae <8 mm thick of very argillaceous siltstone and non-argillaceous siltstone, identical to the laminated siltstone at the South Boulder section. Load casts mark the bases of some siltstone beds.

Thickness of the Upper Cambrian Red Lion Formation is inversely related to thickness of the unconformably overlying Upper Devonian Maywood Formation, indicating that Maywood deposition filled paleotopographic relief eroded on the Red Lion and older strata (Thomas and others, 1996). South of the Willow Creek fault system, the Red Lion ranges in thickness from ~4.5 to 17 m. In sections a few miles north of the Willow Creek fault system, the Red Lion is truncated completely, and the Maywood Formation rests on Pilgrim Limestone. The Red Lion Formation is 5.8 m thick at the Cottonwood Canyon Interstate 90 section north of the Willow Creek fault system, but it is truncated <0.2 mile (<0.3 km) farther northwest at the Cottonwood Canyon section (plate 1; Appendix); the truncation of the Red Lion Formation indicates a minimum of ~6 m of paleotopographic relief along the south side of a pre-Devonian paleovalley (Thomas and others, 1996). The distribution of truncated Red Lion defines a generally linear paleovalley approximately parallel with and a few miles north of the Willow Creek fault system.

Maywood Formation

Devonian strata unconformably overlie Cambrian rocks, indicating craton-wide transgression of the Kaskaskia sequence (Sloss, 1963; Sandberg and others, 1988). Thickness variations in the Upper Devonian Maywood Formation reflect filling of shallow valleys eroded on the Upper Cambrian strata (Sandberg and McMannis, 1964; Meyers, 1980). Regionally, the Upper Devonian Maywood Formation unconformably overlies the Upper Cambrian Red Lion Formation (or equivalent Snowy Range Formation). Locally in contrast, north of the Willow Creek fault system, the Red Lion Formation is truncated, and the Maywood Formation rests unconformably on Upper Cambrian Pilgrim Limestone (plate 1).

The Maywood Formation includes a wide variety of rock types, but the most distinctive rock of the formation is yellow-gray, microcrystalline dolostone in thin beds. Dolostones of the Maywood range in color from yellow to buff and locally pale red, and from light gray to dark gray. The weathering colors range from yellow and buff to light gray. At the Sappington Railroad section, dolostone is mottled yellow, olive, and dull maroon. The dolostone is dominantly microcrystalline to very fine crystalline; fine-crystalline dolostone is very rare. The dolostone is thin bedded, and part of the rock is thinly laminated. Rare beds are massive, and some of the massive beds break with conchoidal fracture. Horizontal burrows are rare.

Part of the dolostone is calcareous, and some beds grade from calcareous dolostone to dolomitic limestone. Parts of the formation include limestone interbeds; some of the limestone is dolomitic. The limestones are all micrite and range in color from gray-white to light buff and yellow; part of the limestone at the Milligan Canyon section is pale red to pink. The limestones are thin bedded to thinly laminated.

Parts of the carbonate-dominated Maywood Formation contain siliciclastic components. Some of the dolostone is silty, and a small part is argillaceous. A limestone unit at the Cottonwood Canyon section contains partings of green clay and green clay chips on bed surfaces. The succession at the Milligan Canyon section includes light brownish yellow dolomitic siltstone to silty dolostone. At the base of the Maywood at the Sappington Railroad section, a dark dull red to maroon and yellow mottled, blocky mudstone grades upward into a dolomitic mudstone and argillaceous dolostone.

At the Cottonwood Canyon section (plate 1), where the Maywood Formation rests unconformably on the Pilgrim Limestone, the basal bed of the Maywood is a dolostone-clast conglomerate. The clasts of medium gray, microcrystalline dolostone are ovoid, round, and <3 cm across. The matrix is buff, microcrystalline dolostone. The clasts are matrix supported, and the dolostone-clast conglomerate is discontinuous, grading laterally into clast-free dolostone.

The uppermost part of the Maywood Formation at the Milligan Canyon section is a dolostone breccia with a light medium gray, very fine-crystalline, calcareous dolostone matrix. The clasts are medium gray, very fine-crystalline dolostone and yellow limestone (micrite). The dolostone clasts are angular and are <15 cm across; angular limestone clasts are <1.5 cm across.

Above the regional sub-Maywood unconformity, where strata of the Cambrian Red Lion Formation are preserved, the Maywood is generally thinner than it is at places where the Red Lion Formation is unconformably absent and the Maywood rests unconformably on the Pilgrim Limestone (plate 1). At the Cottonwood Canyon and Milligan Canyon sections north of the Willow Creek fault system, the Maywood rests unconformably on Pilgrim Limestone and is 21 to 28 m thick. In contrast, south of the Willow Creek fault system at the South Boulder and Sappington Railroad sections, the preserved Red Lion is 17 m and 4.5 m thick, respectively; the overlying Maywood is 9.8 m and 18 m thick, respectively. North of the Willow Creek fault system at the Cottonwood Canyon Interstate 90 section, 14.6 m of Maywood overlie 5.8 m of Red Lion. Paleotopographic relief evidently controlled thickness distribution of Maywood sediment. The bottom of a paleovalley is suggested by the relatively thicker Maywood and lack of preserved Red Lion at the Milligan Canyon and Cottonwood Canyon sections; the south side of the paleovalley is marked by preserved Red Lion and thinner Maywood at the Cottonwood Canyon Interstate 90 section and other sections farther south (plate 1). The westerly trend of the Milligan Canyon–Cottonwood Canyon paleovalley (Meyers, 1980; Thomas and others, 1996) is approximately parallel to and 2 to 3 miles (3 to 5 km) north of the Jefferson Canyon fault. Considering a component of southward translation in oblique slip on the Jefferson Canyon fault (Schmidt and others, 1988), a palinspastic location of the paleovalley is approximately parallel to and several miles north of the Willow Creek fault system. The proximity and approximate parallelism of the sub-Maywood paleovalley to the Willow Creek fault system suggests a possible genetic association. To explain the truncation of the Red Lion and the thickening of the Maywood by structural processes requires a succession of north-side-up fault inversion (erosion of Red Lion) followed by north-side-down fault reactivation (Maywood deposition), each with the same magnitude (fig. 7 in Thomas and others, 1996). A more likely interpretation is simply erosion of a paleovalley (erosion of Red Lion) during regional regression followed by depositional filling of the paleovalley with Maywood strata during regional transgression and deposition of the Kaskaskia sequence (fig. 7 in Thomas and others, 1996). Although fractures (joints) parallel to the Willow Creek fault system might have influenced paleodrainage and erosion into a westerly orientation, thickness distributions of the Red Lion and Maywood Formations do not require synsedimentary fault separation of the sub-Maywood unconformity (Thomas and others, 1996).

Jefferson Dolomite

The Upper Devonian Jefferson Dolomite is characterized by dark-colored dolostones, and the formation is distinctly darker in color than most of the strata above and below. Perhaps the most distinctive aspect of the Jefferson is the “spaghetti beds,” in which millimeter-scale, lighter colored, wavy, tube-shaped to tabular fossil stromatoporoids contrast starkly with the surrounding dark-colored dolostone (Robinson, 1963).

Dolostone in the Jefferson generally ranges from gray-black to medium gray in color, but a distinctive lighter colored member (Birdbear Member) constitutes the upper part of the formation (Sandberg, 1965). A few thin beds of medium gray to light gray and buff dolostone are scattered through the succession. Part of the dolostone has a brownish cast. The dolostones are mostly microcrystalline to fine crystalline; however, a few beds range to medium and coarse crystalline. The Birdbear Member is light to medium gray, buff, and yellow-gray, microcrystalline to fine-crystalline and locally medium- to coarse-crystalline dolostone. Bedding ranges from thin laminations to massive, but most outcrops appear thick bedded. Much of the dark-colored dolostone is distinctly fetid. Part of the dolostone contains chert, which ranges in color from black to medium dark gray and includes vitreous light cream-gray, blue-gray, brown-gray, light medium gray, and medium gray. Chert nodules and discontinuous beds are generally no more than 8 cm thick, but rare nodules are as much as 15 cm thick. Several dolostone beds at the Sappington Railroad section contain silica-rim nodules as much as 5 cm thick. At the Antelope Valley section, partly siliceous dolostone in one interval weathers to a rough surface resembling chert nodules in a dolostone bed.

The Jefferson Dolomite consists mainly of rather uniform crystalline dolostone, but a few beds have distinctive compositions. One dolostone bed at the Milligan Canyon section is intraclastic; dolostone intraclasts are flat and as large as 0.5 by 8 cm. At the Sappington Railroad section, one bed of intraclastic dolostone contains flat clasts as large as 0.33 by 2 cm.

The "spaghetti beds" are scattered throughout the formation but are more common in the lower part (plate 1). The "spaghetti" is formed by light gray, buff, and yellow-gray, fine- to medium-crystalline dolomite and/or calcite in wavy tube-shaped to tabular forms that are <2 mm across and several centimeters long. The fossils are identified as stromatoporoids (Robinson, 1963). Other fossils are very rare in the Jefferson, but molds of brachiopods and a horn coral are preserved locally. One bed at the Antelope Valley section contains thin, wavy laminae, suggesting an algal stromatolite mound ~8 cm high. Stromatolites and oncolites are preserved in one bed at the Cottonwood Canyon section.

Part of the dolostone is calcareous, and the most calcareous dolostones are gradational with dolomitic limestone. Intergranular porosity in some of the crystalline dolostones is partly filled with calcite. The calcite pore-filling cement gives a vigorous, brief reaction to hydrochloric acid. Calcareous to very calcareous dolostones are interbedded with dolomitic limestones at the top of the formation at the Sappington Railroad section.

Limestone interbeds are scattered throughout the succession; however, limestone intervals are relatively thin. Bedding in the limestones ranges from thin laminae to thick beds; part of the bedding is rubbly. Fossils are generally lacking, but a limestone bed at the Cottonwood Canyon East section contains a trilobite fragment. The limestones are medium gray to gray-white and buff micrite; medium dark gray to dark gray micrite is rare. Part of the limestone is dolomitic, and a continuum from dolomitic limestone to very calcareous dolostone is contained within some single beds. At the Milligan Canyon section, some of the limestone is very fine to fine crystalline and is partly recrystallized, and a thin bed of dolomitic limestone at the Sappington Railroad section is recrystallized. Limestone at the Milligan Canyon section contains medium gray to dark gray and yellow-brown chert; nodules and discontinuous beds of chert are as much as 8 cm thick. Limestone at the Sappington Railroad section contains nodules of gray-white to light medium gray and dark gray chert as much as 8 cm thick and silica-rim nodules of the same size.

Siliciclastic components are rare. One dolostone bed at the Sappington Railroad section contains a lens (<10 cm thick) of light medium gray, calcareous, dolomitic to very dolomitic, very fine- to fine-grained, quartzose sandstone with irregular laminae of very sandy dolostone. Rare thin dolostone beds at scattered places are slightly argillaceous. At the Sappington Railroad section, a light gray-yellow, microcrystalline dolostone is slightly argillaceous and weathers lumpy. A few dolostone beds weather to a shaly appearance. Some dolostone beds at the Cottonwood Canyon North section have buff-weathering clay partings. The Cottonwood Canyon Interstate 90 section contains thin interbeds of light medium gray, very calcareous, shaly mudstone to very argillaceous limestone and light gray, fissile clay shale that weathers orange-buff.

Brecciated dolostone is common throughout the Jefferson Dolomite. At the Cottonwood Canyon section, a distinct solution-collapse breccia consists of broken beds in an interval ~1 m thick. Most of the dolostone breccia and brecciated dolostone evidently was generated in place by disruption of lithified dolostone beds. Brecciation ranges from fracture networks to isolated angular fragments of dolostone. The fill of various breccias variously includes yellow to white crystalline calcite, microcrystalline calcite, and microcrystalline dolomite. One breccia, at the Cottonwood Canyon Interstate 90 section, contains dolostone fragments on two scales; angular blocks ~1 cm across constitute much of the fill around angular blocks as large as 20 cm. In addition to dolostone beds brecciated in place, some breccias consist of contrasting clasts and matrix. At the Cottonwood Canyon Interstate 90 section, two beds of dolostone–limestone breccia have a matrix of buff, partly argillaceous, very slightly sandy micrite; angular clasts are gray-black to light gray, microcrystalline to fine-crystalline dolostone as much as 15 cm across and light gray limestone micrite as much as 5 cm across. Also at the Cottonwood Canyon Interstate 90 section, dolostone breccia clasts as much as 8 cm across lie on top of a limestone bed. Like the dolostones, some of the limestone interbeds are brecciated.

Figure 8. Topographic expression of the Birdbear Member of the Jefferson Dolomite (foreground), Three Forks Formation, and overlying Mississippian Lodgepole Limestone (upper slope to skyline) at the Sappington East section (plate 1). Limestone solution-collapse breccia in the Logan Gulch Member of the Three Forks Formation forms the prominent ledge directly behind the geologists on the left. Shales of the Trident Member are exposed in the shallow valley and partly covered slope, and the Sappington Sandstone Member of the Three Forks Formation forms the small, prominent ledge on the lower part of the slope. Photo by W.A. Thomas.

Partly to completely filled vugs are scattered through the dolostones. Vugs as much as 3 cm across are lined, and some are completely filled, with orange to clear calcite. Some dolostones have open vugs as large as 2 cm. At the Antelope Valley and Sappington Railroad sections, vugs as large as 10 cm are lined with quartz crystals. Scattered clots of orange to yellow and white calcite are as much as 8 cm across; in contrast to filled vugs, the clots have irregular gradational margins. Chert at the Milligan Canyon section contains vugs as much as 6 cm across lined with quartz crystals. In one limestone bed, vugs <3 mm across are lined with clear calcite.

The Jefferson Dolomite ranges in thickness from 178 m at the Milligan Canyon section to 196 m at the Cottonwood Canyon East and North sections (plate 1). The local thickness distribution is consistent with regional distribution across the Willow Creek fault system. The lateral consistency of both thickness and facies indicates no synsedimentary relief at the Willow Creek fault system.

Three Forks Formation

The Upper Devonian–Lower Mississippian Three Forks Formation (fig. 8) is subdivided into three regionally extensive members (Sandberg, 1965). The lower member, the Logan Gulch Member, is dominantly limestone and is characterized by solution-collapse breccia. The middle member, the Trident Member, is dominantly clay shale. The upper member, the Sappington Sandstone Member, is a distinctive, ledge-forming sandstone to siltstone.

Logan Gulch Member

The Logan Gulch Member of the Three Forks Formation consists of limestone and limestone breccia. The breccia is commonly interpreted to be the result of solution collapse because of solution of evaporites (Sloss and Laird, 1947; Sandberg, 1965). The limestone is light gray to dark medium gray and tan micrite and medium to coarse bioclastic packstone to grainstone. A minor part of the limestone is intraclastic. Rare nodules of brown chert and silica-rim nodules are <15 cm. Beds range from thin to massive; part of the limestone is thinly laminated. In part of the limestone, the beds are not distorted by collapse; however, other parts of the limestone are jumbled breccia blocks. At the Sappington East section, breccia blocks as large as 85 cm are supported in a “matrix” of angular blocks <5 cm. The larger clasts include interlaminated bioclastic packstone to grainstone and micrite.

In various places, the breccia is filled with calcite, quartz, and calcareous clay; open vugs in the breccia are rare. The breccia is irregularly distributed in laterally discontinuous zones, and part of the breccia is massive, encompassing several meters of the stratigraphic succession. The apparent thickness of the Logan Gulch Member ranges from ~30 to ~46 m (plate 1); however, thickness variations reflect solution collapse rather than depositional thickness.

Trident Member

The Trident Member of the Three Forks Formation is dominantly clay shale but includes some carbonate interbeds. The typical clay shale ranges from light medium gray to dark medium gray and olive-gray. Part of the shale is calcareous, and part is silty. The clay shale is thinly fissile, but some silty mudstone is blocky. Fossils include brachiopods, bryozoans, echinoderm columnals, cephalopods, pelecypods, and possible conularids. Carbonate interbeds include a variety of limestone and some dolostone. The limestones range from medium light gray to dark medium gray, and tan to buff. Limestones are dominantly micrites, but scattered bioclasts are common. Part of the limestone is bioclastic wackestone, and bioclastic packstone is rare. Fossils in the limestones include brachiopods and echinoderm columnals. Intraclastic limestone is very rare. Part of the limestone is argillaceous to very argillaceous bioclastic wackestone and micrite with scattered bioclasts. Very argillaceous limestone grades to calcareous mudstone. Part of the member includes alternate beds of argillaceous limestone and non-argillaceous limestone generally <20 cm thick, and some of the beds are nodular. The argillaceous limestones commonly weather to thin shaly beds and form shaly partings in the interbedded units. A few beds appear massive. Part of the limestone is dolomitic. Rare nodules of dark brown chert are <1 cm thick. Yellow-buff, calcareous, microcrystalline dolostone is argillaceous to very argillaceous and grades into dolomitic mudstone. Parts of the limestone and dolostone are silty. At the Sappington East section, the upper part of the Trident Member includes one thin unit of light brown sandstone to siltstone similar to the very fine-grained sandstone to siltstone in the overlying Sappington Sandstone Member, suggesting an upward gradation to slightly coarser clastic sediment. The sandstone–siltstone, characterized by thin planar laminae to ripple laminae, is very calcareous and contains a few scattered bioclasts. The apparent thickness of the Trident Member ranges from ~55 to ~70 m (plate 1); however, the contacts generally are not exposed.

Sappington Sandstone Member

The upper part of the Three Forks Formation is the distinctive Sappington Sandstone Member (plate 1). The member is characterized by quartzose sandstone to siltstone, which ranges in grain size from very fine-grained sand to silt. The dominant grain size is ~0.0625 mm, the boundary between very fine-grained sand and silt. In addition to quartz, the rock contains calcite cement. The color ranges from light gray and light medium gray to light brown and yellow-brown; weathering commonly produces an orange-buff cliff. A minor part of the sandstone–siltstone is argillaceous, and part of the argillaceous rocks weather to shaly beds. The beds are thin and planar. Generally the beds are no thicker than 20 cm; however, some outcrops appear massive. Thin planar to slightly wavy laminae, very low-angle crossbedding in sets no more than 10 cm thick, and symmetrical ripples are common. Trough crossbed sets are rare and are no more than 5 cm thick. Asymmetrical ripples are rare. Some of the thin planar laminations are defined by alternate layers of differing amounts of calcite cement. At the Antelope Valley section, a vertical succession ~60 cm thick includes (from the base upward) trough crossbeds, very low-angle crossbeds, and symmetrical ripples. At the Cottonwood Canyon North section, the sandstone has vertical burrows, and one internally massive bed ~10 cm thick suggests bioturbation. Siltstones include both vertical and horizontal burrows. The lower part of the member at the Antelope Valley section consists of alternate intervals of light gray, silty, calcareous shale and light gray, calcareous, sandy siltstone. Shale intervals are as much as 15 cm thick in the lower part of the member; thickness of shale partings decreases upward, effecting an upward gradation to siltstone. The lower part of the member at the Sappington East section includes shaly, argillaceous siltstone and thin-bedded, calcareous sandstone–siltstone in alternate units no more than 1 m thick. At the top of the member at the Antelope Valley and Cottonwood Canyon North sections, very calcareous sandstone–siltstone to very sandy limestone forms a single, apparently discontinuous, thin bed. The Sappington Sandstone Member ranges in thickness from 10 to 13 m (plate 1); the small range of thickness and the laterally persistent sandstone facies show no variation associated with the Willow Creek fault system.

Upper Contact of Three Forks Formation

The Three Forks Formation is overlain by the Mississippian Lodgepole Limestone. The contact, which is locally exposed, is abrupt. The basal Lodgepole is a light gray to medium gray, medium to coarse bioclastic packstone to grainstone in thick to thin beds. Minor interbeds include micrite, wackestone, and argillaceous micrite that form shaly partings. The coarse bioclastic rocks are succeeded upward by dark gray micrite and wackestone.

SUMMARY AND CONCLUSIONS

Cambrian through Devonian strata are exposed along the Southwest Montana transverse zone, both in the Cordilleran thrust belt and in the foreland. The Cambrian System consists of a transgressive basal clastic unit overlain by a carbonate-dominated succession that includes subordinate clastic rocks. Upper Cambrian strata are unconformably overlain by carbonate rocks of Late Devonian age, and the upper part of the Devonian succession grades upward to mudstone and sandstone. North of the transverse zone in the Cordilleran thrust belt, the basal Middle Cambrian sandstone rests unconformably (with angular discordance and paleotopographic relief) on a thick succession of clastic sedimentary rocks of the Proterozoic Belt Supergroup; however, south of the transverse zone in the Rocky Mountain foreland, the Middle Cambrian rocks rest unconformably on Archean crystalline basement rocks. The distribution, thickness, and sedimentary facies of the Belt Supergroup indicate a sedimentary basin bounded on the south by basement faults of the Perry line, including specifically the segment of the Perry line that is called the Willow Creek fault system (McMannis, 1963; Robinson, 1963). Despite the substantial differences in Precambrian rocks on opposite sides of the Willow Creek fault system and the large-scale dextral translation of the rocks north of the Jefferson Canyon fault, the Cambrian–Devonian stratigraphy is remarkably uniform throughout the region. Considering the large-scale eastward translation of the Lombard thrust sheet north of the Jefferson Canyon fault (Burton and others, 1993), the palinspastic extent of the region of uniform deposition of Cambrian–Devonian strata was much greater than the area represented by the present distribution of the measured stratigraphic sections described here.

The Middle Cambrian Flathead Sandstone locally pinches out and the Wolsey Shale thins by onlap onto paleotopographic highs (Graham and Suttner, 1974; Thomas and others, 1996). Local facies variations are associated with the onlap. The paleotopographic highs are located on coarse, proximal facies of the Belt Supergroup adjacent to the Willow Creek fault system; the array of highs is aligned with the fault system (Thomas and others, 1996). Corresponding paleotopographic lows are located on finer, more distal facies of the Belt Supergroup some distance north of the Willow Creek fault system and also on crystalline metamorphic rocks south of the fault system. The alignment of paleotopographic highs evidently reflects differential erosion of the various Precambrian rocks and does not require reactivation of the Willow Creek fault system during deposition of the Cambrian Flathead and Wolsey strata (Thomas and others, 1996).

Above the Wolsey Shale, the Cambrian stratigraphic section is remarkably uniform in thickness and facies (plate 1). The Meagher Limestone is of identical thickness in three of the four sections (the other section is faulted), and thin subdivisions of the Meagher (for example, oolitic limestone near the middle of the formation) are also persistent. The Park Shale shows substantial but non-systematic variations in thickness, but these evidently are a result of deformation rather than of original differences in depositional thickness. Details of the Park stratigraphy, such as distinctive thin conglomerate units in the upper part, are similar on both sides of the transverse zone. The Pilgrim Limestone does exhibit local variations in thickness, but the maximum and minimum thicknesses of the formation are in the two sections south of the transverse zone (plate 1). Minor synsedimentary deformation of part of the middle Pilgrim Limestone at the Sappington Railroad section possibly resulted from contemporaneous seismicity; however, no link to any specific fault movement is evident.

The Red Lion Formation at the top of the Cambrian succession is unconformably absent in the sections on the north; however, the northern erosional limit of the formation is some distance north of the Willow Creek fault system, as indicated by the presence of the Red Lion at the Cottonwood Canyon Interstate 90 section (plate 1). Thickness of the Upper Devonian Maywood Formation varies locally as the fill of a system of paleovalleys (Sandberg, 1965). Maximum thickness of the Maywood Formation, presumably indicating the fill of the deepest paleovalleys, coincides geographically with unconformable absence of the Red Lion Formation, further suggesting the importance of local erosion to distribution of the Red Lion. A west-trending paleovalley (Meyers, 1980; Thomas and others, 1996) is approximately parallel to and several miles north of the Willow Creek fault system. Thickness distributions of the Red Lion and Maywood Formations suggest simple erosion and filling of a paleovalley and do not require synsedimentary fault separation of the Cambrian–Devonian unconformity (Thomas and others, 1996).

The Upper Devonian Jefferson Dolomite shows no systematic variations in thickness or facies. The Three Forks Formation varies locally in thickness, but the variation is attributed to solution collapse (Sloss and Laird, 1947).

The Cambrian–Devonian stratigraphy on opposite sides of the Southwest Montana transverse zone exhibits no systematic variations in thickness or facies that indicate synsedimentary reactivation of the Willow Creek basement fault system. Because all of the strata represent deposition in shelf conditions near sea level, small-scale vertical fault separation predictably would cause significant variations in depositional systems, and these rocks should be especially sensitive recorders of fault reactivation. The lack of systematic variations in thickness and facies of Cambrian–Devonian stratigraphic units indicates deposition on a structurally stable shelf and further indicates that the Willow Creek fault system, which had large-scale vertical separation during Precambrian time, was dormant at least from Middle Cambrian to the end of Devonian time.

REFERENCES CITED

Burton, B.R., Lageson, D.R., Schmidt, C.J., Ballard, D.W., and Warne, J.R., 1993, Large-magnitude shortening of the Lombard thrust system, Helena salient, Montana fold and thrust belt: Implications for reconstruction of the Belt basin, *in* Berg, R.B., ed., Proceedings of Belt Symposium III: Montana Bureau of Mines and Geology Special Publication 112, p. 229–243.

Graham, S.A., and Suttner, L.J., 1974, Occurrence of Cambrian islands in southwest Montana: The Mountain Geologist, v. 11, p. 71–84.

Hanson, A.M., 1952, Cambrian stratigraphy in southwestern Montana: Montana Bureau of Mines and Geology Memoir 33, 46 p.

Harris, S.A., 1957, The tectonics of Montana as related to the Belt Series, *in* Graves, R.W., Jr., ed., Crazy Mountain Basin: Billings Geological Society Eighth Annual Field Conference Guidebook, p. 22–33.

Hawley, D., and Schmidt, C.J., 1976, Some aspects of the LaHood Formation and structure in the Jefferson Canyon area: Montana Bureau of Mines and Geology Special Publication 73, p. 151–165.

McMannis, W.J., 1963, LaHood Formation—A coarse facies of the Belt Series in southwestern Montana: Geological Society of America Bulletin, v. 74, p. 407–436.

Meyers, J.H., 1971, Stratigraphy and petrology of the Maywood Formation (Upper Devonian), southwestern Montana [Ph.D. thesis]: Indiana University Bloomington, 274 p.

Meyers, J.H., 1980, Tidal-flat carbonates of the Maywood Formation (Frasnian) and the Cambrian–Devonian unconformity, southwestern Montana, *in* Fouch, T.D., and Magathan, E.R., eds., Paleozoic Paleogeography of the West-Central United States: Denver, Colorado, Rocky Mountain Paleogeography Symposium 1, Rocky Mountain Section, Society of Economic Paleon-

tologists and Mineralogists, p. 39–54.
O'Neill, J.M., Schmidt, C.J., and Genovese, P.W., 1990, Dillon cutoff—Basement-involved tectonic link between the disturbed belt of west-central Montana and the overthrust belt of extreme southwestern Montana: Geology, v. 18, p. 1107–1110.
Robinson, G.D., 1963, Geology of the Three Forks quadrangle, Montana: U.S. Geological Survey Professional Paper 370, 143 p.
Sandberg, C.A., 1965, Nomenclature and correlation of lithologic subdivisions of the Jefferson and Three Forks Formations of southern Montana and northern Wyoming: U.S. Geological Survey Bulletin 1194-N, 18 p.
Sandberg, C.A., and McMannis, W.J., 1964, Occurrence and paleogeographic significance of the Maywood Formation of Late Devonian age in the Gallatin Range, southwestern Montana: U.S. Geological Survey Professional Paper 501-C, p. C50–C54.
Sandberg, C.A., Poole, F.G., and Johnson, J.G., 1988, Upper Devonian of western United States, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World, v. I: Regional Syntheses: Canadian Society of Petroleum Geologists Memoir 14, p. 183–220.
Schmidt, C.J., 1975, An analysis of folding and faulting in the northern Tobacco Root Mountains, southwest Montana [Ph.D. thesis]: Indiana University Bloomington, 480 p.
Schmidt, C.J., 1976, Structural development of the Lewis and Clark Cavern State Park area, southwest Montana: Montana Bureau of Mines and Geology Special Publication 73, p. 141–150.
Schmidt, C.J., and Garihan, J.M., 1983, Laramide tectonic development of the Rocky Mountain foreland of southwestern Montana, *in* Lowell, J.D., ed., Rocky Mountain Foreland Basins and Uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, p. 271–294.
Schmidt, C.J., and O'Neill, J.M., 1983, Structural evolution of the southwest Montana transverse zone, *in* Powers, R.B., ed., Geologic Studies of the Cordilleran Thrust Belt—1982: Denver, Colorado, Rocky Mountain Association of Geologists, p. 193–218.
Schmidt, C.J., O'Neill, J.M., and Brandon, W.C., 1988, Influence of Rocky Mountain foreland uplifts on the development of the frontal fold and thrust belt, southwestern Montana: Geological Society of America Memoir 171, p. 171–201.
Schmidt, C.J., Smedes, H.W., and O'Neill, J.M., 1990, Syncompressional emplacement of the Boulder and Tobacco Root batholiths (Montana–USA) by pull-apart along old fault zones: Geological Journal, v. 25, p. 305–318.
Sepkoski, J.J., Jr., 1977, Dresbachian (Upper Cambrian) stratigraphy in Montana, Wyoming, and South Dakota [Ph.D. thesis]: Cambridge, Massachusetts, Harvard University, 563 p.
Sloss, L.L., 1950, Paleozoic sedimentation in Montana area: American Association of Petroleum Geologists Bulletin, v. 34, p. 423–451.
Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93–114.
Sloss, L.L., and Laird, W.M., 1947, Devonian System in central and northwestern Montana: American Association of Petroleum Geologists Bulletin, v. 31, p. 1404–1430.
Thomas, W.A., Allen, J.L., Mars, J.C., McDowell, R.J., Azevedo, P.A., Buck, B.J., Corner, H.J., and Dodd, J.R., 1996, Willow Creek basement fault system beneath the Southwest Montana transverse zone: Dormant during Cambrian-Devonian time: The Mountain Geologist, v. 33, p. 115–124.
Woodward, L.A., 1982, Tectonic map of the fold and thrust belt and adjacent areas, west-central Montana: Montana Bureau of Mines and Geology Geologic Map 30, scale 1:250,000.

APPENDIX

LOCATION AND MEASUREMENT OF STRATIGRAPHIC SECTIONS

EXPLANATION FOR MAPS A–I

GEOLOGIC MAPS

contact

fault

MEASURED SECTIONS

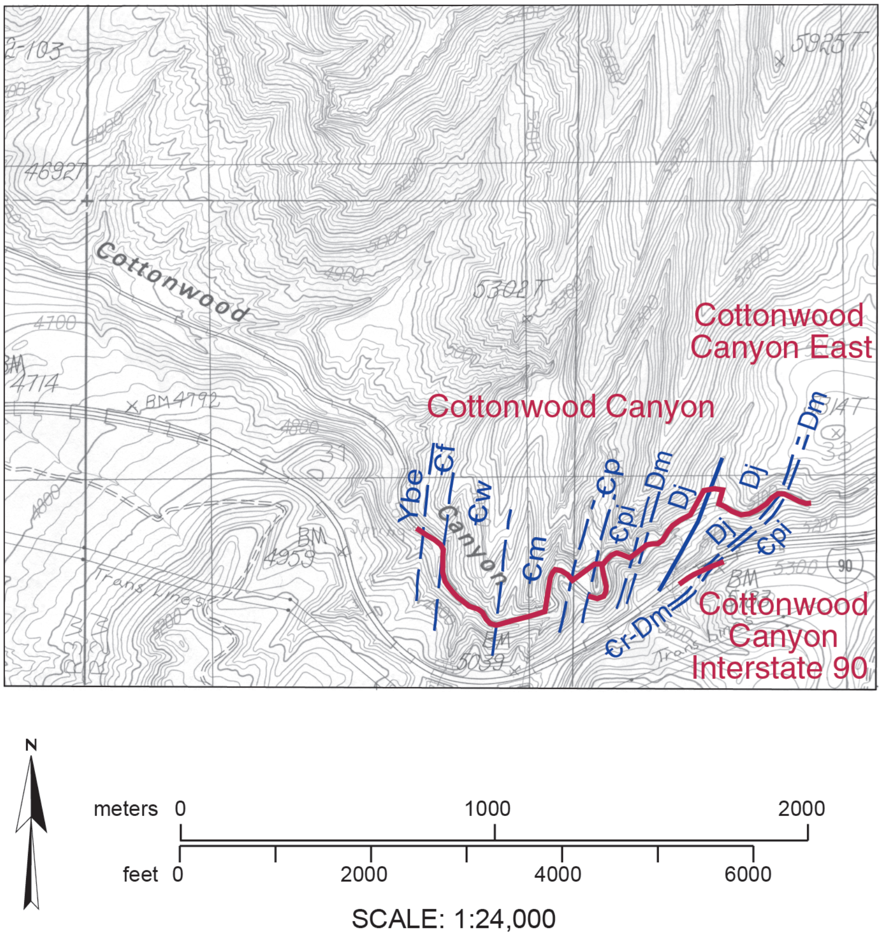
Brunton-and-tape traverse

alidade-and-plane-table traverse

MAP UNITS

Ml	Lodgepole Limestone
MDt	Three Forks Formation
Dj	Jefferson Dolomite
Dm	Maywood Formation
€r	Red Lion Formation
€pi	Pilgrim Limestone
€p	Park Shale
€m	Meagher Limestone
€w	Wolsey Shale
€f	Flathead Sandstone
Ybe	Belt Supergroup
p€g	Precambrian gneiss and granite

MAP A



Cottonwood Canyon (Map A)

Sections 31 and 32, T. 2 N., R. 2 W., Doherty Mountain 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse along graded road along the creek in the bottom of Cottonwood Canyon; the lowermost Pilgrim Limestone and all of the Park Shale were measured in a drainage-diversion tunnel and ditch (fig. 7). A few beds were measured directly. The base of the section is at the unconformable contact between the Cambrian Flathead Sandstone and the underlying Precambrian Belt Supergroup. The section consists of steeply dipping beds with stratigraphic top to the east. The top of the section is defined by a fault in the upper part of the Jefferson Dolomite.

Section measured by William A. Thomas, assisted by Rachel L. Thomas and James M. Montgomery, Jr.

Cottonwood Canyon East (Map A)

Section 32, T. 2 N., R. 2 W., Doherty Mountain 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse along graded road along the creek in the bottom of Cottonwood Canyon. A few beds were measured directly. The base of the section is at the lowest beds exposed in the Pilgrim Limestone in the eastern part of Cottonwood Canyon. The Cottonwood Canyon East section consists of steeply dipping beds with stratigraphic top to the west. The top of the section in the upper part of the Jefferson Dolomite is defined by the same fault that marks the top of the Cottonwood Canyon section.

Section measured by William A. Thomas, assisted by Rachel L. Thomas.

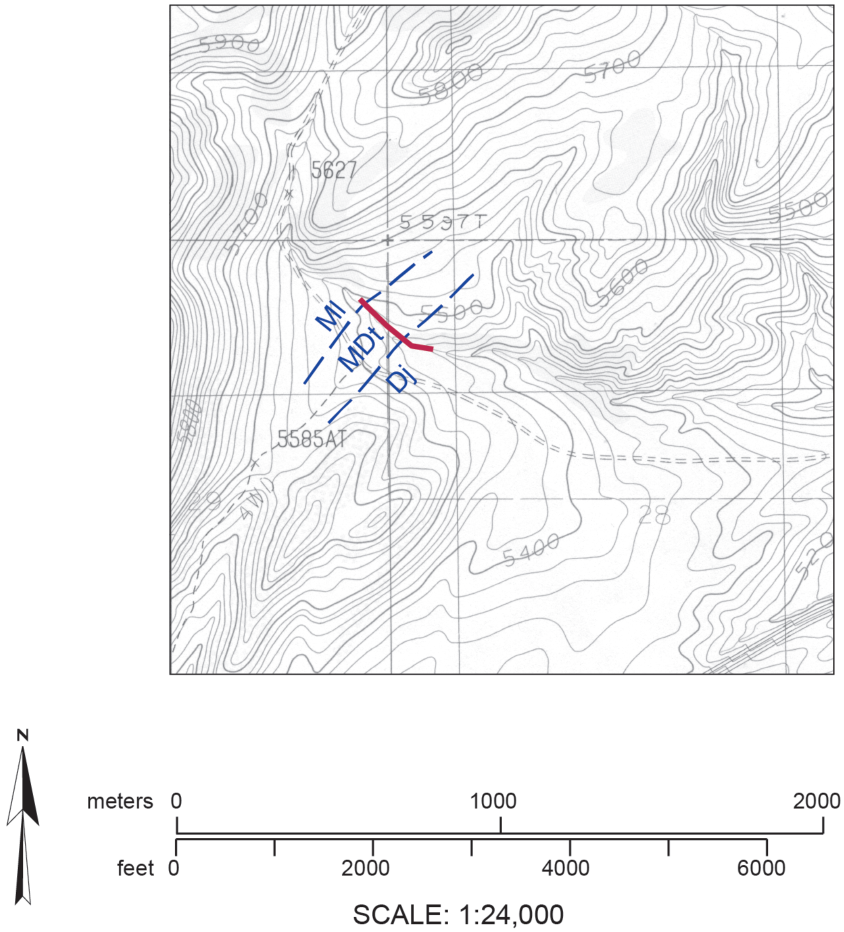
Cottonwood Canyon Interstate 90 (Map A)

Section 32, T. 2 N., R. 2 W., Doherty Mountain 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse along road cut of Interstate 90 on the south side of Cottonwood Canyon. A few beds were measured directly. The base of the section is at the lowest beds exposed in the Pilgrim Limestone in the road cut. The Cottonwood Canyon Interstate 90 section consists of steeply dipping beds with stratigraphic top to the west. The section is directly along the strike from the Cottonwood Canyon East section. The top of the section is at the highest beds exposed in the Jefferson Dolomite in the road cut.

Section measured by William A. Thomas, assisted by James M. Montgomery, Jr.

MAP B



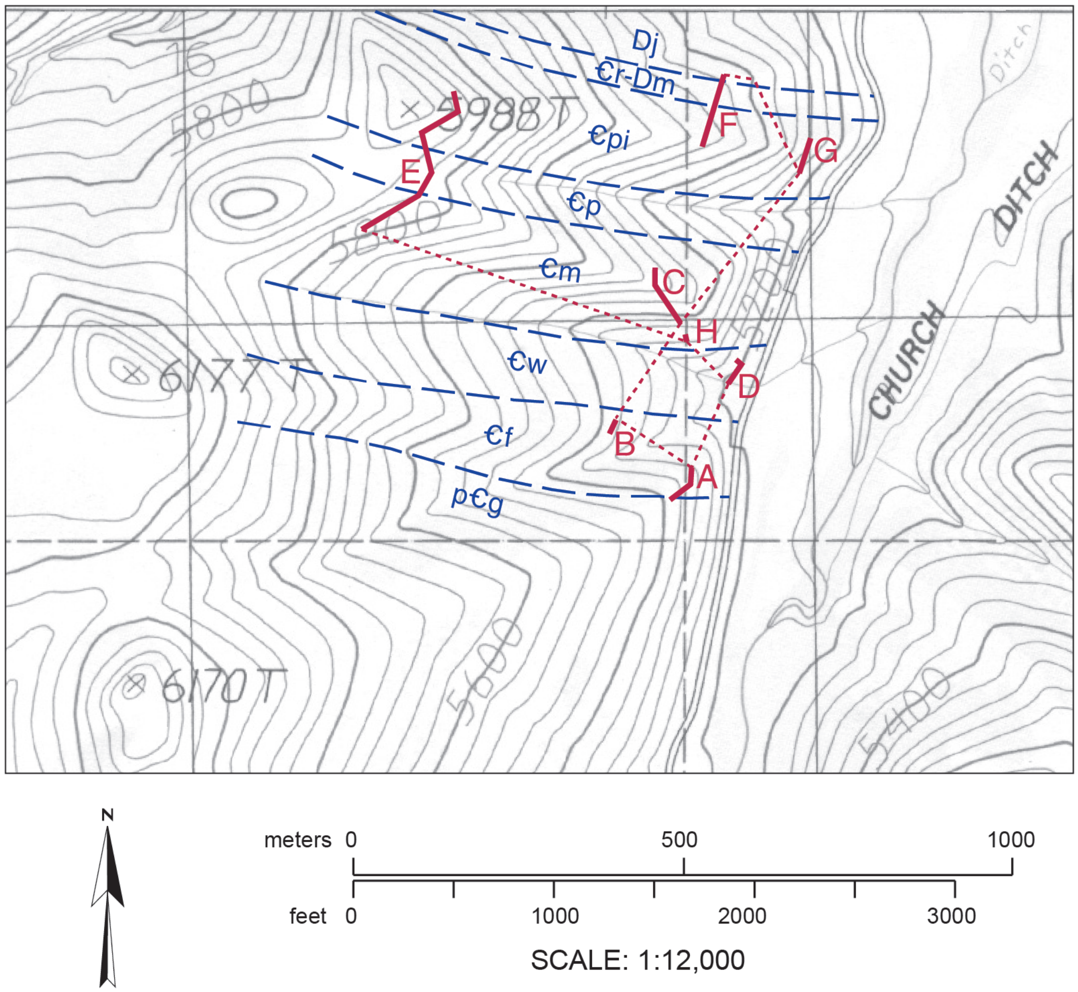
Cottonwood Canyon North (Map B)

Sections 28 and 29, T. 2 N., R. 2 W., Negro Hollow 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse along an east-flowing intermittent stream ~1.4 miles (~2.2 km) north of the point where Interstate 90 crosses the head of Cottonwood Canyon. The base of the section is at the lowest beds exposed in the Jefferson Dolomite. The Cottonwood Canyon North section consists of moderately dipping beds with stratigraphic top to the west. The upper part of the Jefferson Dolomite was traced by geologic mapping from the Cottonwood Canyon North section to the Cottonwood Canyon East section. The top of the section is at the contact between the Devonian–Mississippian Three Forks Formation and the overlying Mississippian Lodgepole Limestone.

Section measured by William A. Thomas, assisted by James M. Montgomery, Jr.

MAP C



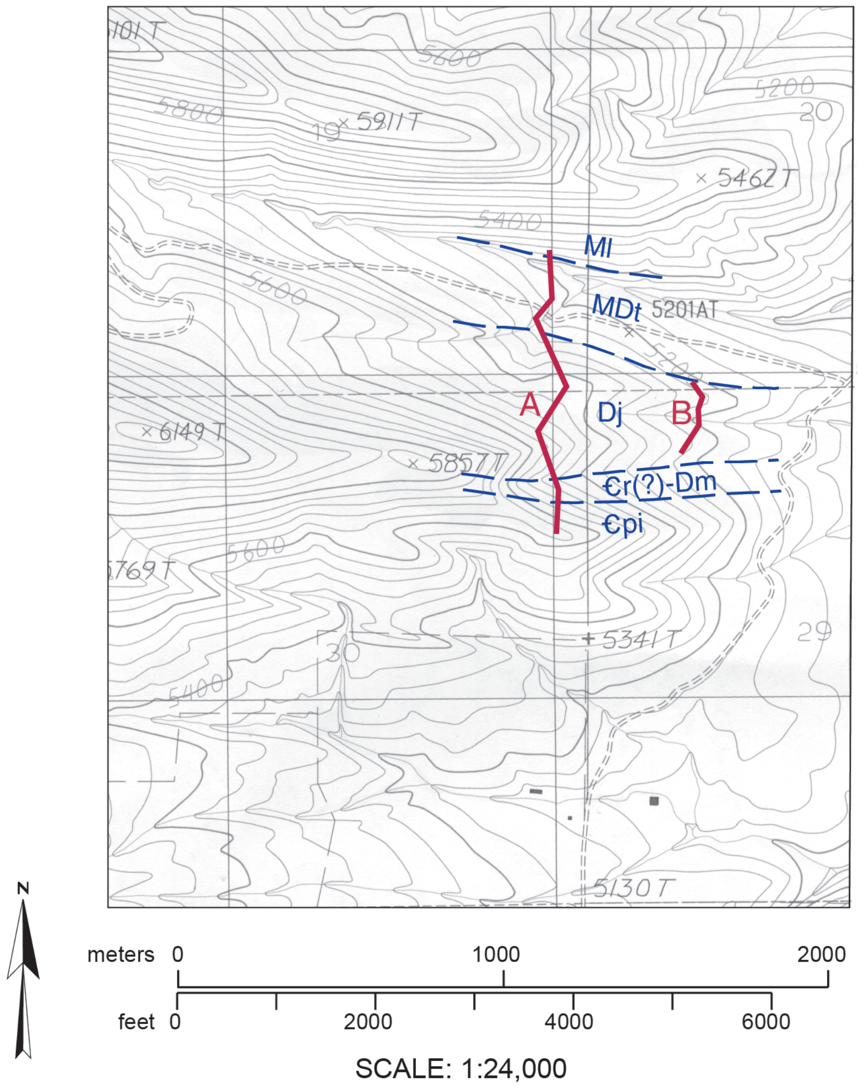
South Boulder (Map C)

Sections 15 and 16, T. 1 S., R. 3 W., Pony 7.5-minute quadrangle, Montana.

Section measured in eight separate segments (A through H) by Brunton-and-tape traverse on the west side of the valley of the South Boulder River. The traverses cross east-draining tributary valleys and eastward-nosing ridges. A few beds were measured directly. The eight segments were assembled by alidade-and-plane-table mapping, supplemented by geologic mapping between segments. The base of the section is at the unconformable contact between the Cambrian Flathead Sandstone and the underlying Precambrian gneiss. The South Boulder section consists of moderately dipping beds with stratigraphic top to the north. The top of the section is in the lower part of the Jefferson Dolomite. The upper Pilgrim to lower Jefferson part of the South Boulder section was traced by regional geologic mapping to the Antelope Valley section.

Section measured by William A. Thomas, assisted by James M. Montgomery, Jr.

MAP D



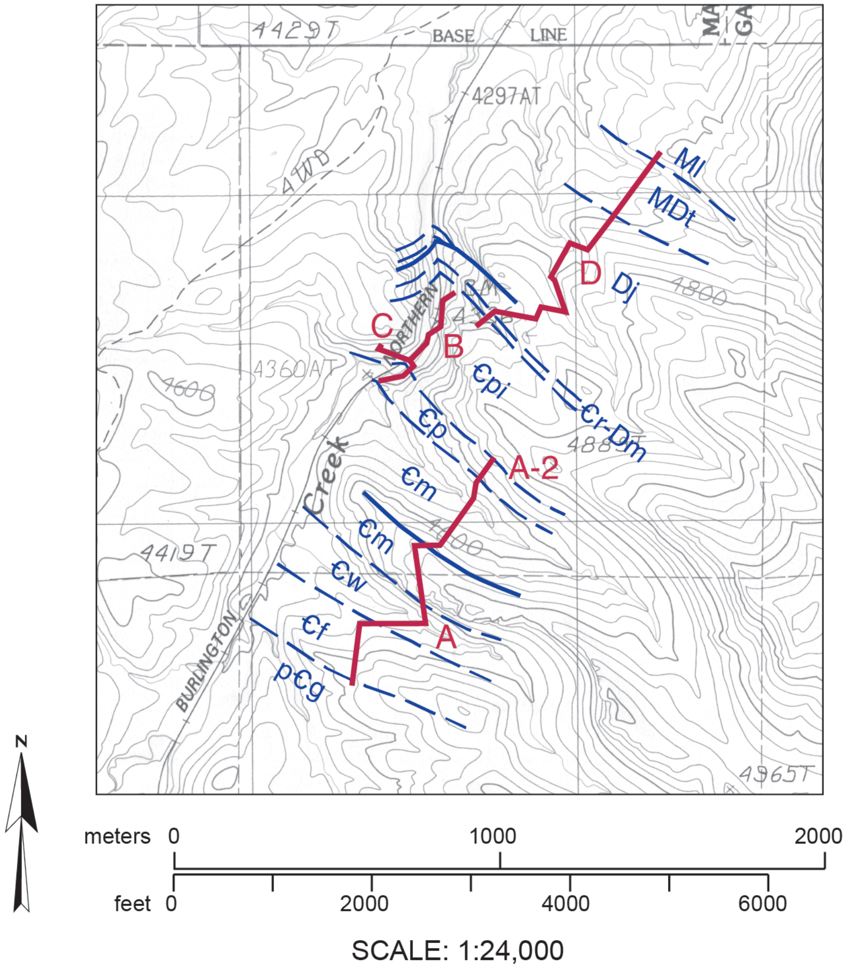
Antelope Valley (Map D)

Sections 19, 20, 29, and 30, T. 1 S., R. 2 W., Pony 7.5-minute quadrangle, Montana.

Section measured in two separate segments (A and B) by Brunton-and-tape traverse on the west side of the valley of Antelope Creek. The traverses cross tributary valleys and eastward-nosing ridges. A few beds were measured directly. The two segments were assembled by geologic mapping to trace specific units between the segments. The base of the section is at the top of a distinctive cliff-forming dolostone in the upper part of the Pilgrim Limestone. The Antelope Valley section consists of moderately dipping beds with stratigraphic top to the north. The top of the section is at the contact between the Devonian–Mississippian Three Forks Formation and the overlying Mississippian Lodgepole Limestone. The upper Pilgrim to lower Jefferson part of the Antelope Valley section was traced by regional geologic mapping to the South Boulder section.

Section measured by William A. Thomas, assisted by James M. Montgomery, Jr.

MAP E



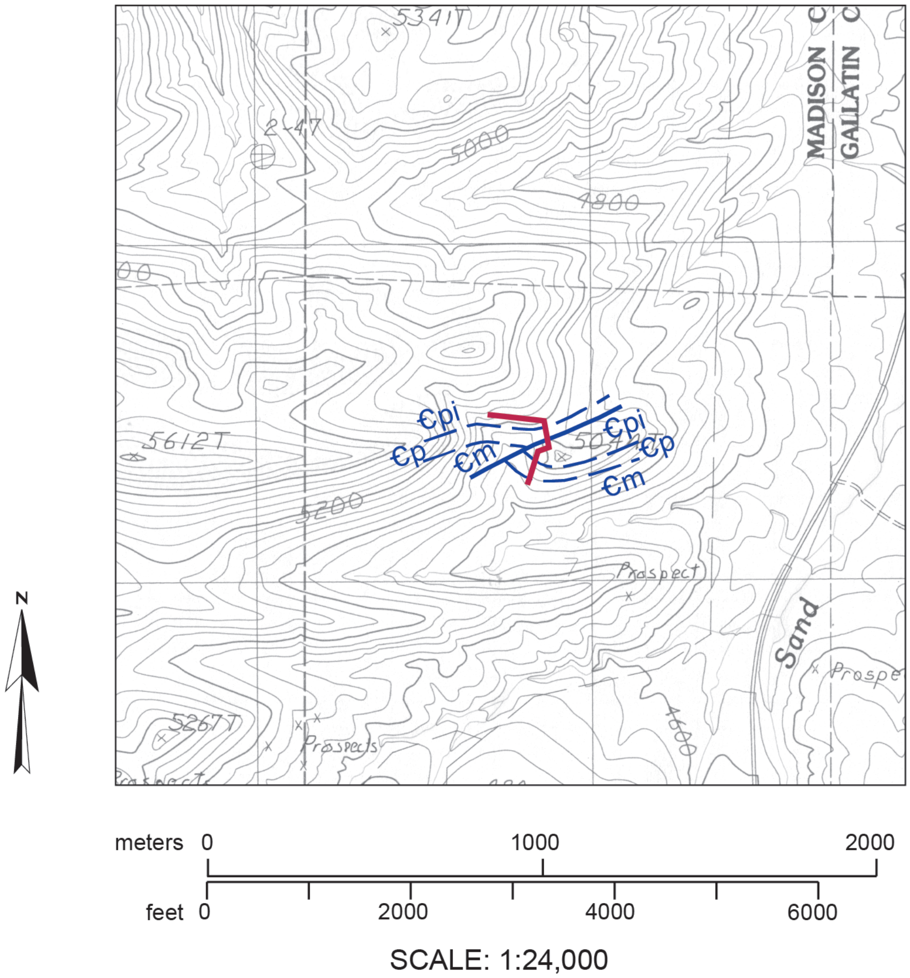
Sappington Railroad (Map E)

Sections 2 and 11, T. 1 S., R. 2 W., Sappington 7.5-minute quadrangle, Montana.

Section measured in four separate segments (A through D) by Brunton-and-tape traverse. A few beds were measured directly. Parts of the traverses cross hills and west-draining valleys on the east side of the valley of Antelope Creek east of the Burlington Northern Railroad; parts of the traverses are along the railroad in the valley of Antelope Creek, ~2.5 miles (~4 km) southwest of Sappington. Short traverses are west of the railroad on the west side of the valley of Antelope Creek. Three of the segments were assembled by geologic mapping to trace specific units between the segments; the distance to the other segment was measured by Brunton and tape. The base of the section is at the unconformable contact between the Cambrian Flathead Sandstone and the underlying Precambrian gneiss and granite. The Sappington Railroad section consists of moderately dipping beds with stratigraphic top to the north. The top of the section is at the contact between the Devonian–Mississippian Three Forks Formation and the overlying Mississippian Lodgepole Limestone.

Section measured by William A. Thomas, assisted by Brenda J. Buck.

MAP F



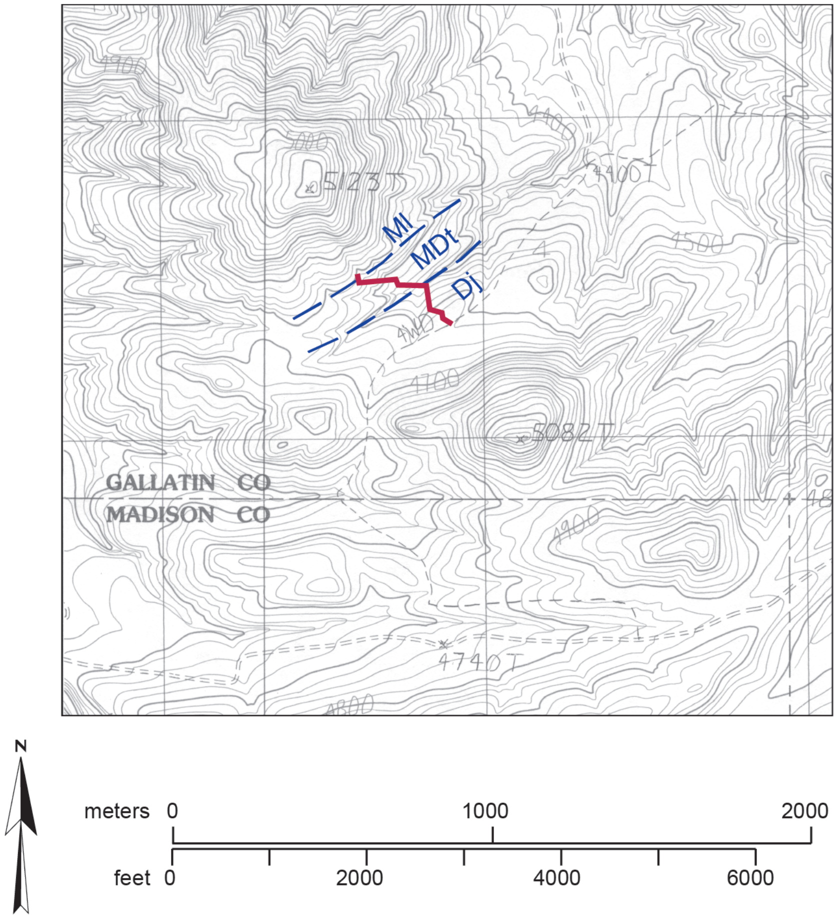
Sappington South (Map F)

Section 7, T. 1 S., R. 1 W., Sappington 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse along the south slope of a high ridge ~1.9 miles (~3 km) south of Sappington (west side of the valley of Sand Creek). The section was measured to supplement the Sappington Railroad section from the upper part of the Meagher Limestone through the lower part of the Pilgrim Limestone. The traverse crosses a fault, and the lower Pilgrim Limestone and upper Park Shale were measured in both fault blocks. The Sappington South section consists of moderately dipping beds with stratigraphic top to the north.

Section measured by William A. Thomas, Joseph L. Allen, Holly J. Corner, and John C. Mars.

MAP G



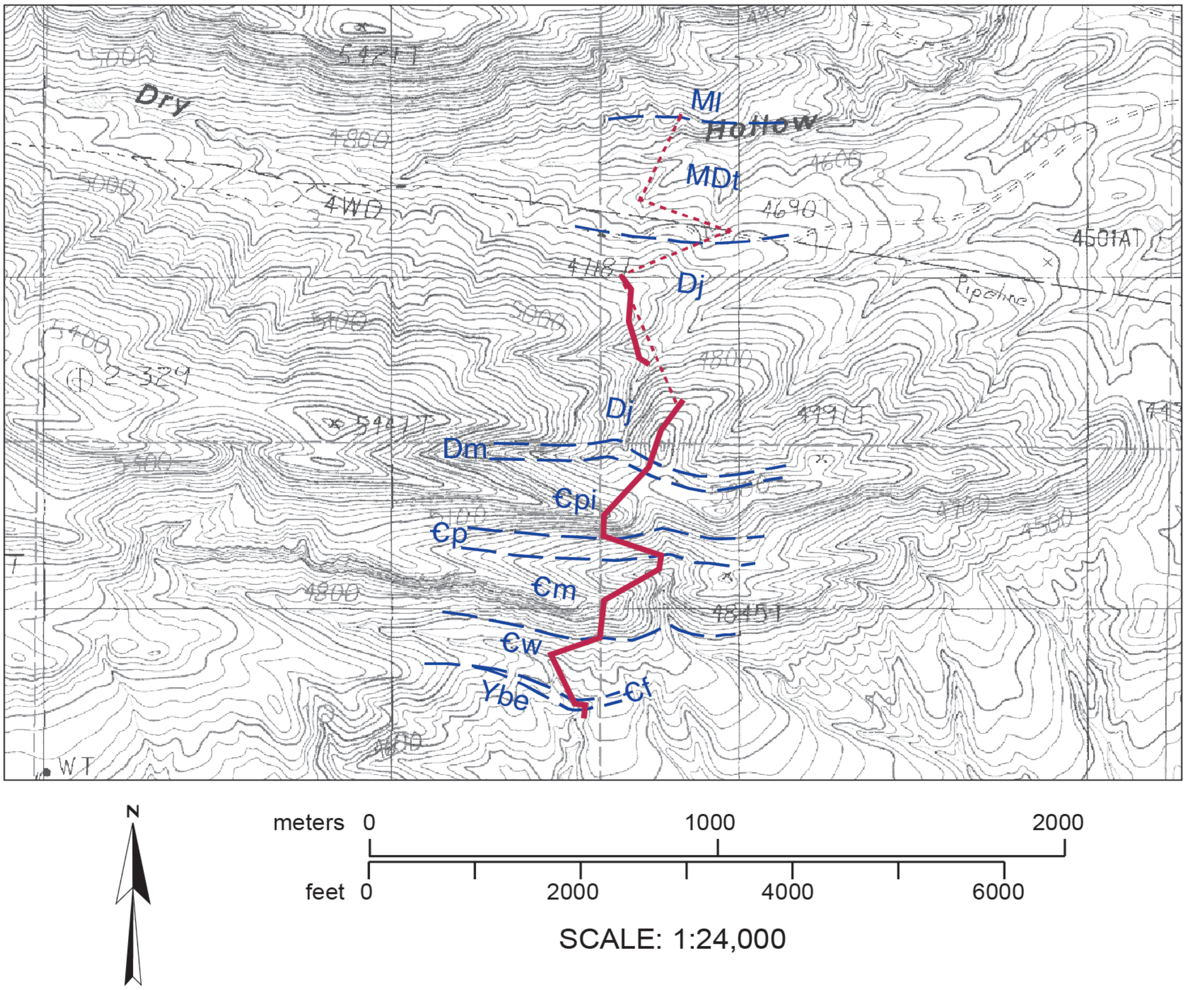
Sappington East (Map G)

Section 4, T. 1 S., R. 1 W., Willow Creek 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse across the head of a northeast-draining valley (tributary to the Jefferson River) ~1.9 miles (~3 km) southeast of Sappington. The section was measured to supplement the Sappington Railroad section of the Three Forks Formation. The Sappington East section consists of moderately dipping beds with stratigraphic top to the north.

Section measured by William A. Thomas, Paul A. Azevedo, Holly J. Corner, and John C. Mars.

MAP H



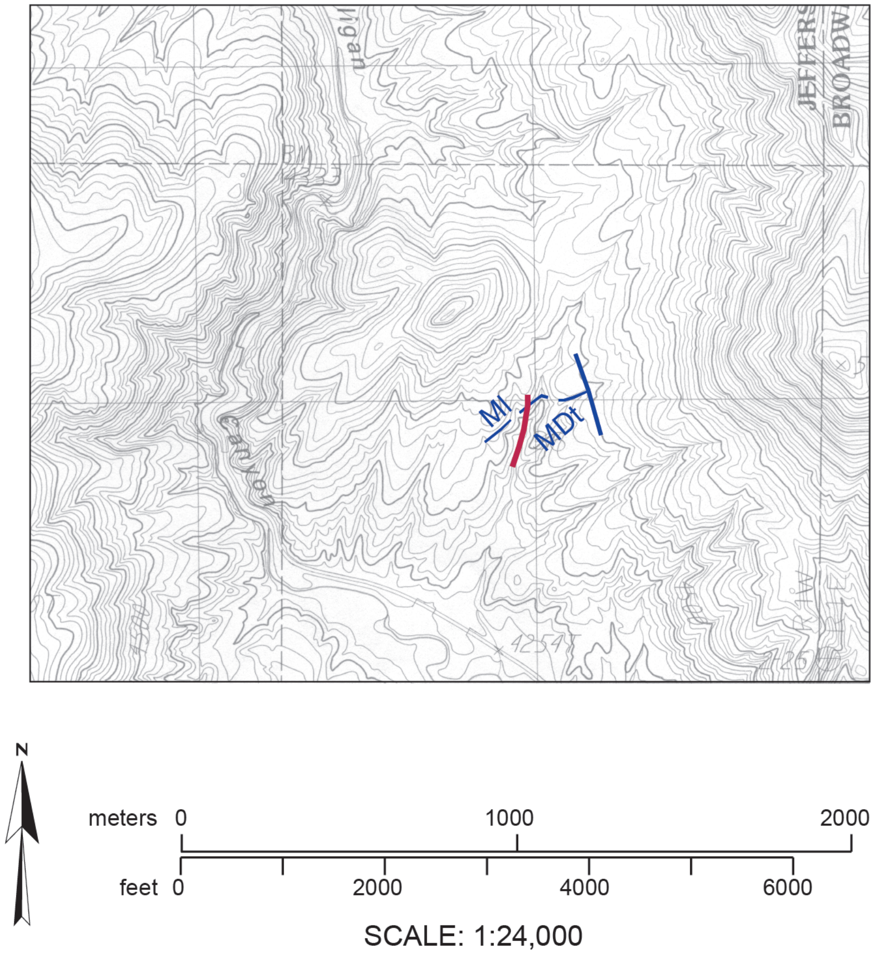
Milligan Canyon (Map H)

Sections 2, 10, and 11, T. 1 N., R. 1 W., Willow Creek 7.5-minute quadrangle, Montana.

Section measured in two Brunton-and-tape traverses connected by alidade-and-plane-table mapping across valleys and ridges ~1.9 miles (~3 km) west of Milligan Canyon. The base of the section is on the south-draining north side of the Jefferson River valley. The traverse crosses high ridges to east-draining Dry Hollow, a tributary of Milligan Creek. Scattered outcrops of parts of the Three Forks Formation were located by alidade-and-plane-table mapping. A few beds were measured directly. The base of the section is at the unconformable contact between the Cambrian Flathead Sandstone and the underlying Precambrian Belt Supergroup. The section consists of moderately dipping beds with stratigraphic top to the north. A single traverse includes the section from the base of the Flathead Sandstone through the lower part of the Jefferson Dolomite, and the other traverse includes the middle and upper Jefferson. The Three Forks Formation was measured by alidade-and-plane-table mapping and by direct measurement of the Sappington Sandstone Member. The top of the section is at the contact between the Devonian–Mississippian Three Forks Formation and the overlying Mississippian Lodgepole Limestone.

Section measured by William A. Thomas, assisted by Brenda J. Buck.

MAP I



Milligan Canyon East (Map I)

Section 36, T. 2 N., R. 1 W., Milligan Canyon 7.5-minute quadrangle, Montana.

Section measured by Brunton-and-tape traverse in a steep southwest-draining tributary canyon on the east side of Milligan Canyon. The section was measured to supplement the Milligan Canyon section of the Three Forks Formation. The Milligan Canyon East section consists of gently dipping beds with stratigraphic top to the north.

Section measured by William A. Thomas and John C. Mars.