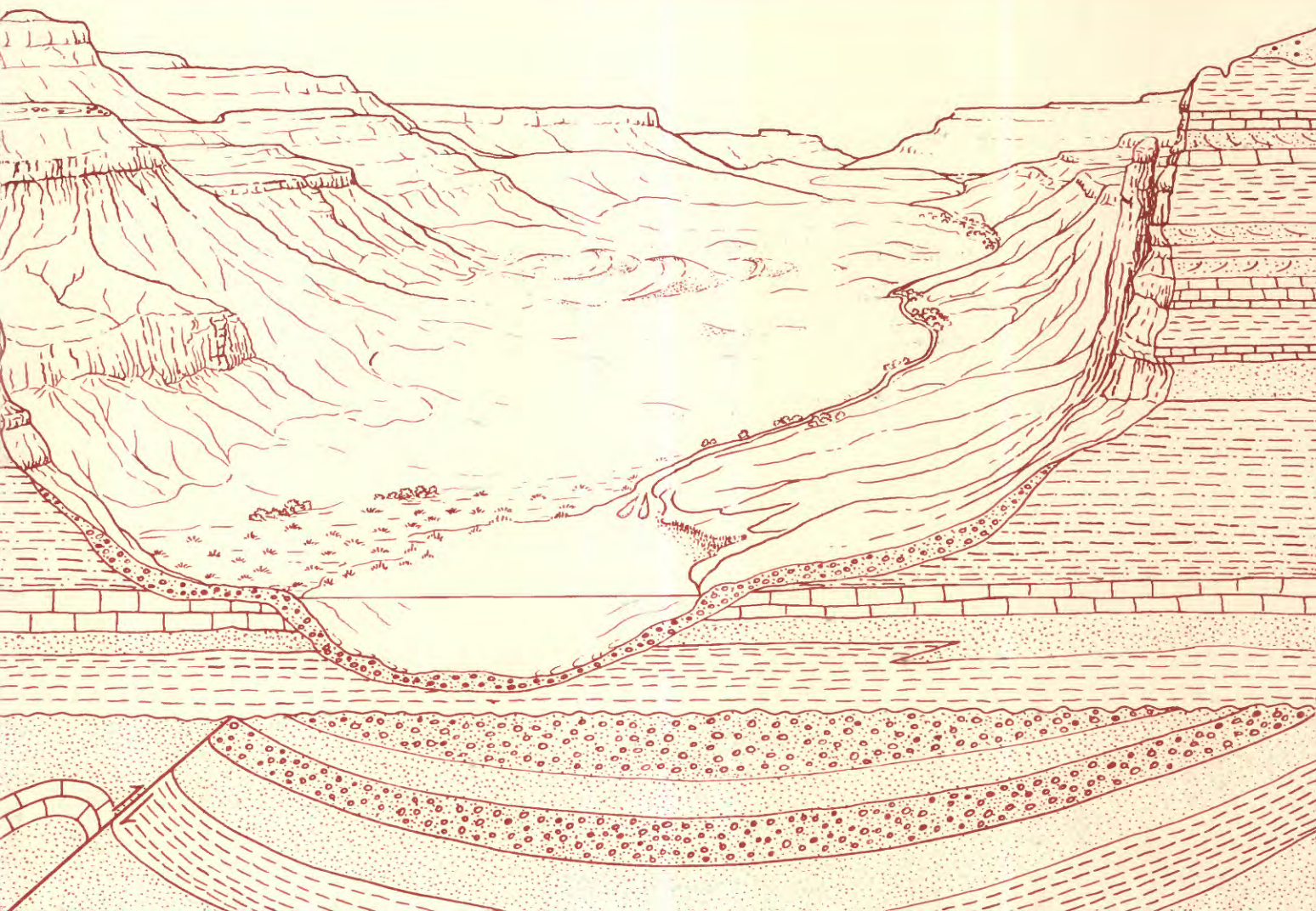


Precambrian to Earliest Mississippian Stratigraphy, Geologic History, and Paleogeography of Northwestern Colorado and West-Central Colorado

Prepared in cooperation with the
Colorado Geological Survey

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Chapter U

Precambrian to Earliest Mississippian Stratigraphy, Geologic History, and Paleogeography of Northwestern Colorado and West-Central Colorado

By JAMES M. SOULE

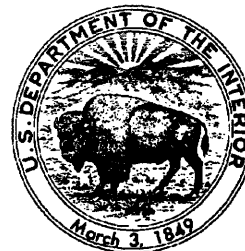
Prepared in cooperation with the Colorado Geological Survey

A multidisciplinary approach to research studies of sedimentary
rocks and their constituents and the evolution of sedimentary
basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary



U.S. GEOLOGICAL SURVEY
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UNITED STATES GOVERNMENT PRINTING OFFICE: 1992

For sale by
Book and Open-File Report Sales
U.S. Geological Survey
Federal Center, Box 25286
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Soule, James M.

Precambrian to earliest Mississippian stratigraphy, geologic history, and paleogeography of northwestern Colorado and west-central Colorado / by James M. Soule.

p. cm.—(Evolution of sedimentary basins—Uinta and Piceance basins ; ch. U) (U.S. Geological Survey bulletin ; 1787)

"Prepared in cooperation with the Colorado Geological Survey."

Includes bibliographical references.

1. Geology, Stratigraphic—Paleozoic. 2. Paleogeography—Paleozoic.
3. Geology—Colorado. I. Colorado Geological Survey. II. Title.
III. Series. IV. Series: U.S. Geological Survey bulletin ; 1787.

QE75.B9 no. 1787-U

[QE654]

557.3 s—dc20

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Late Precambrian to Earliest Mississippian Stratigraphy, Geologic History, and Paleogeography of Northwestern and West-Central Colorado

By James M. Soule¹

Abstract

The early Paleozoic of northwestern and west-central Colorado is represented by continental-shelf and continental-shelf-marginal sedimentary rocks of Late Cambrian, Ordovician, and Late Devonian ages. Differentially epeirogenic movements along fracture systems having Precambrian origins affected sedimentation patterns and probably mostly account for intervening times of erosion or nondeposition; activity along these tectonic elements persisted into the Neogene and possibly continues. These tectonic elements are west-northwest-, south-southeast-, and northeast-trending fracture systems and an east-trending aulacogen in the approximate area of the modern Uinta Mountains. North-central Colorado was emergent land throughout most of this time and shed clastic sediments at varying rates to the west and southwest. Episodic continental motion and the effects of the Antler orogeny to the west are probably the direct causes of these epeirogenic movements.

INTRODUCTION

During the early Paleozoic, northwestern Colorado formed part of the continental shelf in the miogeocline on the western flank of North America, near the paleoequator (Dietz, 1963; Dietz and Holden, 1974; Cook and Taylor, 1975; Cook and Egbert, 1981) (figs. 1, 2). This part of the shelf was at times emergent and characterized by either nondeposition or erosion. As a consequence, sequences deposited during the early Paleozoic contain numerous unconformities, and only about 25 percent of early Paleo-

zoic time is represented in the rock record of northwestern Colorado. Periods of uplift and emergence may have been associated with reactivation of Precambrian crustal structures, which probably had significant control on depositional patterns throughout the Phanerozoic. Moreover, uplifts of Precambrian rocks are the likely source terranes for many of the lower Paleozoic clastic units.

This paper summarizes the early Paleozoic history and stratigraphy of northwestern Colorado. Discussions are based mostly on extensive literature review, remeasurement of one critical reference section of lower Paleozoic rocks (appendix 1), and examination of available borehole logs from wells that penetrate lower Paleozoic rocks (appendix 2). Interpretations are illustrated in a series of schematic paleogeographic maps that show the inferred locations of principal tectonic features and areas of erosion and deposition. The periods shown in these maps represent intervals during which paleogeography is interpreted as relatively constant or changing predictably. Maps for time intervals that are not represented in the stratigraphic record are highly speculative.

Acknowledgments.—This study was supported in part by the U.S. Geological Survey Evolution of Sedimentary Basins Program. John W. Rold and William P. Rogers of the Colorado Geological Survey offered advice throughout the course of the work. Drafts of the manuscript were read and substantially improved by Wallace R. Hansen, Samuel Y. Johnson, and Charles S. Sandberg, and their patience and criticism are gratefully appreciated.

EARLY PALEOZOIC TECTONIC ELEMENTS

The early Paleozoic paleogeography of northwestern Colorado was strongly influenced by several tectonic elements (fig. 3), many of which have remained active well

Manuscript approved for publication March 29, 1991.

¹Colorado Geological Survey, 1313 Sherman Street, Room 715, Denver, Colorado 80203.

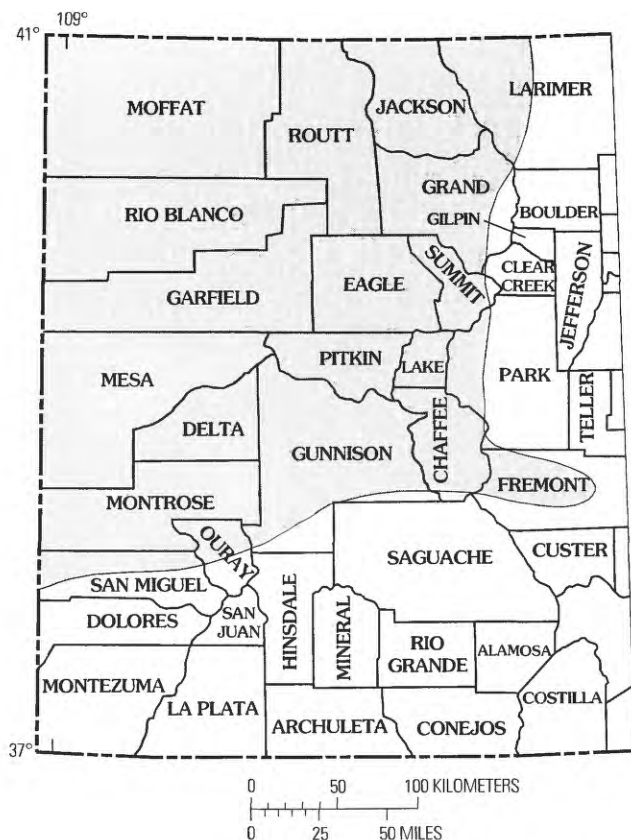


Figure 1. Map of western Colorado showing study area (shaded).

into the late Cenozoic. On a regional scale, Larson and others (1985) and Purucker (1988) offered strong evidence that a late Precambrian to late Paleozoic west-northwest-trending fault or rift system, characterized by episodic tectonic and igneous activity, extended from southeastern Oklahoma into southeastern Utah. Warner (1978, 1980) postulated a "Colorado Lineament" characterized by a system of northeast-trending fractures extending from northwestern Arizona to Lake Superior. Tweto and Sims (1963) noted that this feature corresponds to a Precambrian-originated fault system through the "Colorado Mineral Belt" and further stated that, "This fault system corresponds approximately in location to a Transcontinental Arch which affected lower Paleozoic continental sedimentation on the craton and possibly on the continental shelf; these were persistent for most of the early Paleozoic in northwestern Colorado." The dominant tectonic elements that influenced sedimentation during the Precambrian to Mississippian in northwestern Colorado are described in the following sections.

Uinta Aulacogen

The location of the modern-day Uinta Mountains (fig. 4) has been the site of repeated positive and negative epeirogenesis and compressional or extensional tectonism.

Hansen (1965, 1986a, b), Stone (1975, 1986, 1989), and Sears and others (1982) documented repeated, variously directed faulting in the Uinta Mountains since the early Precambrian, and Hansen and Stone both suggested that this faulting was a major control on regional patterns of sedimentation. Based on interpretation of seismic and drill-hole data, Stone (1986) postulated that many of the exposed faults in the Uinta Mountains are associated with faults in the deep subsurface, that movement on this family of faults has been recurrent, and that lower Paleozoic rocks are preserved in deep, fault-bounded parts of northwestern Colorado basins.

Gore Fracture Zone

Almost as well documented as the Uinta Mountains faulting is the persistence through much of geologic time of an inferred tectonic highland, the western border of which is roughly approximated by the modern-day north-northwest-trending Gore fault. Similarly oriented faults are present to the south-southeast of the Gore Range into Chaffee and Custer Counties and beyond, and this fault system is herein termed the Gore fracture zone. The concept that a "Front Range Highland" of tectonic origin contributed clastic sediments to many lower Paleozoic rock units is well supported (Lovering and Johnson, 1933; Tweto, 1977, 1980a), with the possible exceptions of Canadian time, when the Manitou Formation was deposited, Cincinnati time, when the Fremont Limestone was deposited, and perhaps other time intervals not represented in the rock record.

Uncompahgre Fracture Zone

The area now including the Uncompahgre Plateau and the Gunnison uplift, which together form a physiographic and structural zone or barrier between the Piceance basin and the Paradox basin (to the southwest of the study area in southwestern Colorado and southeastern Utah), contains a system of almost west-northwest-trending faults that Stone (1977) suggested originated in the Precambrian. The parallelism or near parallelism of these faults with (1) known subsurface fractures, (2) igneous bodies of west-northwest strike (Hansen and Peterman, 1968; Hansen, 1981; Ritzma, 1983; Larson and others, 1985), (3) the salt anticlines of the Paradox basin to the southwest of the Uncompahgre Plateau, and (4) the Gore fracture zone suggests that these faults are related in origin and may have had similar effects on regional patterns of sedimentation.

White River Uplift and Ancestral Axial Fault Zone

Although the White River Plateau is generally considered to be a post-Laramide physiographic feature (Tweto, 1975), its structural boundaries may have been

AGE	SERIES	STRATIGRAPHIC UNIT
Early Mississippian	Osagean and Kinderhookian	Leadville Limestone
Earliest Mississippian or Latest Devonian	Kinderhookian or Famennian	Gilman Sandstone
	Famennian	Dyer Dolomite <ul style="list-style-type: none"> Coffee Pot Member Broken Rib Member
Late Devonian	Famennian and Frasnian	Parting Formation
Latest Early Devonian (Silurian and most of Early and Middle Devonian not represented by rocks)		
Late Ordovician	Cincinnatian	Fremont Limestone
	Rocklandian and Black Riveran	Harding Sandstone
Earliest Early Ordovician	Canadian	Manitou Formation <ul style="list-style-type: none"> Tie Gulch Dolomite Member Dead Horse Conglomerate Member Clinetop Member
Latest Late Cambrian	Trempealeuan	Dotsero Formation <ul style="list-style-type: none"> Glenwood Canyon Member
Latest (?) or middle Late Cambrian	Trempealeuan or Franconian	Unnamed beds or Deadmans Gulch Formation (Glenwood Canyon) (Bush and Bush, 1974)
Middle Late Cambrian	Franconian	Peerless Formation
Early Late Cambrian	Dresbachian	Sawatch Quartzite, Lodore Formation
Late Proterozoic	925-1,100 Ma (Tweto, 1987)	Uinta Mountains Group
Early Proterozoic (?) and late Archean	~2500 Ma (Tweto, 1987)	Red Creek Quartzite

Figure 2. Precambrian and lower Paleozoic sedimentary rocks in northwestern Colorado.

influenced or controlled by older basement fractures similar to those along the Uncompahgre uplift and the Uinta aulacogen. The Uinta structural trend, moreover, merges southeastward with similar trends in northwestern Colorado, including the "Ancestral Axial Fault Zone" (Stone, 1986) and faults on the White River Plateau (Hansen, 1965, 1986a). Dula (1981) considered the present White River Plateau fracture system and stress field to be relict from the Laramide, but an older stress and fracture system similar to those in nearby areas is probably likely because west-northwest fault trends predominate (Dula, 1981, fig. 2). This older fracture system probably influenced at least Late Cambrian sedimentation patterns and possibly Mississippian patterns. Stone (1986) did *not* make a case for movement along the ancestral Axial fault zone in the early Paleozoic except during the late Middle Proterozoic to Late Cambrian, but he did present evidence of Pennsylvanian movement. Unfortunately, deep drill-hole data needed to test that hypothesis are scanty in the area (appendix 2). Recurrent early Paleozoic movement along the ancestral

Axial fault zone might be expected, however, because even during the long hiatuses in the lower Paleozoic rock record depositional environments were changing as indicated by the contrasting lithology of preserved strata. Erosional truncation of the Ordovician Harding Sandstone and Fremont Limestone and the deepening level of erosion down to Precambrian levels during the early Paleozoic in the southeastern part of the study area are noteworthy because, with further study, they may provide evidence for almost continuous tectonic activity in the early Paleozoic of northwestern and west-central Colorado.

Northeast-Trending Faults

The northeast-trending system of fractures of Precambrian origin (part of the Colorado lineament) that involves basement and overlying sedimentary rocks in the southeastern part of the study area and continues southeastward into central Colorado probably affected

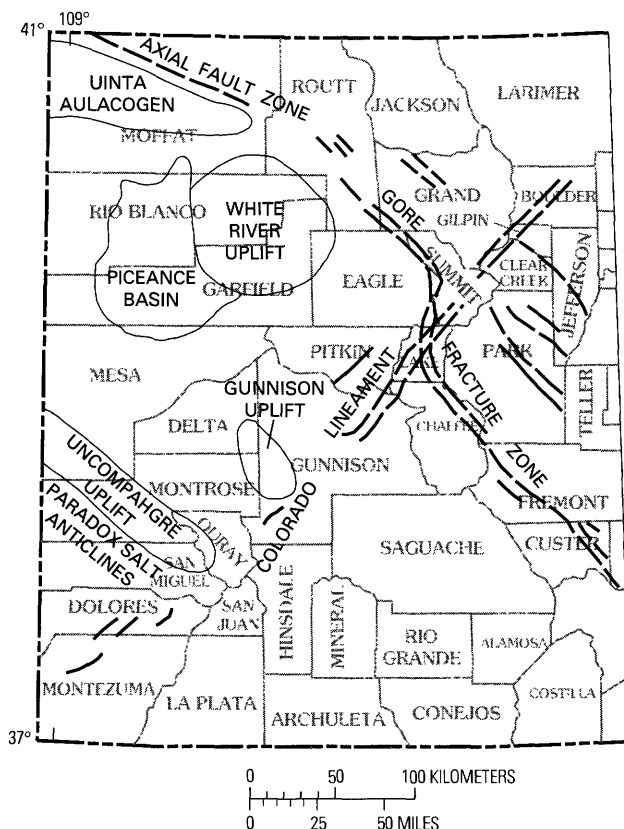


Figure 3. Tectonic elements of study area, west-central and northwestern Colorado.

sedimentation intermittently throughout the early Paleozoic. Movement along these faults probably at least influenced depositional facies changes in the Early Ordovician and erosional patterns in the Middle and Late Ordovician.

PRECAMBRIAN SEDIMENTARY ROCKS

Red Creek Quartzite

The Red Creek Quartzite of Late Archean and Early Proterozoic age, which attains the amphibolite facies of regional metamorphism, is the oldest Precambrian sedimentary rock unit in northwestern Colorado (Hansen, 1965, p. 36). It crops out in Colorado only near Beaver Creek in the Browns Park area, Moffat County (fig. 4). Its stratigraphic thickness is about 3,960–7,000 m (Tweto, 1987). Hansen (1965, p. 31) suggested an age of 2,320 Ma for the Red Creek, but Tweto (1987) regarded this age as a minimum and assigned an age of about 2,500 Ma.

Uinta Mountain Group

The Uinta Mountain Group of Late Proterozoic age unconformably overlies the Red Creek Quartzite in the eastern Uinta Mountains and is exposed in the extreme

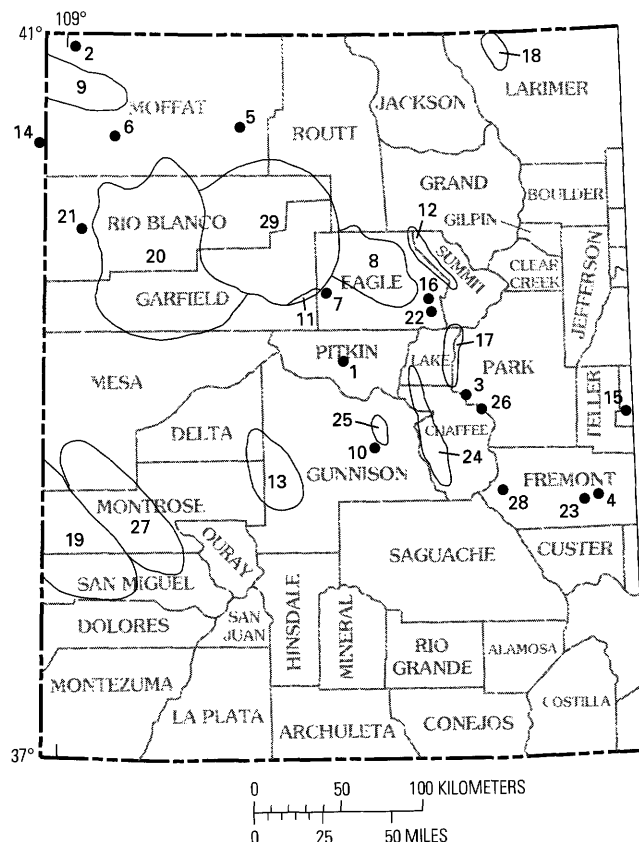


Figure 4. Areas and locations discussed in text: 1, Aspen; 2, Beaver Creek, Browns Park area; 3, Buffalo Peaks; 4, Canon City; 5, Craig; 6, Cross Mountain; 7, Dotsero; 8, Eagle basin; 9, eastern Uinta Mountains; 10, Fossil Ridge; 11, Glenwood Canyon; 12, Gore Range; 13, Gunnison uplift; 14, Jones Hole; 15, Manitou Springs; 16, Minturn quadrangle; 17, Mosquito Range; 18, northern Front Range; 19, Paradox basin; 20, Piceance basin; 21, Rangely; 22, Redcliff; 23, Royal Gorge; 24, Sawatch Range; 25, Taylor Park; 26, Trout Creek Pass; 27, Uncompahgre Plateau; 28, Wellsville; 29, White River Plateau.

northwestern part of Colorado in Moffat County (Hansen, 1965; Rowley and others, 1985) (fig. 4). In the Uinta Mountains, the Uinta Mountain Group has a total thickness of about 7,315 m (Hansen, 1965, p. 33). Tweto (1980b, fig. 1) inferred that these strata extend eastward in the subsurface to Craig, Colorado. The unit consists predominantly of dark-red, medium- to coarse-grained, massive to crossbedded, siliceous sandstone and quartzite and some shale and conglomerate (Hansen, 1965, p. 33). On the basis of its great thickness, its lithology, and a limited set of paleocurrent data, Hansen (1965, p. 37) concluded that the Uinta Mountain Group was deposited in an east-trending (approximating the trend of the Uinta Mountains), probably fault-bounded trough (fig. 5A) (Tweto, 1980b, p. 45; Hansen, 1986a; Stone, 1989). Sediments of the Uinta Mountain Group have an inferred provenance to the north and northeast in south-central Wyoming. Tweto (1987, p. 21) provisionally dated the Uinta Mountain Group at

925 Ma near the top and 1,100 Ma at the base and indicated that it is correlative with the upper part of the Belt Supergroup in Montana and Idaho. It may also be correlative with the Unkar Group of the Grand Canyon Supergroup in Arizona (Elston, 1979, p. 14–16). Assuming these dates are correct, the Uinta Mountain Group and its correlatives predate inception of the Cordilleran miogeocline (Stewart, 1976) at about 850 Ma.

Speculation about Late Precambrian and Early to Middle Cambrian environments in northwestern Colorado (post-Uinta Mountain Group) is problematical considering the lack of rock record. This time interval may have been characterized by a continuation of faulting (Hansen, 1986a, p. 12–14), igneous activity, and related tectonic activity. Tweto (1980b, p. 44–45) further postulated that during this time interval new fracture systems having different geometries developed and erosion was widespread (fig. 5A).

LOWERMOST UPPER CAMBRIAN TO UPPERMOST CAMBRIAN ROCKS

Differences in lithology between the at least partly correlative Sawatch Quartzite and Lodore Formation suggest that the Uinta aulacogen and other basement fractures to the southeast in the vicinity of modern White River Plateau may have been active during this interval. Uplift along these zones may have formed barriers to regional sediment transport that affected Dresbachian sedimentation (fig. 5B).

Lodore Formation

The Cambrian is represented in northwestern Colorado north and west of the White River Plateau by the Lodore Formation, which is considered by most authors to be Dresbachian in age (Unterman and Unterman, 1949; Stevens, 1961, p. 9; Hansen, 1965, p. 38; Ross and Tweto, 1980; Ross, 1986). The uppermost Lodore(?) is possibly latest Early Devonian in age as determined by Richard Lund of Adelphi University (W.R. Hansen, written commun., 1969) based on identification of Devonian fish fragments collected by Hansen and P.D. Rowley near Jones Hole, Dinosaur National Monument, Utah. C.A. Sandberg (U.S. Geological Survey, written commun., 1990), however, recognized a disconformity between the uppermost (fossil-bearing) Lodore (?) and the underlying Cambrian Lodore and suggested that the uppermost Lodore(?) be considered part of the younger Devonian and Mississippian Chaffee Group or the Mississippian Madison (or equivalent Leadville) Limestone.

There are few available data concerning the Lodore Formation, and more research is needed to properly understand its precise age, depositional environment, and

provenance. The Lodore is well exposed at Cross Mountain in the canyon of the Yampa River (Dyni, 1968), in several other places in and near Dinosaur National Monument (Rowley and others, 1985), and along the southern flanks of the Uinta Mountains (fig. 4). At these locations, it unconformably overlies the Uinta Mountain Group and is overlain by Mississippian rocks (Hansen, 1965). Thicknesses are from 91 to 180 m. The Lodore consists of “white to red, coarse poorly sorted, quartzitic and in part arkosic sandstones at top, middle, and base” (Unterman and Unterman, 1949, p. 689). In the type area (Lodore Canyon, Moffat County) and at Jones Hole in Dinosaur National Monument, it contains thick sequences of fossiliferous, glauconitic shale that elsewhere have been removed elsewhere by pre-Mississippian erosion. Hansen (1965, p. 38) believed that the Lodore Formation once extended over the area of the modern Uinta Mountains and was subsequently removed by erosion from a younger Uinta Mountains highland area.

The Uinta Mountain Group is a likely source for the Lodore, as suggested by Stone (1986, p. 20) and Herr and Picard (1981, p. 12), for at least its lower part and also for the presumably correlative basal Sawatch Quartzite sandstones in northwestern Colorado (Ross, 1986, p. 100). The Uinta Mountain Group was tilted and deeply truncated before the Lodore Formation was deposited (Hansen, 1986a); however, a crystalline source is needed to account for the arkosic sandstones in the Lodore Formation. Stone (1986, p. 31–32) cited Hansen and Bonilla (1954) and Wallace (1972) for originating and subsequently reinforcing the concept that the now east trend of the ancestral Uinta Mountains structure existed prior to the Middle Cambrian. Based on subsurface and geophysical data, Stone extended the structural trend of the Uinta Mountains in the subsurface about 160 km eastward into the area of the Pennsylvanian Eagle basin and named it the “Ancestral Axial Fault Zone” (1986, p. 19). South of this trend, Stone (1986, p. 25) showed Precambrian crystalline basement and no Uinta Mountain Group in the subsurface from Rangely to about 160 km eastward. Thus, a structurally high area probably existed south of the ancestral Axial fault zone, and this area could have been a source of the Lodore sediments, including the arkoses. Whether this high area exposed Uinta Mountain Group rocks, other older Precambrian rocks (possibly including the Red Creek Quartzite), or the older Precambrian crystalline basement is unknown.

Sawatch Quartzite

The Sawatch Quartzite (Johnson, 1934; Bass and Northrop, 1953, 1963; Campbell, 1972a; Tweto and Lovering, 1977) is present throughout northwestern Colorado except on the Uncompahgre uplift, where it presumably was deposited but subsequently eroded away during or prior to the Pennsylvanian (Stone, 1977), and northwest of the

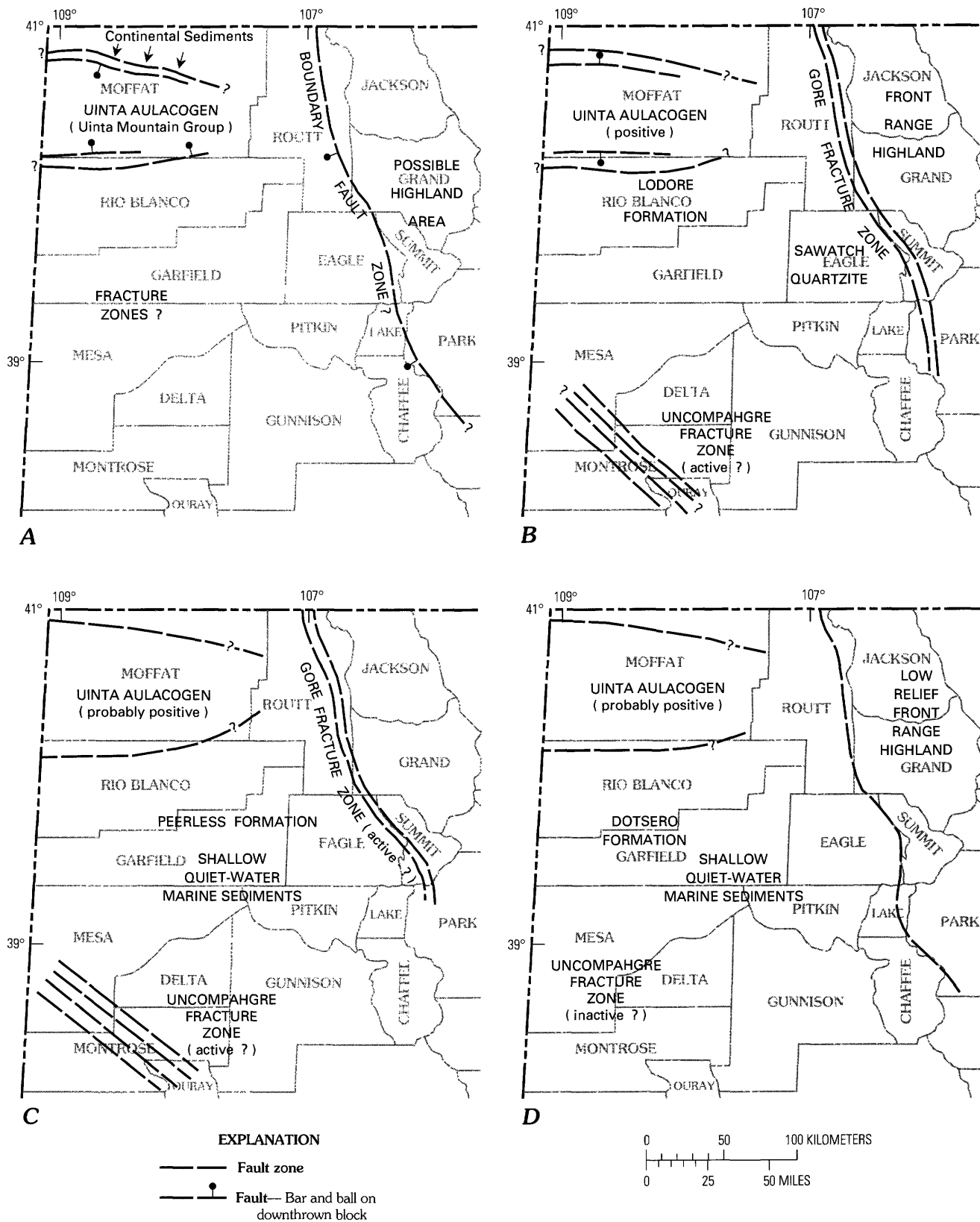


Figure 5. Paleogeography of northwestern Colorado from about 1,400 Ma to the Late Cambrian. *A*, About 900 Ma during time of deposition of Uinta Mountain Group. *B*, Dresbachian (Sawatch Quartzite and Lodore Formation). *C*, Franconian (Peerless Formation). *D*, Trempealeuan (Dotsero Formation).

White River Plateau, where the Lodore Formation is its correlative (Ross, 1986, p. 100). The best outcrops are along the flanks of the Sawatch and Mosquito Ranges, near Redcliff and Minturn, and in the canyons along the southern and eastern sides of the White River Plateau (fig. 4).

The predominant lithology in the Sawatch is buff to grayish-orange-pink (5YR 7/2), vitreous orthoquartzite in beds from 15 cm to 1 m thick. Several other rock types are present with lesser frequency in the Sawatch. In Dead Horse Gulch, a tributary to the Colorado River in Glenwood Canyon (fig. 4), the basal Sawatch consists of 0.1–0.3 m of arkosic quartz-pebble conglomerate unconformably overlying weathered Precambrian schist and pegmatite (fig. 6, appendix 1). In Glenwood Canyon, this contact has as much as 15.2 m of local relief, but it was reported as planar in the Minturn area (Tweto and Lovering, 1977). Above, but still within 15.2 m of the base of the Sawatch in the Dead Horse Gulch section, friable, hematite-stained, planar-tabular crossbedded sandstone is interbedded with the vitreous orthoquartzite (fig. 7, appendix 1). Bass and Northrop (1963) reported a thickness of 157.5 m for the Sawatch section, which includes an upper dolomite unit and an overlying massive orthoquartzite unit. This thickness is greater than that reported to the south and east, where Tweto and Lovering (1977, p. 16–17) reported that the Sawatch is 67 m thick in the Minturn quadrangle and thins to the south (Tweto, 1956, 1974; Tweto and others, 1978).

Chronic (1964, p. 105) reported that the Sawatch is 30 m thick at Buffalo Peaks and absent at Trout Creek Pass. In Taylor Park, Bush and Bush (1974) reported a sequence similar to that in Glenwood Canyon. They assigned the dolomitic beds to the Peerless Formation, which elsewhere overlies the Sawatch, and beds of variable lithology between their Peerless and Lower Ordovician rocks to a newly



Figure 7. Typical friable, hematite-stained, planar-tabular crossbedded sandstone interbedded with quartzite near base of Sawatch Quartzite. Dead Horse Gulch section, Glenwood Canyon (fig. 4). Staff is about 1.5 m long.



Figure 6. Contact between basal Sawatch Quartzite and Precambrian rocks. Dead Horse Gulch, Glenwood Canyon (fig. 4). At this location the contact (arrow) is almost planar, but at other locations nearby it has about 15.2 m of relief. A thin bed of quartz-pebble conglomerate grades upward to quartzite and sandstone. Staff is about 1.5 m long.

named Deadmans Gulch Formation; they assigned 38.7 m of section at Taylor Park to the Sawatch.

Paleontological control for the age of the Sawatch is poor due to generally barren rock types, but where the age has been determined the consensus is that it is Dresbachian (Tweto, 1949; Tweto and Lovering, 1977). Bass and Northrop (1963, p. 5) reported that brachiopods are present in the dolomite unit in Glenwood Canyon but made no age determinations. The uppermost Sawatch is undated. Tweto and Lovering (1977) suggested that the upper dolomite unit of the Sawatch probably is equivalent to the Peerless Formation, which is variously considered to be of Middle to late Late Cambrian age (Behre, 1929, 1953; Johnson, 1934, 1944), Late Cambrian age (Chronic, 1964; Anderson, 1970; Bush and Bush, 1974), or middle Late Cambrian age (Franconian) (Tweto and Lovering, 1977). If the dolomitic unit in my measured section is equivalent to the Peerless, then additional quartz sand was deposited over much of western Colorado and then partly to almost completely eroded before the latest Cambrian, inasmuch as the

overlying Dotsero Formation is latest Cambrian (Trempealeuan) in age (Bass and Northrop, 1953, 1963; Campbell, 1972a, 1976; Tyler and Campbell, 1975). On a regional scale, Palmer (1965, 1981, p. 160) and Sloss (1963, p. 96–99) suggested that a regional disconformity separates Dresbachian and Franconian rocks. Because of uncertain dating, regional correlation of the Upper Cambrian formations including the Sawatch and the Peerless is problematical (see also the discussion by Bryant, 1979, p. 16–17).

If the dolomite unit discussed above is equivalent to the Peerless, then my section of the Sawatch in Glenwood Canyon is 80.5 m thick, a thickness more consistent with surrounding areas than that reported by Bass and Northrop (1963). As noted above, however, the Precambrian-Sawatch contact is undulatory, and thicknesses vary locally.

The most likely source of Sawatch sediment was an eroding highland in the vicinity of the modern Front Range (Lovering and Johnson, 1933; Tweto and Lovering, 1977). The lithic composition of this highland is not known, but it may have been deeply weathered or quartz rich considering the predominantly quartzitic composition of the Sawatch. This highland apparently abruptly terminated at the western side of the modern Gore Range along an episodically active Gore Range fault (Tweto and Lovering, 1977), a hypothesis generally consistent with that of Campbell and others (1976), who believed that the Peerless(?)–equivalent dolomites pinch out to the northeast and thicken to the southwest (Bryant, 1979, p. 17). Sediment in western Colorado in the Late Cambrian was generally moved from east to west (Seeland, 1968).

The latest Middle Cambrian to earliest Late Cambrian probably was a time of tectonic instability in western Colorado, if not most of the western United States (Larson and others, 1985). Cambrian disconformities may reflect either epeirogenic movements or eustatic sea-level changes, or both (Lochman-Balk, 1955, p. 29). Lochman-Balk (1970, p. 3197; 1972) presented regional paleogeographic reconstructions.

Peerless Formation and Unnamed Overlying Rocks

Despite uncertainties concerning the age of the Peerless Formation and its problematical relationship with the underlying Sawatch Formation and overlying rocks, the Peerless Formation is a widely recognized upper Cambrian unit in much of central and northwestern Colorado. Although variable in thickness, lithology, and sedimentary structures, its stratigraphic position and sandy dolomite lithology are distinctive, and the formation can be easily recognized (Tweto and Lovering (1977, p. 19–21). I measured about the same thickness of probably Peerless-equivalent rocks in the Dead Horse Gulch section in

Glenwood Canyon (appendix 1) as Tweto and Lovering (1977) did in the Minturn quadrangle (20 m). The composition of the Peerless is much more variable in the Minturn quadrangle than in the adjacent White River Plateau area. In the Minturn quadrangle the Peerless consists of glauconitic sandy dolomite or dolomitic sandstone, varicolored mudstone, and minor micaceous shale (Tweto and Lovering, 1977, p. 19), whereas in Glenwood Canyon it consists of cliff-forming, massive, brown, sandy dolomite.

The Peerless Formation is also recognized at Aspen (Bryant, 1971, 1979, p. 14–15). Although thicker (30–45 m) than at Minturn and at Glenwood Canyon, these outcrops of Peerless contain similar rock types. Bryant included remnants of the Deadmans Gulch Formation of Bush and Bush (1974) in the Peerless in the Aspen area, but the thickness of these beds was not specified and could not be determined from Bryant's measured section (1979, section 1, p. 130).

Cambrian beds above the Peerless Formation and below the Dotsero Formation or Lower Ordovician rocks need additional study. Their age and the nature of their contact with the overlying Glenwood Canyon Member of the Dotsero Formation (Bass and Northrop, 1953) should be determined. The lithology of these beds in Glenwood Canyon is essentially the same as that of the Sawatch Quartzite, which underlies the Peerless(?)–equivalent dolomite. This similarity is probably why Bass and Northrop (1963, p. 5–7) assigned these beds to the Sawatch. The lithology of the Deadmans Gulch Formation discussed earlier is more variable; the unit consists mainly of quartz sandstone and glauconitic sandy dolomite and contains sedimentary structures that indicate very shallow water deposition (Bush and Bush, 1974, p. 64–68). The panel diagram of Bush and Bush (1974, p. 67) shows the Deadmans Gulch thinning to nil at Glenwood Canyon and suggests either that they believed these uppermost Cambrian quartzites should be included with the Peerless (making the Peerless anomalously thick) or, alternatively, that they ignored these beds. In any case, beds composed of predominantly quartzite and lesser dolomite above the Peerless(?) and below the Dotsero Formation have been reported only from the canyons on the southern and eastern sides of the White River Plateau. Their original extent and the character of the erosional episode that removed them from most of northwestern Colorado are unknown.

Lithology and thickness changes suggest that northwestern Colorado was a shallow shelf sea during the Franconian and that this sea was subject to mild epeirogenic movements (fig. 5C). Minor reactivation of the Gore fracture zone and other now-buried fracture zones to the west and southwest may have occurred. The Dresbachian-Franconian interval most likely was a period of erosion or nondeposition prior to inundation by this sea. Whether other tectonic activity took place is not known.

Dotsero Formation

As first described by Bassett (1939), the Dotsero Formation typically crops out on the eastern and southern side of the White River Plateau; its type locality is near Dotsero, Colorado. Bass and Northrop (1953, 1963) and Campbell (1976) showed that the Dotsero Formation is present across much of the White River Plateau, over an area of 1,037 km² (Campbell, 1976, p. 1331). Johnson (1945, p. 14–15) first demonstrated the Trempealeauan age of these strata. Bass and Northrop (1953) redefined the Dotsero Formation and assigned its upper beds to the conformably overlying Manitou Formation of earliest Ordovician (early Canadian) age. Bass and Northrop (1953) revised the Dotsero Formation into two units, a lower Glenwood Canyon Member and an upper algal-biostrome (stromatolite) limestone that they named the Clinetop Algal Limestone Member. The name Clinetop Algal Limestone subsequently was shortened to Clinetop Member by Campbell (1976).

As discussed earlier, the lower contact of the Dotsero Formation with the underlying unnamed orthoquartzite may be disconformable. In the Glenwood Canyon area (appendix 1), the contact is distinctive and abrupt. Massive orthoquartzite and well-cemented quartz sandstone of the unnamed beds above the Peerless form a ledge (fig. 8) and are overlain by partly slope forming, predominantly sandy dolomite, shaly dolomitic sandstone, and limestone described below. The Clinetop Member and the conformably overlying Dead Horse Conglomerate Member of the Manitou Formation are precisely dated (Bass and Northrop, 1963, p. 10–11), and their contact is regarded as the Cambrian-Ordovician boundary.



Figure 8. Highest beds of massive orthoquartzite of unnamed unit immediately below Glenwood Canyon Member of the Dotsero Formation. Dead Horse Gulch section, Glenwood Canyon (fig. 4). Staff and hammer shown for scale.

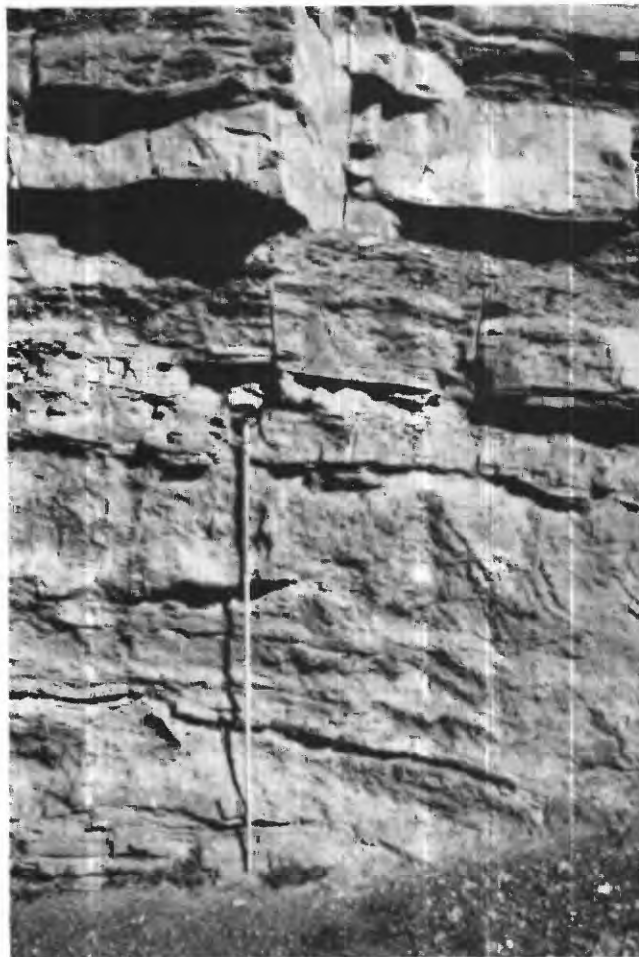


Figure 9. Typical brown silty and sandy dolomite and dolomitic sandstone of Glenwood Canyon Member of the Dotsero Formation. Highway roadcut at east end of Glenwood Canyon (fig. 4) near Garfield County–Eagle County line. Staff is about 1.5 m long.

Glenwood Canyon Member

In the Dead Horse Gulch section (appendix 1), the Glenwood Canyon Member of the Dotsero Formation consists of 27.1 m of silty and sandy dolomite and dolomitic sandstone (fig. 9). Beds are 1.3–7.6 cm thick. Many of these beds, especially in the middle third of the member, have what may be worm tracks or worm burrows (fucoid marks of some authors) on surfaces that otherwise are smooth and planar. A few limestone beds, mainly conglomeratic, grade to dolomitic sandstone beds. Glauconite is present in dolomite beds (Bass and Northrop, 1953, 1963) and locally causes a greenish cast. A few beds are capped by minor sericite. Some tan to greenish shale is interbedded with the sandstone.

Clinetop Member

The most distinctive rock in the Dotsero Formation is pinkish-light-gray (5YR 8/1) to very light gray (N8)

biostromal, algal limestone (Bass and Northrop, 1953, 1963; Campbell, 1976) that weathers white to lavender. In the Dead Horse Gulch section, the Clinetop Member is about 1.7 m thick (appendix 1) (Bass and Northrop, 1963). Campbell (1976, p. 1333) recognized three limestone facies in the Clinetop Member on the White River Plateau: a basal conglomerate, an algal-head unit, and an upper conglomerate. Consistent with Campbell's (1976, p. 1333) section, only the basal conglomerate facies is seen at Dead Horse Gulch. This is surprising in that the Clinetop in this area is apparently at its thickest (Campbell, 1976). The contour of greatest thickness is 1.2 m. The area it encloses passes over Glenwood Canyon about 3.2 km west of the Eagle County–Garfield County boundary. The trend of greatest thickness is northwest-southeast.

Except on the White River plateau and its immediate vicinity, the Dotsero Formation is missing from the lower Paleozoic section in northwestern Colorado, and the overlying Manitou Formation rests on older rocks. It is therefore difficult to estimate the original extent of Dotsero depositional environments (fig. 5D), but the Dotsero may have been much more extensive than is indicated by modern-day Dotsero outcrops. According to Campbell (1976, p. 1334–1335), carbonate rocks of the Glenwood Canyon Member accumulated slowly in a very shallow marine environment that became even shallower in Clinetop time.

ORDOVICIAN ROCKS

Ordovician rocks in northwestern Colorado consist of three formations, in ascending order: the lowest Ordovician Manitou Formation (earliest Canadian) (Ross, 1951; Bass and Northrop, 1953, 1963; Berg and Ross, 1959; Berg, 1960; Chronic, 1964; Gerhard, 1972; Ross and Tweto, 1980; Ross, 1986); the lower Upper Ordovician Harding Sandstone (Black Riveran and Rocklandian) (Sweet, 1954, 1955, 1961; Ross and Tweto, 1980); and the uppermost Ordovician Fremont Limestone (Cincinnatian) (Sweet, 1954, 1961; Ross and Tweto, 1980). In most places in northwestern Colorado these three formations are not all represented, and outcrops of the Manitou outcrop are the most widespread. The Manitou rests on various older rocks including Precambrian rocks in the Trout Creek Pass area (DeVoto, 1962) and at Wellsville in the canyon of the Arkansas River (fig. 4) (Rold, 1961). The Fremont Limestone, however, always overlies the Harding Sandstone (Taylor and Scott, 1972; Taylor, Scott, and Wobus, 1975; Taylor, Scott, Wobus, and Epis, 1975; Ross and Tweto, 1980, p. 52). Only the Manitou Formation is present in the Glenwood Canyon area.

Ordovician formations vary greatly in thickness across northwestern Colorado. Their bounding unconformities apparently represent periods of tectonic instability and (or) marine regression from lands formed by uplift

along the northeast-trending Transcontinental arch. During the Ordovician, the North American paleocontinent moved southward with reference to the paleoequator (McElhinny and Opdyke, 1973; Ross, 1976a, b, p. 109–114; Witzke, 1980; Van der Voo, 1988, p. 314–316).

Manitou Formation

The Manitou Formation in the Glenwood Canyon area was divided into two members by Bass and Northrop (1953, 1963): the lower Dead Horse Conglomerate Member and the upper Tie Gulch Dolomite Member. The French Creek measured section of this report (appendix 1) is from the same locality as that of Bass and Northrop (1963). Although the two sections are similar, I consider some of their dolomite beds to be limestone and I measured a slightly greater thickness (51 versus 47.5 m). The map of Foster (1972, p. 80, fig. 4) suggests that the Manitou changes from predominantly dolomite to limestone as the White River Plateau is approached from the southeast (Manitou Springs area).

In Glenwood Canyon the Manitou consists of four rock types; limestone and dolomite predominate and greenish shale and sandstone are subordinate (appendix 1). Other outcrops in northwestern Colorado are similar to those in Glenwood Canyon, except at Aspen where the Manitou contains more sand and silt (Bryant, 1979, p. 15; Ross and Tweto, 1980). Except on the White River Plateau, the Clinetop Member of the underlying Dotsero Formation is not present. As a result, it is very difficult to determine the base of the Manitou, which may, in part, explain the variability of reported thicknesses.

Dead Horse Conglomerate Member

The lower 15 m of this member consists of gray- to buff-weathering, thin-bedded (5–15 cm), conglomeratic limestone; thin-bedded, gray-weathering, sandy limestone; and thin-bedded shaly limestone. A calcareous maroon and green shale is immediately above the base of the member. The upper 15 m contains thick-bedded, gray, crystalline limestone that consists partly of conglomeratic, thin-bedded sandy limestone and dolomite and includes two beds of massive dolomitic orthoquartzite. One of these orthoquartzite beds is at the top of the member.

Tie Gulch Dolomite Member

In Glenwood Canyon the Tie Gulch Dolomite Member consists of uniformly bedded (1 m), massive, micritic, brown and tan, crystalline limestone and dolomite and buff, sandy dolomite near the top. A thin shale that may



Figure 10. Contact between highest bed of Manitou Formation (Tie Gulch Dolomite Member) and lowest bed of Parting Formation of Late Devonian age. French Creek section, Glenwood Canyon (fig. 4). Note thin shale (arrow) at contact, which can be interpreted to be the remains of a paleosol. The Harding Sandstone and Fremont Limestone are missing from this section. Hammer shown for scale.

be a paleosol is at the upper contact (fig. 10) with the overlying Upper Devonian Parting Formation.

Gerhard (1972, p. 27–33) studied Early Ordovician depositional environments and paleotectonics of central Colorado and suggested that the Manitou was deposited in two provinces: northwest, typified by the Glenwood Canyon section, and southeast, typified by the mostly dolomitic type section near Manitou Springs (Brainerd and others, 1933). He proposed that an alternate type section should be designated for his “northwestern” facies in Glenwood Canyon; this French Creek section is the same section measured by Bass and Northrop (1953) and by me (appendix 1). Gerhard concluded that in both provinces the environment of deposition of the Manitou Formation was tidal and that very shallow marine water covered Colorado during early Canadian time. Gerhard attributed facies changes to mild but regional epeirogenic movements and resulting shifts of tidal zones. He proposed that five cycles of transgression and regression and five intraformational unconformities are represented in the Manitou Formation. These transgressive and regressive cycles and the variable level of the erosion surface on which the Manitou Formation was deposited suggest fault-controlled deposition patterns. This faulting may have been localized on the northeast-trending Colorado lineament (Warner, 1978, 1980, p. 16). The end of Manitou time marked the end of deposition of the Sauk sequence of Sloss (1963), and a continentwide unconformity probably is represented by the interval between the Manitou Formation and the overlying lower Upper Ordovician Harding Sandstone (Sweet, 1954, p. 293) (fig. 11A). Ross and Tweto (1980) indicated that the Manitou generally resembles correlative strata in the central and southeastern United States (Ross, 1976a, b).

Harding Sandstone

The Harding Sandstone consists of sandstone, quartzite, and shale. The Harding has a latest Middle Ordovician (Black Riveran and Rocklandian) age, as determined from conodonts (Sweet, 1954, p. 291–292, 1955; Ross and Tweto, 1980, p. 51). It is highly variable in thickness and crops out only in the southeastern part of northwestern Colorado.

Outcrops of the Harding closest to Glenwood Canyon are in the Minturn quadrangle (Tweto and Lovering, 1977), where the formation is about 11.9 m thick. The formation is as thick as about 48.5 m in Fremont County (Sweet, 1954, p. 290, fig. 2; Scott and Taylor, 1974). It rests unconformably on the Peerless Formation near Minturn (Gilman) in Eagle County (Tweto and Lovering, 1977, p. 22), on the Manitou Formation farther to the south in Lake and Chaffee Counties, and on Precambrian rocks at the southern limit of its outcrop in Custer, Pueblo, and Saguache Counties (Sweet, 1954, p. 290–291).

The origin of the widespread cratonic, shelf-marginal, and miogeoclinal Middle Ordovician quartzites and sandstones in the western United States has been the subject of some speculation inasmuch as these rocks exhibit compositional and stratigraphic similarities over large areas. Chronic and others (1969), Ross (1976b, p. 122, 124, 125, figs. 8, 9), Witzke (1980, p. 8), and Sando and Sandberg (1987, p. 6) all indicated that correlatives of the Harding, having essentially the same lithologic, stratigraphic, and faunal characteristics, are present north of the Transcontinental arch and into the cratonic interior of the continent to the north and east. Ketner (1968) showed that the Canadian Shield was the probable source of these sediments. Ross (1976b, p. 122) concluded that this deposition and movement of sand south and southwestward continued until early Cincinnati time when the Canadian Shield was inundated. Ordovician rocks are not present in Colorado south of the Uncompahgre Plateau and into the Grand Canyon region of Arizona. They probably were never deposited in the Grand Canyon region, but their original extent in west-central, northwestern, and southwestern Colorado is unknown. Sando and Sandberg (1987, p. 4–6) suggested that uplifted islands in northwestern Colorado during Harding time may partly explain the lack of Harding correlatives in adjacent areas of Wyoming (fig. 11B).

Fremont Limestone

The Fremont Limestone (also called Fremont Dolomite in some areas) (Sweet, 1954, p. 294) of Cincinnati age is perhaps the least studied lower Paleozoic unit in northwestern Colorado. It crops out only in the southeastern part of northwestern Colorado at the south end of the Sawatch Range and farther to the south at Trout Creek

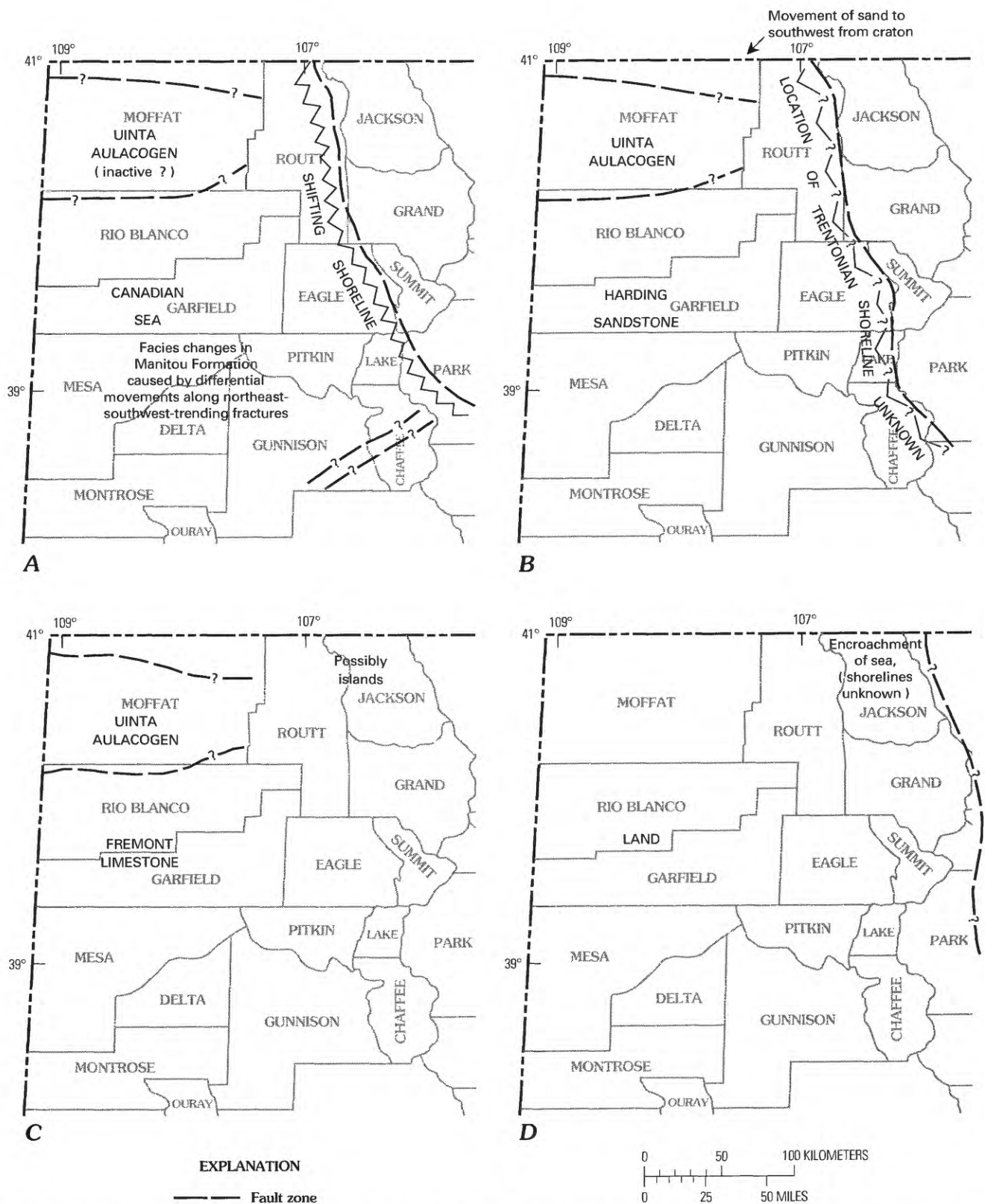


Figure 11. Paleogeography of northwestern Colorado from the Early Ordovician to the Silurian. A, Canadian (Manitou Formation). B, Latest Middle Ordovician (Trentonian?) (Harding Sandstone). C, Cincinnatian (Fremont Limestone). D, Silurian.

Pass. The Fremont is bounded by upper and lower unconformities. The lower unconformity represents a transition from clastic shelf to marine carbonate sedimentation, not only in Colorado, but throughout much of the western United States (Ross, 1976a, b). Strata that correlate wholly or partly with the Fremont include the Bighorn Dolomite of the northern Rockies, the Fish Haven Dolomite of northern Utah, the Viola Limestone of the Midcontinent (Foster, 1972, p. 82, fig. 6), and the Montoya Group of New Mexico, west Texas, and Arizona (Hayes, 1975, 1978). This widespread deposition of carbonate can be attributed to the inundation of much of North America by shallow epicontinental seas (Ross, 1976b, p. 130).

The extent of these Ordovician seas in Colorado is unknown because the limit of the Fremont Limestone is an eroded edge wherever it has been observed. The sea(s) must have extended at least to the northern end of the Front Range where exotic carbonate rocks in diatremes have yielded fossils that are the same age as the Fremont (Chronic and McCallum, 1969; Chronic, 1972). The abrupt end of carbonate deposition accompanied major environmental changes, including a major glaciation, at the end of the Ordovician (Sheehan, 1988, p. 408).

The best outcrops of the Fremont Limestone are near Canon City in Fremont County. Sweet (1954, p. 295) measured a section near Royal Gorge near Canon City that consists of a lower massive dolomite member about 63.5 m thick and an upper dolomite member about 22.9 m thick that has shale at its base. The Fremont is considerably thinner in the Sawatch Range where Johnson (1944) measured as little as 8.5 m; rocks similar to those at Royal Gorge are 13.5–15 m thick on Fossil Ridge at the southern end of Taylor Park (Zech, 1988). Evidence presented in the reports cited above indicates that the Fremont must have been much more extensive than its present outcrop distribution suggests. Sweet (1954, p. 303) noted, moreover, that no clastic shoreward facies of the Fremont has ever been recognized (fig. 11C).

SILURIAN ROCKS

With the exception of fossiliferous carbonate rocks preserved as exotic blocks in diatremes in the northern Front Range, no Silurian rocks have been recognized in Colorado. The time between Late Ordovician (Cincinnatian) and possibly earliest Late Devonian (Frasnian), and probably latest Late Devonian (Famennian), lacks a rock record. There is almost no reference, therefore, to Silurian history in the geologic literature of Colorado.

Paleontological data (Chronic and others, 1969, p. 154) indicate that most of Silurian time is represented in the lone known occurrence of Silurian rocks in Colorado. Regionally, the nearest well-dated Silurian rocks are in northwestern Utah (Sheehan, 1980), where Lower Silurian (Wenlockian) strata are present, and in the Williston basin

of northern Wyoming and northwestern South Dakota, where the Interlake Formation is Late Ordovician to latest Wenlockian in age (Sandberg and Mapel, 1967; Gibbs, 1972, p. 87) and the uppermost beds are undated. Sheehan (1980) believed that the Silurian environment of northwestern Utah was a shallow marine shelf until at least latest Wenlockian and that the slope on the margin of the North American miogeocline was probably a short distance to the west. Gibbs (1972) concluded that the depositional environment of the Interlake carbonates was a highly oxidized, warm-water sea characterized by low energy and restricted circulation. Any coexisting landmass was remote and of presumably low relief. Witzke (1980, p. 15, fig. 9) showed that Colorado was in an arid climatic belt south of the paleoequator and ancestral North America was moving south. Climatic patterns resembled those for the Late Ordovician prior to the latest Ordovician glacial period (Ross, 1976a, b; Sheehan, 1980, p. 19; Van der Voo, 1988, p. 316).

Tweto (1980a, p. 7) inferred that epeirogenic movements occurred repeatedly in Colorado from earliest Silurian to Middle Devonian, but little or no evidence of such movements has been documented. If the fracture systems that originated in the late Precambrian influenced sedimentation in the Silurian as they did before and since (Tweto, 1980a, p. 5), then Silurian rocks were perhaps deposited and subsequently eroded away in western Colorado. More likely, however, western Colorado was a land area in Silurian time, and a continental shelf and sea were to the west. Silurian rocks in the Front Range diatremes could be attributed to deposition in a seaway that was somehow connected to the Midcontinent sea. The rocks are anomalous because the Front Range has been apparently structurally high during most of geologic time (fig. 11D).

DEVONIAN AND MISSISSIPPIAN ROCKS

In northwestern Colorado the Devonian is represented by the Chaffee Group of Famennian (late Late Devonian) age and, in the redefined usage of this group name by Tweto and Lovering (1977), possibly earliest Mississippian (Kinderhookian) age. C.A. Sandberg (written commun., 1990) indicated that conodont age determinations demonstrate a late Famennian age for all Devonian rocks in west-central and northwestern Colorado. The Chaffee Group includes the Parting Formation, Dyer Dolomite, and Gilman Sandstone. The Devonian is probably the best studied lower Paleozoic system in northwestern Colorado.

The Upper Devonian sequence in southwestern Colorado and southeastern Utah south of the Uncompahgre uplift (Beus, 1980) is very similar to the Parting Formation of northwestern Colorado. These formations probably were continuous before the Uncompahgre uplift was (re-) activated in Pennsylvanian time (Kelley, 1955, p. 76–80; Stone, 1977; Larson and others, 1985, p. 1370–1371).

Devonian rocks produce oil from the Aneth Formation of the Paradox basin in southeastern Utah. Baars and Campbell (1968, p. 35) considered the Aneth to be earliest Frasnian in age and suggested that it is correlative with the lowest part (Unit A of Campbell, 1970a) of the Parting Formation, the oldest rocks in the Chaffee Group. The Aneth Formation is known only in the subsurface (Baars, 1972, p. 91; Beus, 1980, p. 61) and is overlain by the McCracken Sandstone Member of the Elbert Formation. C.A. Sandberg (written commun., 1990) believed that the Parting is much younger than the Aneth. In Glenwood Canyon, Sandberg and Poole (1977, p. 168–171) found conodont zones that indicate the Parting is Famennian, and they discount prior Frasnian age determinations based primarily on Late Devonian fossil-fish fragments (Bryant and Johnson, 1936; Poole and others, 1967; Tweto and Lovering, 1977, p. 26). Tweto and Lovering (1977, p. 23–24) seem to concur with Sandberg and Poole. Sando and Sandberg (1987, p. 7) correlated the Parting Formation of the Chaffee Group with their newly named Fremont Canyon Sandstone in the northern Laramie Range of Wyoming, although biostratigraphic control of the age of this new formation is lacking. The lower part of the Englewood Formation, which conformably overlies the Fremont Canyon Sandstone, has produced Famennian conodonts (Sando and Sandberg, 1987, p. 9–11). Other possible correlatives are present farther to the north (Sandberg and Mapel, 1967).

The predominantly dolomitic Dyer Dolomite of Famennian age (Campbell, 1970a, p. 319–324; Sandberg and Poole, 1977) overlies the Parting north of the Uncompahgre uplift in northwestern Colorado. Its correlative in southwestern Colorado is the Ouray Limestone (Baars and See, 1968). The Dyer conformably overlies the Parting, just as the Ouray overlies the Elbert. On the White River Plateau, Campbell (1970a) divided the Dyer into the Broken Rib Member and the overlying Coffee Pot Member. Sandberg and Poole (1977) accidentally transposed the names Broken Rib Member and Coffee Pot Member, but their samples are in proper stratigraphic order (C.A. Sandberg, written commun., 1990). Sandberg and Poole (1977, p. 167–174) indicated that correlatives of the Dyer are present in adjacent States, but exact age determinations based on conodont biostratigraphy are uncertain.

In their revision of the Chaffee Group, Tweto and Lovering (1977) indicated that the uppermost Dyer may be earliest Mississippian in age and the unconformably overlying Gilman Sandstone latest Devonian or earliest Mississippian. Before this revision, the Gilman Sandstone had been regarded as the lowest member of the overlying Leadville Limestone. Gutschick and others (1980) assigned the lowest Leadville to late Kinderhookian with a regional disconformity between it and the underlying uppermost Devonian–lowermost Mississippian. As summarized by Craig (1972), the entire Leadville had previously been assigned to the Osagean.

Parting Formation

On and near the White River Plateau, the Parting Formation consists of quartzite, shale, and dolomite. It is about 19–30 m thick. Campbell (1970a, p. 315) indicated that the Parting is 19 m thick at Grizzly Creek (N¼ sec. 34, T. 5 S., R. 88 W.). Bass and Northrop (1963, p. 19) indicated that the Parting is 19.2–29 m thick in 10 measured sections (locations unspecified). I remeasured the Parting section (fig. 12) that Bass and Northrop (1963, p. 18–19) reported in detail, which is located in the cliffs on the north side of Interstate Highway 70, directly west of the Eagle County–Garfield County line, and obtained a thickness of 30 m. Sandberg and Poole (1977, p. 169–171) studied this same section for conodont faunas. Although Campbell (1970a) divided the Parting into three units (A, B, C) that he said can be traced over much of the Parting outcrop area in northwestern Colorado, I was unable to reconcile these units with the section I measured or with the data of Bass and Northrop (1963). Campbell used 31 surface and subsurface sections on or adjacent to the White River Plateau but not the one reported in this study. His lithologic descriptions, however, are consistently similar for all reported sections.

In the Glenwood Canyon section, the Parting consists of quartzite, green shale, and dolomite. The quartzite, which consists of well-cemented quartzite grains and minor feldspar and rock fragments, is distinctive and forms minor ledges. Quartzite beds are generally 0.15–0.3 m thick., but bedding thicknesses of other rock types are highly variable. The green shale is commonly interbedded with thin and discontinuous quartzite lenses. The dolomite is typically fine crystalline micrite (Folk, 1959) and commonly sandy and (or) calcareous. Dolomite is gray on fresh fractures and



Figure 12. Section of Chaffee Group measured at east end of Glenwood Canyon near Garfield County–Eagle County line (fig. 4). The highest ledge is the Leadville Limestone of Early Mississippian age. Glenwood Canyon sign is for the west-bound lane of Interstate Highway 70.

weathers buff to tan. I could not accurately identify fragmental macrofossils, but Bass and Northrop (1963, p. 20) reported fossil-fish fragments at this locality and C.A. Sandberg (written commun., 1990) found large fish plates.

The petrology and origin (fig. 13A) of the sandstones (quartzites) of the Parting were studied by Campbell (1967, 1972b), who concluded that the Parting was deposited in a shallow-marine environment (1972b, p. 264). Sediment was transported from the east during deposition of the lowest part of the Parting and from the northeast to north during deposition of the upper part of the Parting (p. 265). Campbell postulated that these sediments were derived from the Front Range highland located in the same area as the possible source of the Cambrian Sawatch Quartzite sediments discussed earlier in this paper and by Tweto and Lovering (1977). Subsequently, Thomas (1971) studied this same interval to the south in northern Gunnison County and concluded that essentially none of the Parting could have originated from the Uncompahgre uplift to the southeast, which, as noted by Bryant (1979, p. 19), would contradict the proposal by Pampe (1970) that the Uncompahgre uplift was a sediment source for the Parting (fig. 13A).

Dyer Dolomite

In the White River Plateau, the Dyer Dolomite is predominantly limestone in its lower part (Broken Rib Member) and dolomite in its upper part (Coffee Pot Member). I measured 42 m of Dyer in the Glenwood Canyon section; Bass and Northrop (1963, p. 18) reported 46.3 m at this locality. At another location in Glenwood Canyon (SW $\frac{1}{4}$ sec. 16, T. 5 S., R. 87 W.), Campbell (1970b, p. 320, fig. 12) reported a thickness of 18.9 m for his predominantly limestone lower Broken Rib Member and 30.5 m for his predominantly dolomite Coffee Pot Member. Minor uplift and erosion terminated Dyer deposition (Campbell, 1970a, p. 97) before the Dyer was overlain disconformably by the Gilman Sandstone.

Broken Rib Member

The Broken Rib Member forms a distinctive ledge (fig. 14) of "knobbly" weathering limestone (Bass and Northrop, 1963) containing uncommon dolomite lenses and stringers. Fossils are common in the Broken Rib, but I made no attempt to identify them because Bass and Northrop (1963, p. 22, table 1) had already done so. The Broken Rib Member is interpreted to have formed in a shallow, sublittoral marine environment (Campbell, 1970b, p. 97).

Coffee Pot Member

The Coffee Pot Member consists of thin to thick beds of gray (tan weathering) dolomite, dolomitic limestone, and limestone. The fossil faunas of the Coffee Pot have been

described by Bass and Northrop (1963, p. 21–26), Campbell (1970a, p. 323–324), and Sandberg and Poole (1977, p. 169–171). The most distinctive sedimentary features of this sequence are abundant rip-up clasts (some with upturned edges suggesting a desiccated mudflat origin), stromatolitic algae, intraformational dolomite breccias, thin laminations of micrite, and possibly bioturbated bedding. Campbell (1970a, p. 94–95) inferred that the Coffee Pot Member was deposited in a shallow to subaerially exposed, muddy tidal flat on the margins of a regressing latest Devonian (and earliest Mississippian?) sea (also see Baars and Campbell, 1968). Campbell (1970a, p. 322–323) attributed sedimentary structures in the Coffee Pot Member to intertidal channels and burrowing organisms (fig. 13B).

Gilman Sandstone

As previously stated, Tweto and Lovering (1977) reassigned the Gilman Sandstone from the Leadville Limestone to the uppermost Chaffee Group. Tweto and Lovering (1977, p. 24) placed it in the Chaffee Group because "of its close relation to the Dyer in character, origin, and probably age" and indicated that it is "probably of eolian origin although obviously reworked in water." Most earlier authors (Rothrock, 1960, p. 19; Nadeau, 1972, p. 86) considered this thin sequence of sandstone or quartzite, dolomite sandstone, and shale to represent the basal transgression of the continental-shelf-margin sea that produced the Leadville Limestone and its correlatives (Madison Limestone, Escabrosa Group, Redwall Limestone) throughout much of the western United States. This concept is now believed to be erroneous because of a regional disconformity that intervenes between uppermost Famennian–lowest Kinderhookian and uppermost Kinderhookian rocks (Gutschick and others, 1980).

In the two places in Glenwood Canyon where I examined the Gilman Sandstone (appendix 1), in the section where the rest of the Chaffee Group was measured and in the cliffs on the south side of Interstate Highway 70 about a third of a kilometer east of the French Creek highway crossing, the Gilman is highly variable, consisting of dolomite and sandstone. Although it is about 5 m thick at the Garfield County–Eagle County boundary, it is much thinner at French Creek to the point of being difficult to locate beneath the Leadville cliff. At French Creek the loose debris is predominantly a ferruginous friable sandstone. I did not observe the sedimentary breccias in the Gilman that Bryant (1979, p. 21) considered to be distinctive of the formation in the Aspen area. The thinness of the Gilman, its varied lithology, and its bounding upper disconformity suggest that it was deposited in a changing environment of very shallow water, probably accompanied by mild epeirogenesis (fig. 13C) that was possibly related to the strengthening Antler orogeny in western Utah and Nevada (Johnson, 1971).

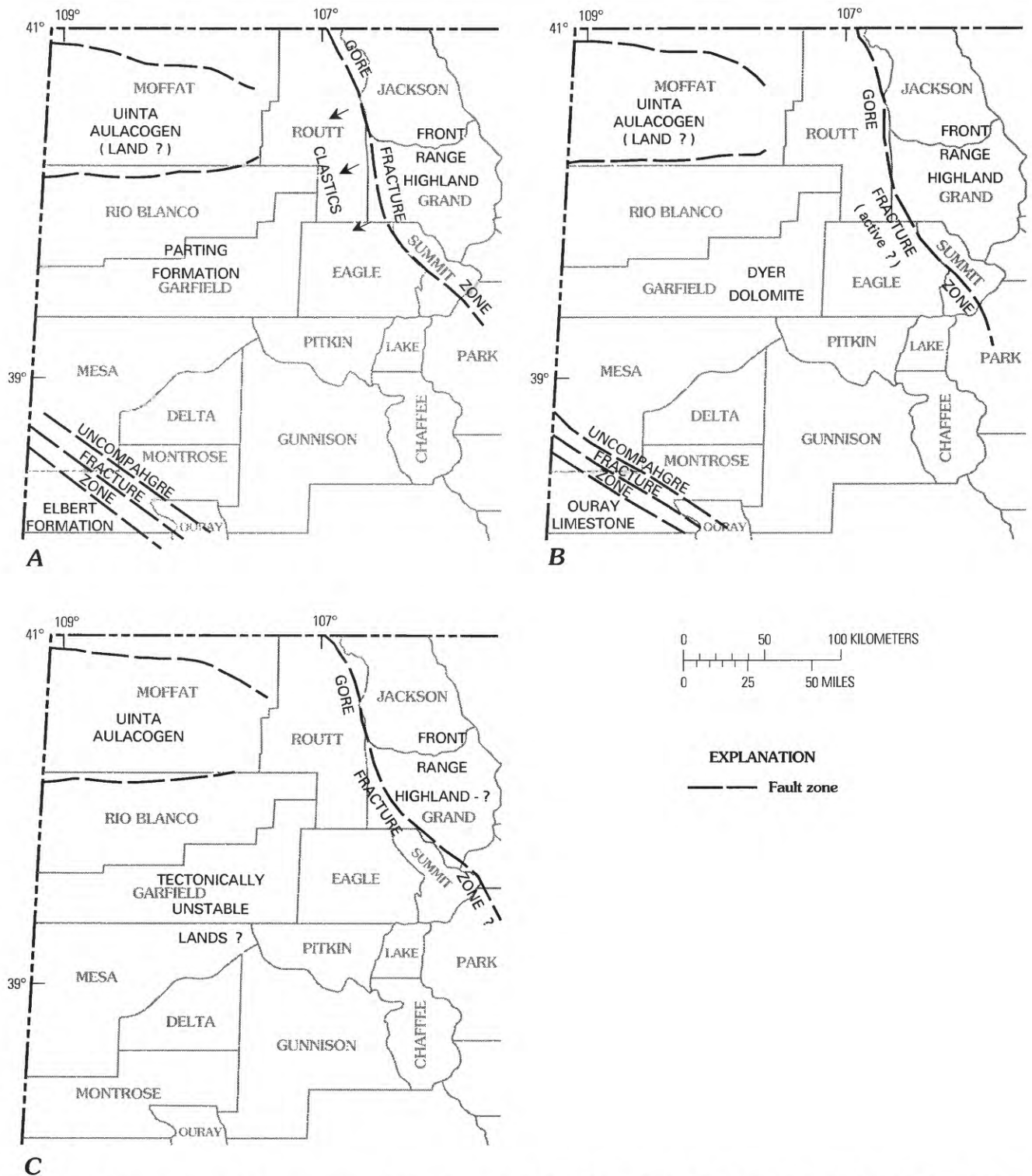


Figure 13. Paleogeography of northwestern Colorado from the Late Devonian to the Early Mississippian. *A*, Frasnian(?) or Famennian (Parting Formation). *B*, Famennian (Dyer Dolomite). *C*, Famennian or earliest Mississippian (Kinderhookian) (Gilman Sandstone).

Devonian Lodore(?) Formation

As indicated earlier in this paper, recent paleontological studies of the top of the Lodore(?) Formation

indicate that it may be, in part, Devonian in age. Recent work by Herr and others (1982, p. 116–119) indicates that an average glauconite age of two samples from the upper Lodore(?) is Devonian (387 ± 5 Ma), but Herr and others



Figure 14. Distinctive gray nodular limestone near base of Broken Rib Member of the Dyer Dolomite. Outcrop is about 400 m north-northeast of the Interstate Highway 70 bridge over French Creek, Glenwood Canyon (fig. 4). Hammer shown for scale.

indicated that the dates might be in error because of analytical difficulties and would not refute a Cambrian age for the Lodore. The ichnofossil determinations of Herr and others range over too much time to be conclusive. If the Lodore is even partly Devonian, the geologic history of extreme northwestern Colorado needs some reinterpretation. Herr and others (1982) offered evidence that the Lodore(?) is a relatively thin clastic unit that was deposited on the craton in a shallow marine trough and was never deeply buried. Because the Lodore(?) was deposited on and near the site of the Uinta Mountains and because apparently nearly continuous tectonic activity is associated with the Uinta Mountains (Hansen, 1986a, b), a thin Lodore(?) Formation suggests that subsidence rates in this area were minimal well into the early Paleozoic. If these highest Lodore(?) rocks are in fact Devonian, a heretofore unrecognized disconformity must separate them from the Cambrian rocks, and an additional formation name would be warranted, provided the limits of the formation could be ascertained. Serious questions remain about the age of the Lodore(?), and additional study of its age range, provenance, and sedimentology might be profitable.

CONCLUSIONS

The lower Paleozoic sedimentary sequence in northwestern Colorado and adjacent areas is a result of several episodes of shallow-marine transgression and regression that accompanied mild epeirogenesis and probably eustatic sea-level changes. The patterns and locations of sedimentation and erosion probably were partly controlled by regional fault and fracture systems established in the Precambrian and subsequently intermittently reactivated. The thinness of all these rock units and their predominantly shallow-water carbonate and mature sandstone lithology suggest that extensive shallow seas, widely shifting

shorelines, and low-relief land masses were prevalent environments from the Late Cambrian to latest Devonian in northwestern Colorado. The inception of the latest Devonian to Mississippian Antler orogenic event(s) to the west in the area of the modern-day Great Basin probably affected sedimentation close to and on the craton.

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Appendix 1. Measured sections

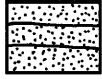
LITHOLOGIC TYPES (combination of symbols indicates variation in individual units)



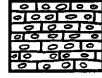
Igneous and metamorphic rocks



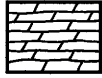
Nodular limestone



Orthoquartzite



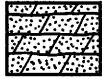
Conglomeratic limestone



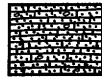
Dolomite



Stromatolitic limestone



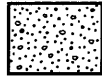
Sandy dolomite to dolomitic sandstone



Sandy limestone to calcareous sandstone



Dolomitic shale to shaly dolomite



Sandstone

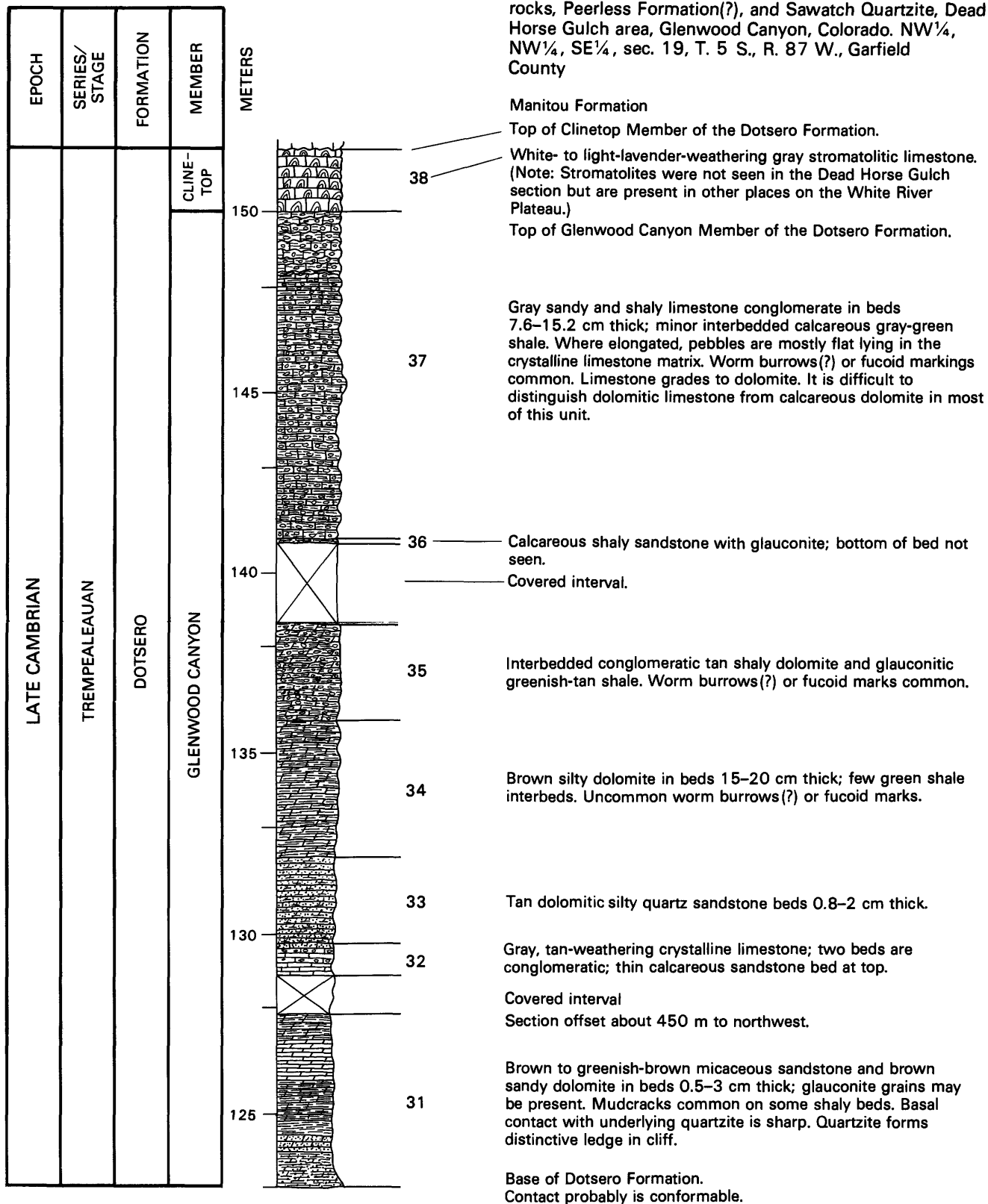


Limestone

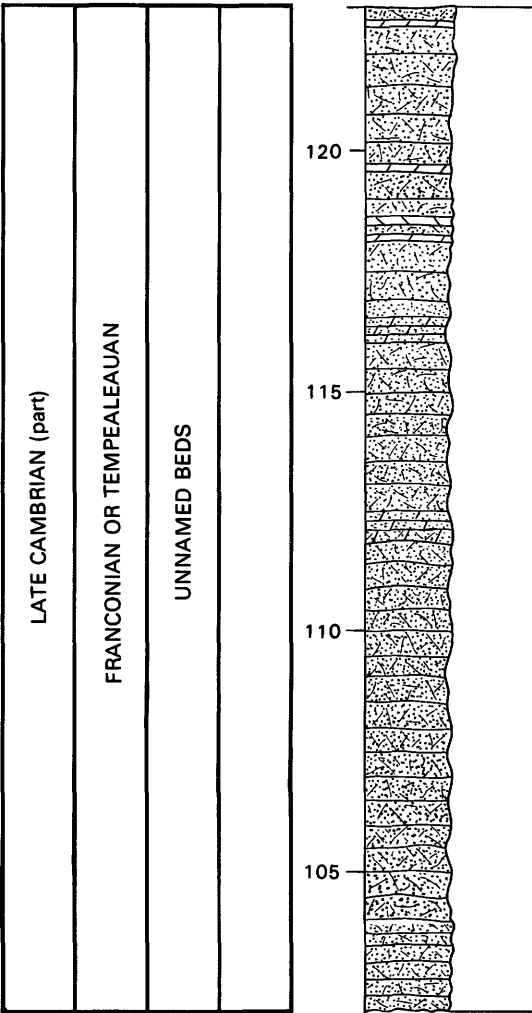


Shale

Appendix 1. Measured sections—Continued



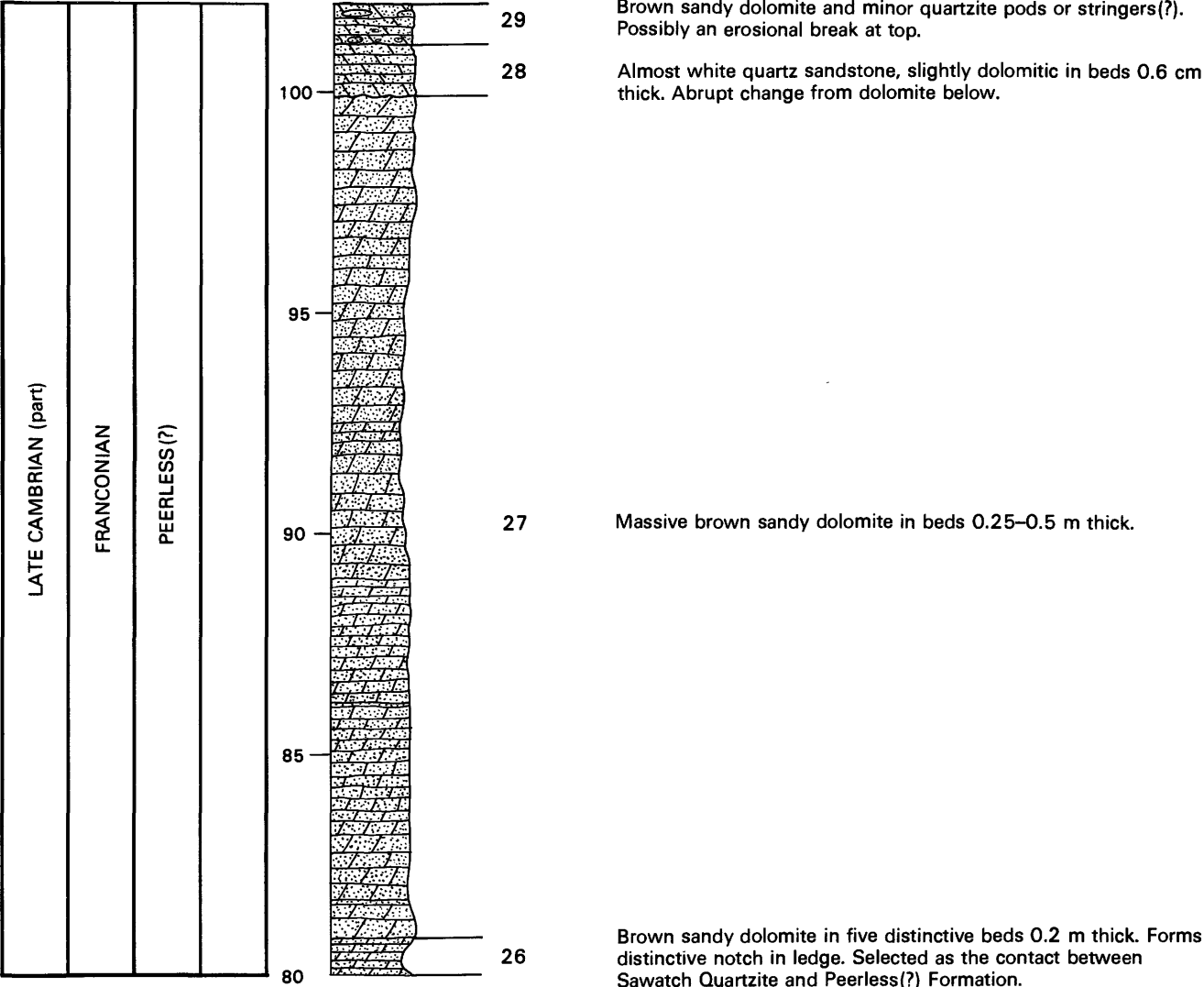
Appendix 1. Measured sections—Continued



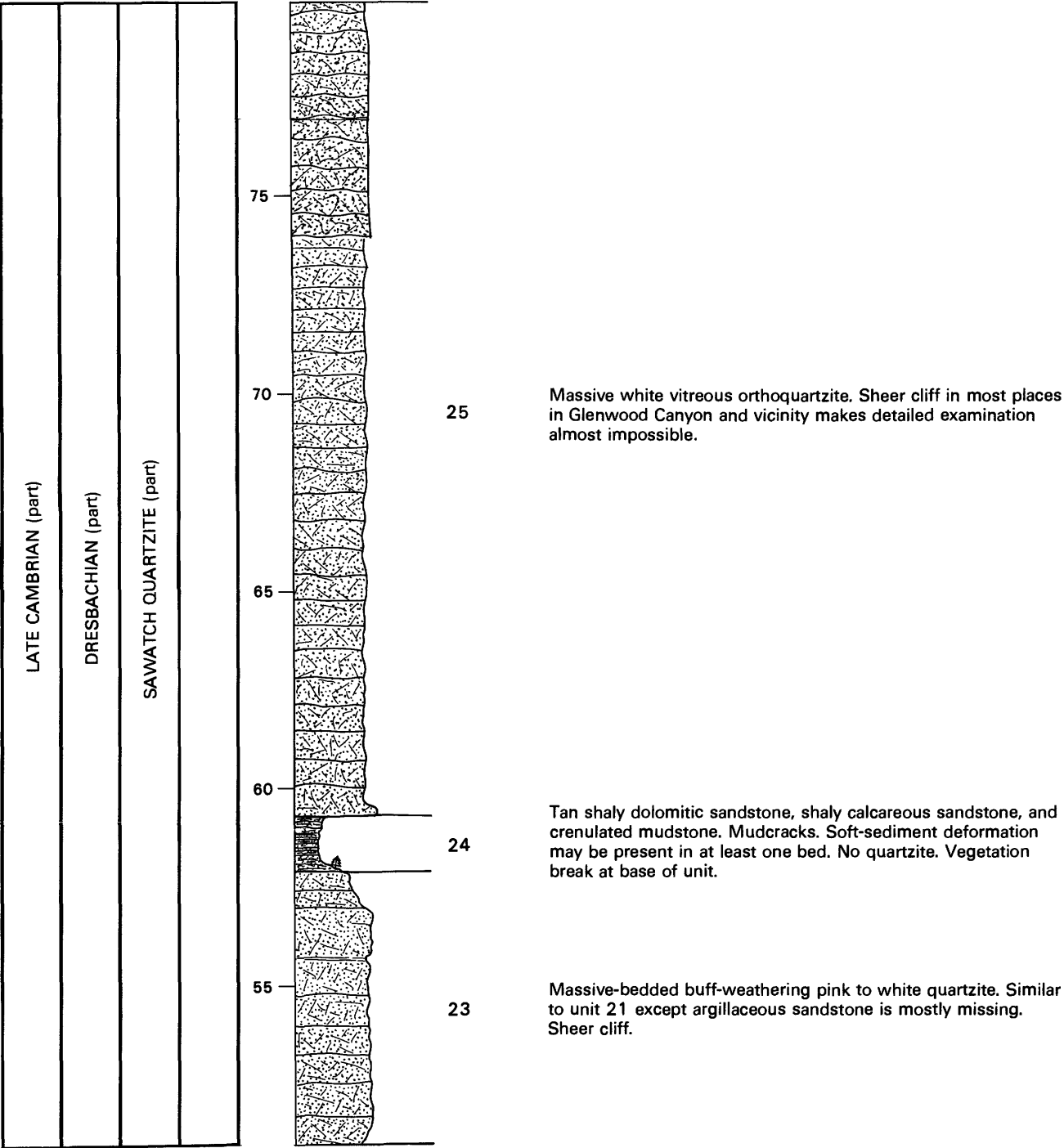
30

Almost white, slightly tan weathering, clean, well-sorted quartzite and minor tan-weathering light-tan sandy dolomite beds near top. Forms sheet cliff at top of Sawatch Quartzite.

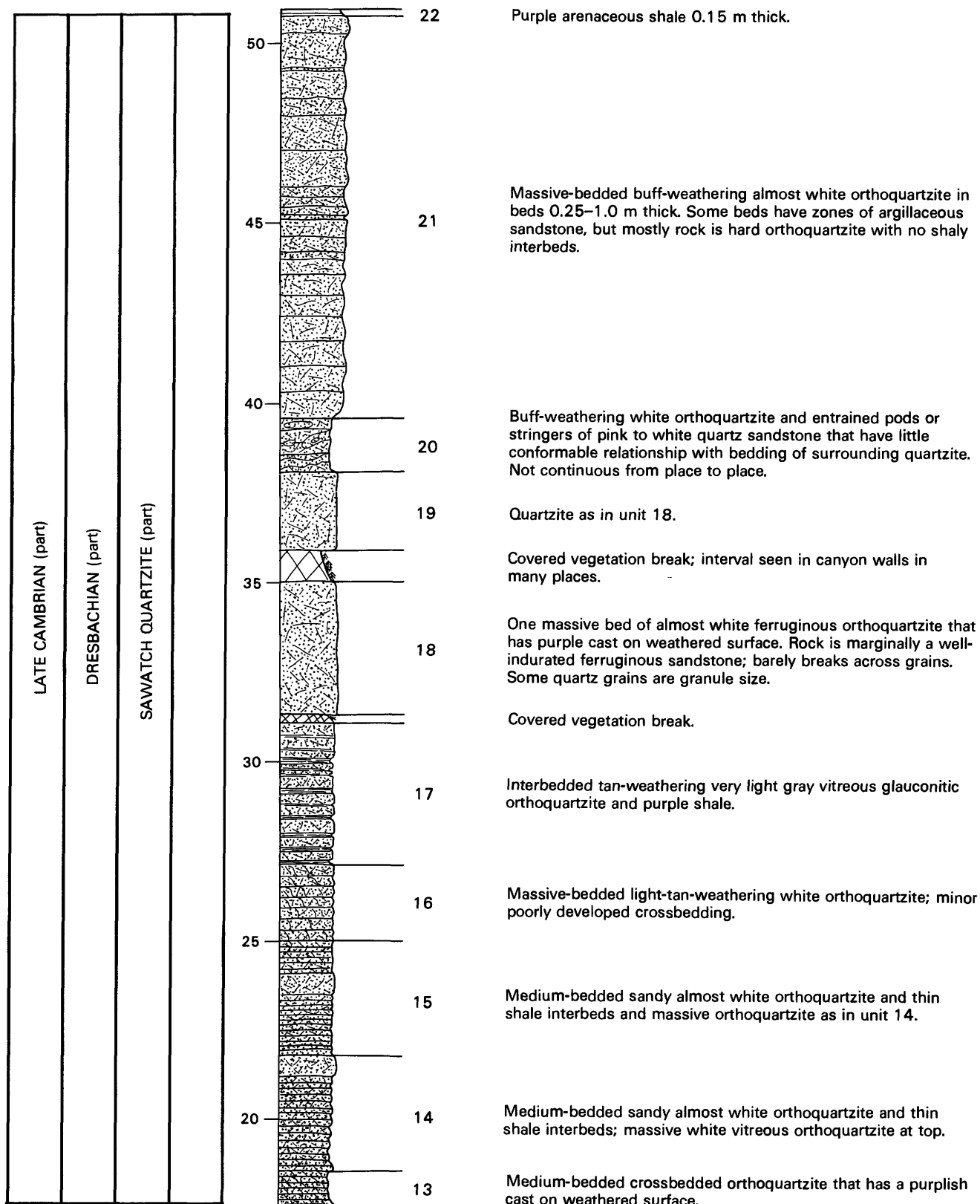
Appendix 1. Measured sections—Continued



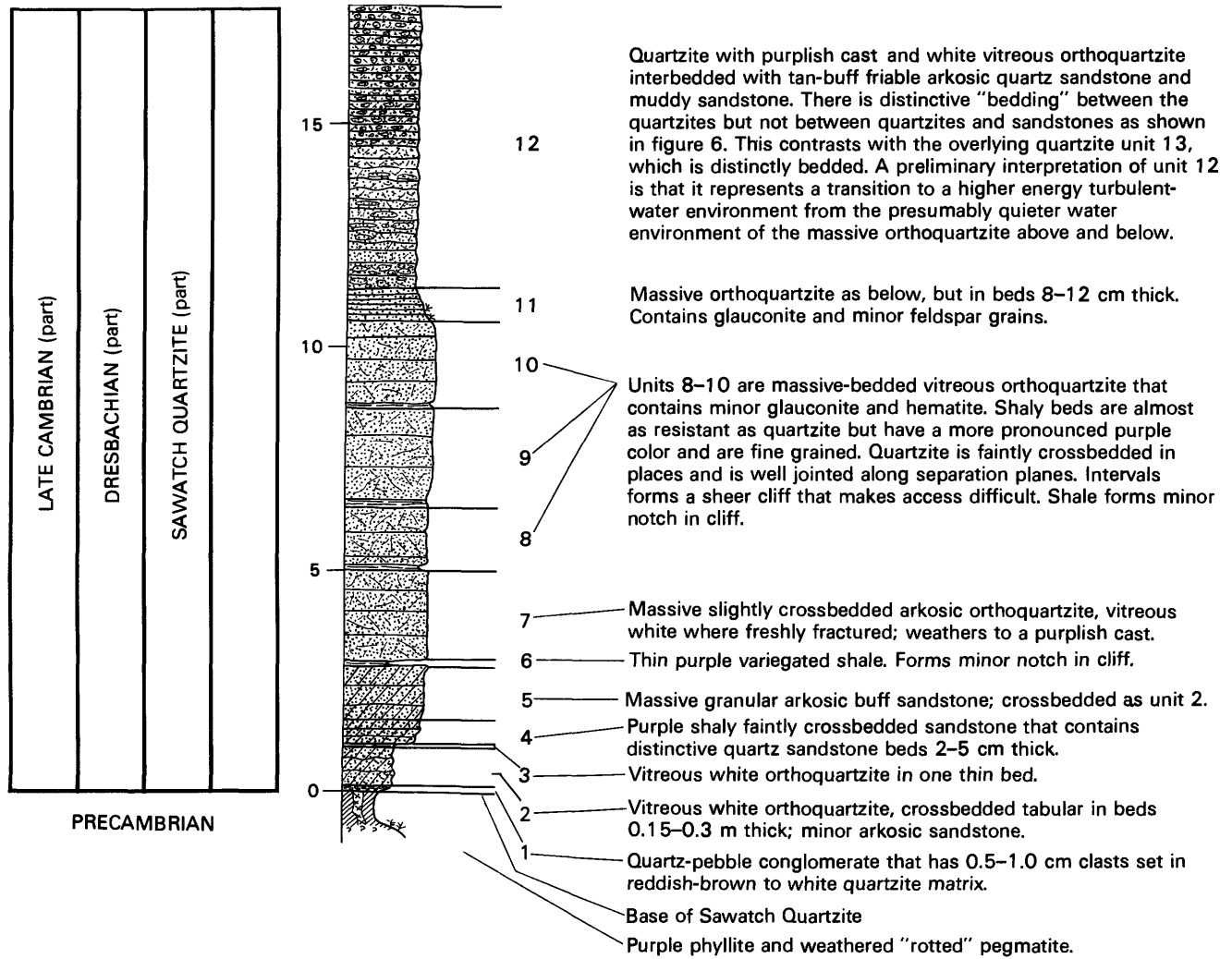
Appendix 1. Measured sections—Continued



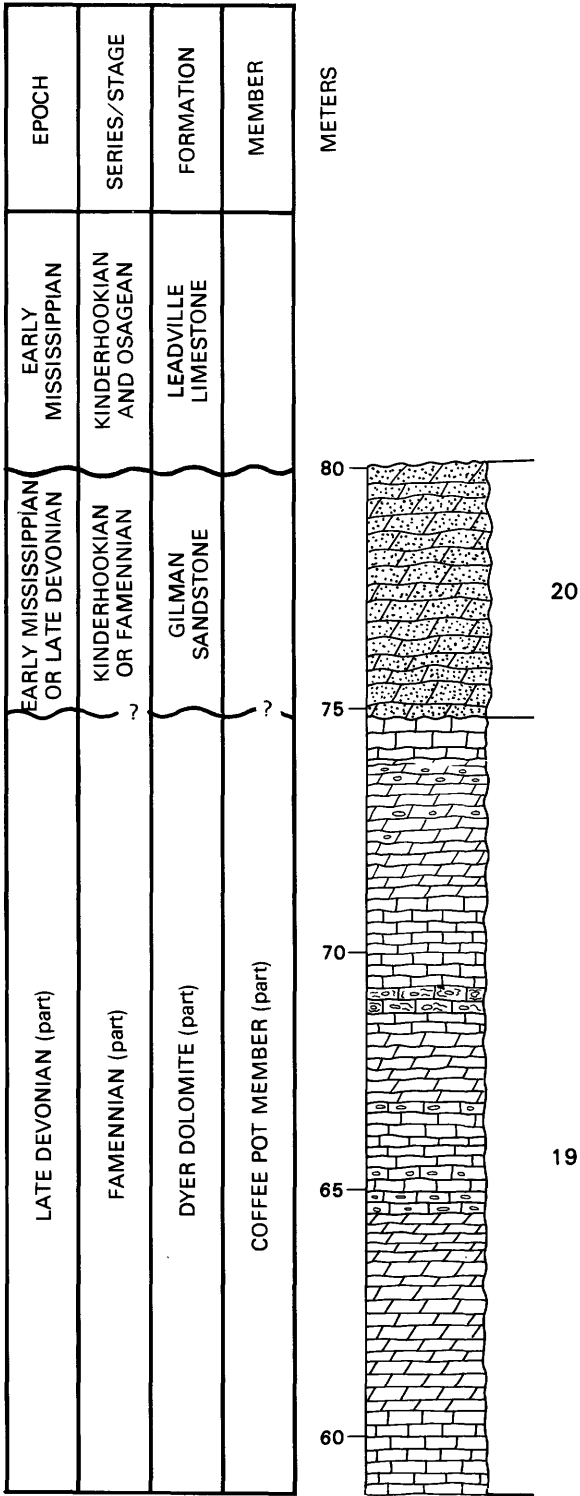
Appendix 1. Measured sections—Continued



Appendix 1. Measured sections—Continued



Appendix 1. Measured sections—Continued



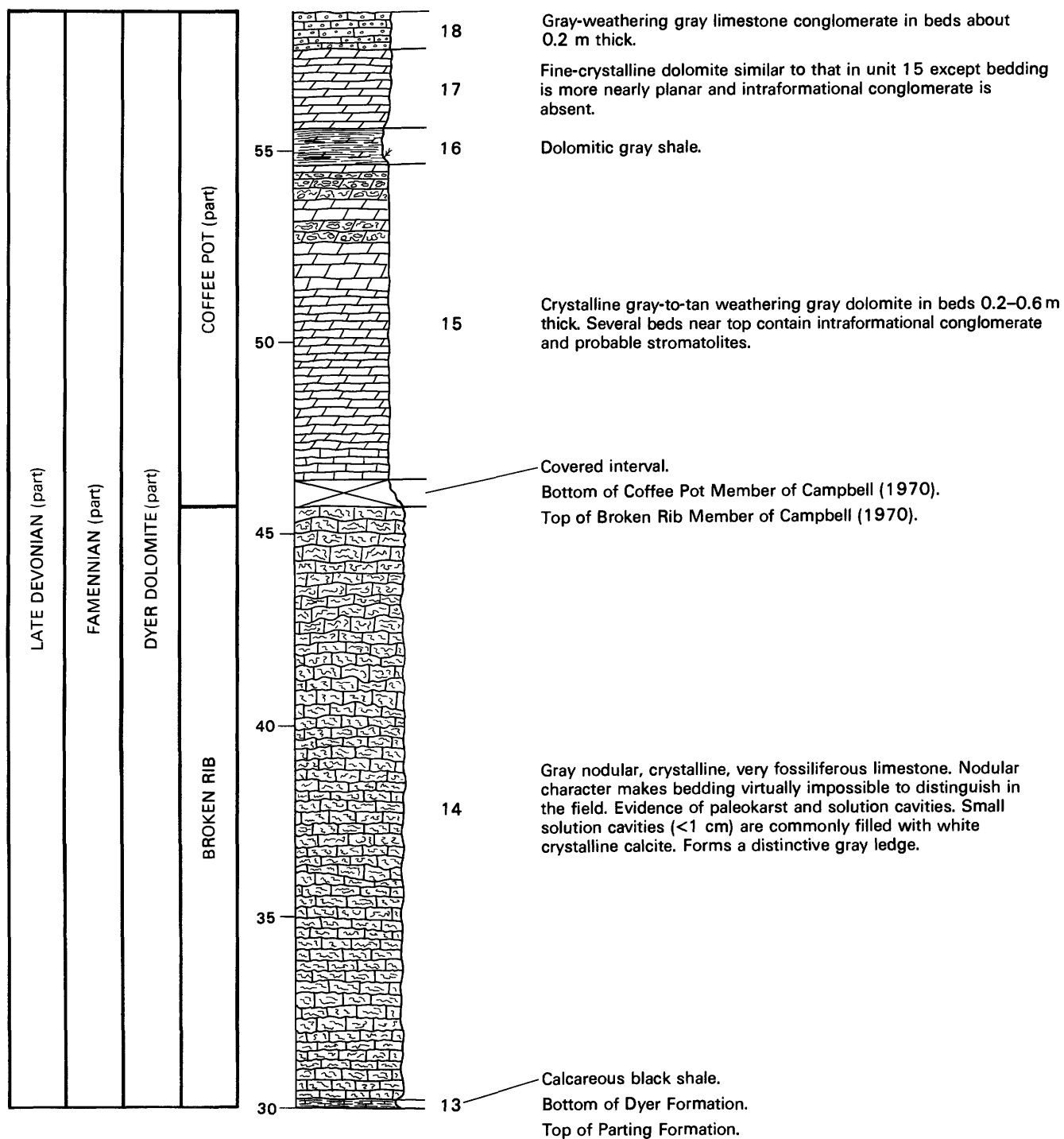
Section of Chaffee Group*, east end of Glenwood Canyon near Garfield–Eagle County Line, Garfield County, Colorado. S½, sec. 11, T. 5 S., R. 87 W.

*Redefined usage of Tweto and Lovering (1977).

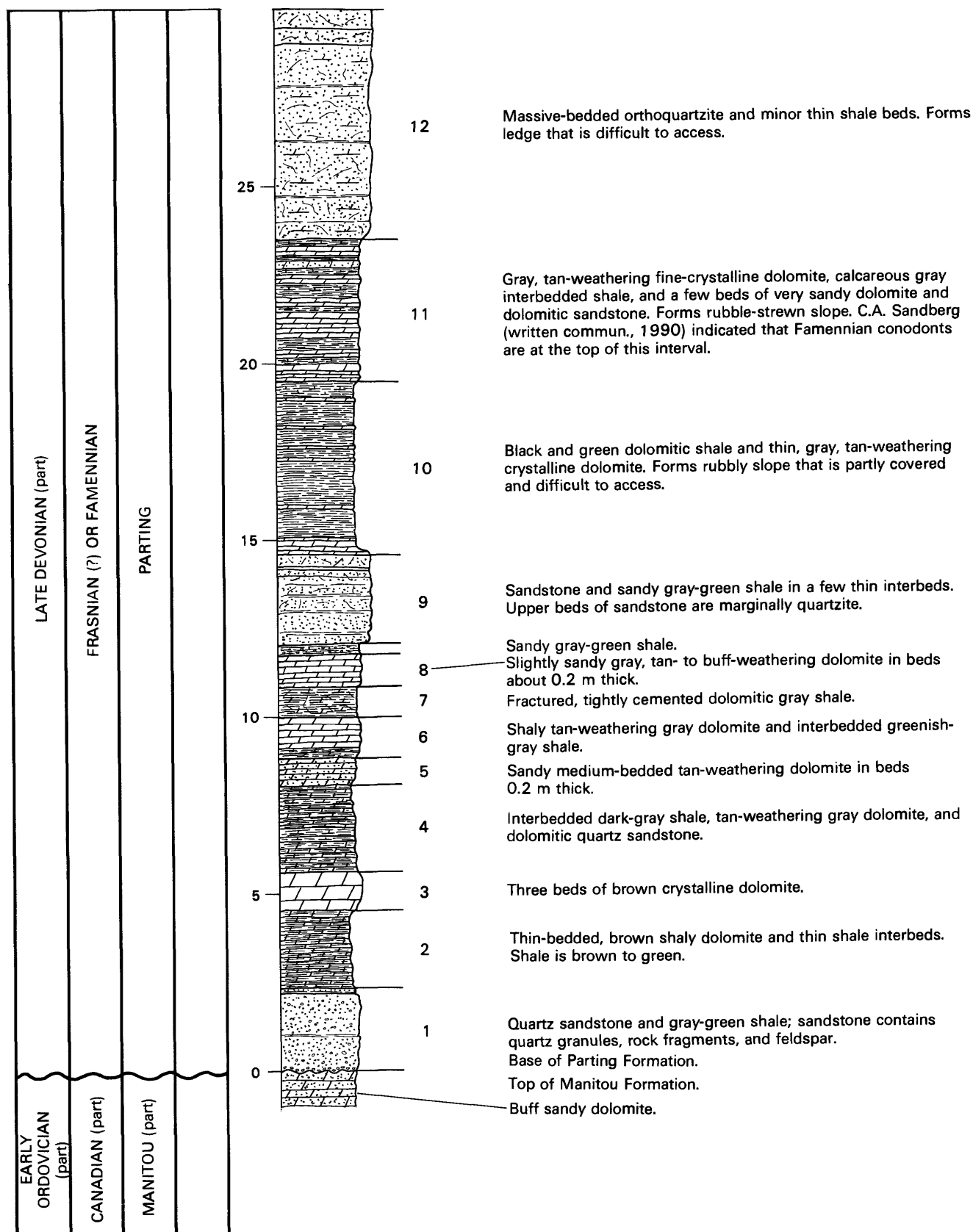
Tan-weathering gray dolomitic sandstone and light-tan-weathering gray sandy dolomite. Bedding 0.1–0.3 m thick. Forms a cliff that weathers to rubbly debris.

Interbedded tan- and gray-weathering gray fine-crystalline limestone and dolomite in beds less than 0.6 m thick. Some beds contain minor amounts of gray-white chert. Some beds contain intraformational conglomerate such as that in unit 15.

Appendix 1. Measured sections—Continued

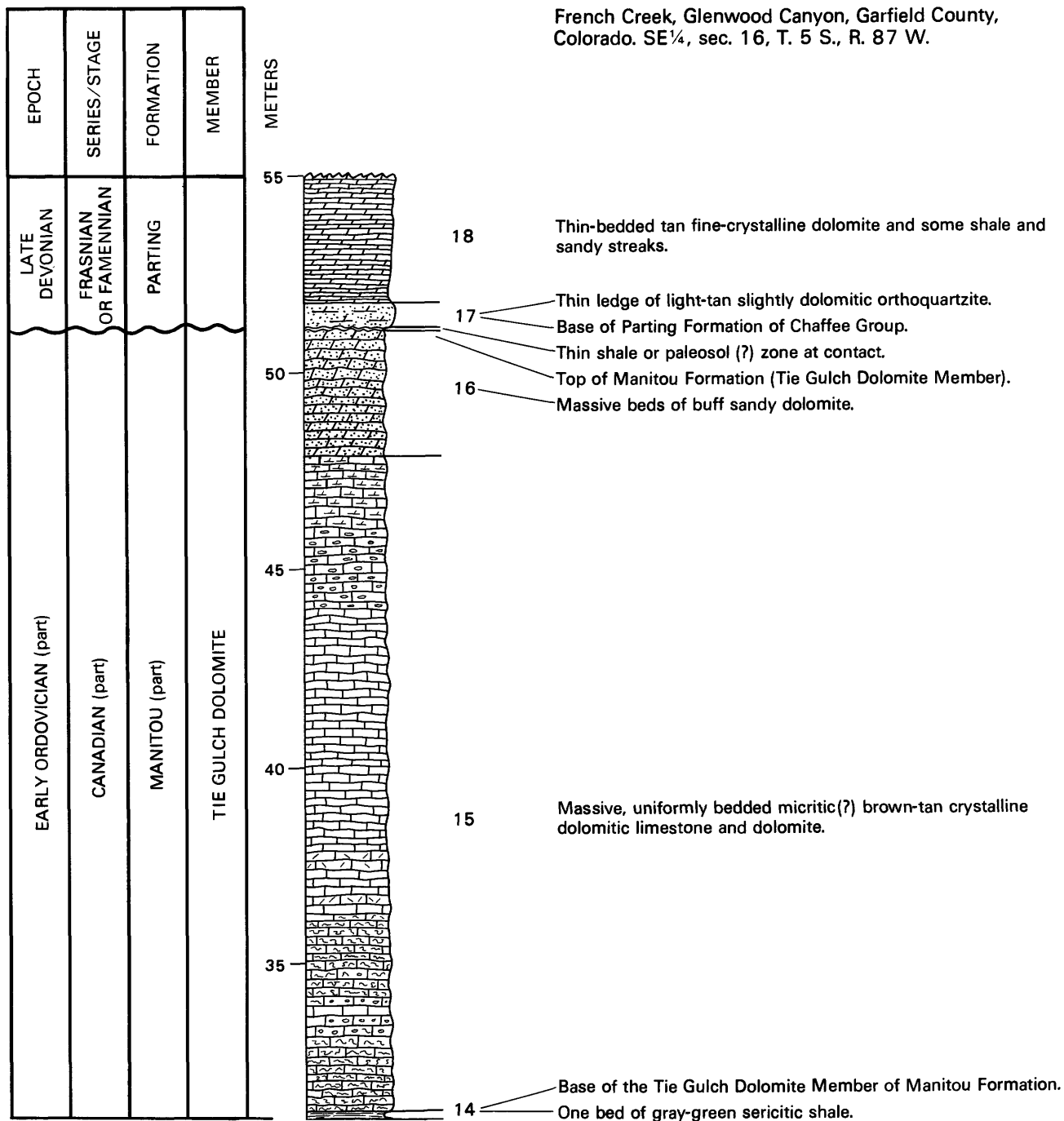


Appendix 1. Measured sections—Continued

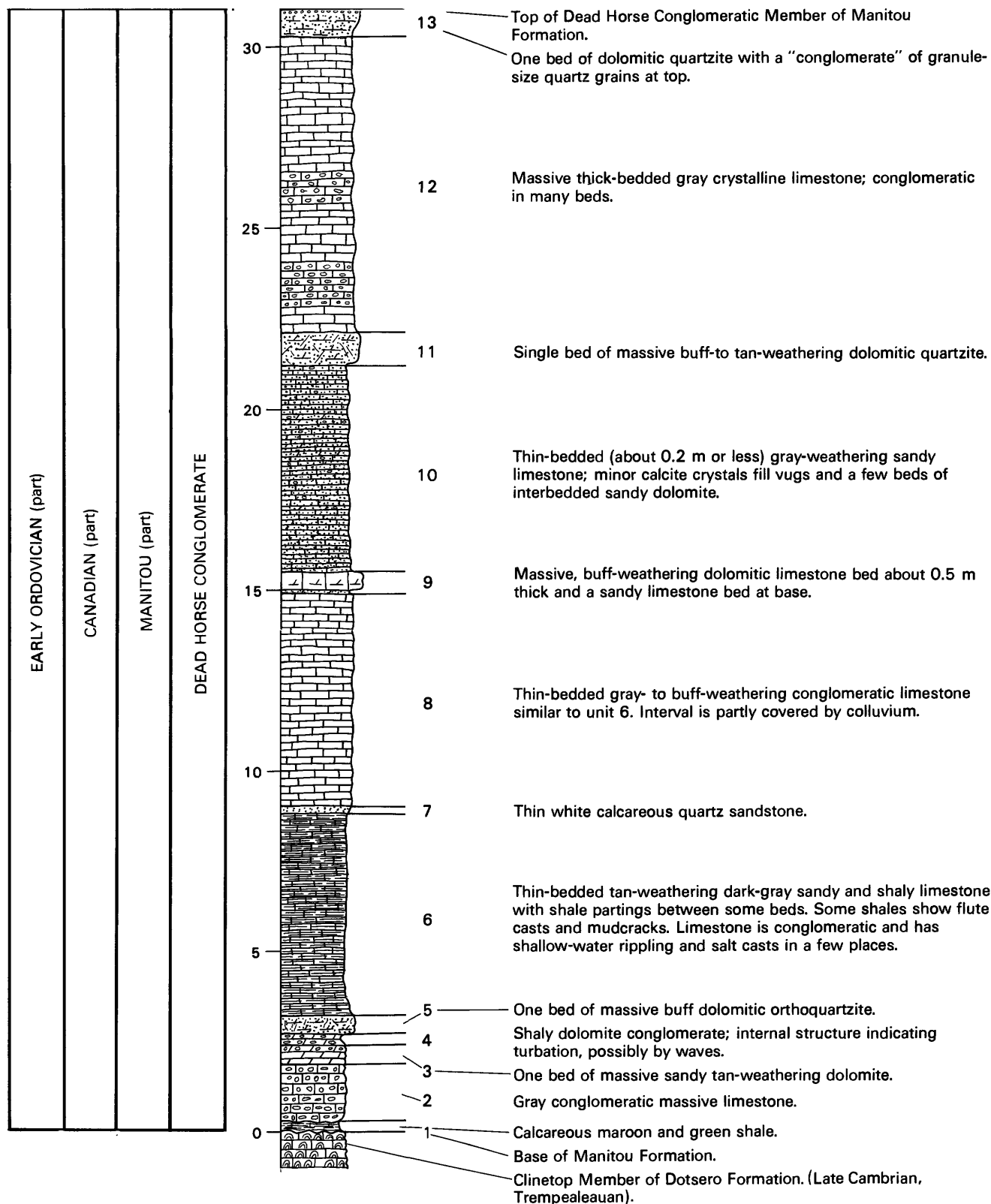


Appendix 1. Measured sections—Continued

French Creek, Glenwood Canyon, Garfield County,
Colorado. SE¼, sec. 16, T. 5 S., R. 87 W.



Appendix 1. Measured sections—Continued



Appendix 2. Oil and gas wells and test bores that penetrate Devonian and older rocks, northwestern Colorado

The oil and gas test bores listed are in the records of the State of Colorado Oil and Gas Conservation Commission and are the bores that I could find that penetrate Devonian and older rocks in northwestern Colorado. Available subsurface geophysical logs for these bores were also examined. A few important points about these drill holes are as follows.

1. Very few bores penetrate the Leadville (Madison) Limestone considering the size of the area studied. Almost all of those that do terminate in the Mississippian rocks in order to ensure that the entire Pennsylvanian section, the presumed exploration objective, has been drilled. The Mississippian limestones are easily identified in drill cuttings and geophysical logs.
2. Most of the bores that penetrate Devonian and older rocks were drilled to the Precambrian, which has been interpreted in some places to be in fault blocks that have overridden exploration objectives in younger rocks in the subthrust. Due to lack of correlations between sample- and geophysical-logs and surface sections and a paucity of knowledge about lower Paleozoic rocks in the deep parts of northwestern Colorado basins, I did not attempt to interpret further the geophysical logs. Most other interpretations have been aided by deep seismic data, most of which are proprietary and unpublished (see Stone, 1986, for recent published data). Geophysical log signatures are not distinctive enough to permit reliable interpretations of the lower Paleozoic section without additional information.

Oil or gas well or test bore and location	Comments
American Metal Climax Unit No. 1 Atchee. Sec. 24, T. 6 S., R. 104 W., Garfield County.	Vicinity of Uncompahgre uplift. See discussion of Garmesa fault zone in Stone (1977).
Arco 1–36 Sheepstead. Near corner of Tps. 8, 9 N., Rs. 99, 100 W., Moffat County.	Entered Uinta Group at 4,354 ft (1,327 m).
Arco 1–12 Sparks. Sec. 12, T. 8 N., R. 100 W., Moffat County.	Drilled Precambrian from 2,573 ft (784 m) to total depth at 11,464 ft (3,494 m) in an unsuccessful attempt to drill into younger rocks in footwall of fault.
Benedum-Trees Oil No. 1 Government Dougherty. Sec. 9, T. 1 N., R. 88 W., Garfield County.	See Campbell (1970a).
Champlin Refining No. Black. Sec. 9, T. 5 S., R. 84 W., Eagle County.	See Campbell (1970a). Near Eagle, Colorado.
E. American No. 1 Tulley. Sec. 35, T. 4 N., R. 103 W., Moffat County.	Total depth 10,231 ft (3,118 m) in Lodore Formation. See Powers (1986, p. 184).
Forest Oil No. 1 Government. Sec. 2, T. 7 S., R. 104 W., Garfield County.	Possible total depth in lower Paleozoic rocks.
Louisiana Land and Exploration Axial Federal Unit 11–23. Sec. 23, T. 5 N., R. 94 W., Moffat County.	Drilled 30 ft (9.1 m) of Devonian rock and 20 ft (6.1 m) of dolomite that may be Devonian or Ordovician Manitou Formation (Ross, 1986).
Louisiana Land and Exploration 31–22 Main Elk. Sec. 29, T. 4 S., R. 91 W., Garfield County.	Proposed as Precambrian test to 14,000 ft (4,267 m). See Osmond (1986, p. 217). No data available.
Miami Oil Producers, Inc. O'Brien 1. Sec. 14, T. 4 N., R. 90 W., Moffat County.	Bottomed in Precambrian Uinta Mountain Group; Beaver Creek anticline area.
Natomis North American 1–17 Rangely. Sec. 17, T. 1 N., R. 100 W., Rio Blanco County.	Total depth 14,013 ft (4,271 m) in Cambrian Sawatch Quartzite. See Osmond (1986).
Phillips Petroleum No. 1 Hells Hole Canyon, Sec. 12, T. 2 S., R. 104 W., Rio Blanco County.	Total depth 12,580 ft (3,834 m) in Devonian(?).

Appendix 2. Oil and gas wells and test bores that penetrate Devonian and older rocks, northwestern Colorado—Continued

Oil or gas well or test bore and location	Comments
Phillips Petroleum No. 15 Unit. Sec. 14, T. 1 S., R. 102 W., Rio Blanco County.	None.
Pure Oil Company No. 1 Blue Mountain Unit. Sec. 35, T. 4 N., R. 102 W., Moffat County.	Drilled 2,688 ft (819 m) of Precambrian rocks. See Powers (1986, p. 184). Willow Creek anticline area.
Southern Union Pagoda Government 26–35. Sec. 26, T. 4 N., R. 89 W., Routt County.	Bottomed in Precambrian granite.
Tenneco Oil Company No. 1 Margie Hicks. Sec. 3, T. 3 N., R. 103 W., Moffat County.	Drilled Lodore Formation in Willow Creek thrust fault(?). See Powers (1986, p. 184). Willow Creek anticline area.
Texaco Unit 66 (Wilson Creek Field). Sec. 34, T. 3 N., R. 94 W., Rio Blanco County.	See composite log in Stone (1975).
Texas Co. No. 70–30 UPRR (Rangely Field). Sec. 32, T. 2 N., R. 102 W., Rio Blanco County.	Total depth 9,360 ft (2,853 m) in Cambrian(?) rocks.

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