Fallen arches: Dispelling myths concerning Cambrian and Ordovician paleogeography of the Rocky Mountain region

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ABSTRACT

High-resolution sedimentologic, biostratigraphic, and stable isotope data from numerous measured sections across Colorado reveal a complex architecture for lower Paleozoic strata in the central Cordilleran region. A lack of precise age control in previous studies had resulted in misidentification and miscorrelation of units between separate ranges. Corrections of these errors made possible by our improved data set indicate the following depositional history. The quartz-rich sandstone of the Sawatch Formation was deposited during onlap of the Precambrian erosion surface in the early Late Cambrian. The overlying Dotsero Formation, a regionally extensive carbonate- and shale-rich succession records blanket-like deposition with only minor facies changes across the state. An extremely widespread, meter-scale stromatolite bed, the Clinetop Bed, caps the Dotsero Formation in most areas. However, a latest Cambrian erosional episode removed 9–11 m of the upper Dotsero Formation, including the Clinetop Bed, from just east of the Homestake shear zone in the Sawatch Range eastward to the Mosquito Range.

The overlying Manitou Formation differs in character, and thus in member stratigraphy, on the east vs. west sides of the state. These differences were previously interpreted as the result of deposition on either side of a basement high that existed within the Central Colorado Embayment or Colorado "Sag," a region of major breaching across the Transcontinental Arch. This paleogeographic reconstruction is shown herein to be an artifact of miscorrelation. Biostratigraphic data show that the northwestern members of the Manitou Formation are older than the members exposed in the southeastern part of the state and that there is little or no overlap in age between the two areas. This circumstance is the result of (1) removal of older Manitou Formation strata in the southeast by an unconformity developed during the *Rossodus manitouensis* conodont Zone, and (2) erosion of younger Manitou strata in central and western Colorado along Middle Ordovician and Devonian unconformities.

Deciphering these complex stratal geometries has led to invalidation of long-held views on western Laurentian paleogeography during the Cambrian and earliest Ordovician, specifically the existence of the Colorado Sag and a northeast-trending high within the sag that controlled depositional patterns on either side. The mid-*Rossodus* uplift and resultant unconformity eliminated any and all Upper Cambrian and Lower Ordovician deposits in southern Colorado and northern New Mexico, and thus their absence should not be misconstrued as evidence for earlier nondeposition in this region. Lithofacies distribution patterns and isopach maps provide no evidence that highlands of the Transcontinental Arch existed in Colorado prior to the mid-*Rossodus* age uplift event. In fact, regional reconstructions of earliest Paleozoic paleogeography along the entire length of the purported Transcontinental Arch should be reevaluated with similarly precise biostratigraphic data to reconsider all potential causes for missing strata and to eliminate topographic elements not supported by multiple stratigraphic techniques. This study illustrates how seriously paleogeographic reconstructions can be biased by the presumption that missing strata represent periods of nondeposition rather than subsequent episodes of erosion, particularly in thin cratonic successions where stratigraphic gaps are common and often inconspicuous.

Keywords: Ordovician, Cambrian, Colorado, Transcontinental Arch, biostratigraphy.

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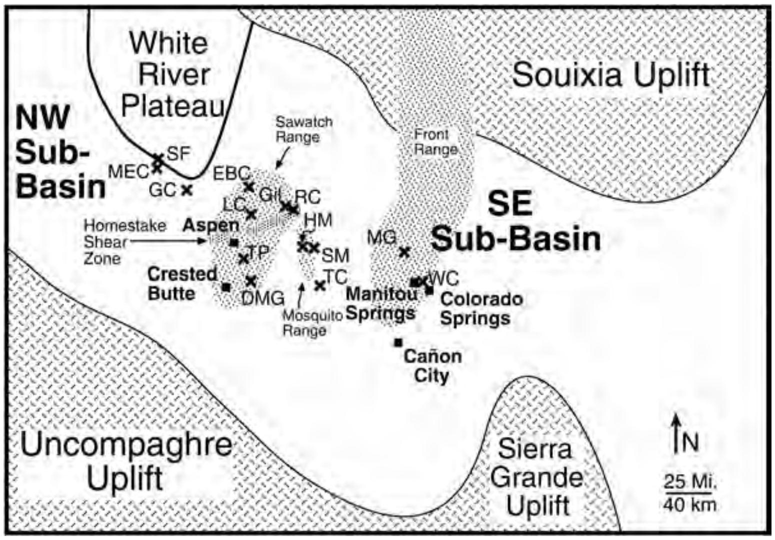


Figure 1. Location map with traditional interpretation (e.g., Lochman-Balk, 1970) of Cambrian–Ordovician paleogeography of Colorado Sag region (white) (modified from Gerhard, 1972, 1974), largely invalidated by present study. Location abbreviations: SF—South Fork; MEC—Main Elk Creek; GC—Glenwood Canyon; EBC—East Brush Creek; Gil—Gilman; RC—Red Cliff; LC—Lime Creek; LP—Lambertson's Peak; HM—Horseshoe Mountain; TP—Taylor Pass; SM—Sheep Mountain; TC—Trout Creek; DMG—Dead Man's Gulch; MG—Missouri Gulch; WC—Williams Canyon. The mountain ranges and White River Uplift are modern topographic features.

INTRODUCTION

Upper Cambrian and Lower Ordovician rocks in the Colorado Rocky Mountains have historically played an important role in the reconstruction of lower Paleozoic paleogeography in North America. Early depictions show a Transcontinental Arch trending diagonally through the middle of the state with a major breach, the Colorado Embayment (Lochman-Balk, 1970, 1971) or Colorado ''Sag'' (Gerhard, 1972), oriented orthogonally (northwest to southeast) to its length (Fig. 1). Most of central and northern New Mexico, along with small parts of western Texas, southern Colorado, and western Oklahoma composed an upland area, the Sierra Grande Highlands, that was emergent throughout the Cambrian (Lochman-Balk, 1970). Furthermore, Gerhard (1972, 1974) used stratigraphic data to argue that the Colorado Sag was divided into two subbasins separated by a low ridge that affected sedimentation patterns on either side during times of uplift and/or sea-level fall. His main lines of evidence were differences in the facies patterns in carbonate-platform deposits of the Ordovician Manitou Formation, as well as lithologic differences in the Cambrian units (Dotsero, Peerless, and Sawatch Formations) below the Manitou, on opposite sides of the purported high (Fig. 2). In Gerhard's reconstruction (Fig. 1), the high separated the Colorado Sag into a northwestern subbasin connected to the paleo-Pacific margin and a southeastern subbasin connected to the Midcontinental Sea. Allen (1994) posited that the interbasin high corresponded to the Homestake shear zone (Fig. 1), a reactivated Precambrian northeast-striking basement fault system that occurs in the zone of facies transitions. This paleogeographic scheme has received general acceptance and has been utilized in a number of studies (Ross, 1976; Ethington et al., 1987; Myrow et al., 1995, 1999a, 1999b; among others) to analyze a variety of stratigraphic data.

In this paper, we present a synthesis of the depositional and tectonic history of the lowermost Paleozoic deposits of Colorado based on high-resolution sedimentologic, physical stratigraphic, chemostratigraphic, and paleontological data from numerous localities across the state. Age control provided by new conodont and trilobite collections allows more accurate reconstruction of the spatial distribution of lithofacies through time as well as assessment of the roles of uplift, eustasy, and erosion on stratigraphic patterns in this region. Our revised correlations reveal that the aforementioned subbasins of the Colorado Sag, and perhaps even the existence of a well-defined Transcontinental Arch, are artifacts of miscorrelation between mountain ranges across Colorado. The following sections provide a review of the preexisting lithostratigraphic nomenclature, an explanation of lithostratigraphic revisions required to correct several critical miscorrelations, and a chronological history of the depositional and tectonic events that produced a deceptively complex architecture within the lower Paleozoic strata in this region.

In a more general sense, this study illustrates how integrated and detailed stratigraphic data can reveal flaws in long-standing paleogeographic reconstructions and in the methodologies used in their construction. For example, the lateral thinning or disappearance of lithostratigraphic units has commonly been attributed by default to nondeposition on paleotopographic highs, rather than to removal of strata by subsequent erosion. In the terminology utilized by Wheeler (1964), those investigators failed to discriminate the part of the total gap (lacuna) caused by erosion (degradational vacuity) from that resulting from nondeposition (the hiatus). The flawed methodology results in a proliferation of purported highlands, whose existence is not supported by stratigraphic data.

CAMBRIAN–ORDOVICIAN LITHOSTRATIGRAPHY OF COLORADO

Numerous studies, particularly those conducted during the first half of the twentieth century, were aimed at mapping specific regions of Colorado, and Cambrian and Ordovician rocks were mapped in a number of mountain ranges, many at high elevations. Correlation of widely scattered, poorly fossiliferous outcrops within and between ranges proved to be a difficult problem that was exacerbated by local variation in lithofacies and the superimposed effects of several unconformities developed from the Late Cambrian through Devonian. As a result, separate stratigraphic schemes and nomenclatures were proposed for different areas, and attempts at correlation were flawed because of misidentification and miscorrelation of units in the absence of precise age control. Consequently, stratigraphic data summarized in fence diagrams, correlation figures, isopach maps, and lists of unit thicknesses in previous studies must be analyzed carefully to determine whether they are reliable for reconstruction of depositional patterns.

The oldest lower Paleozoic cover unit in Colorado is the Upper Cambrian Sawatch Formation (Fig. 2), named by Eldridge (1894) for a white quartzite unit in the Sawatch Range.

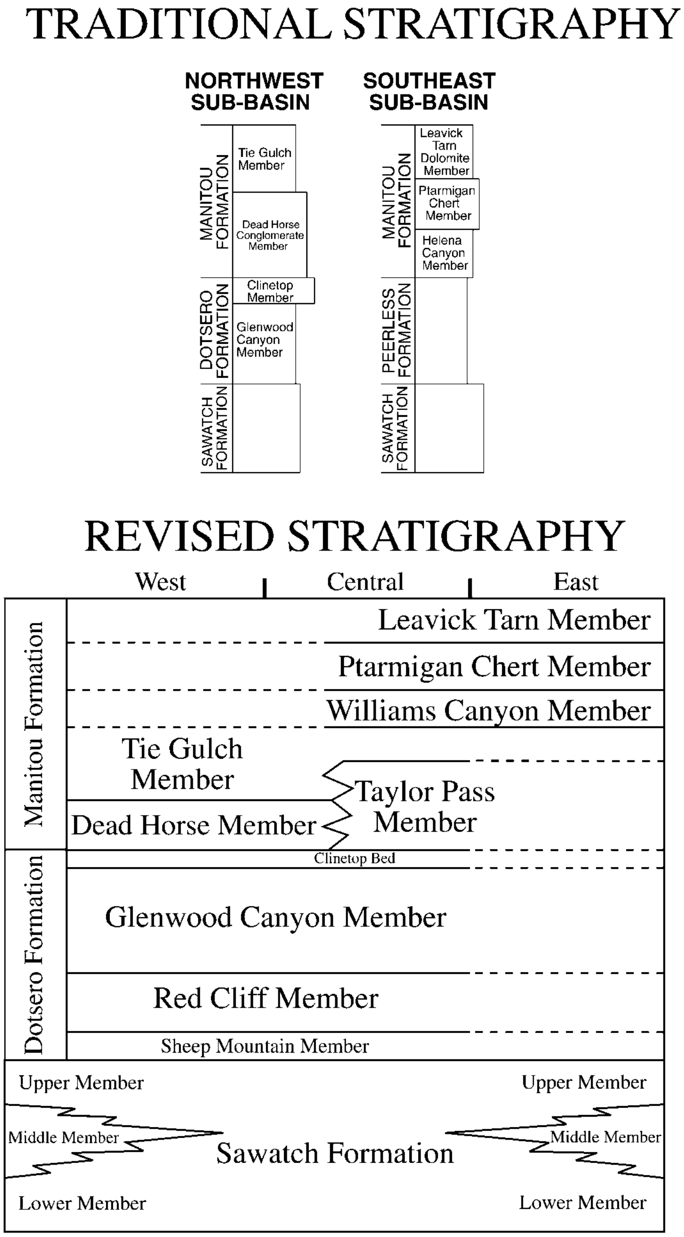


Figure 2. (Upper) The traditional lithostratigraphy of Cambrian and Ordovician deposits of Colorado, including Gerhard's (1972, 1974) member stratigraphy of the Manitou Formation. (Lower) A revised stratigraphy for the entire state shows new members of Dotsero and Manitou Formations, as well as revised age relationships of the Manitou members.

Singewald and Butler (1930; see also Johnson, 1934) described four informal subdivisions of the formation: ''lower quartzite,'' ''thin-bedded limy,'' ''upper quartzite,'' and ''purple quartzite.'' The uppermost unit—referred to previously as ''transition shale'' (Emmons, 1882, 1886), and in other accounts as ''red-cast beds''—was designated as the Peerless Shale Member of the Sawatch Formation by Behre (1932). This member of the Sawatch Formation was elevated to formation rank by Singewald (1947, 1951). The lower three informal members of the Sawatch Formation—lower and upper white quartzite members, separated by a middle glauconitic sandstone member (= thin-bedded limy member)—have been useful for mapping in the western Sawatch Range and to the west on the White River Plateau (Johnson, 1944, 1945; Mackay, 1953). Isopach maps of the Sawatch Formation for the central and western parts of the state show that it thickens to the west (Ross and Tweto, 1980). In addition, the middle member of the Sawatch Formation becomes more distinct and richer in glauconite and dolomite in that direction (Allen, 1994). These members have not been recognized in most of the eastern Sawatch Range or in the Mosquito Range, where the formation consists entirely of silica-cemented and carbonate-cemented quartz sandstone (Fig. 3A). Similarly, the middle glauconitic member was not recognized in the Front Range, and thus the Sawatch Formation was not divided into members in that area.

Mixed siliciclastic and carbonate rocks of the overlying Upper Cambrian Peerless Formation (~25 m thick) (Fig. 4A) have been mapped within the Front Range, Mosquito Range, and Sawatch Range. The type section is in the Mosquito Range where it was defined as having a distinctive purple quartzite bed at its base and a cap of ''red-cast beds'' (Behre, 1932). Later workers, including Singewald (1951) and Anderson (1970), extended the top of the formation to higher levels and unwittingly crossed a major unconformity that spans the Cambrian/Ordovician boundary, including strata better assigned to the overlying Manitou Formation (Myrow et al., 1999a). Behre (1939) and Singewald (1951) both recognized lower sandstone/shale and upper carbonate-rich (''red-cast beds'') divisions within the Peerless Formation.

The Dotsero Formation is a unit of thickness similar to that of the Peerless Formation (~25 m) that was originally mapped in the White River uplift (Bass and Northrop, 1953). This formation occupies the same stratigraphic position as the Peerless, between the underlying Sawatch Formation and the overlying Manitou Formation (Fig. 2). Bass and Northrop (1953) divided the Dotsero into a lower Glenwood Canyon Member and an upper Clinetop Member, the latter comprising a single submeter-scale stromatolite bed with basal and upper limestone flat-pebble conglomerate divisions. The Glenwood Canyon Member consists of shale, grainstone, and flat-pebble conglomerate. The two latter lithologies have produced a suite of Late Cambrian trilobites (Myrow et al., 1999a; Taylor, 2001).

The Manitou Formation was first described by Cross (1894) for Front Range localities, including Manitou Springs. An Ordovician age is readily apparent from a wide range of fossil taxa. Gerhard (1974) proposed a tripartite division of the formation in the eastern part of the state, recognizing the Helena Canyon, Ptarmigan Chert, and Leavick Tarn Dolomite Members, in ascending order. The Helena Canyon Member consists of meter-scale peritidal cycles (Myrow, 1995; Fig. 5A). The Ptarmigan Chert member includes chert-bearing

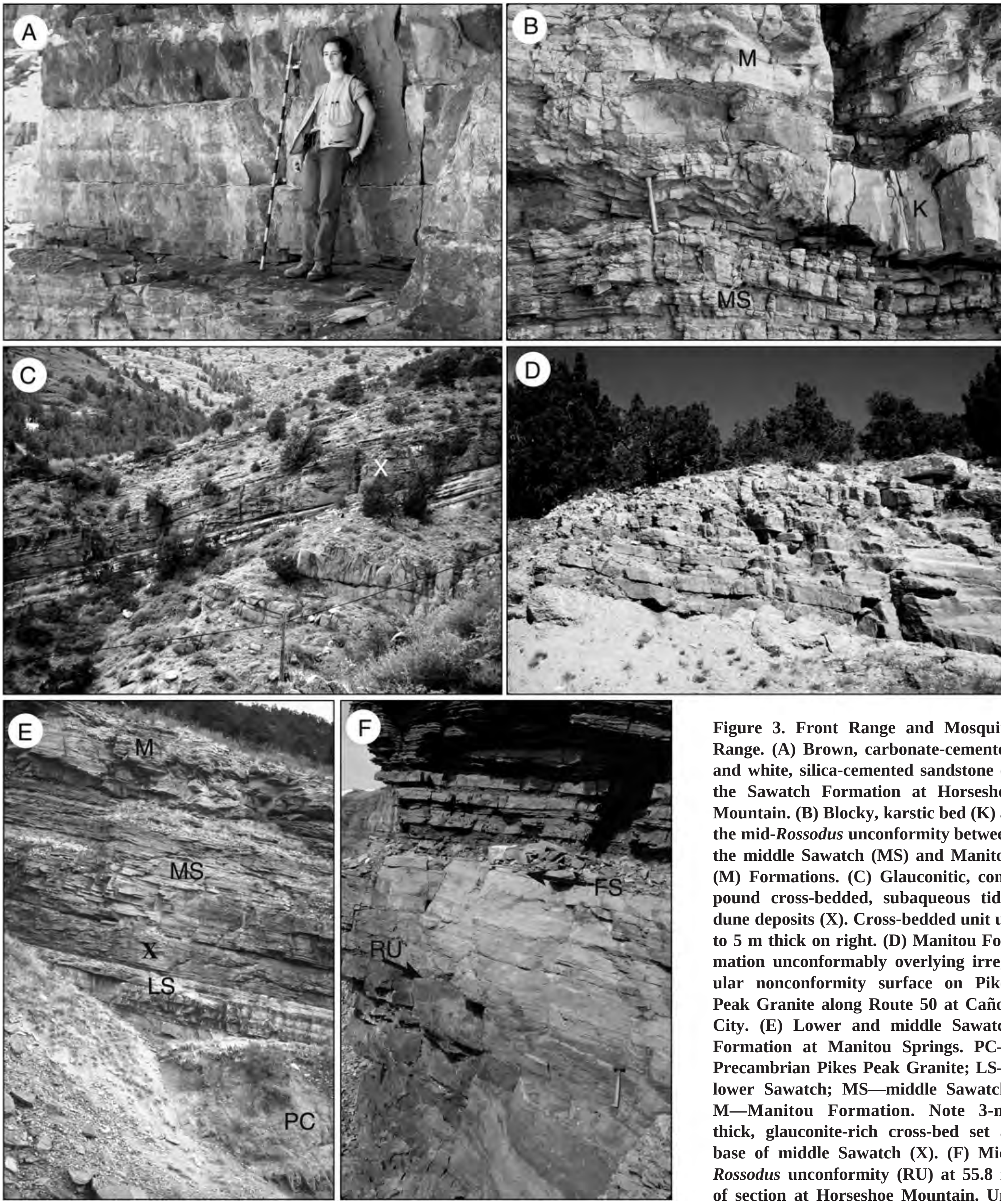


Figure 3. Front Range and Mosquito Range. (A) Brown, carbonate-cemented and white, silica-cemented sandstone of the Sawatch Formation at Horseshoe Mountain. (B) Blocky, karstic bed (K) at the mid-*Rossodus* unconformity between the middle Sawatch (MS) and Manitou (M) Formations. (C) Glauconitic, compound cross-bedded, subaqueous tidal dune deposits (X). Cross-bedded unit up to 5 m thick on right. (D) Manitou Formation unconformably overlying irregular nonconformity surface on Pikes Peak Granite along Route 50 at Cañon City. (E) Lower and middle Sawatch Formation at Manitou Springs. PC—Precambrian Pikes Peak Granite; LS—lower Sawatch; MS—middle Sawatch; M—Manitou Formation. Note 3-m-thick, glauconite-rich cross-bed set at base of middle Sawatch (X). (F) Mid-*Rossodus* unconformity (RU) at 55.8 m of section at Horseshoe Mountain. Unconformity is at top of "red-cast beds." Profound flooding surface (FS) within lower Manitou Formation marked by transition to shaly facies.

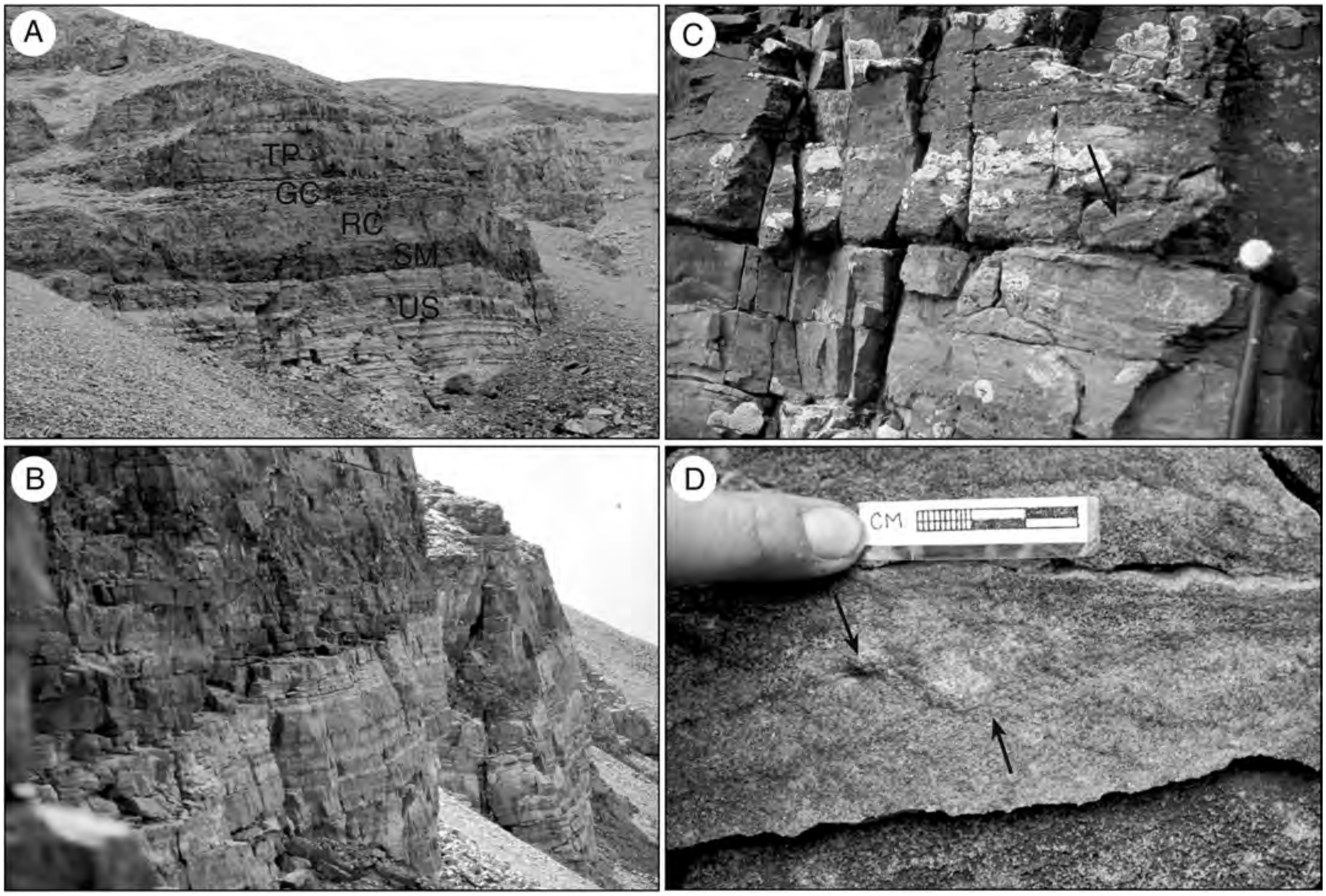


Figure 4. (A) Upper Sawatch and Dotsero Formations at Sheep Mountain, Mosquito Range. US—Upper Sawatch Formation. SM—Sheep Mountain Member, RC—Red Cliff Member, and GC—Glenwood Canyon Member of Dotsero Formation. TP—Taylor Pass Member of Manitou Formation. (B) Contact between Sawatch Formation and basal Sheep Mountain Member of Dotsero Formation. (C) Close-up of contact of Sawatch–Sheep Mountain contact; note large intraclasts (arrowed). Hammer for scale. (D) Paired clay drapes (arrows) in Sheep Mountain Member.

nodular lime mudstone (Fig. 5B), interbedded coarse-grained grainstone, and complex units with stromatolites and coarse-grained grainstone that contain sponge fossils (Rigby and Myrow, 1999). The Leavick Tarn Member consists of blocky-weathering, tan, fine-grained dolomitic grainstone.

Bass and Northrop (1953) defined the Manitou Formation in the northwest part of the state as consisting of a lower Dead Horse Conglomerate and an upper Tie Gulch Dolomite. The former includes flat-pebble conglomerate, grainstone, and shale. This member is identical in lithologic character to the underlying Glenwood Canyon Member of the Dotsero Formation. Although it contains flat-pebble conglomerate, it is in fact a mixture of lithologies, and thus we herein amend the name of this unit to the Dead Horse Member. The transition into the Tie Gulch Dolomite is marked by a change from shale and flat-pebble conglomerate to thin-bedded, fine-grained grainstone. This transition was also defined as coinciding with a shift from limestone to dolostone, although this is not true at all locations, so we similarly amend the name of this unit to the Tie Gulch Member.

CONFUSION IN THE FRONT RANGE: UPLIFT AND THE MID-*ROSSODUS* UNCONFORMITY

Berg and Ross (1959) were the first to use the name ''Peerless'' for rocks in the Front Range. They noted that a glauconitic, mixed siliciclastic, and carbonate unit occurs in this region above the quartzite of the Sawatch Formation and below the carbonate of the Manitou Formation (Figs. 2 and 4A). This unit was correlated to the Peerless Formation of the Mosquito and Sawatch Ranges on the basis of this stratigraphic position and gross lithologic similarity. A Franconian—now lower Sunwaptan (Ludvigsen and Westrop, 1985; Westrop, 1986)—trilobite assemblage was collected from high within the formation at Illinois Gulch (Berg and Ross, 1959) near the disconformable contact with the overlying Ordovician Manitou Formation (Fig. 3D). Lower Sunwaptan trilobites were also reported from the Peerless Formation in the Gilman and Alma mining districts of the eastern Sawatch and Mosquito Ranges (Johnson, 1934; Resser, 1942; Crawford and Gibson, 1925). However, in many cases, these were identifications of specimens collected much earlier by C.D. Walcott and others, for which locality and stratigraphic information is scant. In summary, the identification of the Peerless Formation in the Front Range by Berg and Ross (1959) was consistent with most of the trilobite data available at that time, although none of the

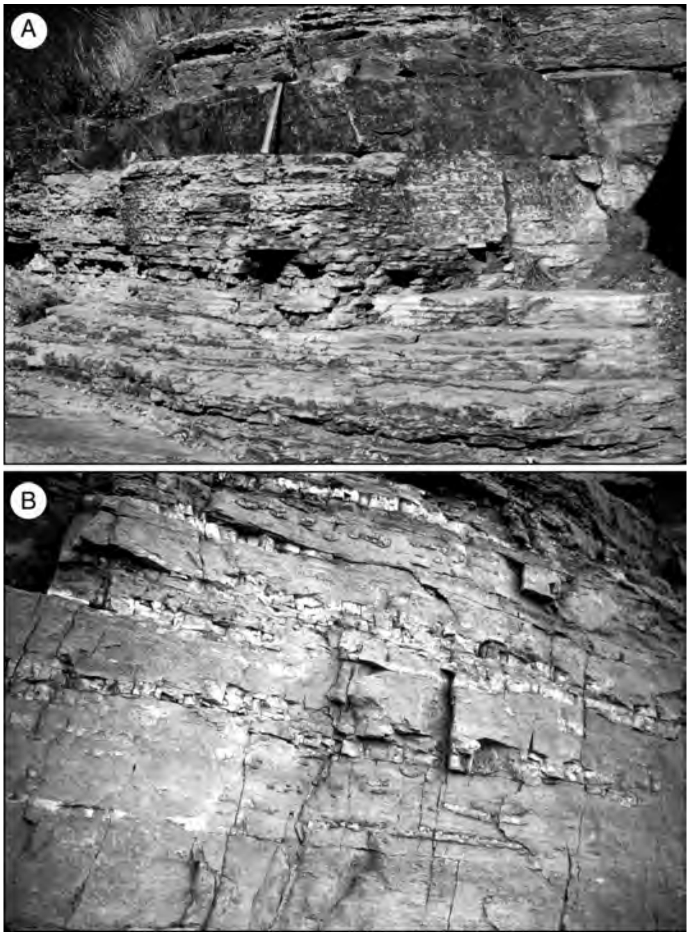


Figure 5. Manitou Formation. (A) Meter-scale carbonate cycles in Helena Canyon Member. Flat hard-ground marking base of cycle at lower left; hammer rests against grainstone bed at base of next cycle. (B) Ptarmigan Chert Member with abundant chert nodules at Horseshoe Mountain.

data was tied to a measured section, particularly the type section.

The first well-defined biostratigraphic data for the Peerless Formation in its type section, on the flanks of Horseshoe Mountain next to the Peerless Mine, were presented by Myrow et al. (1995). Their data establish that at least the top 4 m of the 20.5-m-thick Peerless Formation contain conodonts of the *Eoconodontus* Zone (the lower *Eoconodontus notchpeakensis* Subzone), whereas the base of the overlying Manitou Formation yields conodonts of the *Rossodus manitouensis* Zone (Figs. 3F, 6, and 7). As with the sections at Illinois Gulch and Missouri Gulch in the Front Range, these data document a lacuna that spans much of the Cambrian–Ordovician boundary interval. However, the *Eoconodontus* Zone conodonts from the type Peerless Formation are Trempealeauan—now upper Sunwaptan (Westrop, 1986)—forms, far too young to be correlated with the lower Sunwaptan strata in the Front Range. The conodont data from Horseshoe Mountain are in agreement with Chronic's (1964) report of an upper Sunwaptan trilobite, *Saukia coloradoensis* Walcott, from somewhere within the Peerless Formation at its type locality.

Berg and Ross (1959) demonstrated, by faunal and stratigraphic patterns, that a major break exists between their ''Peerless'' Formation and the overlying Manitou Formation in the Front Range. They showed that uplift in southern Colorado prior to deposition of the Manitou Formation caused progressive erosional cut-out of the Cambrian units toward the south and subsequent onlap of the Manitou Formation from north to south (Fig. 8). In localities south of Colorado Springs, such as Cañon City, the Manitou Formation rests directly on Precambrian granite (Figs. 3E, 8), where the basal beds presumably contain the youngest onlapping strata of the formation. At Missouri Gulch to the north, the basal Manitou Formation is much older, by at least three trilobite zones, and rests on lower Sunwaptan sedimentary rocks. Conodonts from the basal Manitou Formation at Missouri Gulch are currently assigned to the long-ranging *Rossodus manitouensis* Zone (Fig. 9). Because strata of this age also rest unconformably on younger *Eoconodontus* Zone rocks at Horseshoe Mountain to the northwest (Figs. 3F and 6), we interpret this surface as the same unconformity of *R. manitouensis* age that removed both the ''true'' Peerless Formation and the upper quartzite member of the Sawatch Formation to the south. The highly glauconitic unit that Berg and Ross (1959) identified as ''Peerless'' Formation in the Front Range is in fact the middle member of the Sawatch Formation. The unconformity rises to even higher levels to the west and rests on *Rossodus* age strata at Taylor Pass (Fig. 10A), so it must have developed during the *Rossodus* interval and is thus named herein the ''mid-*Rossodus* unconformity.''

A close comparison of the lithologic characteristics of the Front Range ''Peerless'' Formation with those of units farther to the west also supports the conclusion that the former represents the middle member of the Sawatch Formation. Johnson (1944, p. 312) defined the middle glauconitic sandstone member as a unit with quartzite, sandstone, glauconitic sandstone, calcareous sandstone, impure limestone, and calcareous sandy shale. These lithologies match well with those of the lithologically mixed unit that Berg and Ross (1959) attributed to the Peerless Formation along the Front Range. Careful examination of the type section of the Peerless Formation reveals that it in fact contains little glauconite and is therefore not that similar lithologically to the Front Range deposits. The middle member of the Sawatch Formation has never been identified in areas southeast of the Homestake shear zone of the Sawatch Range (see Allen, 1994), but only because it has been misidentified as the Peerless Formation along the Front Range. The middle member of the Sawatch Formation is not present in the central part of the state, in the Mosquito Range, or in parts of the eastern Sawatch Range, but occurs with increased glauconite content toward the west. Our recognition of this unit in the Front Range indicates that it was also deposited eastward of the central part of the state. Sedimentologic analysis of this unit (under the name Peerless Formation) indicates that it formed as a result of rapid deepening (Myrow, 1998). The distribution of glauconite in the middle Sawatch Formation across the state would therefore indicate a general deepening

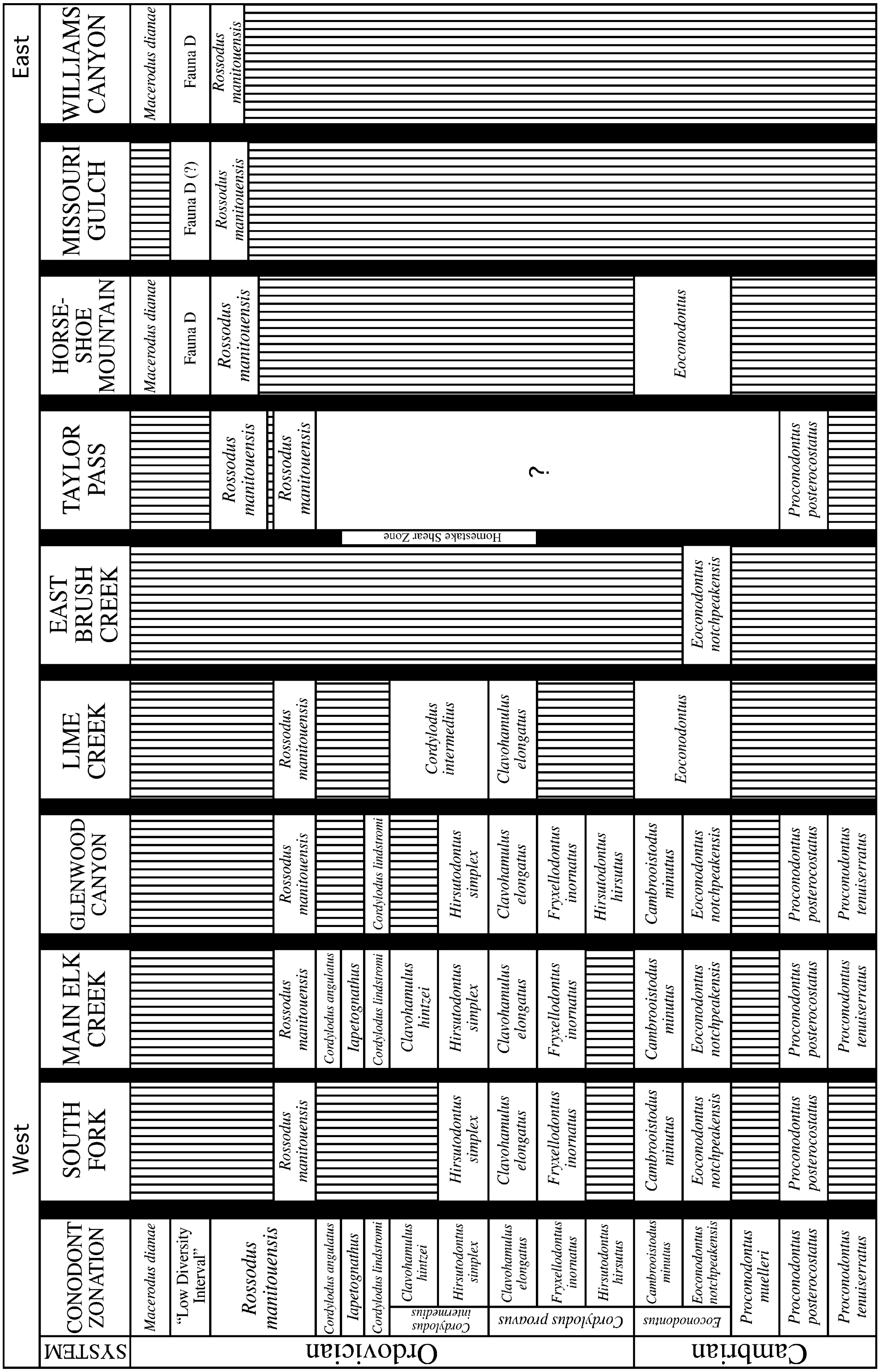


Figure 6. Conodont biostratigraphy for selected locations in Colorado. Areas with vertical lines denote lacunae—intervals missing at unconformit ies. Note large number of zones/subzones present in sections to the northwest.

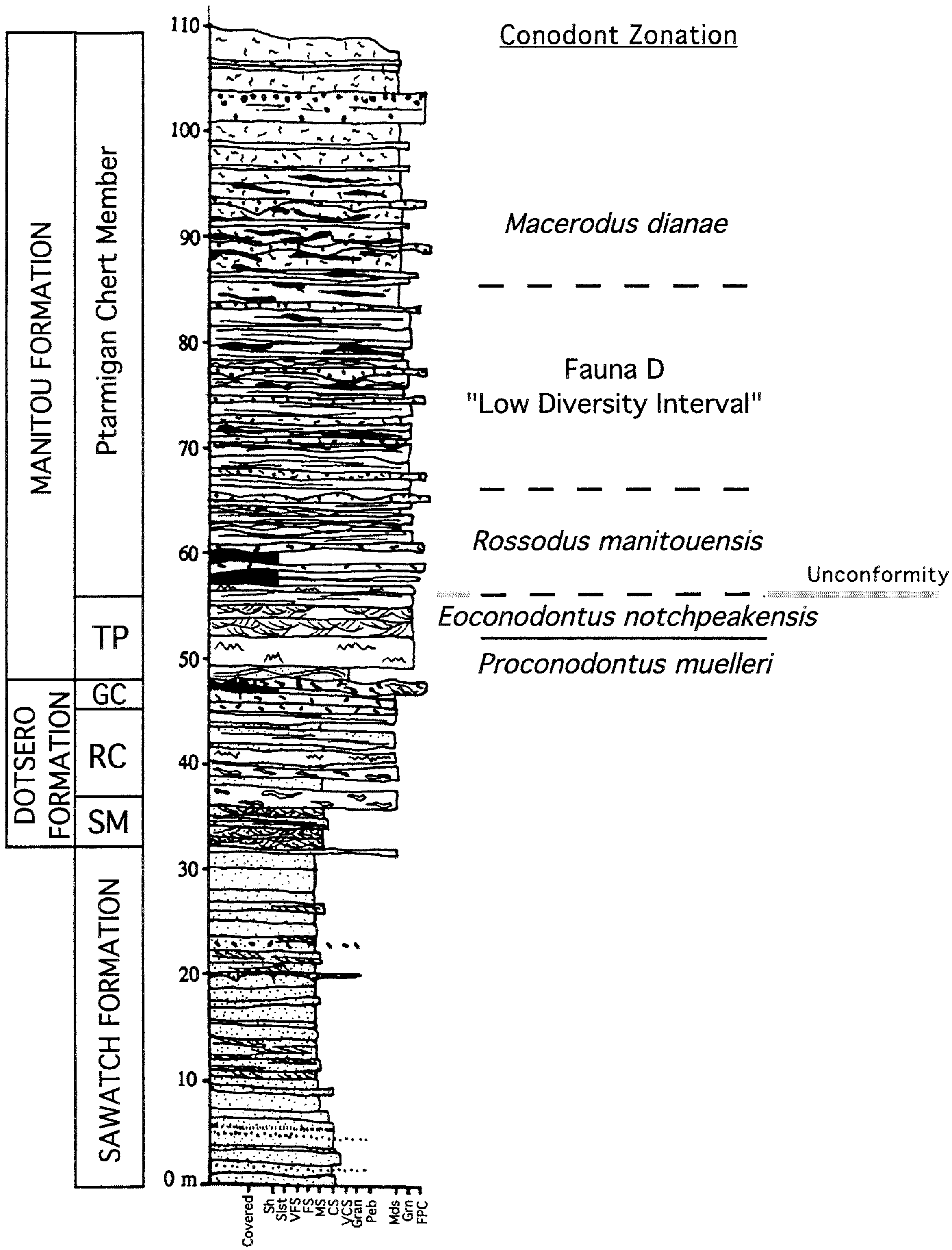


Figure 7. Generalized stratigraphic column of Horseshoe Mountain with conodont zonations. The stratigraphic boundaries of the old Peerless Formation are shown, as well as new members of the Dotsero and Manitou Formations. SM—Sheep Mountain Member, RC—Red Cliff Member, and GC—Glenwood Canyon Member of Dotsero Formation. TP—Taylor Pass Member of Manitou Formation.

both eastward and westward from the Sawatch and Mosquito Range area (Fig. 2).

UPPER CAMBRIAN DEPOSITION: LEVELING THE PLAYING FIELD

Sawatch Formation

Little is known about the paleoenvironments of the Sawatch Formation except for the work of Myrow (1998), who examined an anomalously thin (4.5 m) lower quartzite member and middle glauconite member along the Front Range in the vicinity of Manitou Springs (Fig. 3E). These members are interpreted as transgressive deposits that include large-scale, glauconite-rich, subaqueous, but tidally influenced dune deposits that lie on a flooding surface at the base of the middle member (Myrow, 1998) (Figs. 3C, 3E). Although no regional comprehensive depositional study has been made of the Sawatch Formation, the quartz sandstones of the upper and lower members display conspicuous evidence for shallow-marine deposition, including pervasive bioturbation, *Skolithos* piperock, and hummocky cross-stratification. Isopach patterns (discussed subsequently) and the sedimentologic analysis of Myrow (1998) indicate that the glauconite- and carbonate-rich middle member represents a deepening event between deposition of the upper and lower quartzite members.

Allen (1994) constructed isopach maps for the Sawatch Formation for the central and western parts of the state, where it ranges from 0 to 127 m thick. These maps show thickening to the west, which is consistent with a westward increase in development of the glauconitic middle member and deepening in that direction. The formation also thickens to the south and southwest, but is sharply truncated by the mid-*Rossodus* unconformity already described. The absence of the Sawatch Formation in the southern part of the state and in northern New Mexico led Lochman-Balk (1956, 1970) and others to suggest that a highland existed to the south at this time. Not much can be said, however, about the original patterns of deposition for the southeastern part of the state during Sawatch Formation deposition, largely because thickness patterns are strongly controlled by post-Sawatch erosion.

Several thickness anomalies indicate that the Sawatch Formation was deposited during transgression onto a somewhat irregular Cambrian landscape. For example, Allen (1994) documented facies and thickness variations that suggest that the Sawatch Formation onlapped a paleohigh bounded by reactivated segments of the Homestake shear zone in the northeastern Sawatch Range. In addition, a substantial local high with ~50 m of relief exists at Lime Creek Canyon in the western Sawatch Range, where the formation is represented by as little as 2.14 m of quartzarenite (e.g., Allen, 1994). The 4.5 m of the lower member of the Sawatch Formation quartzite at Manitou Springs is also anomalously thin; the member triples in thickness just 35 km north-northwest at Missouri Gulch.

Deposition of the Sawatch Formation appears to have filled an inherited topography; the lower member filled most of the irregularities. Development of the glauconitic middle member in the eastern and western parts of the

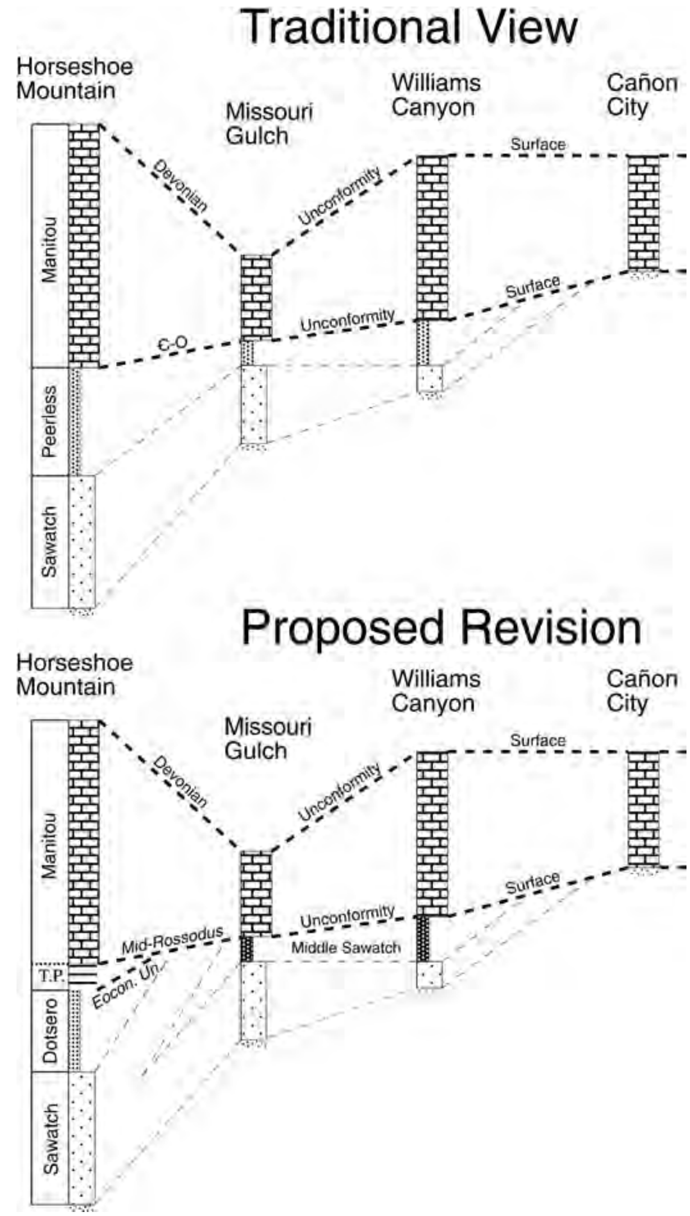


Figure 8. Comparison of correlation schemes for the Front Range and Mosquito Range. The "traditional view" (e.g., Berg and Ross, 1959) correlates glauconitic and dolomitic deposits along the Front Range (Missouri Gulch, Williams Canyon, Deadman's Canyon) with the Peerless Formation whose type section is exposed at Horseshoe Mountain. Conodonts recovered from the Peerless at the type section indicate a much younger age, and hence the Front Range deposits are correlated with the glauconite-rich middle member of the Sawatch Formation in the "proposed revision." T.P.—Taylor Pass Member of Manitou Formation; *Eoconodontus* un.—*Eoconodontus* unconformity.

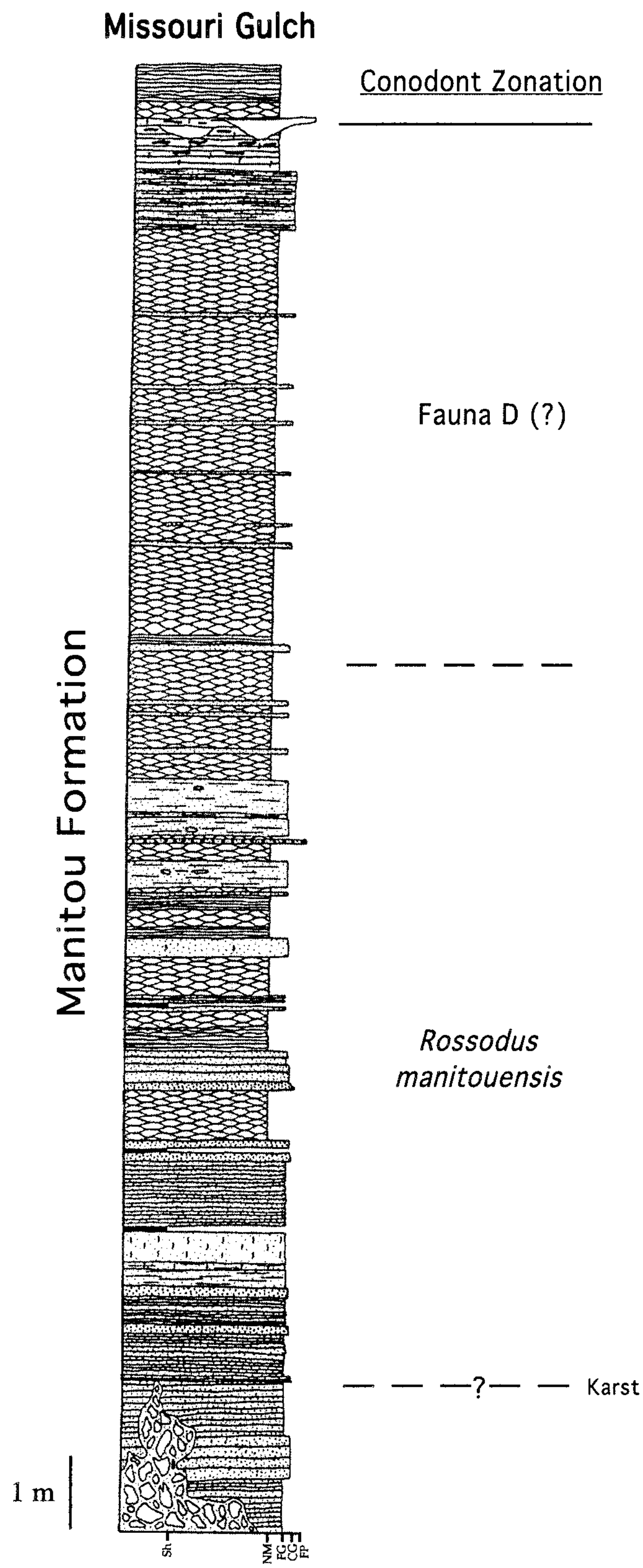


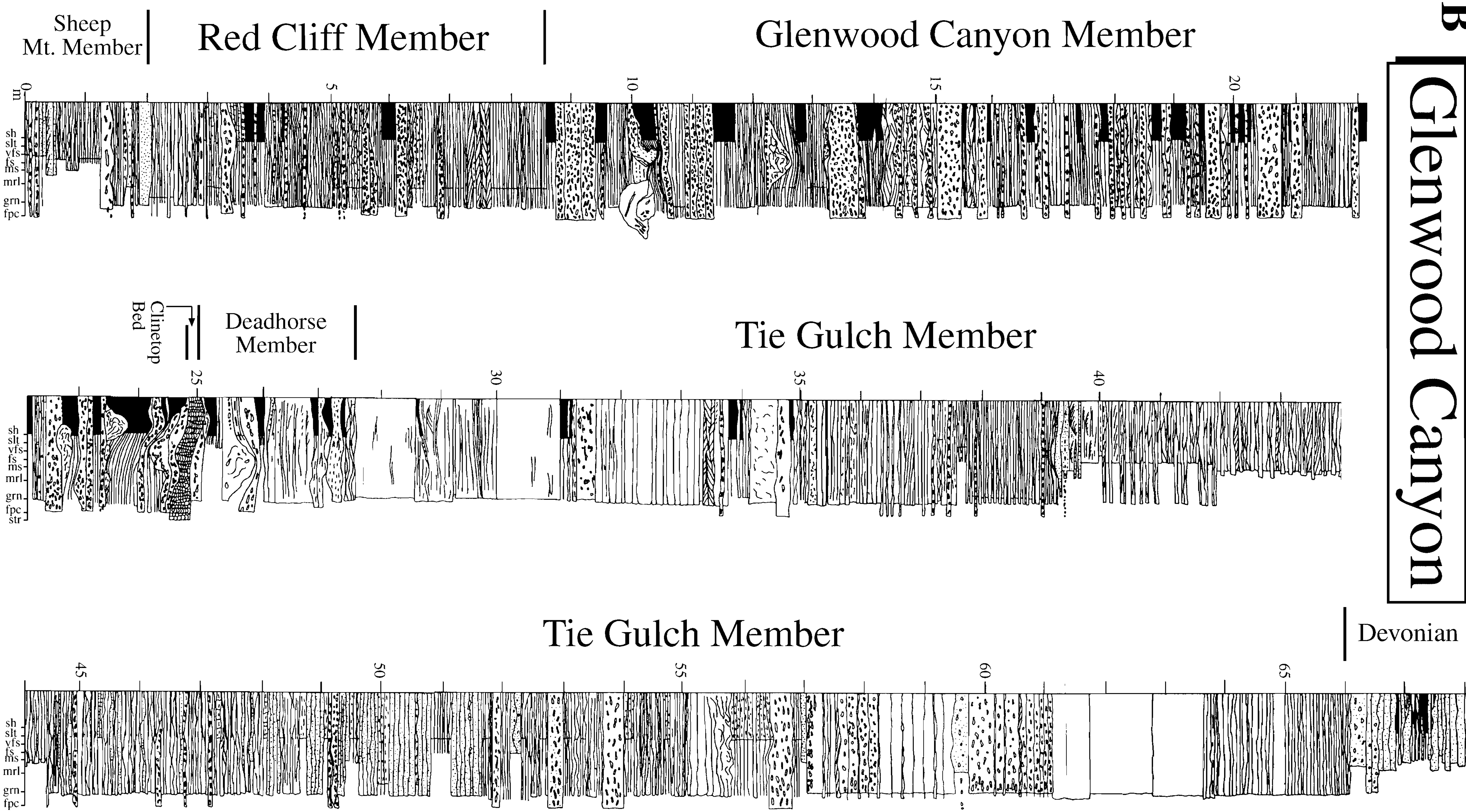
Figure 9. Generalized stratigraphic column of Manitou Formation at Missouri Gulch. All strata are from the *Bellefontia-Xenostegium* Trilobite Zone. Lithologies: Sh—shale, NM—nodular carbonate mudstone, FG—fine-grained grainstone, CG—coarse-grained grainstone, FP—flat-pebble conglomerate.

state indicates deeper-marine conditions in those directions, but little is known about north-south patterns except that isopach maps show no evidence of regional thinning with onlap of the Sawatch Formation in either direction. Lack of data to the north is due to absence of outcrop, and to the south the members are gradually truncated by the mid-*Rossodus* unconformity. Some geologic maps (Tweto et al., 1976; Tweto, 1979) indicate that the southern limit of the Sawatch Formation is at least locally controlled by a pre-Ordovician fault located ~28 km northwest of Trout Creek Pass. However, Allen (1994) demonstrated that the Sawatch Formation is present and uniform in thickness on both sides of the fault. The formation thins beneath the mid-*Rossodus* unconformity south of the fault to <3.5 m along Limestone Ridge ~12 km northwest of Trout Creek Pass and is truncated entirely at the southern end of the ridge.

Dotsero/Peerless Formations

As a result of the stratigraphic revision just presented, the Peerless Formation is now known to be restricted to the Mosquito and eastern Sawatch Ranges. The complex relationship between the Peerless Formation and the Dotsero Formation of western Colorado was finally resolved by tracing members within the Dotsero Formation from west to east into the Mosquito Range.

Although previous studies recognize only two members within the Dotsero Formation, there are in fact four lithologically distinct intervals that are traceable across wide areas. The basal unit is a trough cross-bedded, medium- to coarse-grained sandstone that is iron rich and weathers to a purple color in the central part of the state (Fig. 4). This unit is defined herein as the Sheep Mountain Member. Its type section is at Sheep Mountain, 7.5 km east of Horseshoe Mountain, 9 km east-southeast of Fairplay in Park County in the Mosquito Range. This member is best developed in central Colorado and less well developed in the western localities. The quartz-rich sandstone has variable but generally low amounts of glauconite, which is more abundant along cross-bed set boundaries and foreset surfaces. The rock also contains abundant dark gray to red hematitic cement. Cross-bed sets range from 3 to 8 cm thick (average, 5 cm) and locally contain paired clay drapes (Fig. 4D). The thickness of this member is remarkably consistent, ranging from 2.08 m at Main Elk Creek to 2.50 m at Horseshoe Mountain, a distance of 150 km (Fig. 1). It is largely covered at South Fork and Lime Creek, but well ex-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Red Cliff Member
Glenwood Canyon Member
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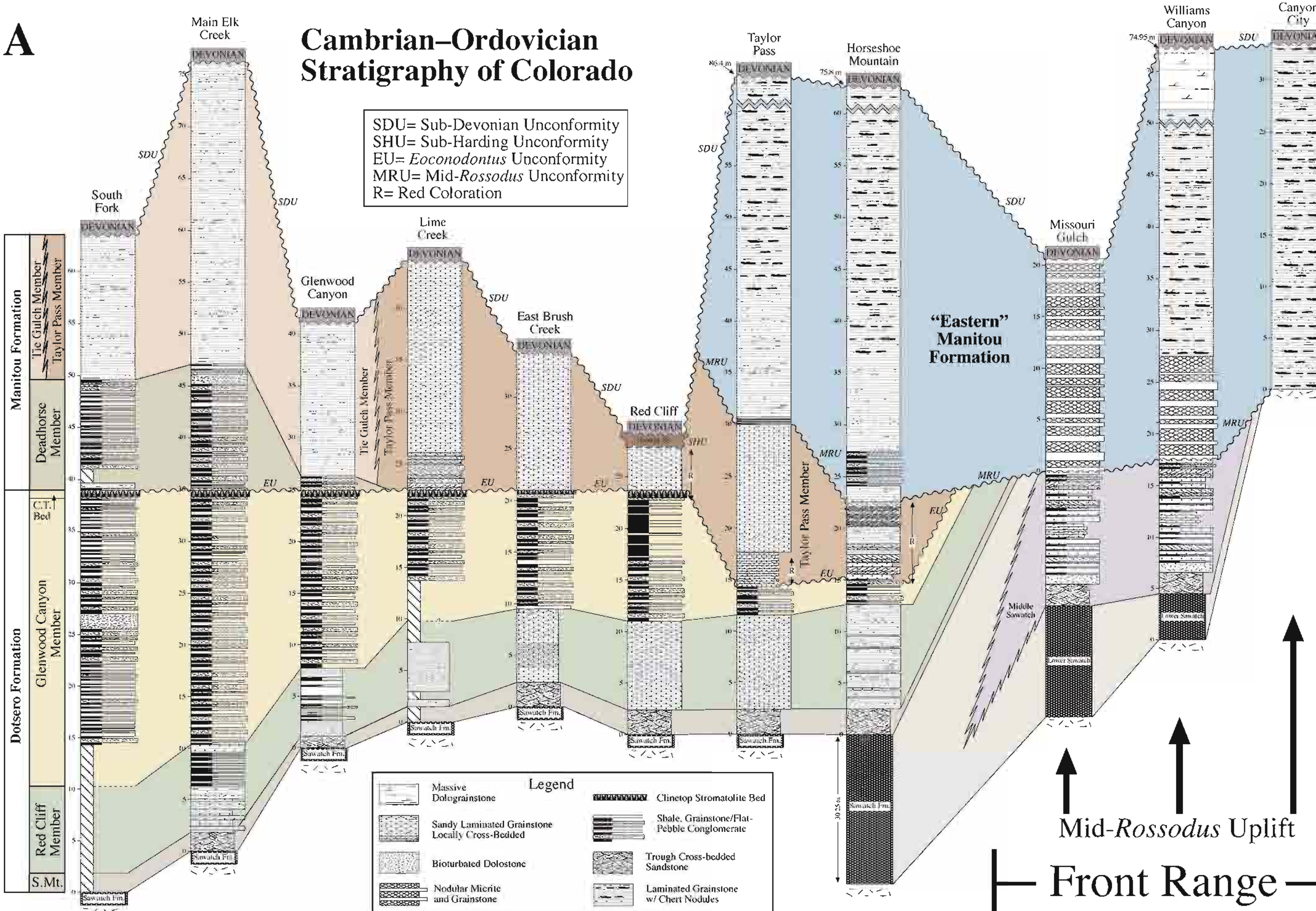

A
Cambrian–Ordovician Stratigraphy of Colorado
SDU= Sub-Devonian Unconformity
SHU= Sub-Harding Unconformity
EU= Eoconodontus Unconformity
MRU= Mid-Rossodus Unconformity
R= Red Coloration
South Fork
Main Elk Creek
Glenwood Canyon
Lime Creek
East Brush Creek
Red Cliff
Taylor Pass
Horseshoe Mountain
Missouri Gulch
Williams Canyon
Canyon City
DEVONIAN
Sawatch Fm.
Manitou Formation
Tie Gulch Member
Taylor Pass Member
Deadhorse Member
Dotsero Formation
C.T. Bed
Glenwood Canyon Member
Red Cliff Member
S.Mt.
"Eastern" Manitou Formation
Middle Sawatch
Lower Sawatch
Legend
Massive Dolograinstone
Sandy Laminated Grainstone Locally Cross-Bedded
Bioturbated Dolostone
Nodular Micrite and Grainstone
Clinetop Stromatolite Bed
Shale, Grainstone/Flat-Pebble Conglomerate
Trough Cross-bedded Sandstone
Laminated Grainstone w/ Chert Nodules
Mid-Rossodus Uplift
Front Range

posed at other localities in central Colorado with a consistent thickness (2.14–2.5 m) (Fig. 10A).

The Sheep Mountain Member directly overlies the white quartzite of the upper member of the Sawatch Formation. This member of the Dotsero Formation is similar in characteristics to the glauconitic middle member of the Sawatch Formation, which also rests on white quartzite (lower member of Sawatch Formation). In the Front Range, the middle Sawatch contains highly glauconitic (up to 80%), compound cross-bedded tidal dune facies (Myrow, 1998; Fig. 3C) that are interpreted as condensed deposits that accumulated above a flooding surface. The Sheep Mountain Member contains less glauconite but does contain abundant iron-bearing minerals and also likely formed as condensed deposits after rapid flooding. Development of paired clay drapes indicates that tidal forces were important locally in the deposition of this unit. Transgression is implicated in many instances with development of glauconite-rich tidal deposits (e.g., Narayan, 1963, 1971; Allen and Narayan, 1964; Nio, 1976).

The second unit, the Red Cliff Member (new), is more variable in composition and is composed of 8–10 m of sandy dolomite and dolomitic sandstone. The type section of this member is in the cliffs on the east wall of the canyon of the Eagle River, immediately north of Gilman, 4–5 km northwest of the town of Red Cliff. Very thin- to medium-bedded, laminated and bioturbated, dolomitic fine- to medium-grained sandstone dominates the Red Cliff Member in the Lime Creek and East Brush Creek sections. It becomes less sandy to the east; it is primarily sandy dolomite at the Red Cliff and Taylor Pass sections and dominantly dolomite farther east at Horseshoe Mountain. Similarly, this unit becomes much less sandy, more bioturbated, and richer in glauconite, flat-pebble conglomerate, and shale toward the west (Glenwood Canyon and Main Elk Creek). Distinction between this member and the overlying deposits is less pronounced in the western sections.

There are few, if any, diagnostic sedimentary structures in the Red Cliff Member. The transition from the sandstone of the underlying Sheep Mountain Member likely represents continued flooding and deposition in clearer-water carbonate settings. The presence of quartz-rich sand at the Lime Creek and East Brush Creek sections indicates mixed siliciclastic-carbonate environments that were wave and current influenced and thus free of siliciclastic mud.

The third unit consists of complexly interbedded lithofacies that include shale with laminae to very thin beds of grainstone, thin- to medium-bedded grainstone, and thin- to thick-bedded flat-pebble conglomerate (Fig. 11A). This unit is the amended Glenwood Canyon Member, which is redefined herein to include the shale-rich interval below the Clinetop Bed (see subsequent definition) and above the newly defined Red Cliff Member (Fig. 10B). In western sections its thickness cannot be established with precision because the unit is gradational with the Red Cliff Member. It is better defined in central Colorado and ranges from 10.75 to 12 m thick in the Sawatch Range from Lime Creek east to Red Cliff. The shale contains locally abundant *Teichichnus* burrows. Grainstone beds are generally less than 25 cm thick, although some reach 90 cm. They contain parallel lamination, wave-ripple lamination, and small- to medium-scale hummocky cross-stratification. Carbonate flat-pebble beds are more abundant in the upper half of the Glenwood Canyon Member, locally comprising nearly 50% of the strata. These beds are tabular and generally range from 7 to 30 cm thick, although a few beds exceed 1 m in thickness. Slump structures are abundant in the upper 15 m of the Dotsero Formation and the lower 2 m of the Manitou Formation (Myrow et al., 1999a; Fig. 10B). These features include enigmatic isolated, coherent blocks and contorted folds that appear to have originated as locally derived seafloor slumps and slides. The lithofacies of this member are common in the inner-shelf deposits of North America and dominate coeval, slightly more distal deposits in Wyoming and Montana.

The fourth unit in the Dotsero Formation is the Clinetop Bed (emended), a regionally extensive meter-scale stromatolitic biostrome with thin upper and lower flat-pebble conglomerate layers. Although considered a member of the Dotsero (Clinetop Algal Limestone Member) in previous studies, the thin nature of the unit warrants reduction of its rank to a lower level in the hierarchy of lithostratigraphic units. This marker bed was previously thought to occur only in the White River Plateau area (e.g., Campbell, 1976). In this study, the bed was discovered far to the southeast in the northern Sawatch Range (East Brush Creek to Red Cliff, Fig. 1), increasing its extent by thousands of square kilometers. The isopach map and regional cross section on the Clinetop Bed presented by Campbell (1976) are inaccurate on several counts. Besides extending far to the southeast, the bed may have extended farther to the north and west, as it is of considerable thickness in the northwesternmost exposure at South Fork (57 cm of stromatolitic boundstone, as opposed to <15 cm shown in Fig. 4 of Campbell [1976]).

In several of these locations in the Sawatch Range, the strata within which the Clinetop Bed occurs were mapped as Peerless Formation (see subsequent discussion). In nearly all localities, the distinctive tall, conical stromatolites overlie a thin flat-pebble conglomerate, and the upper surface is a flat hardground that truncates stromatolitic lamination (Figs. 12A, 12B). The hardground is, in most exposures, overlain directly by a wave-rippled grainstone bed that is locally glauconitic. Red silt–filled fractures interpreted as paleokarst features occur within the Clinetop Bed at Glenwood Canyon. Such paleokarst features also occur at several horizons within 2–3 m of section directly below and above the Clinetop at numerous locations. The upper surface of the Clinetop Bed at a remote locality on the White River Plateau also contains deeply incised channels filled with coarse-grained, yellow grainstone.

Conodonts recovered from the Clinetop Bed and the immediately underlying 0.5 m of strata in all sections represent the *Eoconodontus notchpeakensis* Subzone of the *Eoconodontus* Zone. However, conodont and trilobite data from several sections indicate that a significant stratigraphic break exists ~1–2 m below the Clinetop Bed. The recovery of conodonts characteristic of the *Proconodontus tenuiserratus* Zone <2 m below the base of

Figure 10. (A) New stratigraphic framework for uppermost Cambrian and lowermost Ordovician strata in Colorado. Lateral distributions of members of the Dotsero and Manitou Formations are shown, as well as the location of three prominent unconformities: EU—*Eoconodontus* unconformity; MRU—mid-*Rossodus* unconformity; SDU—sub-Devonian unconformity. (B) Detailed measured section of the Glenwood Canyon Section, ~0.6 km west of the eastern end of Glenwood Canyon. Lithologies: sh—shale, slt—siltstone; vfs—very fine-grained sandstone; fs—fine-grained sandstone; ms—medium-grained sandstone; mrl—marl; grn—grainstone; fpc—flat-pebble conglomerate.

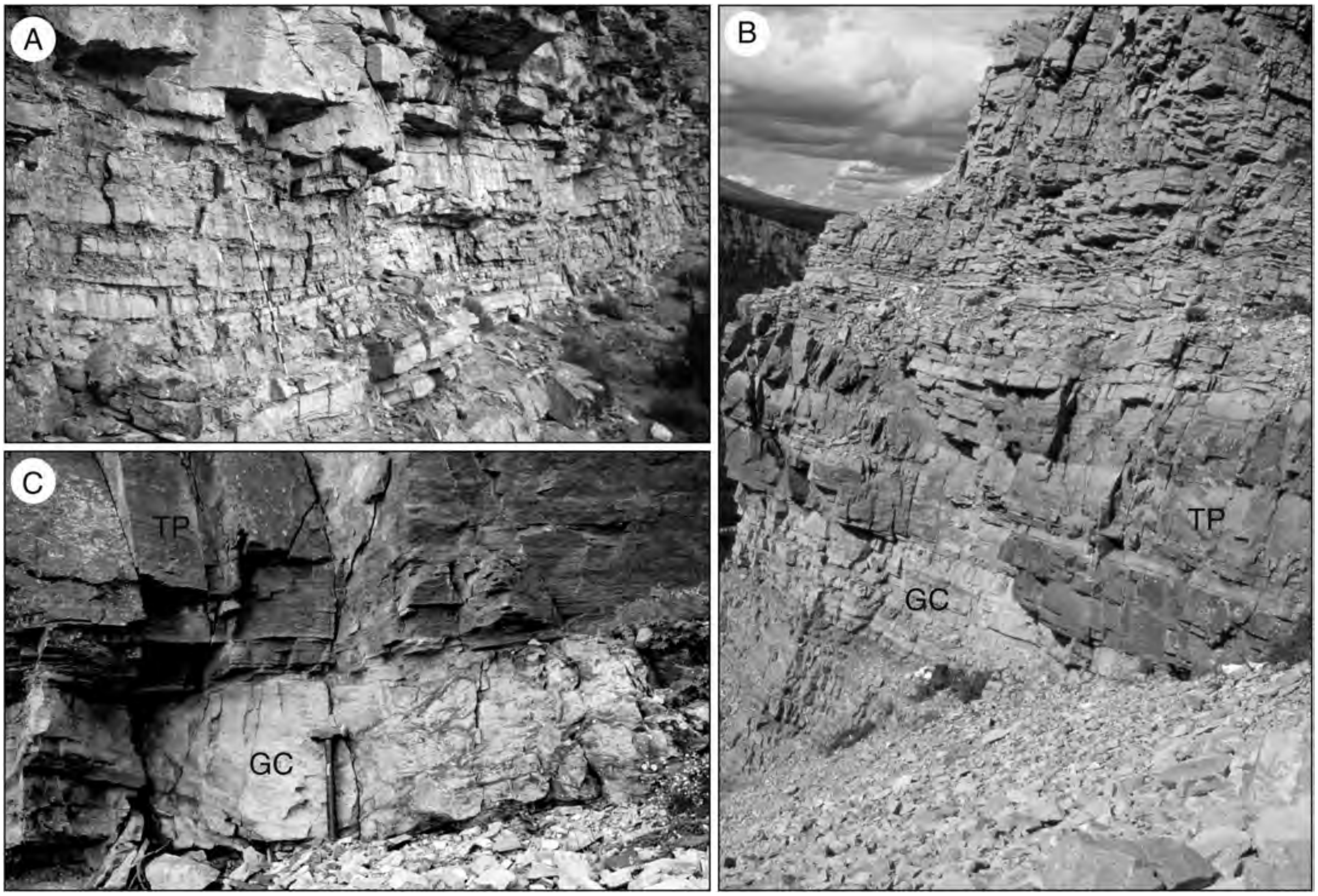

Figure 11. (A) Grainstone, flat-pebble conglomerate, and shale of Glenwood Canyon Member of Dotsero Formation. Scale has 10 cm divisions. (B) Taylor Pass Member of Manitou Formation (TP) and underlying Glenwood Canyon Member (GC) of Dotsero Formation at Sheep Mountain. (C) Close-up of B showing karstic dolostone bed at top of Glenwood Canyon Member (GC). Note irregular karst fill to right of hammer.

the Clinetop Bed in several sections suggests the absence of the overlying *Proconodontus muelleri* Zone. Similarly, the beds just 2–3 m below the base of the Clinetop yielded trilobite species (*Monocheilus truncatus* and *Clelandia typicalis)* characteristic of the lower part of the *Illaenurus* Zone, suggesting that the upper part of that zone and perhaps the lower part of the *Saukia* Zone are missing. Paleokarst horizons at this same level in nearly all sections in western Colorado probably record the erosion and/or nondeposition that created this lacuna. The trilobite *Wilcoxaspis bulbosa* Westrop, a species characteristic of the overlying *Saukia* Zone, was recovered from the wave-rippled grainstone bed that immediately overlies the Clinetop Bed at Glenwood Canyon. This species is known only from the upper part of the *Saukia* Zone (Westrop, 1986), suggesting that the sharp, karstic, and locally channeled upper surface of the Clinetop Bed is a minor disconformity (Myrow et al., 1999a).

Several extremely widespread stromatolite beds also occur in the Upper Cambrian–Lower Ordovician strata of the Great Basin, and these beds appear to mark a widespread resurgence of stromatolites at this time (Shapiro, 1998; Shapiro and Awramik, 2000). This resurgence was likely due to relatively high sea levels and an equatorial position of Laurentia. The bed itself may record a relative sea-level rise and fall. In this scenario, the flat-pebble base represents a transgressive lag, and the stromatolites are the sea-level highstand deposits. Karst features and channeling at the top of the bed developed from exposure associated with subsequent relative sea-level fall.

All three members of the Dotsero Formation, including the Clinetop Bed, are recognizable from South Fork in the northwest to Red Cliff in the Sawatch Range, a distance of 145 km (Fig. 10A). The formation differs in thickness between these sections by only 17.5 m. There is a difference of 4 m between Red Cliff and Glenwood Canyon (80 km) and then a uniform increase of another 13.5 m between there and South Fork over a distance of 65 km. If one were to assume that the Clinetop Bed was a horizontal datum and that the difference in thickness of the formation was due to inherited accommodation space, then the regional slope on the upper surface of the underlying Sawatch Formation would be a remarkably low 0.007°. There does appear to be a hinge line in the vicinity of Glenwood Canyon with a calculated slope of $<0.003°$ to the east and 0.012° to the west. Explaining the thickness differences as a function of differential subsidence would produce very low values as well. (The age control unfortunately is inadequate for such a calculation.)

The uniformity in thickness of the Dotsero

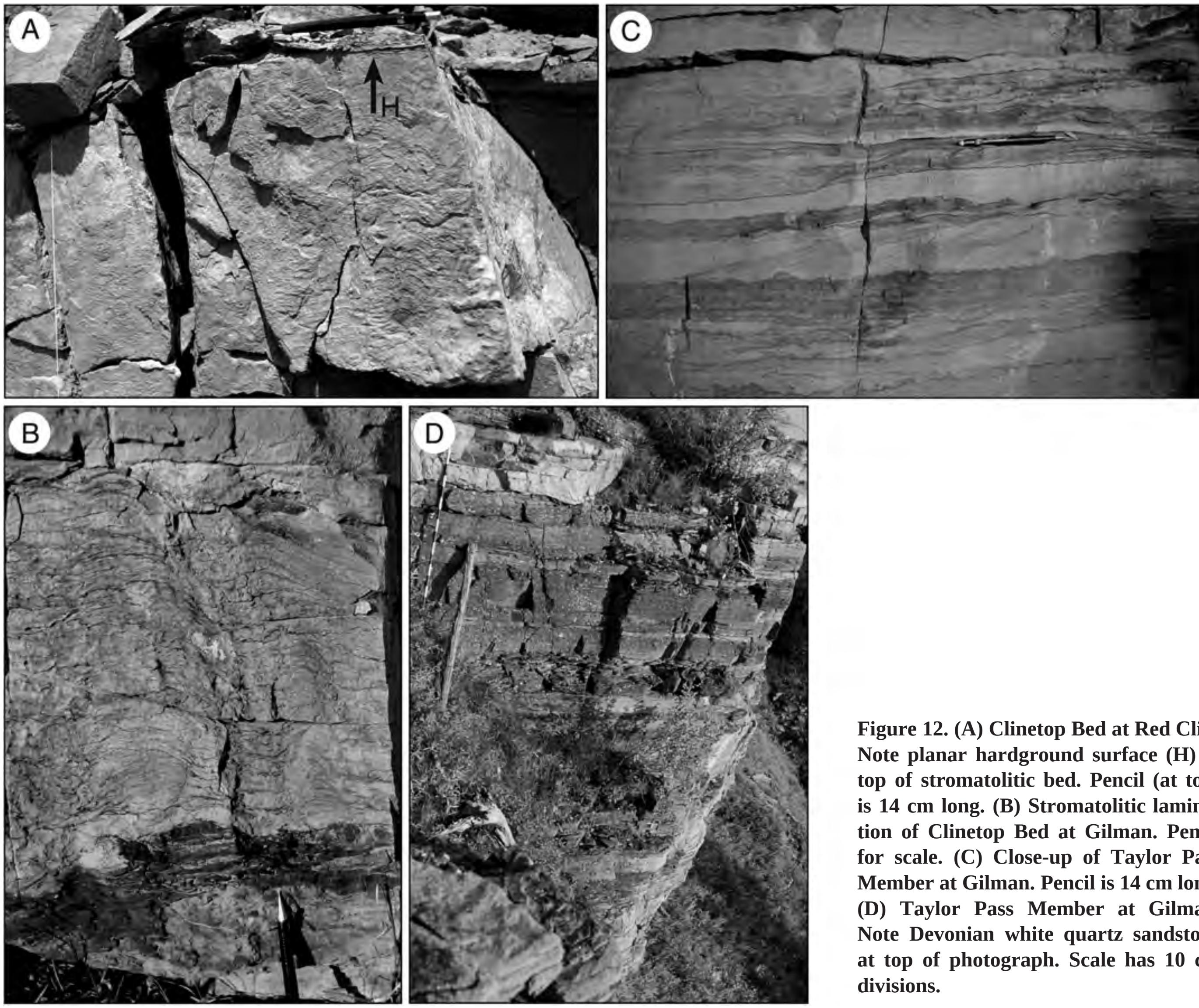

Figure 12. (A) Clinetop Bed at Red Cliff. Note planar hardground surface (H) at top of stromatolitic bed. Pencil (at top) is 14 cm long. (B) Stromatolitic lamination of Clinetop Bed at Gilman. Pencil for scale. (C) Close-up of Taylor Pass Member at Gilman. Pencil is 14 cm long. (D) Taylor Pass Member at Gilman. Note Devonian white quartz sandstone at top of photograph. Scale has 10 cm divisions.

Formation across a nearly 150 km transect is remarkable (Fig. 10A). The distinction between the Red Cliff and Glenwood Canyon Members becomes less defined toward the west, and the specific changes in character indicate gradual deepening in that direction. The other units, however, are very consistent in thickness and character. This is particularly true for the Clinetop Bed, which is almost uniformly 75 cm in thickness, contains a basal flat-pebble conglomerate bed, and has a very flat upper hardground surface that is directly overlain by a thin bed of wave-rippled grainstone.

EOCONODONTUS UNCONFORMITY

The Clinetop Bed was found only in outcrops northwest of the Homestake shear zone (Fig. 10A), a northeast-striking structural lineament in the Sawatch Range that was initiated during the Precambrian and was reactivated several times during the Phanerozoic (Allen, 1994). In outcrops northwest of the shear zone at Lime Creek Canyon, Red Cliff, and Gilman, basal strata of the Manitou Formation, which directly overlie the Clinetop Bed, consist of mixed dolomitic sandstone and sandy dolomite (Figs. 12B, 12D). Coeval strata in western Colorado are composed of shale and carbonate lithologies. The Sawatch Range outcrops were thus deposited closer to a source of siliciclastic sand. This sandy facies yields very few conodonts, but recoveries from Lime Creek indicate that it spans the *Eoconodontus* to *Rossodus manitouensis* Zones in that section. Similarly, a sample near the top of this sandy interval at Taylor Pass also yielded *R. manitouensis*. Thus, these sandstone-rich strata in the Sawatch Range are equivalent in age to the Dead Horse Member and the lower Tie Gulch Member of the Manitou Formation in sections farther west in the White River uplift.

Outcrops 22–30 km or more southeast of the shear zone in the Sawatch and Mosquito Ranges (e.g., Taylor Pass, Sheep Mountain, and Horseshoe Mountain, Figs. 1 and 10A) contain the lower two members of the Dotsero Formation and part of the third. The lower two members are similar in thickness, and all three are similar in lithologic character to those exposed in outcrops west of the shear zone. However, the shaly Glenwood Canyon Member in these outcrops is less than 3 m thick because of truncation by a sharp and irregular surface that is directly overlain by medium- to coarse-grained sandstone. At Taylor Pass, 22 km southeast of the Homestake shear zone, the sandstone is nearly 3.5 m thick. This sandstone is overlain by 13 m of sandy dolostone and dolomitic sandstone similar to that found above the Clinetop Bed (i.e., at the base of the Manitou Formation) as little as 8 km northwest of the shear zone. This sandy part of the Manitou Formation is here designated the Taylor Pass Member for its fullest development at that locality, which is designated as its type section. The base of the Taylor Pass Member in nearly all sections is an unconformity that, in outcrops 22–30 km southeast of the Homestake shear zone, removed ~8–10 m of the upper Dotsero Formation, including the Clinetop Bed (Fig. 10A). The unconformity postdates Clinetop deposition and is also likely responsible for the well-developed paleokarst features in this bed in the western sections. At Horseshoe Mountain, 7.5 m of strata above the unconformity, and referable to the Taylor Pass Member, correspond directly with the ''red-cast beds'' of previous reports (Figs. 4A, 11C, 11D). The member yields very few fossils, but at Horseshoe Mountain it yields conodonts of the *Eoconodontus* Zone. The Clinetop Bed in other sections also contains conodonts of this zone; hence the unconformity developed during deposition of this conodont zone and is therefore referred to as the *Eoconodontus* unconformity. The *Eoconodontus* unconformity has tens of centimeters of relief in outcrops in the Mosquito Range. At Sheep Mountain, the uppermost carbonate beds of the underlying Glenwood Canyon Member contain abundant karst features (Figs. 11B, 11D).

The Horseshoe Mountain outcrop is the type section of the Peerless Formation, which was defined as having a distinctive purple sandstone at its base (defined herein as the Red Cliff Member of the Dotsero Formation) and the ''red-cast beds'' at the top (Behre, 1932; Fig. 7). According to this definition, the type Peerless Formation encompasses the Sheep Mountain and Red Cliff Members and part of the Glenwood Canyon Member of the Dotsero Formation as well as the lower part of the Taylor Pass Member of the Manitou Formation (''red-cast beds''). The Peerless Formation was defined before the Dotsero Formation and should, in accordance with rules of stratigraphic nomenclature, take precedence over the latter. However, because the type Peerless Formation contains an important (*Eoconodontus* Zone) unconformity and also includes part of a previously defined formation (Manitou Formation), it is herein rejected as a valid lithostratigraphic term.

The presence of more than half of the Dotsero Formation as far east as Horseshoe Mountain extends the northwest-southeast distribution of the formation to 280 km. This transect covers both sides of the Colorado Sag, including the northwestern and southeastern subbasins of Gerhard (1972, 1974), with its proposed highland that defines the boundary between these areas. The continuity of thickness and character of the well-defined lower three units of the Dotsero Formation across the central and western parts of present-day Colorado conclusively indicates that there were no significant paleotopographic features at this time.

The northwest-southeast orientation of the outcrop belt of Cambrian and Ordovician rocks likely also had a strong influence on the depiction of the Colorado Sag as a feature having this orientation. There are no data to suggest that facies of the Dotsero Formation change in any appreciable way in a northwest-southeast direction, except that to the northwest, particularly in western Colorado, northern Wyoming, and southern Montana, temporally equivalent strata are more shaly and therefore more distal. The Dotsero Formation appears to have formed an extensive muddy and carbonate-rich blanket with no indication of an exposed basement-cored highland that could have served as a source of siliciclastic sediment. It is likely that the removal of the Dotsero Formation to the south below subsequent unconformities, particularly the mid-*Rossodus* unconformity, led workers to think that Cambrian strata were not deposited in southern Colorado. The uplift to the south that produced the mid-*Rossodus* unconformity clearly established a southern highland area, herein called the mid-*Rossodus* uplift, with basement exposure (Fig. 13). The paleogeographic limits of that uplift are very poorly defined. The sandy Taylor Pass Member suggests that a source of siliciclastic sand was exposed during deposition of the earlier *Eoconodontus* strata, presumably from erosion of the Sawatch Formation and/or Precambrian basement. The unconformity at the base of the Taylor Pass Member cuts downward to the southeast, but the geometry of the uplift surface cannot be reconstructed to the south and east of the Mosquito Range and central Sawatch Range because the mid-*Rossodus* unconformity removed all record of the Dotsero Formation (Fig. 13). The *Eoconodontus* unconformity may record a regional but smaller-scale tectonic event that was a precursor to the event that created the *Rossodus* uplift. Removal of section below the *Eoconodontus* unconformity is demonstrated only for outcrops to the southeast of the Homestake shear zone. If one assumes a hinge line in its vicinity, a gently north-dipping surface of only ~0.36–0.45 m/km (0.021°–0.026°) would result in removal of the missing 8–10 m of uppermost Dotsero Formation at Taylor Pass 22 km southeast of the Homestake shear zone. In this situation, the entire Dotsero Formation would have been removed just ~56–70 km south-southeast of the Homestake shear zone, at which point exposure of the upper Sawatch Formation would have provided a source of sand.

Thus, the vicinity of the Homestake shear zone could have served as a hinge zone for a post–Clinetop Bed uplift in the southern part of central Colorado that exposed the Sawatch Formation and possibly the Precambrian basement to erosion. On the basis of detailed geologic mapping, Allen (1994) documented significant basement-fault reactivation along some components of the shear zone just prior to deposition of the Sawatch Formation and some time after deposition of the Manitou Formation. Although the mapped components of the shear zone provide no evidence for post-Clinetop reactivation as a discrete brittle fault, it is possible that reactivation prior to deposition of the Sawatch Formation resulted in crustal weakening that allowed for the subsequent development of a very subtle hinge zone in latest Cambrian time.

Tyler and Campbell (1975) suggested that a highland existed in the northeastern part of the White River Plateau region on the basis of a purported abundance of sandstone and sandy dolomite in the upper half of the Dotsero Formation 16 km east of the South Fork locality. However, we examined this exposure and found no evidence of sandstone or sandy dolomite in the Dotsero or overlying Dead Horse Member of the Manitou Formation. Less than 5 m of sandstone and sandy dolomite occurs at the top of the lower Paleozoic succession there, but these units yielded conodonts characteristic of the *Cordylodus proavus* Zone. These strata are assigned accordingly to the Taylor Pass Member of the Manitou Formation.

DEMISE OF THE DEADMAN'S GULCH

Bush (1973; Bush and Bush, 1974) introduced the term Deadman's Gulch Formation for a sandstone unit with a purported stratigraphic position between the Peerless/Dotsero Formation and the Manitou Formation. Reassessment of the outcrops where this formation

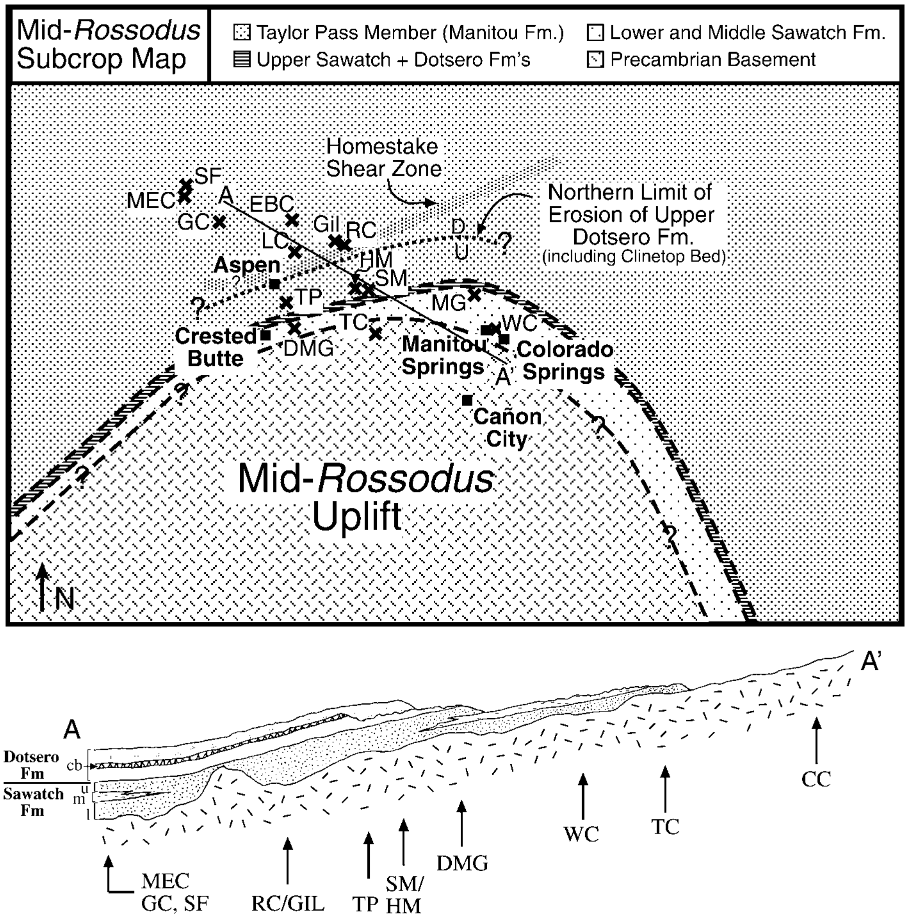

Figure 13. Geologic map of paleotopography and subsurface geology onlapped by mid-*Rossodus* transgression. A–A′ is a cartoon cross section showing the stratigraphy at particular sections generally from north-northwest to south-southeast. This cross section is not intended to be a depiction of any particular line of section. The surface, which represents the mid-*Rossodus* unconformity, is vertically exaggerated. Placement of measured sections below cross section is schematic and not drawn to scale. Cross section shows lower (l), middle (m), and upper (u) Sawatch Formation and Dotsero Formation with Clinetop Bed (cb). For abbreviations, see Figure 1 plus CC—Can ˜on City.

was identified by Bush indicates that, for the most part, he was mapping the sandy dolomite and dolomitic sandstone that overlies the *Eoconodontus* unconformity, i.e., strata that we assign to the Taylor Pass Member of the Manitou Formation. As discussed earlier, these strata become less sandy toward the west and grade laterally into the Dead Horse and Tie Gulch Members. It is reasonable to recognize the Taylor Pass Member as a separate lithostratigraphic unit; however, Bush thought that this unit was below, not part of, the Manitou Formation. What is more important is that at his type section for the formation at Deadman's Gulch, west of Crested Butte, Colorado, the interval chosen to represent the formation is lithologically different from most other sections in the Sawatch Range where it was mapped. There, it consists of a vitreous, white, quartzarenite that is in fact the upper member of the Sawatch Formation. It is directly overlain in that section by the Manitou Formation above the mid-*Rossodus* unconformity. Bush (1973) and Bush and Bush (1974) made the same error as Berg and Ross (1959) by misidentifying the middle Sawatch Formation as the Peerless Formation, and thus the upper quartzite member of the Sawatch Formation was thought to represent a unit above both the Sawatch and Peerless Formations. The term ''Deadman's Gulch'' must therefore be rejected as a valid stratigraphic term because the type section is part of an already defined formation (Sawatch) and its purported stratigraphic position at the type section, above the Dotsero/Peerless Formations, is inaccurate.

ORDOVICIAN ERRORS: PULLING THE LINCHPIN ON COLORADO SAG PALEOGEOGRAPHY

A contrast in lithofacies and derivative member stratigraphies within the Manitou Formation in the eastern vs. the western half of the state provided much of the justification for reconstructing the Colorado Sag to consist of two subbasins separated by a presumed highland (Gerhard, 1972, 1974; Figs. 1, 2). However, conodont biostratigraphic data from the western part of the state indicate that the formation ranges in age from the *Eoconodontus* Zone, directly above the Clinetop Bed, to the lower *Rossodus manitouensis* Zone below the sub-Devonian unconformity (Fig. 6). In contrast, strata of the three members of the Manitou Formation from the eastern part of the state, from Horseshoe Mountain to Manitou Springs, range in age from the highest *Rossodus manitouensis* to the *Macerodus dianae* Zones. The thickness of *R. manitouensis* Zone strata at the base of the Manitou Formation decreases from north to south along the Front Range as a result of onlap that followed development of the mid-*Rossodus* unconformity (Figs. 6, 8). This relationship was recognized by Berg and Ross (1959), who documented the appearance of progressively older trilobite biozones at the base of the formation northward along the Front Range.

As described earlier, erosion associated with the mid-*Rossodus* uplift event removed all Cambrian and Ordovician strata in the southern part of Colorado. Some of these strata were removed at least as far north as the Mosquito Range (Fig. 13), where the mid-*Rossodus* unconformity marks the sharp top of the ''redcast beds'' of the type Peerless Formation (= Taylor Pass Member of Manitou Formation herein) (Fig. 10A). The hematitic staining of these beds likely reflects oxidation that resulted from subaerial exposure during development of the unconformity.

The extent of stratigraphic overlap of Manitou strata within the thick *Rossodus manitouensis* Zone on opposite sides of the Homestake shear zone is a critical issue regarding the postulated paleogeography. The degree of age overlap can be evaluated by using chemostratigraphic data from several key sections. One of the thickest successions of uppermost *R. manitouensis* Zone strata in the eastern half of the study area is at Horseshoe Mountain, where it is ~11 m thick. The maximum thickness of the lowermost part of this zone in western Colorado is 19 m at Main Elk Creek. Figure 14 compares carbon isotope curves from these and other sections. The stra-

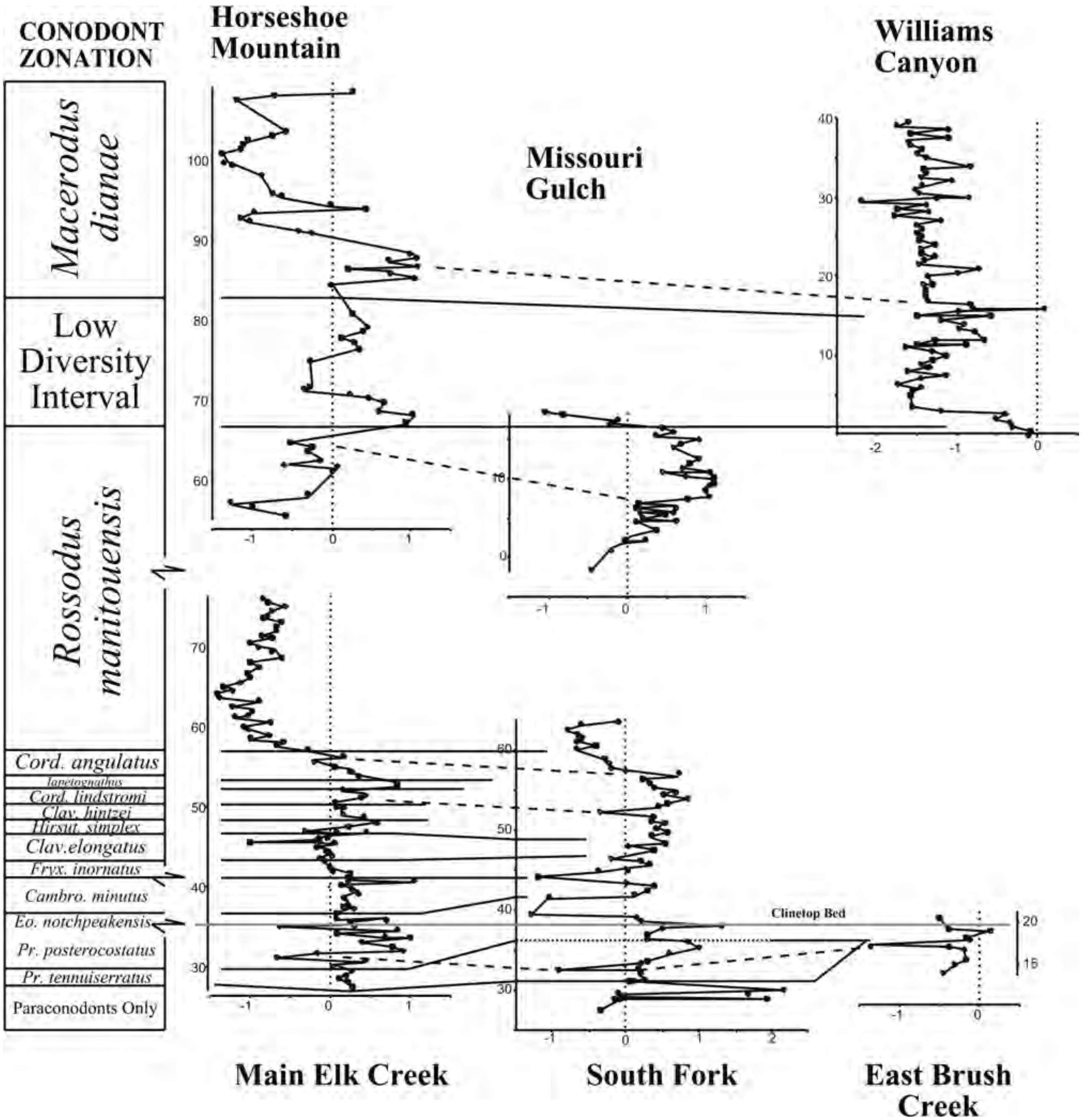

Figure 14. Carbon isotope stratigraphy of selected sections across Colorado based on whole-rock analysis. The datum for lower sections is Clinetop Bed and upper sections is base of Low Diversity Interval. Fine-grained lithologies were preferentially sampled. Conodont zones in the two western sections, South Fork and Main Elk Creek, range from *Proconodontus tenuiserratus* to *Rossodus manitouensis* (abbreviations correspond to zones shown in Fig. 6). The eastern sections cover the uppermost *Rossodus manitouensis* Zone, low-diversity interval, and *Macerodus dianae* Zone. Elongate z-shaped lines in conodont zonation indicate unconformities.

ta directly overlying the Cambrian/Ordovician unconformity at Horseshoe Mountain show a rise in $\delta^{13}C$ values from −1‰ to +1‰ in strata from 55.8 to 67 m above the base of the Sawatch Formation, the interval representing the *R. manitouensis* Zone. The carbon isotope curves for sections in the west show a steady decline from positive values starting below the *R. manitouensis* Zone to a low slightly less than −1‰ in the basal part of the zone. The rest of the zone shows long-standing low-amplitude oscillations around −0.7‰. In none of the sections in the west do values increase at the top of the zone; in the east all sections show either the rise to positive values or all positive values. Therefore, these data suggest that there is no overlap in the ages of Manitou Formation strata on opposite sides of the Homestake shear zone.

Trilobite data also indicate that most, perhaps all, Manitou Formation strata on the western side of the shear zone represent time that falls within the lacuna of the mid-*Rossodus* unconformity on the eastern side. Similarly, the time represented by the three eastern members of the Manitou Formation falls within the large stratigraphic gap between the youngest Manitou strata and overlying Devonian rocks in the western sections. At Williams Canyon, near the type section at Manitou Springs, the basal bed of the Manitou Formation yielded the trilobite *Leiostegium*, confirming that the formation there contains no strata older than the *Leiostegium-Kainella* Zone. To the north, at Missouri Gulch, beds at the base of the Manitou Formation contain species characteristic of the underlying *Paraplethopeltis* Zone and, still lower (basal 1.5 m), those of the highest subzone (*Bellefontia chamberlaini* Subzone) of the *Bellefontia* Zone (J.D. Loch, 2002, personal commun.). In contrast, trilobites recovered from the Manitou Formation west of the shear zone document the presence of (in ascending order) the *Saukia*, *Missisquoia*, and *Symphysurina* Zones and the lowest subzone (*Bellefontia franklinense* Subzone) of the *Bellefontia* Zone, but nothing younger. Thus, the contrast in lithofacies and member stratigraphy (e.g., the presence or absence of chert) between northwestern and southeastern exposures of the Manitou Formation, which formed the basis of the reconstruction that depicted separate subbasins, can be attributed to differences in the ages of the strata rather than paleogeographic isolation.

The sandy equivalent of the western members of the Manitou Formation, the Taylor Pass Member, spans the Homestake shear zone and, in fact, underlies the Ptarmigan Chert Member of the eastern Manitou at several localities east of the Homestake shear zone. Therefore, the Homestake shear zone was not a barrier to deposition during accumulation of the lower part of the Manitou Formation. In contrast, the distribution of younger eastern Manitou members is directly related to movement on the Homestake shear zone. Outcrops with cherty carbonate of the Ptarmigan Chert Member are exposed <1 km to the southeast of the main shear zone, but no chert-bearing outcrops are found anywhere northwest of the fault zone. At one locality just south of the Homestake shear zone in the Sawatch Range, an outcrop contains Middle Ordovician Harding Formation resting unconformably on chert-bearing Manitou Formation (Allen, 1994). Just 800 m away, on the northwest side of the shear zone, the Harding rests on red strata of the Taylor Pass Member, indicating post-Manitou and pre-Harding uplift and erosion. On the basis of the stratigraphic offset, there was ~30 m of down-to-the-south movement on the fault (Allen, 1994). Uplift on the shear-zone faults caused erosion of the Manitou Formation to the west prior to deposition of Devonian rocks, whereas down-faulting to the southeast helped preserve the younger Manitou Formation rocks. In summary, the erosion that created the mid-*Rossodus* unconformity and the uplift associated with post-Manitou faulting (combined with pre-Devonian erosion) produced the contrast in ages between eastern and western Manitou Formation strata. The Homestake shear zone does not appear to have influenced patterns of deposition or erosion during accumulation of most of the Dotsero or Manitou Formations. The shear zone's influence appears to have been control on the location of uplift and erosion during the development of the *Eoconodontus* unconformity and later removal of younger (eastern) Manitou strata to the west prior to deposition of the Harding Formation.

SUMMARY OF HISTORY

Stage 1: Deposition of the Sawatch Formation

Dramatic changes in thickness of the Sawatch Formation across the state of Colorado indicate deposition over an irregular landscape. The distribution of the glauconitic facies of the middle member of the formation indicates possible deepening to both the east and west from the central part of the state. However, exposures are inadequate to determine the degree to which these facies may vary in a northeast-southwest orientation. Therefore, there is no conclusive evidence of highlands in these directions.

Stage 2: Deposition of the Dotsero Formation

Facies patterns in the Dotsero Formation indicate very little variability over significant distances. Increased accommodation space for sediment accumulation to the northwest is indicated by an increase in thickness and subtle facies changes from Horseshoe Mountain to South Fork. These changes are remarkably subtle given the distance involved, and they point to considerable uniformity of deposition and blanket-like deposition with only minor facies changes.

Stage 3: Erosion of the Dotsero Formation

Removal of the Clinetop Bed and part of the underlying Glenwood Canyon Member of the Dotsero Formation occurs from just east of the Homestake shear zone in the Sawatch Range eastward to the Mosquito Range, producing an *Eoconodontus* Zone unconformity. Karst features in the Clinetop Bed may represent this unconformity in the west.

Stage 4: Deposition of the Lower Manitou Formation

Exposures of the Dead Horse Member in western Colorado record relatively continuous deposition through the Cambrian–Ordovician boundary interval from the *Eoconodontus* Zone through the lower *Rossodus manitouensis* Zone. Unconformities with lacunae of modest (subzonal) magnitude are also marked by karstic surfaces in these strata, but most of the conodont and trilobite zones in this interval are present despite the thin and condensed nature of the Colorado succession relative to more outboard sections in Utah and Nevada. In central Colorado, a local source of siliciclastic sand resulted in deposition of the Taylor Pass Member of the Manitou Formation immediately above the *Eoconodontus* unconformity on both sides of the Homestake shear zone. A decrease in sand content and increased shale to the northwest indicate deepening in that direction. Conversely, the lower Manitou Formation is less sandy in the Mosquito Range than in the Sawatch Range, but data are insufficient to reconstruct a regional trend, identify any highland source area(s), and/or establish transport direction(s) for the sand.

Stage 5: Differential Uplift and Erosion

Uplift during the time represented by the *Rossodus manitouensis* Zone caused complete removal of Cambrian and Ordovician strata in southern Colorado. The effects are less pronounced to the northwest; hence, the resulting mid-*Rossodus* unconformity climbs section in this direction to rest progressively on the lower, middle, and upper members of the Sawatch Formation, then the Dotsero Formation, and eventually the lower Manitou Formation (Fig. 8). The unconformity is not recognized in western Colorado exposures because it has been truncated, along with the three younger members of the eastern Manitou Formation (stage 6), by the sub-Devonian unconformity (Fig. 10).

Stage 6: Deposition of the Upper Manitou Formation

All outcrops of younger Manitou strata assigned to the upper *R. manitouensis* Zone, low-diversity interval, and *Macerodus dianae* Zone occur east of the Homestake shear zone. These deposits comprise the three members of the Manitou Formation that Gerhard (1974) assigned to his southeast subbasin. These young Manitou Formation strata onlap the mid-*Rossodus* unconformity surface from the northwest toward the southeast and eventually rest directly on Precambrian basement rocks at the southern end of the Front Range. In most sections the strata immediately below the unconformity are those of the middle Sawatch Formation or the Dotsero Formation; locations where younger Manitou strata overlie the more resistant quartzite of the lower or upper Sawatch Formation are rare. Apparently, the contrast in erosional resistance of the quartzite units and the intervening dolomitic units produced a paleo–cliff-and-bench topography (Fig. 13) on which the cliff-forming quartzite units offered little area for the onlapping strata to accumulate.

Stage 7: Erosion Following Manitou Formation Deposition

Upper Manitou strata were presumably removed in western Colorado as a result of up-to-the-northwest motion on the Homestake shear zone some time after deposition of the Manitou Formation, followed by erosion associated with sub-Devonian but pre-Harding Formation erosion. (The Ordovician Harding Formation and its unconformity are generally missing in western Colorado owing to sub-Devonian erosion.) Chert-bearing carbonate of the middle part of the Ptarmigan Chert Member are exposed within 1 km of the shear zone, suggesting that the eastern members of the Manitou Formation likely extended across Colorado to the west prior to sub-Devonian erosion.

DISCUSSION

The Transcontinental Arch is routinely reconstructed as trending south-southwest from Minnesota to northern New Mexico (Lochman-Balk, 1971; Carlson, 1999). This structural feature was demonstrated to have been active at various stages throughout the Phanerozoic and to have had a strong influence on depositional patterns in western and central Laurentia. Middle Cambrian deposits occur in Wyoming and Montana and in areas west of Colorado, but not in Colorado or in the rest of the Midcontinent. This distribution suggests advance of the paleo–Pacific Ocean onto the continent at this time with a generally north-trending shoreline that to the north of Colorado extended slightly farther east. The age of the oldest sedimentary cover rocks in Colorado and many other parts of the Midcontinent is Late Cambrian. This fact indicates that transgression onto the craton pushed the shoreline farther inland in the Late Cambrian when relative sea level presumably rose to a point that flooding occurred over a broad, relatively flat continental interior. So then what evidence is there for a linear arch in west-central Laurentia during the Late Cambrian and Ordovician and for a "sag" in that arch within present-day Colorado?

At the time the Colorado Sag was proposed (Lochman-Balk, 1956), physical stratigraphic and biostratigraphic data were too incomplete to allow recognition of the mid-*Rossodus* unconformity and its effects. The work of Berg and Ross (1959) revealed some of the stratigraphic effects of this unconformity, despite misidentification of the middle Sawatch Formation as the Peerless Formation. However, the full importance of this surface became clear only as a large amount of biostratigraphic, chemostratigraphic, and physical stratigraphic data was gathered from across the state in the present study. Because the entire Upper Cambrian and lowermost Ordovician deposits were eliminated by the mid-*Rossodus* erosional event in southern Colorado, and presumably in northern New Mexico, there simply is no evidence with which to reconstruct pre–mid-*Rossodus* paleogeography in this region. The event in question created relief and upland areas onto which *Rossodus manitouensis* Zone and younger strata onlapped, namely, the mid-*Rossodus* uplift. However, the lack of a record of pre-*Rossodus* deposits can in no way be construed as confirmation of nondeposition in this region. There is in fact no evidence, such as facies changes, to indicate that any of the Upper Cambrian deposits lapped out against a pre–mid-*Rossodus* highland to the south. Isopach maps of the Sawatch and Manitou Formations (Allen, 1994) suggest sharp, postdepositional erosional truncation rather than syndepositional thinning to the south. Parsimonious interpretation of the available data should therefore eliminate any highland from paleogeographic reconstructions that predate the mid-*Rossodus*-age uplift event.

Similarly, there are almost no data with which to define the early history of the Souixia uplift to the northeast and, in particular, to demonstrate that it was a positive area during deposition of part or all of the Cambrian–Ordovician boundary interval. Development of the middle Sawatch Formation on opposite sides of the state confirms the existence of an inherited basement high at that time. However, the lateral continuity of units within the overlying Dotsero and lower Manitou Formations argues strongly against any positive topographic features during the latest Cambrian and Early Ordovician (pre–mid-*Rossodus manitouensis* Zone). Thus, there is no evidence to support the idea of a Colorado Sag or that Cambrian and Ordovician strata of northwest and southeast Colorado represent different facies belts separated by a highland region. These ideas resulted from miscorrelation and a paucity of biostratigraphic data.

The results of our study demonstrate the need for reevaluation of the stratigraphic data used to reconstruct lower Paleozoic paleogeography in areas proximal to the Transcontinental Arch along its entire length. Significantly, recent integrated sedimentologic and biostratigraphic studies in the Upper Cambrian of the northern Midcontinent also reveal no evidence of a strong influence of the Transcontinental Arch on sedimentation patterns (Runkel, 1994; Runkel et al., 1998). Nonetheless, the long-standing view that the Transcontinental Arch and Colorado Sag existed during the Cambrian to Early Ordovician is still found in recent publications (e.g., Carlson, 1999). Careful stratigraphic analysis of other parts of western and Midcontinent North America utilizing similarly precise and varied data are needed to better define the timing of development and influence of the Transcontinental Arch.

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