Stratigraphy, Depositional Environments, and Paleogeography of Coal-Bearing Strata in the Upper Cretaceous Mesaverde Group, Central Grand Hogback, Garfield County, Colorado

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By DAWN J. MADDEN

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New correlations of the Trout Creek Sandstone Member and adjacent sandstone members between Rifle Gap and New Castle and new paleogeographic sketches for the oscillating shorelines at the time of Exiteloceras jenneyi *and* Didymoceras cheyennense

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By DAWN J. MADDEN

ABSTRACT

Marine and nonmarine strata in the upper part of the Iles and lower part of the Williams Fork Formations of the Mesaverde Group form the richest coal section between Rifle Gap and New Castle, Colorado. Within these strata, the ammonites *Exiteloceras jenneyi* and *Didymoceras cheyennense* indicate a late Campanian age for the section, which is 1,000–1,400 feet (305–430 meters) thick. This study distinguishes formal members, the Trout Creek Sandstone Member and Cozzette Sandstone Member of Young (1982) of the Iles Formation, and new informal units. Unit contacts coincide with horizons separating offshore marine, and fresh to brackish-water nonmarine strata. Differences in paleosalinity are indicated by marine mega- and microfossils, and great trace-fossil diversity; brackish-water gastropods and pelecypods (some occurring in bioturbated intervals); and fresh-water gastropods.

Sedimentary structures provided evidence for reconstructing paleobathymetry. Outer-offshore deposits are structureless silty mudstone, bearing grain-lined tubes of *Terebellina*; inner-offshore deposits are storm-deposited, scour-based, hummocky-bedded sandstone, and silty mudstone, locally bearing a diverse trace-fossil assemblage. Shoreface sandstone contains low-angle trough crossbedding and *Ophiomorpha*.

Seven depositional cycles are recorded in the stratigraphic section. Each of these cycles, from base to top, consists of offshore, shoreface, and onshore delta-plain strata. The latter are fluvial deposits with minor coal and brackish-water bayfill.

Paleocurrent data indicate that shoreline-normal storm scour occurred in the offshore; shoreline-parallel sand transport to the south occurred in the shoreface; and seaward sediment transport occurred onshore. Coastal deposition was controlled by deltas supplying sediment to shallow, longshore-migrating, bar-trough systems. Delta shifting resulted in interfingering of marine and nonmarine strata and in shoreline realignments recorded by paleocurrent indicators.

New correlations of marine-sandstone members of the upper part of the Iles Formation along the central Grand Hogback presented here are based on field mapping. The sandstone commonly referred to as the Cozzette Sandstone Member in Rifle Gap can be traced to the Rollins Sandstone Member at New Castle, where the sandstone is overlain by the Wheeler coal bed. This interpretation differs from previous correlation of the Trout Creek Sandstone Member in Rifle Gap with the Rollins Sandstone Member at New Castle. The new interpretation presented here suggests that the Trout Creek and Rollins sandstones are separated by 310–450 feet (94–135 meters) of strata along the central Grand Hogback, with the Rollins lying stratigraphically below the Trout Creek. The new correlation of these marine-sandstone members influences the paleogeographic reconstruction of the local, late Campanian shoreline.

Manuscript approved for publication, March 23, 1988.

INTRODUCTION TO STRATIGRAPHIC PROBLEMS ALONG THE GRAND HOGBACK

The Grand Hogback winds through west-central Colorado from Meeker southeastward to the area of Redstone (fig. 1). Its central part contains the Grand Hogback coal field, which is approximately 60 miles (97 km) northeast of Grand Junction. The study area is within this coal field, along the 12-mile (19.3 km) length of hogback stretching from Rifle Gap to the site of New Castle, on the Colorado River (fig. 2). Access is from Interstate Highway 70, which is parallel to the Colorado River.

The sequence discussed in this report is exposed along the central Grand Hogback among steeply dipping Upper Cretaceous strata of the Mesaverde Group. This group is subdivided into the Iles and Williams Fork Formations (fig. 3). The part of the group under study ranges in thickness from 1,000 ft (305 m) to 1,400 ft (427 m) and dips 50°–80° to the southwest. This structural inclination resulted from regional Laramide tectonic stress which deformed the rocks sometime between the middle Eocene and early Oligocene (Tweto, 1975). The study section spans the upper part of the Iles and lower part of the Williams Fork Formations and is further subdivided into formal members and informal units of intertonguing marine, brackish- and fresh-water, coal-bearing strata. Description of marine strata in the lower part of the Williams Fork Formation is especially significant. As much as 800 ft (244 m)

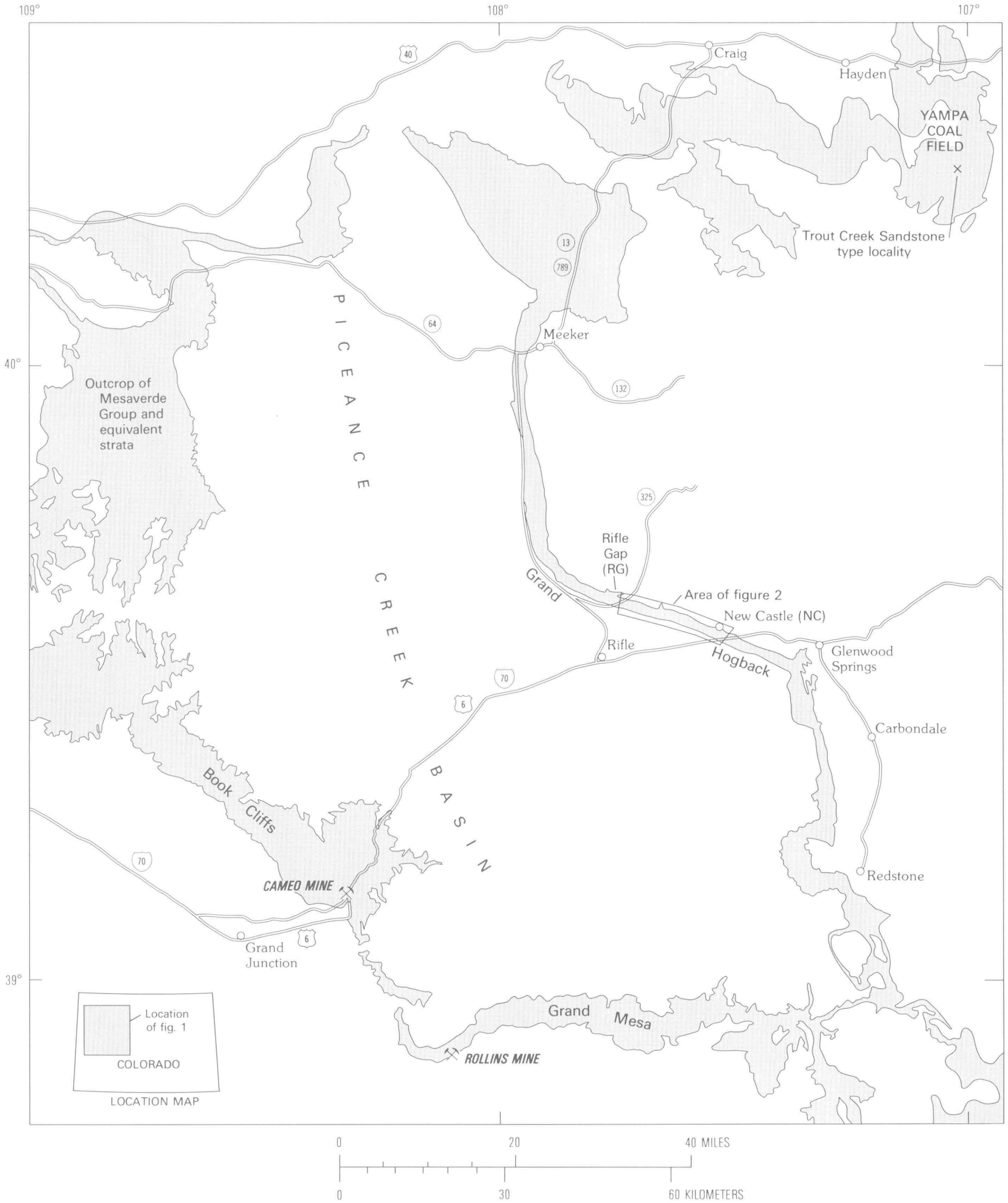

Figure 1.—Index map of northwestern Colorado.

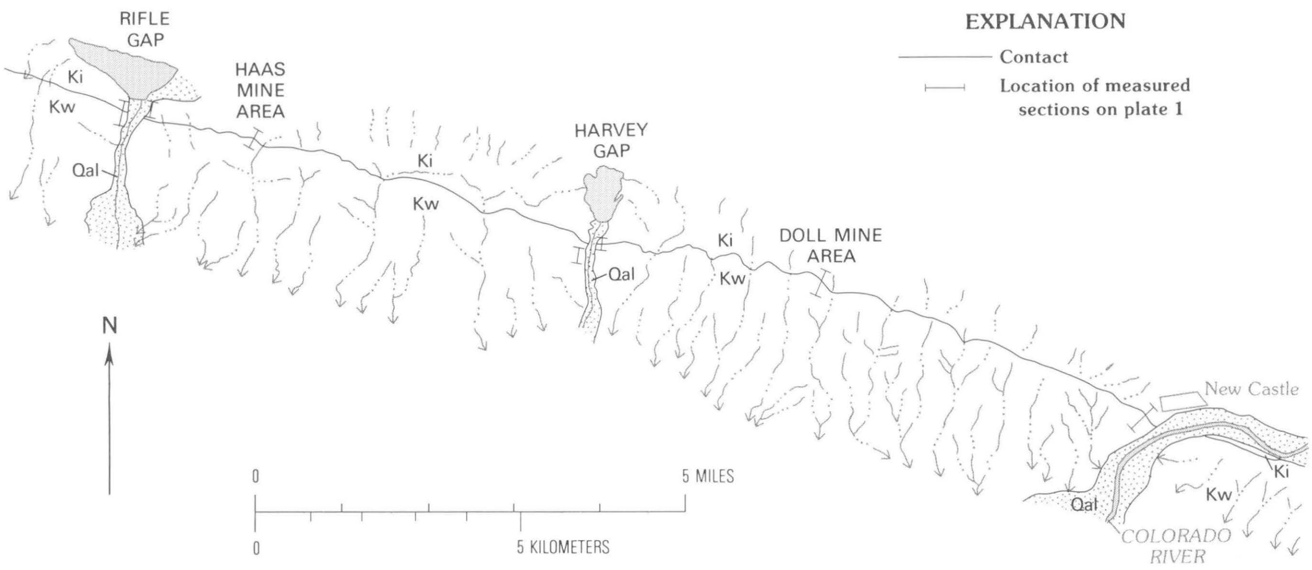

FIGURE 2.—Map of central Grand Hogback showing locations of measured sections. Qal, alluvium; Ki, Iles Formation; Kw, Williams Fork Formation; dash-dot lines, drainages; shaded areas are reservoirs.

of the lower part of the Williams Fork Formation, formerly considered nonmarine, is interpreted here as intertonguing marine and nonmarine strata.

The presence of coal in the central Grand Hogback led me to a field study of these deposits to determine correlations among sandstones and coal zones, thickness and extent of the coal beds, environments of deposition of the coal-bearing strata, and the nature of this part of the Late Cretaceous coastline. Earlier workers studying other areas of the southern Rocky Mountains interpreted Upper Cretaceous strata as the deposits of two different coastal types: barrier-bar and lagoonal deposits of an interdeltaic coast (Young, 1955; Masters, 1967), and delta-plain and delta-front deposits (Weimer, 1961; Newman, 1965a; Collins, 1970; van de Graaf, 1972; and Boyles and others, 1981).

Correlations of marine sandstones provide essential data for making coal-resource calculations and for determining the shape of the oscillating, Late Cretaceous shoreline. Two formal sandstone members, the Cozzette and Trout Creek, already had been carried through the central Grand Hogback area by Warner (1964), who correlated units by matching measured sections. In this manner, he had correlated his Rollins Sandstone Member of the Mesaverde Formation at New Castle to the Trout Creek Sandstone Member of the Iles Formation in Rifle Gap. He did not trace individual beds continuously either on the ground or on aerial photographs (Warner, 1964, p. 1098). Later, Murray (1966, p. 81) raised doubt about these established correlations when he could not trace the Trout Creek Sandstone Member southeastward from Harvey Gap to Fourmile Creek, using aerial photographs. This led to the question of what became of the Trout Creek Sandstone Member southeast of Harvey Gap. Did the Trout Creek thin out seaward to be replaced by a slightly higher, thick marine sandstone called the Rollins?

To find out the extent of the Trout Creek Sandstone Member southeast of Harvey Gap, I field traced the sandstone southeastward to New Castle. During my mapping, it became evident that to the east of Harvey Gap the Trout Creek loses its white-weathered top and thins considerably. In addition, its overlying coal-bearing sequence thins drastically, and pinches out at New Castle. These are the reasons why the unit cannot be traced on aerial photographs between Harvey Gap and Fourmile Creek (Murray, 1966).

To determine environments of deposition in the central Grand Hogback, several questions needed to be answered. Were the coal-rich rocks deposited on vast delta plains ribbed by distributary channels? If so, did channel-fill deposits preserved above scour surfaces exist as evidence for deltaic sedimentation? Or, alternatively, were the rocks deposited along an interdeltaic coastline, in marshes and swamps inland from barrier-bar and lagoonal environments? And if this alternative setting existed, was the expected evidence preserved—in the form of thick lagoonal sequences of marine and brackish-water deposits, interlayered with fresh-water deposits, above the nearshore marine sandstone units? What were the dominant sediment-transport directions in the different units? What were the shoreline orientations? How did the Late Cretaceous shoreline compare with modern ones? In particular, how did it compare

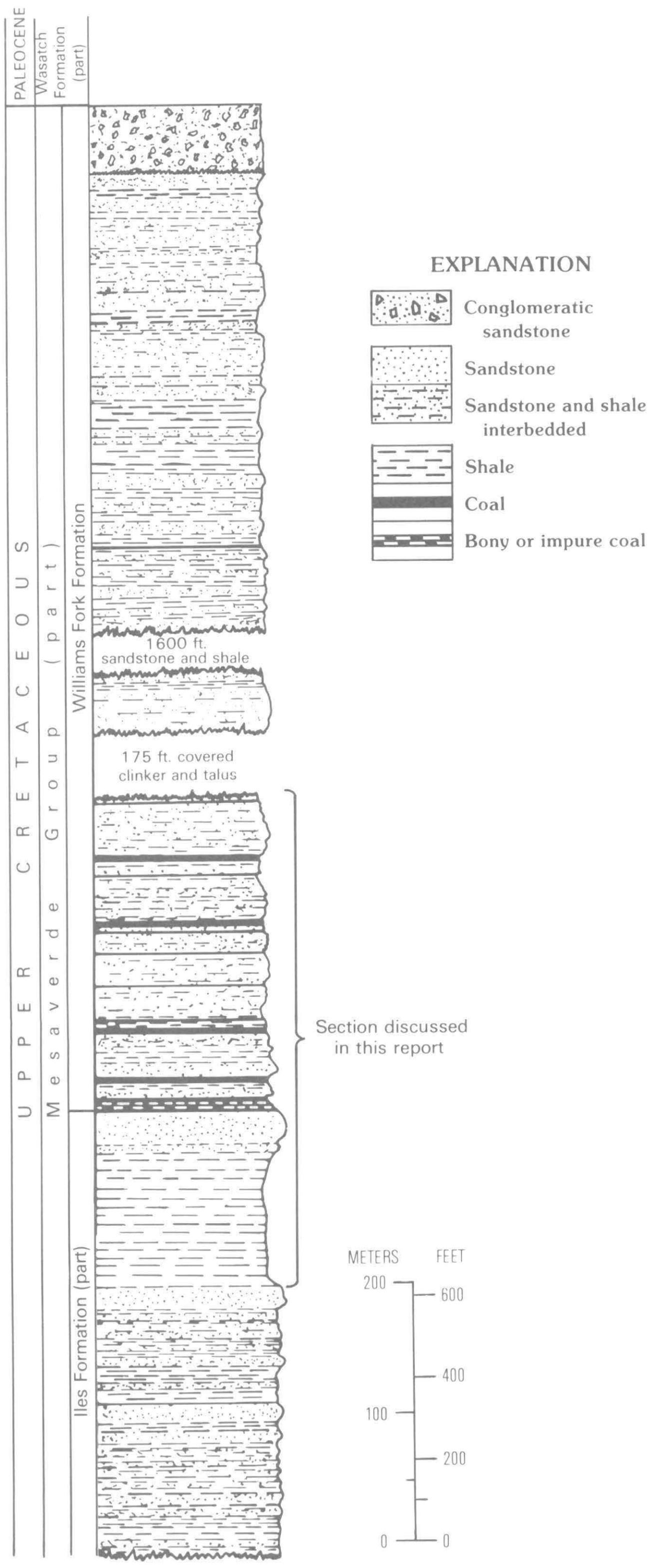

FIGURE 3.—Stratigraphic column of the Mesaverde Group in Rifle Gap, showing section discussed in this report. Compiled from Horn and Gere (1959), Warner (1964), Murray (1966), and Collins (1976).

with the modern, barred coastline of the African Niger Delta, which has served as a standard for comparison with Upper Cretaceous deposits in central and eastern Utah (van de Graaf, 1972) and the Piceance Creek basin in western Colorado (Collins, 1970, 1976).

I collected specific field data to address these questions about the formation of the coal-rich strata, which are exposed in barely accessible canyons and ridges of the steep and rugged central hogback. I traced coal beds and thick, massive-weathering sandstone units between the most accessible canyons, and I measured sections in these canyons to describe lithology, grain size, bedding thickness, primary sedimentary structures, paleocurrent directions, soft-sediment deformation, presence of root zones, types of trace fossils, degree of bioturbation, and types of body fossils (pl. 1). The paleocurrent data were corrected for tilt in the field, following the method of Briggs and Cline (1967) and Potter and Pettijohn (1977). Only sparse data were collected because of the nature of the outcrops and limited field time. However, the data which are available show internal consistency and thus are used to support hypotheses about nearshore depositional processes and shoreline orientations.

This study documents evidence for deposition along wave-dominated, sand-rich, deltaic and strand-plain coasts that swept across the area which is now the eastern Piceance Creek basin. Local embayment of the coastline is indicated by the lateral facies relations of marine strata distributed west-northwest of (inland from) thick coal deposits. The deltaic and wave-dominated nature of both embayed and unembayed coasts is indicated by these characteristics of the strata: (1) thick, dominantly shoreface-sandstone units on the scale of 100 ft (30.5 m); (2) dominantly longshore sediment-transport to the south and southwest, recorded in shoreface deposits; (3) few distributary-channel-fill beds above shoreface deposits, in contrast to strata formed in river-dominated deltas; and (4) minor amounts of brackish-water deposits and lack of thick, lagoonal sequences above shoreface deposits (pl. 1). These coasts were prime areas for the formation of very thick, lenticular peat deposits because of the balance between the rates of sedimentation and subsidence. These peat deposits altered through ages of burial to become beds of high-volatile C bituminous coal (Collins, 1976).

The coal-resource potential of the central Grand Hogback was of interest because of the history of coal mining in the area and the very thick beds of bituminous coal known at New Castle. One of these coal beds, the Wheeler, was reported to be 45 ft (14 m) thick (Gale, 1910). Perhaps additional thick coal beds remained to be discovered. At the same time, however, the coal-resource potential of the area was questionable because most of the central hogback contained clinker, where coal beds had burned. How much coal remained unburned? Also, old, abandoned mines and prospects were numerous. So, did any thick coal beds remain which were unmined? As a partial answer to this last question, during field mapping in 1979, I found numerous thick coal beds (pl. 2) in accessible areas far from Rifle Gap, Harvey Gap, and New Castle.

The geologic map (pl. 2) shows coal beds traced along the central Grand Hogback. The beds occur in the Iles and lower part of the Williams Fork Formations. Most beds are stratigraphically higher than the Cozzette Sandstone Member of Warner (1964) at Rifle Gap and lower than the totally nonmarine, upper part of the Williams Fork (pls. 1 and 2), with two exceptions. One exception is the coal mapped, but not otherwise discussed here, above the Corcoran Sandstone Member of Warner (1964) in Rifle and Harvey Gaps. Coal in this interval was mined in the Zeiseniss and McLearn "Big Three" mines in Rifle Gap and in the Harvey Gap Nos. 2 and 3 mines. Elsewhere, to the east-southeast, no minable coal overlies the Corcoran Sandstone Member, so the sandstone is not mapped on most of plate 2. The other exception occurs high in the Williams Fork Formation where beds in the Keystone coal zone were mapped and shown on plate 2. No detailed sections were measured in this interval, so neither this zone nor its enclosing strata are discussed in this report or included on plate 2.

This report contains discussions of stratigraphy and paleogeography followed by conclusions. The section on regional stratigraphy provides a regional stratigraphic framework for discussion of local stratigraphy. Following the section on regional stratigraphy, the sections on local stratigraphy describe eight units of marine shale, nearshore-marine sandstone, and coal-rich intervals. Seven of these units are informal, named only for ease in discussion; the other is the formal Trout Creek Sandstone Member of the Iles Formation. Underlying these eight principal units is the formal Cozzette Sandstone Member of Warner (1964) in Rifle Gap, which is briefly discussed. The stratigraphic discussions present descriptive data regarding lithology, sedimentary structures, and fossils followed by interpretations under the subheading of "depositional conditions." Following the stratigraphic discussions are paleogeographic descriptions for each marine unit.

ACKNOWLEDGMENTS

This report benefited from the support of many people. K.R. Newman contributed in the field and offered suggestions during writing. J.M. Boyles provided valuable discussion and suggestions during early field studies. W.A. Cobban identified the marine and brackish-water body fossils, and A.K. Rindsberg helped identify trace fossils. C.A. Wallace, P.K. Theobald, D. Seeland, V.L. Freeman, and R.A. Scott provided helpful reviews which improved the manuscript. A. Moore-Nall helped prepare the illustrations. C. Lisowski, M. Billone, and C. Vassalluzzo typed the manuscript.

REGIONAL STRATIGRAPHY

REGIONAL SETTING AND TIME-STRATIGRAPHIC CORRELATIONS

The study section is within the Mesaverde Group. The Mesaverde is part of a clastic wedge shed eastward during Late Cretaceous time from the Sevier uplift in Utah toward an interior seaway that extended from north to south across the center of the continent. This wedge consists of intertonguing marine and nonmarine rocks in northwestern Colorado, grading westward to predominantly nonmarine deposits and eastward to predominantly marine deposits. To the west, time-correlative nonmarine deposits in central Utah are grouped together into the Price River Formation (McGookey and others, 1972). To the east, time-correlative marine strata in eastern Colorado are grouped together into the Pierre Shale (Weimer, 1960; McGookey and others, 1972).

Regionally, the section described here correlates in age with portions of Upper Cretaceous regressive sequences in the Rocky Mountain region based upon collections of fossil marine molluscs. Northward, the section correlates in age with part of the middle part of the Montana Group of the Western Interior reference section (McGookey and others, 1972). In the central Rocky Mountains it correlates with part of the R_3 regional regression of Weimer (1960), parts of the upper Iles transgression (TC) and lower Williams Fork regression (RD) of Zapp and Cobban (1960, p. B248), and the lower portion of the regionally recognized R9 regression of Kauffman (1977, p. 85).

MESAVERDE GROUP

The Mesaverde Group of northwestern Colorado consists of sandstone, shale, and coal overlying the Upper Cretaceous Mancos Shale and lying unconformably below the Paleocene and Eocene Wasatch Formation. The Mesaverde Group crops out from the Yampa coal field westward through the town of Meeker and southward along the Grand Hogback through the town of New Castle, on the Colorado River (fig. 1). Farther southward, where the sequence has not been divided, these strata have been called Mesaverde Formation rather than Mesaverde Group (Lee, 1909, 1912; Burbank and others, 1935; Poole, 1954; Hanks, 1962; Warner, 1962, 1964; and Murray, 1966). Outcrop thickness of the group ranges from 2,500–3,500 ft (763–1,068 m) in the Yampa coal field (Fenneman and Gale, 1906, p. 23) to more than 5,000 ft (1,525 m) along the Grand Hogback (Warner, 1964, p. 1093). The Mesaverde Formation thins southwestward to 2,500 ft (763 m) in the southern Grand Mesa (Young, 1955).

The Mesaverde Group is composed of the Iles and Williams Fork Formations. Their contact is at the top of the Trout Creek Sandstone Member of Fenneman and Gale (1906), which caps the Iles Formation. Though the Trout Creek Sandstone Member has been considered to be generally the highest marine sandstone in the Mesaverde Group in the northern Piceance Creek basin (Granica and Johnson, 1980), higher marine-sandstone units occur in the central Grand Hogback. Johnson (1982) documented one in Rifle Gap, and Madden (1983) differentiated four nearshore-marine-sandstone units above the Trout Creek Sandstone Member in Harvey Gap. Both the Iles Formation and the lower part of the Williams Fork Formation consist of intertonguing marine and nonmarine strata. The difference between the two formations is the presence in the Iles of thick, dark-gray, marine-shale sequences that do not occur in the overlying, sandier Williams Fork Formation. To the south, the Mesaverde Formation consists of sandstone, shale, and coal. The base of the Mesaverde Formation is the base of a prominent, massive sandstone with a white top called the Rollins Sandstone Member (Lee, 1909, 1912).

The stratigraphic terminology of Hancock (1925) is used in this paper. This terminology involves the use of the term Mesaverde Group in the northern Piceance Creek basin. In the southern Piceance Creek basin, the strata comprise only one formation rather than two; as stated, this formation is called the Mesaverde Formation. The Mesaverde lacks a member called the Trout Creek Sandstone Member and includes a basal member called the Rollins Sandstone Member. The two sandstone members once were considered equivalent units but this study indicates that they are not equivalent. Use of Mesaverde Group and Trout Creek terminology in the central Grand Hogback is appropriate because (1) the Iles and Williams Fork Formations and the Trout Creek Sandstone Member all have been traced from their type localities through the central Grand Hogback by earlier workers; (2) the Trout Creek Sandstone Member of the central hogback is underlain by additional marine-sandstone units and their associated coal zones which are characteristic of the Iles Formation and not of the Mancos Shale; and (3) the name Trout Creek of Fenneman and Gale (1906) has priority over the name Rollins of Lee (1909). Because of this priority and new correlations, the name Trout Creek Sandstone Member should be retained in the central Grand Hogback and not replaced with the name Rollins Sandstone Member.

COAL-BEARING STRATA OF THE CENTRAL GRAND HOGBACK

Two to seven shoaling sequences constitute the coal-bearing strata, and these sequences have been divided into formal and informal units. The lowest sequence begins in the upper part of the Iles Formation with the Rifle shale unit, a thick marine mudstone (110–310 ft, 34–95 m), and grades upward through the nearshore-marine Trout Creek Sandstone Member which is sharply overlain by coal-bearing deposits of the Songer coal-bearing unit. Higher sequences lack the thick basal marine mudstone. The sequences have been divided into the Rifle shale unit and Trout Creek Sandstone Member of the Iles Formation and the Songer coal-bearing unit, Doll sandstone unit, Haas sandstone unit, Silt coal-bearing unit, and Harvey and Henry sandstone units of the Williams Fork Formation (fig. 4). The Haas and Harvey sandstone units each record two shoaling sequences.

These late Campanian strata correlate in age with strata of other areas based on collections of ammonites. *Exiteloceras jenneyi* occurs in the Rifle shale unit in Rifle Gap, and *Didymoceras cheyennense* occurs in the Haas sandstone unit near New Castle (fig. 4). The time correlation of these ammonites and the lithology of the rocks in which they occur provide data for regional paleogeographic reconstructions.

SANDSTONE-MEMBER CORRELATIONS

The Cozzette and Trout Creek Sandstone Members are formal members of the Iles Formation following the use of Young (1982). These formal-member names are the ones used by Warner (1964) and later workers in Rifle Gap and are retained here because they have been used so widely. New data in this report suggest that the earlier correlations of the Cozzette, Trout Creek, and Rollins Sandstone Members must be modified in the Grand Hogback.

Young (1955) named the Cozzette Sandstone Member of the Price River Formation in the Book Cliffs, and Warner (1964) traced it to the central Grand Hogback

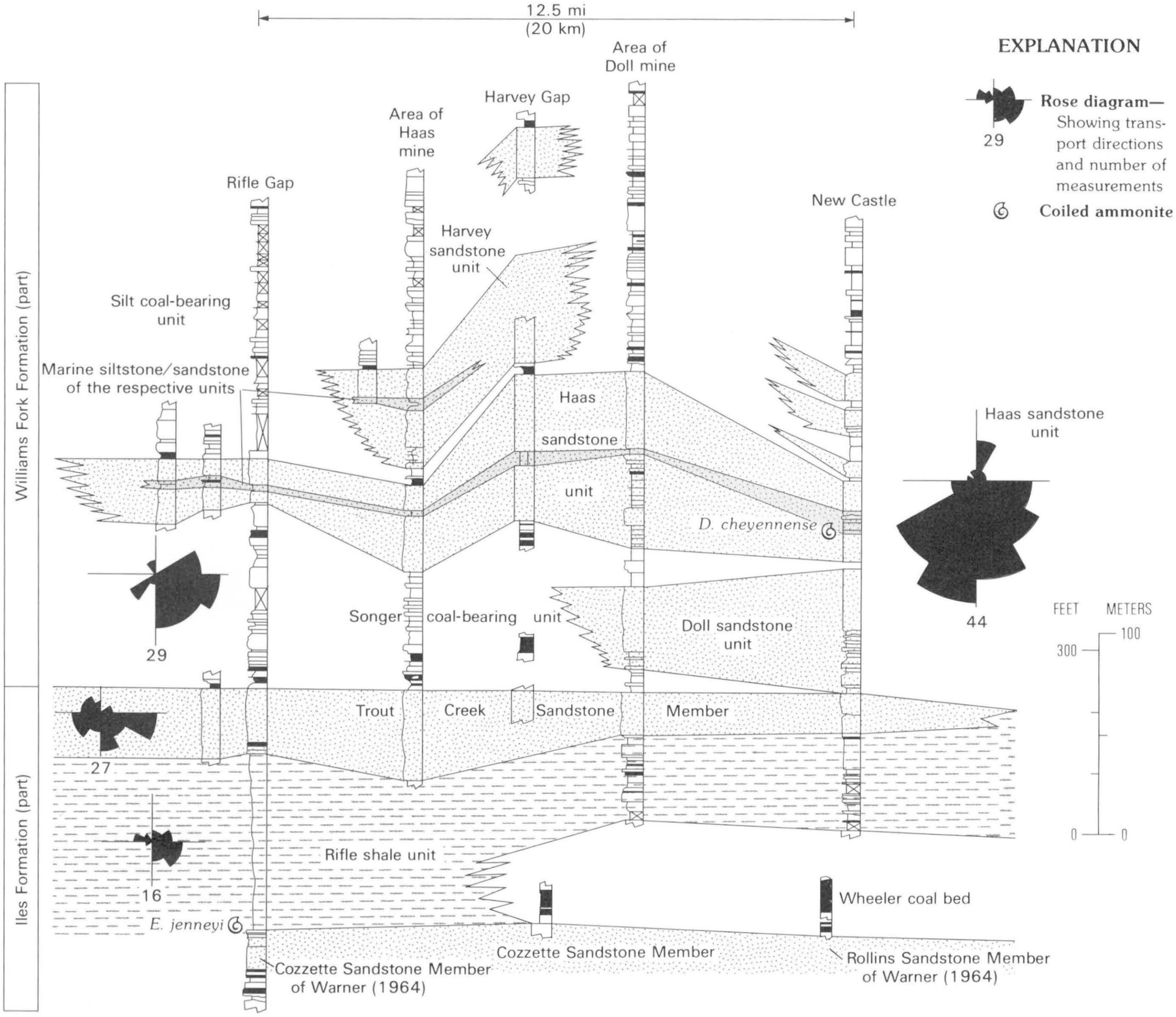

FIGURE 4.—Correlated, measured sections in the central Grand Hogback, from Rifle Gap to New Castle, showing units, sediment-transport directions, and ammonite localities. Ammonites are *Exiteloceras jenneyi* and *Didymoceras cheyennense*.

from its type locality. To do this, he traced the sandstone eastward through the subsurface to the southern Grand Hogback, then matched measured sections northwestward through the central and northern Grand Hogback. He did not trace individual beds on the ground or on aerial photographs, but matched marine shales based on what he thought were consistent thicknesses of these units (Warner, 1964).

Warner's identification of the Cozzette Sandstone Member in Rifle Gap has been used frequently in subsequent studies. He applied the name to a sandstone which underlies both a phosphate-nodule horizon and a collection of *Exiteloceras jenneyi* in Rifle Gap. The same two features overlie the Cozzette Sandstone Member in the southern Piceance Creek basin, which is more directly related to the type area because it lies in the direction from which Warner (1964) made his correlation. In the southern part of the basin the Cozzette shows a "nearly constant relationship to *E. jenneyi*," and the sandstone locally is overlain by phosphate nodules in both the Woody Creek quadrangle (V.L. Freeman, written commun., 1984) and in North Thompson Creek (Gill and Freeman, 1978).

Warner (1964) retained the name Trout Creek in Rifle Gap for the thick, white sandstone traced by surface correlations from its type locality on Trout Creek in the Yampa coal field southwestward to the central Grand Hogback (Gale, 1906, 1907, 1910; Hancock, 1925;

Hancock and Eby, 1930; Burbank and others, 1935; Horn and Gere, 1959; Tweto, 1979).

Established correlations of these formal sandstone members in the Iles Formation are reassessed here. One, the Trout Creek Sandstone Member, northern Piceance Creek basin, lies within the coal-rich sequence of the central Grand Hogback. Horn and Gere (1959) identified this sandstone in Rifle Gap, and later workers correlated it to the Rollins Sandstone Member of the southern Piceance Creek basin at New Castle (Warner, 1962, 1964; Collins, 1976; Johnson, 1982; Lorenz and Rutledge, 1987). However, more recent field mapping of these sandstones in the central Grand Hogback indicates that this correlation is not correct and that the Trout Creek and Rollins Sandstone Members are separated by 310–450 ft (95–137 m) of strata (fig. 5). When Warner (1962, 1964) first correlated the two sandstones, he suggested that the Trout Creek was lower in the section than the Rollins, but that the Trout Creek climbed stratigraphically to the southeast to connect with the Rollins. But the reverse is true in the central Grand Hogback: the Rollins Sandstone Member of Warner (1964) at New Castle lies about 450 ft (137 m) below the interval of the Trout Creek Sandstone Member of Rifle Gap. The miscorrelation of the two sandstones was first published by Gale (1910, plate XI, fig. 7), who correlated a sandstone and coal sequence along the central Grand Hogback. He correlated the Wheeler coal bed together with a thick, white underlying sandstone, from New Castle to Rifle Gap, without walking out the units. Gale's work influenced later correlations. Though Gale correlated unnamed sandstones, these sandstones were formally named elsewhere and eventually traced over great distances to the Grand Hogback long after Gale's work.

In descending order, beneath the Trout Creek Sandstone Member in Rifle Gap, are the Cozzette, Corcoran, and Sego Sandstone Members of Young (1955) interbedded with tongues of Mancos Shale. Young (1955) named these members in the Price River Formation of the Book Cliffs. From the Book Cliffs, Warner (1962, 1964) traced these sandstones through the subsurface to the Mancos Shale of the southern Grand Hogback. He then correlated them northwestward along the

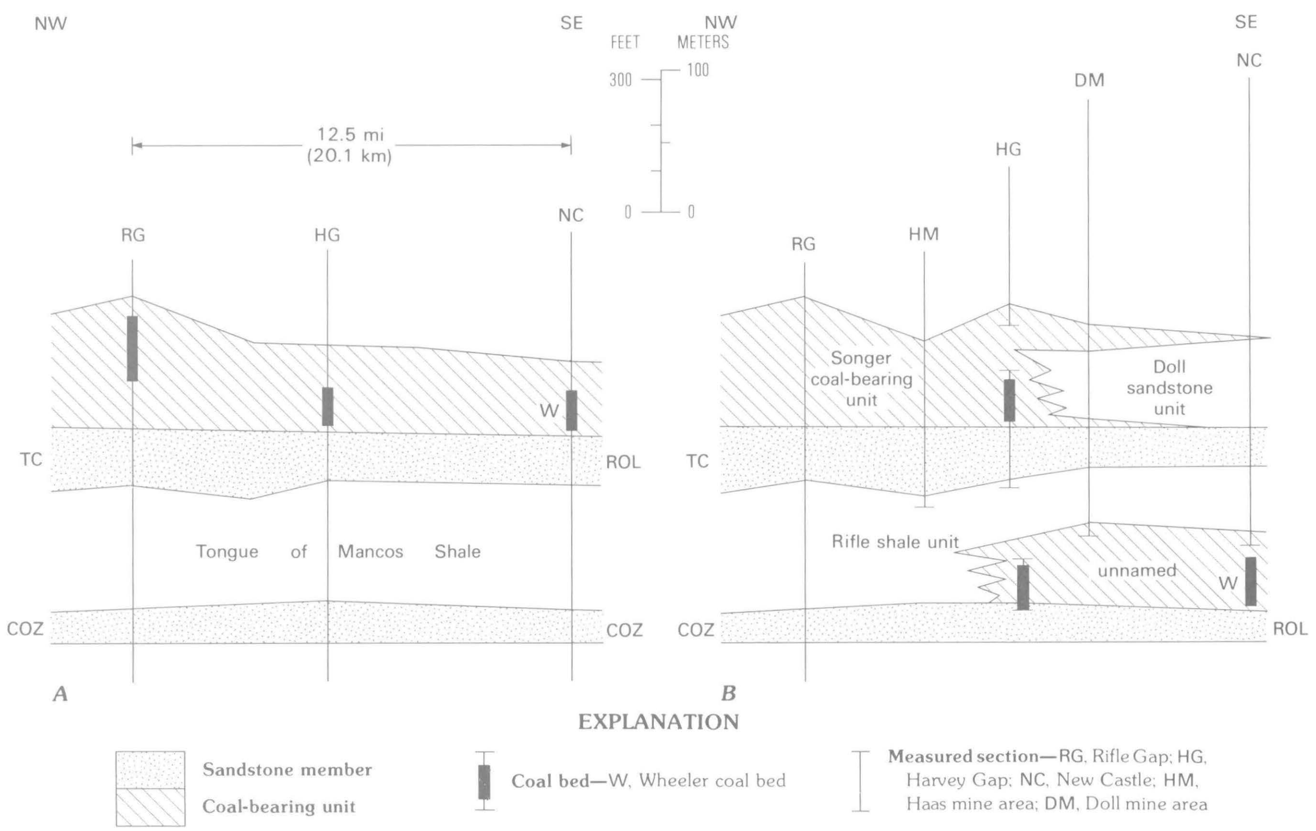

FIGURE 5.—Sketch showing comparative correlations of formal sandstone members, central Grand Hogback. TC, Trout Creek Sandstone Member of the Iles Formation; COZ, Cozzette Sandstone Member of the Iles Formation of Young (1982); ROL, Rollins Sandstone Member of Warner (1964), Mesaverde Formation. *A*, previous correlations (Gale, 1910; Horn and Gere, 1959; Warner, 1964; Johnson, 1982); *B*, new correlation (Madden, 1983).

Grand Hogback into the Iles Formation, passing through New Castle and Harvey and Rifle Gaps, by matching measured surface sections. However, my mapping of beds in the field between Warner's sections at New Castle and at Harvey Gap yields a correlation that is different from Warner (1964). For example, the Rollins at New Castle can be correlated with the Cozzette at Harvey Gap.

In this report, the formal sandstone names are based on lithologic correlations of previous workers, whereas the paleogeographic reconstructions are based on age correlation. The lithologic correlations are done by mapping and form the basis for extending unit names. Regional age correlations are based on fossil range zones and form the basis for sketches of the Late Cretaceous shoreline. Such sketches are based on the identification of time-equivalent strata throughout the region.

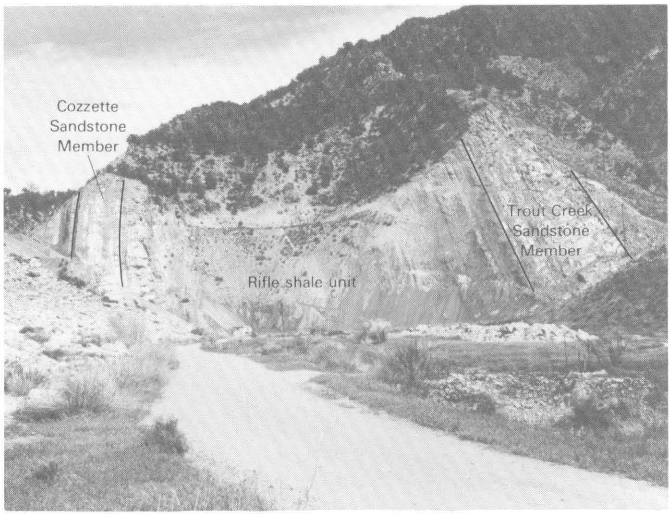

FIGURE 6.—The Rifle shale unit, east side of Rifle Gap.

RIFLE SHALE UNIT, ILES FORMATION

The oldest unit that I measured and fully described during this study is a silty mudstone within which beds of sandstone increase upward in number and in thickness. This unit is called the Rifle shale unit (Madden, 1985) for the excellent exposures on both sides of Rifle Gap (fig. 6). The Rifle shale unit is an informal unit between the Cozzette Sandstone and Trout Creek Sandstone Members of the Iles Formation identified by Warner (1964) and Horn and Gere (1959) in Rifle Gap. This shale is a tongue of the Mancos Shale which also has been called the "Trout Creek shale" (Madden, 1983) because of its position beneath the Trout Creek Sandstone Member.

The Rifle shale unit extends through much of northwestern Colorado. Its time-stratigraphic equivalence throughout the area is the result of deposition during a rapid, regional transgression. The shale crops out northward along the Grand Hogback through the Danforth Hills to the Williams Fork Mountains; it may underlie the Piceance Creek basin and crop out to the west in the Book Cliffs (Bass and others, 1955; Warner, 1962 and 1964; and Gill and Hail, 1975), though age correlation westward is uncertain because *Exiteloceras jenneyi* and *Didymoceras cheyennense* have not been found in the Book Cliffs.

Along the central Grand Hogback, the Rifle shale unit thins from Rifle Gap east-southeastward toward New Castle where it interfingers with underlying nonmarine, coal-bearing rocks. In Rifle Gap the unit is 310 ft (95 m) thick (fig. 6) and at New Castle it is only 110 ft (34 m) thick. The correlation is based on physically tracing the unit between the two areas. This east-southeastward thinning is due to thickening of an underlying wedge of coal-bearing strata that includes the 45-ft (14-m) Wheeler coal bed of Gale (1910).

Most of the shale is concealed beneath slope wash, but the lower and particularly the upper portions, near its contacts, are generally better exposed along the central hogback. The lower contact, above the Cozzette Sandstone Member, is well exposed and sharp in Rifle Gap. In this section, gray phosphate nodules and phosphatized twigs lie at the base of the Rifle shale unit. To the east-southeast this lower contact remains sharp, but it overlies nonmarine, coal-bearing rock beyond Harvey Gap. The upper contact with the Trout Creek Sandstone Member is locally sharp, but more commonly gradational because of the gradual upward increase in the number of sandstone beds and in bedding thickness in the Rifle shale unit.

LITHOLOGY

The composition of the Rifle shale unit varies gradationally upward from mudstone to interbedded sandstone and mudstone. The lower two-thirds of the Rifle shale unit is dark-gray, silty mudstone with thin interbeds of lower very fine grained sandstone. Calcareous siltstone concretions are most noticeable in this portion of the Rifle shale unit. Upward, bedding thickness and the abundance of sandstone increase. The upper one-third contains the most sandstone interbeds, and these contain organic detritus concentrated on bedding planes. Bedding thickness increases up to more than 6 in. (15.2 cm) within higher sandstone bodies.

DEPOSITIONAL SEDIMENTARY STRUCTURES

Hummocky cross-stratification and associated depositional structures dominate over features of bioturbation in the upper one-third of the Rifle shale unit, though a variety of isolated trace fossils occurs (discussed later). Structures commonly observed are (1) hummocky and flat bedding (fig. 7); (2) hummocky sequences H-F-M, H-X-M, and X-M, as described by Dott and Bourgeois (1982); (3) micro-hummocky, lens-shaped sandstone beds overlying erosional, first-order surfaces (Dott and Bourgeois, 1982); and (4) interbeds of fissile mudstone with finely macerated plant debris on bedding planes.

Scour surfaces are abundant in the hummocky cross-stratified sequences. These surfaces occur beneath sandstone overlying mudstone and within continuous beds of sandstone. For example, where sandstone cuts underlying mudstone, there are elongate, shallow erosional surfaces in mudstone (fig. 8) underlying some hummocky cross-stratified beds. In addition, internal, first-order erosional surfaces occur within seemingly continuous sequences of hummocky and flat-bedded sandstone. These surfaces would go unnoticed, being sandstone-on-sandstone contacts, except that they locally truncate underlying trace fossils, thus providing evidence for erosion.

The hummocky, cross-stratified sequences show varying degrees of burrow mottling. Most beds of sandstone are unburrowed, but a few beds are burrow mottled and some are completely bioturbated. Interbedded mudstone also ranges from unburrowed to completely bioturbated.

In the field, I took 16 measurements to determine paleocurrent directions. Seven of these measurements are from the orientations of elongate directions of shallow scour surfaces just mentioned, and nine of these measurements are directions normal to ripple bedforms and parallel to current lineations exposed on bedding surfaces. These measurements have a vector mean of 112°, and a standard deviation of 92°. The direction of flow of the scouring currents and the direction of sediment transport above the elongate, shallow scour surfaces could have been either to the southeast, or to the northwest, or both in an oscillatory current. The convention used in this study was to arbitrarily choose either a southeasterly or a northwesterly direction. The choice of direction was based on the orientation of inclined bedding overlying the scour surface. In fact, the scour and the deposition of the overlying bed may be separate and unrelated processes, as will be discussed in a later section.

BIOGENIC STRUCTURES

Bioturbation by burrowing organisms destroyed most of the depositional sedimentary structures in the silty mudstone comprising the lower two-thirds of the Rifle shale unit; upward in the member, the abundance of preserved depositional structures increases and the extent of bioturbation decreases. In the uppermost portion of the member, biogenic structures are limited mostly to shaly interbeds between hummocky sandstone beds, and to sparse burrow mottling within some sandstone beds.

Two trace-fossil types occur throughout the Rifle shale unit:

1. Isolated, white, grain-lined tubes called *Terebellina* (="*Schaubcylindrichnus*") are the only distinct

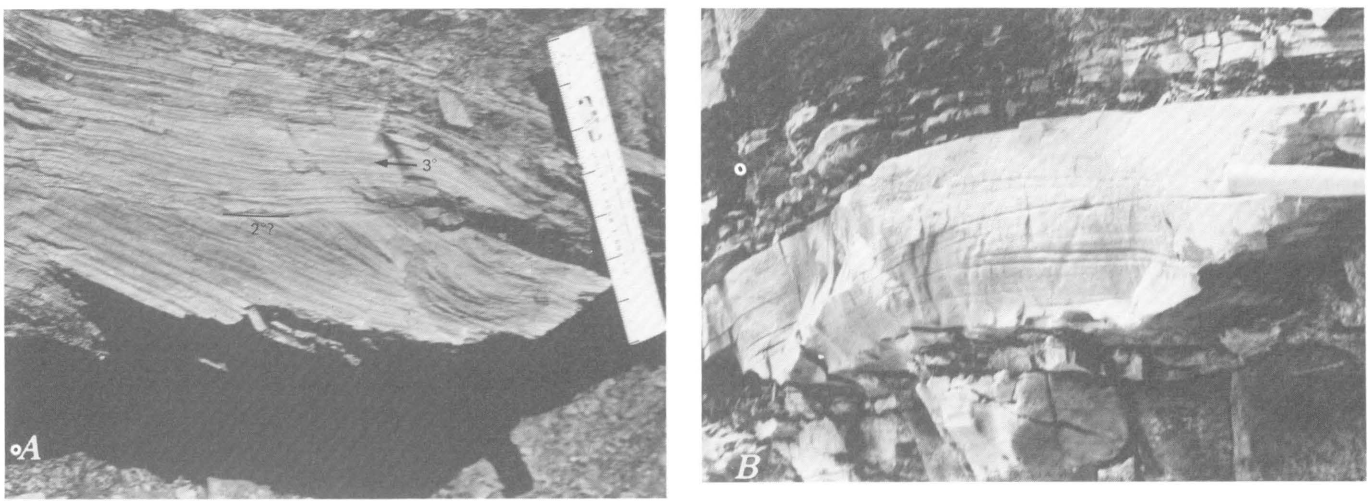

FIGURE 7.—Hummocky cross-stratification, Rifle shale unit, Rifle Gap. *A*, Hummock (antiform) preserved over second-order(?) scour surface. Note subtle thinning of laminae over hummocks and thickening in swales. Scale 7 in. (17.5 cm) long. *B*, Hummock (antiform) preserved in H-F-M sequence (see Dott and Bourgeois, 1982, p. 664). Hammer handle to right for scale.

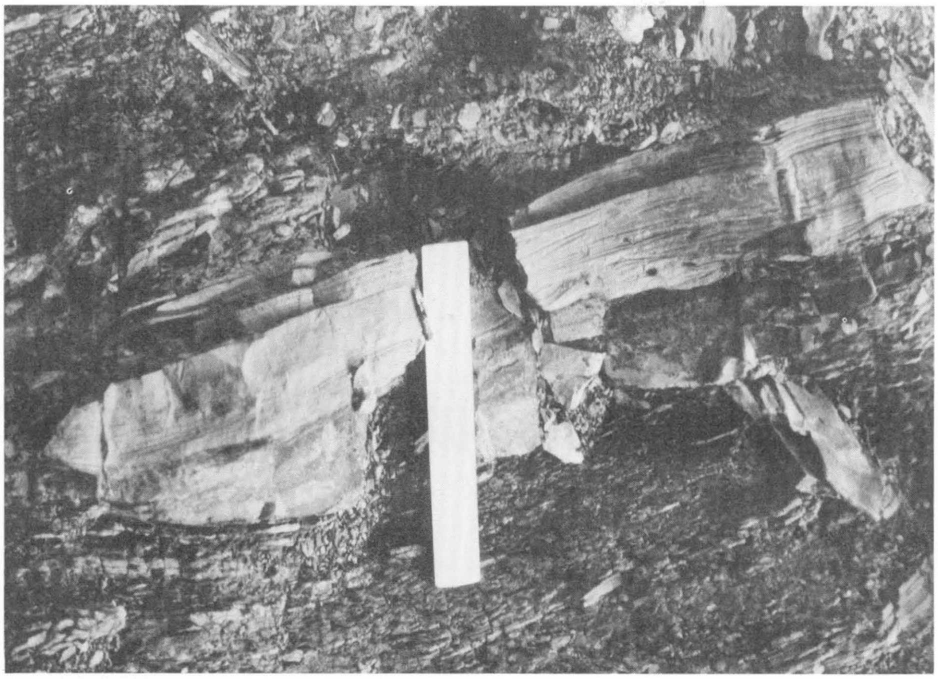

FIGURE 8.—A shallow erosional surface overlain by a lenticular bed of hummocky, cross-stratified sandstone, Rifle shale unit. Scale 7 in. (17.5 cm) long.

trace fossils found throughout the lower, bioturbated, silty mudstone of the Rifle shale unit member.

2. *Thalassinoides* occurs locally in convex hyporelief on sandstone bedding planes.

Six more genera of trace fossils occur in the upper one-third of the Rifle shale unit:

3. *Ophiomorpha* occurs sparsely in sandstone beds high in the member.
4. An unnamed trace fossil referred to as the "depression-of-bedding" trace (fig. 9) occurs in some sandstone beds in the uppermost Rifle shale unit. It is locally concentrated along thin intervals in hummocky-bedded sandstone.
5. *Diplocraterion* occurs locally cutting through thin (2-in., 6-cm) beds of sandstone.
6. *Rhizocorallium* occurs in concave hyporelief on sandstone bedding planes near the top of the member.
7. Vertically oriented, cylindrical, thick-walled burrows were found on one upper(?) bedding surface in the uppermost Rifle shale unit.
8. A very poorly preserved *Cylindrichnus*? (="*Asterosoma* Form *Cylindrichnus*") also was found.

FOSSILS

Several different kinds of marine fossils occur in the Rifle shale unit. Shells and internal molds of *Inoceramus* are the most common body fossils to be found, but a more varied assemblage has been collected. J.R. Gill, R.E. Burkholder, and W.A. Cobban (written commun.) found *Crassostrea* sp., *Anomia* sp., *Leptesthes* sp. (="*Corbicula*" sp.), *Inoceramus* sp., *Solenoceras* sp., and *Exiteloceras jenneyi* (Whitfield) in the lower part of the Rifle shale unit, and *Inoceramus* cf. *I. vanuxemi* Meek and Hayden, and *Baculites* sp. in the upper Rifle shale unit, on the west side of Rifle Gap. An organic wall or inner lining of a foraminifer (affinities unknown) occurs in a palynological sample from the lower portion of the Rifle shale unit.

The Rifle shale unit also contains detrital miospores and marine dinoflagellates. Scanning of six samples indicates that dinoflagellates make up approximately 6 percent of the palynomorphs. Most of these are chorate dinocysts (containing spiny projections), cf. *Oligosphaeridium* Davey and Williams (1966) (in McIntyre, 1974, pl. 9, figs. 9 and 11; pl. 10, figs. 1 and 2); a few are proximate dinocysts, cf. *Lajeunia kozlowskii* Gorka (1963) (in McIntyre, 1974, pl. 4, figs. 2 and 3).

AGE

The Rifle shale unit is late Campanian in age as indicated by *Exiteloceras jenneyi*. This ammonite occurs along the Grand Hogback in Rifle Gap and 38 mi

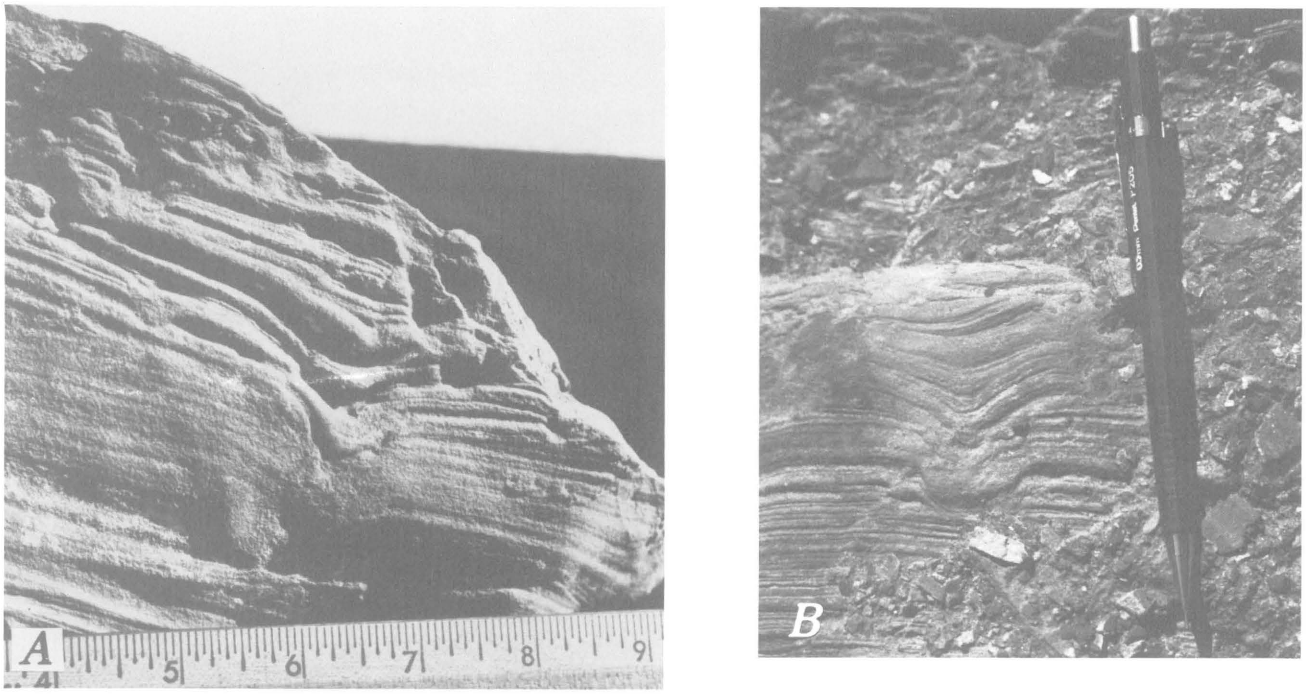

FIGURE 9.—Unnamed trace fossil referred to as the depression-of-bedding trace, uppermost Rifle shale unit. Resembles distortion of bedding above open burrow made by *Callianassa* in Pleistocene and Holocene deposits. (See Howard, 1971, p. 200, 205–206, and Frey, Howard, and Pryor, 1978, p. 212, figs. 7E, 8G, 9.) *A*, ruler in inches; *B*, pencil for scale.

(60 km) to the southeast in North Thompson Creek (Donnell, 1959); it also occurs 38 mi (60 km) to the northeast near the type locality of the Trout Creek Sandstone Member (Izett and others, 1971). In the vicinity of the Trout Creek type locality, *Exiteloceras jenneyi* lies in a marine-shale interval beneath the Trout Creek Sandstone Member. This fossil is the basis for the age correlation of strata used in reconstructing the paleogeography of the overlying Trout Creek Sandstone Member.

DEPOSITIONAL CONDITIONS

The Rifle shale unit at Rifle Gap records a series of events beginning with a period of nondeposition of clastic material in a sediment-starved marine bay. This was followed by open-marine, offshore deposition of increasingly coarser clay, silt, and sand falling from suspension. The final event was the approach of the shoreline and deposition of the Trout Creek Sandstone Member.

The presence of an initially sediment-starved marine embayment in the Rifle Gap area is indicated by lateral-facies distribution and by phosphatic nodules and phosphatized wood at the base of the Rifle shale unit. Such phosphatic deposits occur today in areas lacking much clastic sedimentation, where chemical precipitates such as phosphates, elsewhere too diluted by clastic sediments to be noticed, become more conspicuous. The required near cessation of clastic sedimentation in the Rifle Gap area may have been caused by diversion of land-derived sediment to the east in stable distributary channels. A stable, diversionary channel pattern, maintained long enough, would keep clastic material from the Rifle Gap area and at the same time provide a constant, stable platform for the development of thick peat deposits in undisturbed swamps at New Castle. The exact age correlations between strata of the lower part of the Rifle shale unit at Rifle Gap, and the thick Wheeler coal bed at New Castle, are unknown. However, the thick coal deposits at New Castle may correspond to the thin, phosphatic, basal portion of the Rifle shale unit at Rifle Gap. This would be analogous to previously studied sections in which thin, marine, phosphatic horizons correlate with thicker intervals of rocks bearing a lengthy stratigraphic range of fossils, showing that these phosphatic intervals represent marine diastems (Goldman, 1922; Heckel, 1972).

The embayed delta plain eventually drowned during a regional transgression and the nearshore marine bay environments of the Rifle Gap area became offshore-marine environments as the shoreline moved rapidly to the northwest. The marine environments were inhabited by organisms such as ammonites (*Exiteloceras jenneyi*), foraminifera, and dinoflagellates, and by more salinity-tolerant *Crassostrea* sp. and *Anomia* sp.

The distant shoreline lying to the northwest began a faltering advance and clastic sedimentation of silt and clay increased in the Rifle Gap area, covering the phosphatic deposits. Whether this sedimentation was continuous or sporadic cannot be ascertained, because the primary sedimentary structures were destroyed as the deposits were reworked by benthic, detritus-feeding organisms. These organisms probably lived at the top of and within the sediment, where they strained nutritious organic detritus from clay and silt at the oxygenated sediment-water interface. Their endeavors are recorded in the bioturbated texture of much of the lower two-thirds of the Rifle shale unit at Rifle Gap.

Beneath the water-saturated surface sediments, the more cohesive, partially dewatered substrata were inhabited by deposit-feeding, polychaete-like seaworms. Their permanent dwellings were single, isolated, lined tubes called *Terebellina*, built as the worm added new quartz grains to the unfinished end of the tube and perhaps secreted mucus to cement the grains in place (Danner, 1956; Frey and Howard, 1981).

With approach of the shoreline where the Trout Creek Sandstone Member was forming, clastic sedimentation increased in rate and in grain size. Thus, the upper part of the Rifle shale unit contains more sandstone in thicker beds and a greater variety and abundance of physical depositional structures than the lower part.

Approach of the shoreline caused the area that is now Rifle Gap to be above the level of storm-wave base, as indicated by the presence of hummocky cross-stratified sandstone. During storms, large quantities of sediment were lifted into suspension. The suspended material was transported seaward, sorted, and deposited between the passage of individual storm-wave trains. Sorting was efficient; during and immediately following large waves, only very fine grained sand fell to the bottom. This sand fell into oscillating, sediment-laden bottom currents and then was molded into smooth, undulating hummocks and swales (Dott and Bourgeois, 1982). The storm-caused oscillating bottom currents had velocity as high as that of the upper flow regime (Dott and Bourgeois, 1982; Harms and Fahnestock, 1965, pl. 1). The hummocky structures produced by these oscillating currents are therefore analogous to flat bedding produced in the upper flow regime (Dott and Bourgeois, 1982). These hummocky structures were produced when this area lay below fair-weather wave base, below the influence of daily wave and tidal currents; thus, the storm-deposited hummocky structures were preserved.

During the greatest intensity of each storm, large waves generated bottom-scouring currents. These currents scoured the bed surface from the depth of storm-wave base shoreward through the shoreface. This scouring in deep-offshore-bottom environments produced shallow channels which were elongate in a direction approximately normal to the coastline. Such storm-wave scour is a more likely cause for these narrow, elongate channels than are rip currents or turbidity currents. Rip currents may reach far offshore into deep water (Reimnitz and others, 1976), and are potential depositional agents in the offshore zone. However, rip currents generally are unlikely to scour the deep-offshore bottom. Turbidity currents have the potential to scour the offshore-bottom surface. However, turbidite deposits were not observed in the Rifle shale unit. More observations are needed in modern environments, particularly below fair-weather wave base following major storms. Additional processes, such as storm-surge ebb flow and unusually deep-scouring tides, are not known well enough in modern environments to evaluate their influence on structures in ancient sedimentary rocks.

Between storms, during fair-weather intervals, benthic organisms reworked the sediment. They left remnants of their dwellings, traces of their suspension and deposit-feeding activities, and trails recording their travels. A suspension-feeding, amphipod crustacean or polychaete seaworm built the spreite of *Diplocraterion* in response to fair-weather fallout sedimentation or storm erosion (Howell, 1957; Seilacher, 1967; Fürsich, 1974b). A filter-feeding organism constructed the permanent dwelling called *Cylindrichnus* (="*Asterosoma* Form *Cylindrichnus*") (Frey and Howard, 1970) (Häntzschel, 1975). Arthropods (or worms or gastropods?) formed *Isopodichnus* by their plowing or raking and resting activities on the offshore bottom (Seilacher, 1970; Häntzschel, 1975). *Isopodichnus* is essentially the same as the Paleozoic genera called *Cruziana* and *Rusophycus* which were made by trilobites (Häntzschel, 1975; Trewin, 1976). Though described in past studies only from fresh- and brackish-water deposits, *Isopodichnus* here is in marine deposits. It occurs on the same bedding plane as the marine trace fossil called *Asteriacites*, which is the resting trace of ophiuroids and starfish.

TROUT CREEK SANDSTONE MEMBER, ILES FORMATION

The Trout Creek Sandstone Member is a thick, massive-weathering sandstone at the top of the Iles Formation. This sandstone has a prominent, white-weathered top commonly referred to as a white cap. The sandstone lies above the Rifle shale unit and below a zone of numerous, locally thick coal beds in the lower part of the Williams Fork Formation. Previous workers traced this sandstone from its type locality in the Yampa coal field to the central Grand Hogback. In both areas the Trout Creek Sandstone Member is similar in both its lithology and its stratigraphic position above marine shale and below a principal coal zone. Along the Grand Hogback, the Trout Creek Sandstone Member is thick and well exposed on a roadcut in Rifle Gap (fig. 10), but

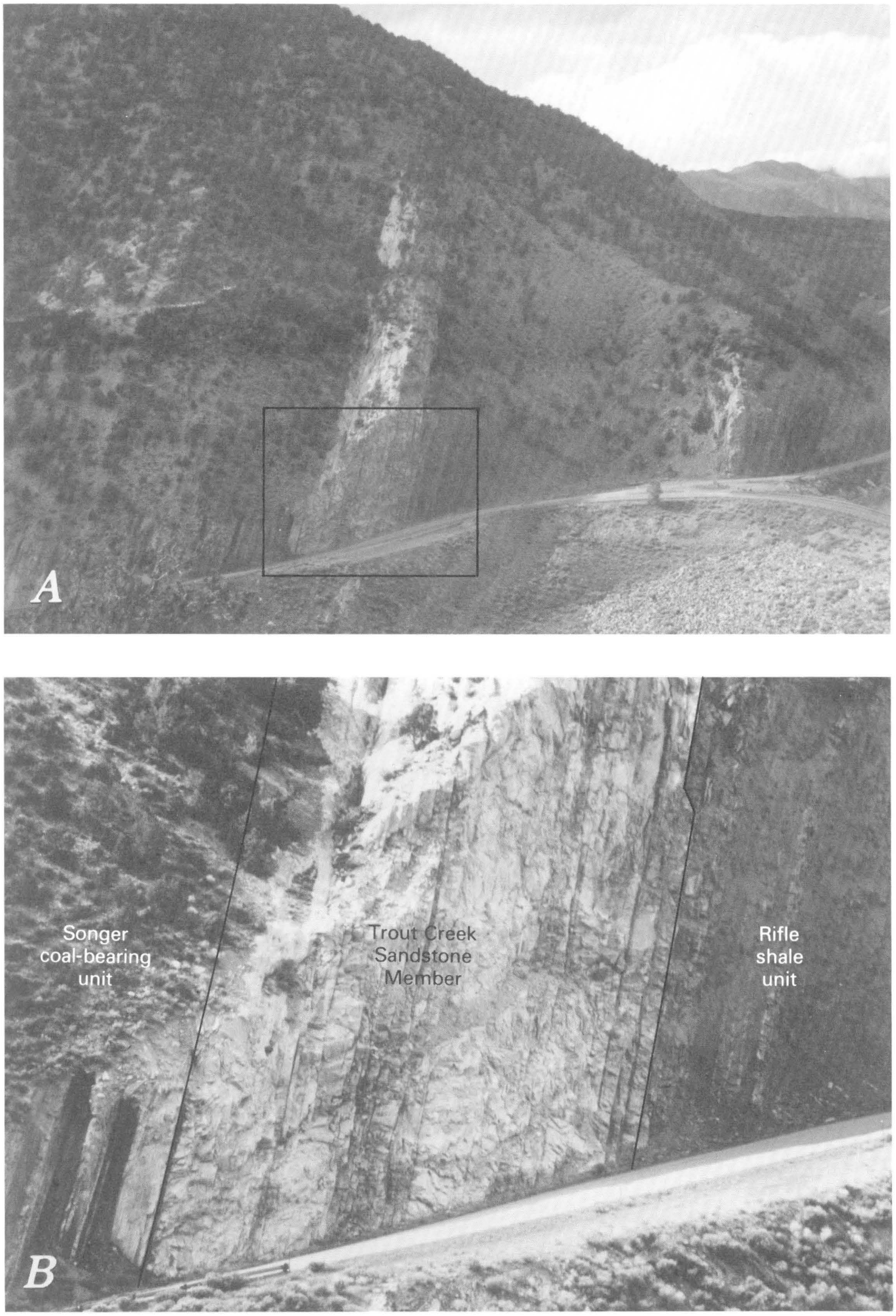

FIGURE 10.—Rifle Gap roadcut, view toward the northwest. *A*, View from a distance; photo courtesy of K.R. Newman. *B*, Closer view of area outlined in *A*. Trout Creek Sandstone Member on the roadcut, where its stratigraphic thickness is about 100 ft (30 m).

exposures are less distinctive due to thinning of the sandstone to the east-southeast near New Castle (fig. 11). The Trout Creek Sandstone Member in the Grand Hogback and the Trout Creek Sandstone Member in the Yampa coal field are the same age based on collections of the ammonite *Exiteloceras jenneyi*, which occurs in underlying marine shale in both areas (Izett and others, 1971, fig. 2; Madden, 1983, p. 67, 146, plate 1).

The thickness and lithology of the Trout Creek Sandstone Member vary laterally and vertically along the central Grand Hogback. Thickness varies irregularly from 60 ft (18 m) to 160 ft (50 m), but generally the thickness decreases east-southeastward toward New Castle (pl. 1). Besides thinning toward New Castle, the Trout Creek develops characteristics suggesting a deeper marine, less nearshore depositional environment east-southeastward toward New Castle. At New Castle the sandstone has lost its white-weathered top, and it contains few if any lag deposits of shells and claystone clasts, or horizons littered with plant fragments, all so typical of more nearshore western exposures. In addition, overlying fresh-water, coal-bearing deposits thin southeastward and coal is absent above the Trout Creek Sandstone Member at New Castle. In western exposures the lower portion of the Trout Creek Sandstone Member weathers to light brown and the upper portion (14 ft to 110 ft, 4.3 to 34 m) weathers to white. The color boundary locally cuts bedding planes. To the east-southeast toward New Castle (fig. 11), the entire Trout Creek Sandstone Member is light brown. In any given western section of the sandstone, its grain size and degree of sorting increase upward, and in some areas the composition varies upward as follows: the lower portion is generally lower fine-grained[1] to very fine grained, well- to moderately well sorted, lithic and arkosic arenite; the upper portion is coarser and better sorted being generally lower medium- to upper fine-grained, well-sorted, arkosic arenite.

[1]In discussing the grain size of these rocks, it is useful to use the words "upper" and "lower" as qualifiers for very fine, fine, and medium grain sizes because of the narrow range of sandstone grain size in the stratigraphic section. These qualifiers occur throughout the descriptions below. From the finest to coarsest these qualifiers are as follows: lower very fine (4.0–3.5ϕ), upper very fine (3.5–3.0ϕ), lower fine (3.0–2.5ϕ), upper fine (2.5–2ϕ), lower medium (2.0–1.5ϕ), and upper medium (1.5–1.0ϕ).

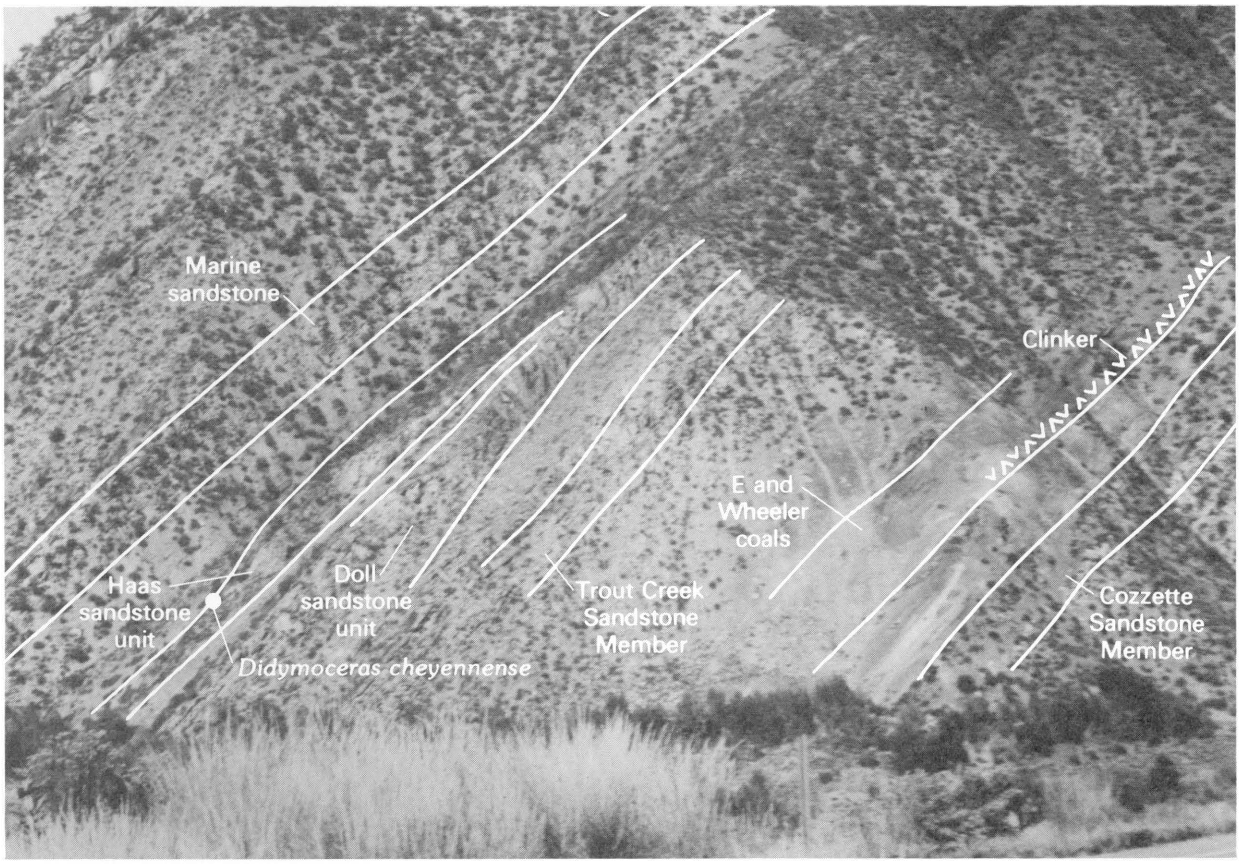

FIGURE 11.—Section of primary interest on ridge at New Castle.

CORRELATIONS

Fenneman and Gale (1906, p. 26) applied the name Trout Creek to a prominent, white, ledge-forming sandstone exposed on Trout Creek in the Yampa coal field. The unit then was extended westward and southward by later workers who traced the Trout Creek Sandstone Member from its type area through the Grand Hogback to the town of New Castle (Gale, 1906, 1907, 1910; Hancock, 1925; Hancock and Eby, 1930; Burbank and others, 1935; Horn and Gere, 1959; Tweto, 1979). Warner (1962, 1964) extended the terminology by correlating the Trout Creek Sandstone Member with the Rollins Sandstone Member of Lee (1909) in the southern Piceance Creek basin. Warner (1964, p. 1099 and fig. 3) believed that a laterally continuous Rollins (or Trout Creek) Sandstone Member existed and that it could be recognized easily, north to south, along the length of the Grand Hogback. He showed it schematically stepping upward stratigraphically in a seaward direction along the length of the Grand Hogback. This representation implied that the sandstone is continuous and rising in the section from the White River near Meeker (where it is called the Trout Creek Sandstone Member) to North Thompson Creek (where it is called the Rollins Sandstone Member).

Studies that followed Warner (1964) showed that the Trout Creek and Rollins Sandstone Members were not continuous in outcrop along the length of the Grand Hogback between New Castle and Harvey Gap. Murray (1966, p. 79 and 81) could not trace the Trout Creek Sandstone Member southeastward from Harvey Gap, using aerial photographs. Madden (1983, p. iv, 45–49, and pls. 1 and 2) found that the Trout Creek Sandstone Member thins southeastward from Harvey Gap and loses its white cap, becoming an all-brown sandstone at New Castle, and also discovered that the Rollins Sandstone Member of the Mesaverde Formation at New Castle (Warner, 1964, fig. 3, section 4) could be traced northwestward along the outcrop to what Warner (1964) called the Cozzette Sandstone Member of the Mesaverde in Harvey Gap (Warner, 1964, fig. 3, section 5). Warner's (1964) miscorrelation, involving approximately 450 ft (137 m) of strata, probably was based upon faulty correlations originally made by Gale (1910, p. 119–120, fig. 7) and taken as correct by later workers, including Johnson (1982) and Lorenz and Rutledge (1987). Plate 1 and table 1 show sandstone and coal-interval correlations that result from my detailed tracing of individual sandstone units and their overlying coal-bearing units between Rifle Gap and New Castle.

CONTACTS AND LITHOLOGY

The Trout Creek Sandstone Member lies between marine mudstone and sandstone below and coal deposits above. The lower contact with the underlying, marine Rifle shale unit is generally gradational but is locally a sharp scour surface; the upper contact with coal deposits is generally sharp.

Generally, bedding thickness and grain size both increase upward from the Rifle shale unit through the Trout Creek. Bedding thickness increases from about 6 in. (15 cm) to more than 1 ft (30.5 cm). Grain size coarsens abruptly from very fine (4.0–3.0ϕ) to fine or lower medium (3.0–1.9ϕ) at a sharp sandstone-on-sandstone contact within the member. This contact rises east-southeastward within the Trout Creek Sandstone Member from the middle of the member at Rifle Gap, to a position 40 ft (12.2 m) from the top in the Haas mine area, to an even higher position only 15 ft (4.6 m) from the top in the Doll mine area. Further southeast, the grain-size boundary could not be identified at New Castle where all of the sandstone consists of very fine (4.0–3.0ϕ) grains.

The western exposures of the Trout Creek Sandstone Member, in the Rifle Gap and Haas mine areas, contain some features that do not occur east-southeastward toward New Castle. The features are lag deposits of fragments or whole shells of *Inoceramus*, and lag deposits of claystone clasts on bedding planes in lower portions of the sandstone. In addition, finely comminuted, oxidized plant fragments are abundant on bedding planes in western exposures.

The Trout Creek Sandstone Member is lithic and arkosic arenite ranging in grain size from very fine to medium. The arenite is mineralogically immature, but texturally mature as determined by the study of 12 thin sections. These thin sections of arenite contain metamorphic-rock fragments, chert, claystone, rare siltstone, and local soft claystone fragments compacted between harder framework grains. Accessory minerals are zircon and tourmaline. Quantitatively, the mean grain size of the 12 thin sections of arenite ranges from 3.2ϕ to 1.9ϕ; they are moderately sorted to well sorted, having standard deviations ranging from 0.81ϕ to 0.39ϕ. The degree of sorting and the roundness of framework grains indicate the textural maturity of these samples. This textural maturity might be questioned in some samples which have an abundance of what appears to be matrix material; however, this material consists of compacted rock fragments and probable authigenic chlorite, rather than true detrital matrix material. The mineralogical immaturity of the arenite is indicated by an abundance of rock fragments; the presence of feldspar, including plagioclase in a few samples; and minor polycrystalline quartz. In addition to the just-named components, the arenite also contains a small proportion of multicycle grains which were eroded from preexisting sedimentary strata.

TABLE 1.—*Coal-interval correlations, Grand Hogback coal field*

[Data from author's field studies and from earlier reports, interpreted in this study]

System	Stage	Group	Formation	Unit	North Canyon (Horn and Gere, 1959)	Rifle Gap	Area of abandoned Haas coal mine	Harvey Gap	Area of abandoned Doll coal mine	New Castle	Southward to Coal basin (Collins, 1976, pl. 2)
UPPER CRETACEOUS (PART)	Campanian (part)	Mesaverde Group (part)	Williams Fork Formation (part)		No coal?	T. Maxfield Mine (Horn and Gere, 1959).	Two beds (2.2 ft, 4.0 ft) 1/4 mi to east (pl. 2).	6-ft bed 1/4 mi to east (pl. 2).	3.2-ft bed, 1/2 mi to northwest (pl. 2).	Keystone bed, Keystone Mine (Gale, 1910, pl. XI).	No coal?
				Henry sandstone unit	Coal beds O to S (Horn and Gere, 1959). Coal beds L to N (Horn and Gere, (1959).	No coal? Wheeler bed, 30 ft (Gale, 1910, fig. 6).	No coal? No coal?	Four beds (pl. 2): 2.5, 4.9, 5.5, 7.0 ft. Nu Gap No. 3 Mine (Collins, 1975).	1.3-ft bed (pl. 2)	C bed and "small coals" (Gale, 1910, pl. XI).	Coal Ridge coal group including Placita bed.
				Harvey sandstone unit	K bed	Unnamed, 16-ft bed (Gale, 1910, fig. 6).	4-ft bed (pls. 1, 2)	4-ft bed (pl. 1)	No coal?	Three beds (pl. 1): 2.0, 1.5, 1.0 ft.	South Canyon coal group, includes Dutch Creek bed.
				Haas sandstone unit	J bed I bed	Unnamed, 5.3-ft bed (Gale, 1910, fig. 6). Unnamed, 4-ft bed (Gale, 1910, fig. 6).	12-ft bed, burning (pls. 1, 2).	11-ft bed, 1/4 mi west (pls. 1, 2).	Two beds (4.2 ft, 2.2 ft) (pl. 2). Allen/Anderson beds (Gale, 1910).	Unnamed, 4-ft bed (Gale, 1910, pl. XI).	
				Trout Creek Sandstone Member	No coal? D bed	Burned intervals 2.0, 1.5, 4.0 ft (pls. 1, 2). Songer 4.5 ft (Horn and Gere, 1959).	Beds E to H (Horn and Gere, 1959). Bed D (Horn and Gere, 1959). Two beds (11.5 ft, 4 ft) (pl. 2).	20.5-ft bed (pls. 1, 2). - - - - - - - - 25-ft bed, Lou Bendetti Mine (pls. 1, 2).	6.0 ft (pls. 1, 2) Doll sandstone unit Unnamed bed (Gale, 1910) 3.4 ft (pl. 2).	Allen bed (15-22 ft) ash (Gale, 1910, pl. XI). - - - - - - - - No coal	
			Iles Formation (part)	Cozzette Sandstone Member	No coal	No coal	No coal	30.4 ft bed exposed 1 mi to east (pls. 1, 2).	D bed (Gale, 1910, fig. 5, Doll Mine) 3.0 ft (pl. 2).	Wheeler bed, 45 ft and E bed, 16 ft (Gale, 1910, pl. XI).	Bowie Shale Member, Coal basin coal bed.
				Corcoran Sandstone Member	No coal B bed No coal	C bed (Horn and Gere, 1959) split into two beds (1 ft, 1 ft) (pl. 2). B bed (McLearn Mine, Gale, 1910, p. 121) 5-ft bed (pl. 2). A bed (Horn and Gere, 1959) split into two beds (2 ft, 2 ft) (pl. 2).	Covered interval.	E bed (Gale, 1910) in Harvey Gap Nos. 2 and 3 Mines. 15.3 ft in No. 3 (pl. 2).	Wheeler bed and E bed (Gale, 1910, fig. 5).	No coal	No coal.

These grains are comprised of well-rounded chert and quartz, and rounded, detrital, secondary quartz overgrowths.

Authigenic minerals include calcite (up to 6 percent by volume), hematite (up to 8 percent by volume), magnetite (up to 2 percent by volume), ilmenite (up to 2 percent by volume), and possibly chlorite (up to 12 percent by volume). Pressure solution is evident along some grain boundaries. Secondary quartz overgrowths are rare and generally appear to be part of the detrital grain and thus inherited from a preexisting sedimentary rock.

PHYSICAL SEDIMENTARY STRUCTURES

Flat bedding and hummocky bedding are the dominant structures in lower portions of the Trout Creek Sandstone Member; flat and low-angle bedding dominate towards the middle; and low-angle trough and (or) tabular cross-stratification dominate in upper portions of the sandstone. The lower portion contains elongate, shallow scour surfaces with less than 3.9 in. (10 cm) of relief, overlain by hummocky-bedded sandstone. These scour features are similar to ones found in the upper part of the Rifle shale unit discussed earlier. The lower part of the Trout Creek Sandstone Member also contains amalgamated hummocky-sandstone sequences up to 12 ft (3.7 m) thick in which sandstone-on-sandstone scour surfaces occur without mudstone interbeds. These surfaces are oriented with their lengths toward east-southeast, like those in the underlying shale. The vector mean of 13 observations is 137°, and the standard deviation is 80°.

Cross strata in the upper portion of the Trout Creek Sandstone Member commonly dip southwestward. The vector mean of seven measurements made on cross strata is 215° and the standard deviation is 64°. Other smaller features such as ripples and current lineations also were measured in the upper part of the Trout Creek Sandstone Member. The vector mean of 14 measurements, including the seven cross strata, is 219°, and the standard deviation is 68°.

Features of local interest are local westward-dipping cross strata in the middle portion and local scour surfaces in the upper portion of the Trout Creek Sandstone Member. The westward-dipping trough cross strata with high-angle (30–35°) dips occur locally in the middle of the sandstone in the Rifle Gap and Haas mine areas. These trough-cross-stratified bed sets are less than 1 foot (30.5 cm) thick. These cross strata lie just below the horizon of abrupt grain-size increase which was mentioned earlier. The scour surfaces of sandstone-on-sandstone occur in the upper portion of the Trout Creek, 0.15 mi (0.24 km) west of Rifle Gap. The uppermost scour contact is overlain by low-angle, trough-cross-stratified, upper fine to lower medium grained sandstone with abundant log impressions and compressions at the base. Some of the log compressions contain *Teredolites*, which are casts of bores in wood, apparently made by bivalves (Frey and Howard, 1982, p. 2; Häntzschel, 1975, p. W 135).

BIOGENIC STRUCTURES

Trace fossils include various forms of *Ophiomorpha*, *Terebellina*, an unnamed trace fossil, and root impressions. *Ophiomorpha* occurs as individual isolated burrows and also in local concentrations along various horizons throughout the Trout Creek Sandstone Member. These occurrences include what may be the first field occurrence in North America of *O. borneensis* Keij, which is discussed in Frey, Howard, and Pryor (1978, p. 223). More of the *Ophiomorpha* have horizontal burrow orientations than vertical or oblique orientations. Diameters of their burrows are 0.5–1 in. (1.3–2.5 cm). In addition to *Ophiomorpha*, there is one occurrence of *Terebellina* which consists of 10 horizontal grain-lined tubes stacked vertically, one on top of the other, and scoured at the top. This is not the usual form for *Terebellina*, which is found more commonly as individual grain-lined tubes. The unnamed trace fossil is a vertically oriented, U-in-U-shaped, depression of strata which occurs in the middle of the sandstone in Rifle Gap. This structure is 5 in. (12.7 cm) deep and only 2–3 in. (5.1–7.6 cm) wide at the top, and it extends downward several feet (0.61–0.92 m) as a single long tube. At the top of the sandstone, root structures disrupt stratification below coal beds.

FOSSILS

Inoceramus occurs throughout the lower portion of the sandstone, as shell fragments and as unbroken, disarticulated shells lying concave side down. Local concentrations of gastropod shells occur in a concretionary zone in the lower portion of the sandstone on the west side of Rifle Gap.

DEPOSITIONAL CONDITIONS

The Trout Creek Sandstone Member formed in the transitional environment between the offshore and the lower shoreface where storm processes were active. This is indicated by scour surfaces and storm deposits in the lower 40–60 ft (12–18 m) of the Trout Creek Sandstone Member.

Fair-weather reworking of storm deposits began to have its effect with shoaling and advance of the shoreface. In the shoreface, sediment migrated along shore in shallow bar-and-trough systems driven by oblique wave approach. The bar-trough substrate was non-cohesive and inhabited by suspension feeders requiring clear water and constant current flow. Some of these organisms dug deep, lined burrows called *Ophiomorpha*, which were highly preservable because of their depth and their lining. Shoreface deposits (40–60 ft, 12–18 m thick) of the middle to upper part of the Trout Creek Sandstone Member were locally scoured by tidal channels (20 ft, 6 m thick), covered by beach dunes (20–40 ft, 6–12 m thick), and overlapped by foreshore sand (10–15 ft, 3–5 m thick) and swamps. The foreshore deposits are generally white, structureless, root-mottled sandstone at the top of the Trout Creek Sandstone Member.

STORM DEPOSITS

During deposition of the Trout Creek Sandstone Member, the shoreline advanced seaward to the area of Rifle Gap. This area was already above storm-wave base and with shoaling it became progressively sandier and affected by more frequent waves. Effects of storm waves were more severe than in the deeper, offshore environment of the Rifle shale unit. Above the Rifle shale unit, the lower part of the Trout Creek Sandstone Member formed in an environment transitional between offshore and shoreface. Storm scouring in this transitional environment left several features in this sandstone: (1) shallow erosional surfaces, elongate perpendicular to the shoreline, (2) lateral cutouts of mudstone interbeds, and (3) vertically aligned trace fossils with eroded tops. The scour surfaces were covered and preserved by overlying storm deposits.

Storm deposits consisted of sediment that originated in shallower, shoreward areas. In these shallower areas, high-energy storm surf ground marine shells and eroded coastal areas down through cohesive, partially dewatered clay drapes creating clasts of claystone (Boyles and Scott, 1982, p. 503). Material eroded by storm surf was transported seaward by high-velocity storm currents. These currents carried unsorted shell fragments and claystone clasts offshore and deposited them as shell and claystone lag. Lag deposits interbedded with local hummocky cross-stratified sandstone formed below fair-weather wave base. These lags are preserved in the lower part of the Trout Creek Sandstone Member where deposition was too rapid for efficient reworking and winnowing of fine-grained material and complete breakdown of clasts. Rapid deposition is indicated by relatively poor sorting, and by the local abundance of claystone clasts seen in outcrop and lithic fragments seen in thin section. Between storms, the benthic fauna that inhabited the bottom is recorded by only the deepest, lined burrows such as *Ophiomorpha*, which had the greatest potential for preservation below scour surfaces in the partly cohesive sand.

SHOREFACE SANDBARS

The southeastward-advancing Trout Creek shoreface swept the area of the central Grand Hogback. Deposition in the shoreface was dominated by fair-weather, wave-related processes. These processes reworked storm deposits. Fair-weather transport of sediment occurred in shallow, migrating offshore bars and troughs trending parallel or obliquely to the shoreline. The bars migrated along shore, driven by oblique wave approach from the east. Longshore-trough deposits were better preserved than bar deposits because of greater water depths and less disturbance by storm scour in the troughs.

Deposition in a migrating longshore bar system, driven by oblique wave approach, is indicated by transport directions. A predominance of west-southwesterly transport directions is preserved in larger scale structures in shoreface deposits. These deposits contain large, low-angle cross strata with gently dipping foresets indicating transport of sand in migrating dunes and megaripples having low-angle slip faces. Transport was parallel to the shoreline, as shown in the paleoshoreline constructed by McGookey and others (1972). Such longshore sand transport occurs along modern coastlines (Hunter and others, 1979; Kent, 1976).

The substrate in the shoreface was noncohesive, and a current of clear water swept the environment; these factors helped to support a fauna of immobile suspension feeders such as makers of *Ophiomorpha*. The noncohesive character of the sand is indicated by the collapse structures in sandstone laminae overlying burrows. The presence of clear, flowing water is indicated by *Ophiomorpha*, made by suspension feeders. Suspension feeders favor clear rather than turbulent water because suspended clay and silt particles clog and choke them; and they need current to renew nutrients (Heckel, 1972, p. 250).

The larger scale physical sedimentary structures, mostly trough cross-stratification, dip approximately parallel to the ancient shoreline trend for the most part. This is a simplified interpretation. Actually, there is scatter in paleocurrent directions. However, this scatter probably is due in part to changing bar configurations and preservation of some fair-weather ripple cross-lamination showing shore-normal transport directions.

Paleogeographic shoreline orientations are based upon paleocurrent data. Most of these data consist of shoreline-parallel dip directions of trough crossbedding in the upper portions of the nearshore-marine-sandstone members, including the Trout Creek. In the lower portions of these sandstone members, the elongated erosional channels overlain by hummocky-bedded sandstone are oriented in a direction that is normal to trough-crossbed-dip directions and normal to the paleoshoreline.

TIDAL-CHANNEL SANDSTONE, RIFLE GAP

A sandstone body about 60 ft (20 m) thick, interpreted as a fluvially influenced, active, tidal-channel fill, occurs within the Trout Creek several hundred feet above the roadcut in Rifle Gap. The tidal-channel interpretation is based on several observations: the sandstone overlies a deep scour surface eroded into the underlying shoreface sandstone; the sandstone coincides with an abrupt grain-size increase; the basal surfaces of its beds expose compressions of logs having *Teredolites* boring casts; and this sandstone is far less burrowed than enclosing sandstone, containing only one exposed, very small *Ophiomorpha*. Below this outcrop, on the roadcut, the sandstone shows more marine and fewer fluvial aspects and is interpreted as an active, tidal-channel deposit.

The tidal-channel sandstone which is exposed in the Rifle Gap roadcut contains larger, more abundant *Ophiomorpha* than the same sandstone interval above the roadcut, and the basal surfaces of its beds expose *Inoceramus* shells as well as wood fragments and claystone clasts. Additional characteristics of this tidal-channel deposit are as follows: it coincides with an abrupt grain-size increase; it contains multiple scour surfaces throughout its lower 17 ft (5.2 m); it is trough cross-stratified; and it lies stratigraphically between upper shoreface and foreshore sandstone and just seaward (0.15 mi, 0.23 km) from the channel deposit exposed above the roadcut. Exposures are not sufficient to identify with certainty bimodal directions of cross-stratification exposed in three dimensions, although dip directions of foreset beds exposed in the roadcut are variable and appear to be bimodal. In summary, this tidal-channel complex consists of sandstone whose features suggest deposition from periodic, high-energy, landward and seaward current.

DUNE DEPOSITS, HAAS MINE AREA

An interval of sandstone 12 ft (3.9 m) thick, exposed in the upper portion of the Trout Creek Sandstone Member near the Haas mine (1.5 mi, 2.4 km east of Rifle Gap) is interpreted as a dune deposit. This deposit consists of large, low-angle, sweeping trough sets which are more than 5 ft (1.6 m) thick and 20 ft (6.5 m) long. It lacks the lined burrows, lag deposits, and mudstone interbeds characteristic of the marine deposits that make up the rest of the Trout Creek Sandstone Member. The dune deposit occurs above heavily burrowed, upper shoreface and foreshore deposits and below root-bioturbated sandstone at the top of the Trout Creek. The sparse, carbonaceous sandstone lenses within the dune deposit, separating sets of crossbeds, represent compressed remains of sand-dune vegetation.

SANDBAR DEPOSITS

In exposures on the east side of Rifle Gap, the Trout Creek contains local intervals of sandstone interpreted as deposits of upper shoreface and foreshore sandbars. These intervals consist of sets of steep, northwest-dipping, tabular- to trough-cross-stratified sandstone. These sandbars may have formed during periods of intense storm-wave activity. Once formed, they migrated landward at varying rates: more rapidly during storms than during fair weather.

FORESHORE AND BACKSHORE DEPOSITS

The top of the Trout Creek commonly is a zone of structureless sandstone locally containing root casts. This zone is interpreted as a root-bioturbated foreshore and backshore deposit based on its stratigraphic position above upper shoreface sandstone and commonly below coal beds, and on the presence of the root casts.

SONGER COAL-BEARING UNIT, WILLIAMS FORK FORMATION

The Songer coal-bearing unit overlies the Trout Creek Sandstone Member of the Iles Formation and forms the base of the Williams Fork Formation. The coal in this unit has been extracted for many years from mines in gaps and deep canyons cutting the central Grand Hogback, particularly at Rifle Gap, Harvey Gap, and New Castle. The coal is generally high-volatile C bituminous (Collins, 1976, p. 50). The unit's name, Songer, was once applied to the lowest coal bed mined in this interval in Rifle Gap and to a coal mine (Gale, 1910, p. 120, fig. 3), but it is no longer used as a coal-bed name. The Songer coal-bearing unit was called the "Trout Creek coal unit" in an earlier report (Madden, 1983) because of its position above the Trout Creek Sandstone Member. This coal-bearing interval is the same age as the base of the Williams Fork Formation and the "middle coal group" in the Yampa coal field (Fenneman and Gale, 1906, p. 26; Hancock, 1925; Gaffke, 1979). The age correlation is based on stratigraphic position of the ammonite *Exiteloceras jenneyi*, found in underlying marine units in both areas. The interval also corresponds in age with the basal Williams Fork Formation at Hayden, 65 mi (105 km) north-northeast and at Meeker, 34 mi (55 km) north-northeast, as indicated by Normapolles pollen with limited time-range zones: *Myrtaceoipollenites peritus* Newman (1965) and *Trudopollis meekeri* Newman (1965) and species of *Vacuopollis* (*Conclavipollis*), *Pseudoplicapollis* (*Sporopollis*), and *Plicapollis* (Newman, 1965b; Madden-McGuire and Newman, 1988). Locally along the central Grand Hogback, my mapping has allowed new lithologic correlations of coal intervals (see table 1).

THICKNESS, CONTACTS, AND LITHOLOGY

The Songer coal-bearing unit forms a continuous, eastward-thinning outcrop along the central Grand Hogback. It thins from 310 ft (95 m) in Rifle Gap (fig. 12) to 200 ft (61 m) a mile eastward, and splits into two thinner tongues, 40 and 60 ft (12.2 m and 18.3 m) thick, separated by a nearshore-marine sandstone east of Harvey Gap. At New Castle the upper tongue is less than 10 ft (3.1 m) thick and the lower one does not appear, having pinched out into marine strata. Upper and lower contacts of the coal-bearing unit are sharp.

The unit is brightly varicolored in contrast to underlying sandstone and shale units. Where coal beds have burned in place, the adjacent rocks are baked red and carbonaceous material is burned to an ashy, white residue. Adjacent siltstone is locally blackened. Unbaked mudstone is gray, or red and green. The colorful lithologies include clastic rocks ranging from sandstone to mudstone, and minor amounts of coal in beds up to 25 ft (7.6 m) thick. The grain size of the sandstone is generally close to that of the underlying Trout Creek Sandstone Member. The average sand grain size in the Songer coal-bearing unit is upper very fine (3.5–3.0ϕ), but the range is from lower very fine to upper fine (4.0–2.0ϕ) based on field observations. Bedding thickness in this unit ranges from thin laminae up to sandstone beds thicker than 1 foot (30.5 cm).

Local thick bodies of sandstone that are very thickly bedded in the Songer coal-bearing unit are interpreted to be distributary-channel deposits. One such sandstone on the roadcut in Rifle Gap, about 180 ft (84 m) above the base of the unit, is 30 ft (9 m) thick and overlies a thick zone of clinker. The base of the sandstone is heavily fractured and broken, whereas the upper portion is more coherent and massive. Beds are generally more than 6 in. (15.2 cm) thick, and grain size is coarser than

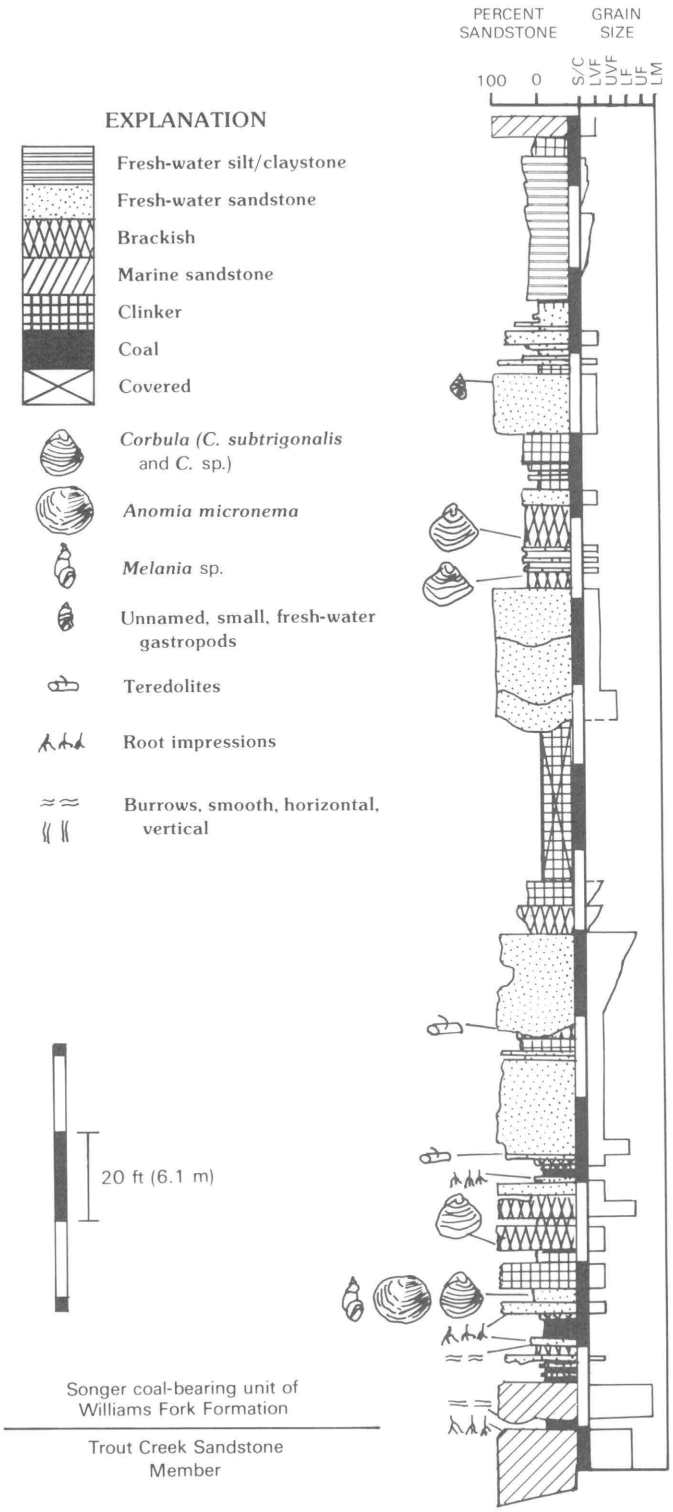

FIGURE 12.—Sketch of measured section through the Songer coal-bearing unit in Rifle Gap. Grain size terms: S/C, silt and clay, or coal; LVF, lower very fine; UVF, upper very fine; LF, lower fine; UF, upper fine; LM, lower medium.

the average in the unit. The sandstone is fine grained (3.0–2.0ϕ) at the base and it fines upward within the body to 3.5–3.0ϕ. My interpretation of this as a distributary-channel, active-fill sandstone is based on its stratigraphic position, its thick bedding, and the fact that it is coarser and dirtier, having a lower proportion of quartz, than any underlying sandstone. This is the most massive appearing, thickly bedded sandstone in the unit. Lower in the unit, 70–120 ft (21–36 m) from its base, are two sandstone sequences which are more thinly bedded, but which contain log impressions and claystone clasts on their basal bedding surfaces. These, too, are interpreted as active-fill deposits of distributary channels.

PHYSICAL SEDIMENTARY STRUCTURES

Primary sedimentary structures include laminae, various types of ripple cross-lamination, minor wavy, rhythmic sand/mud bedding (Reineck and Singh, 1975, fig. 165, p. 99), and low-angle trough cross-stratification. This unit contains more ripple cross-lamination than do lower units, and its sandstone commonly contains claystone clasts and wood impressions and compressions on bedding bases.

Paleocurrent directions are generally to the southeast, as indicated by measurements from ripple cross-lamination and from lineations on sandstone-bedding bases overlying erosional surfaces. The vector mean of 29 observations is 139°; the standard deviation is 53°.

BIOGENIC STRUCTURES

The two most common, distinct, biogenic sedimentary structures are (1) *Teredolites* boring casts, both large (11 mm wide) and small (3 mm wide), occurring with carbonaceous debris of wood compressions, and (2) root casts preserved in sandstone. Locally, finer grained siltstone and sandstone appear to be bioturbated and cut by indistinct, smooth, vertical and oblique burrows. Vertical burrows(?) backfilled with white sandstone cut the lowest coal bed in Rifle Gap.

FOSSILS

Internal molds and external impressions of brackish-water bivalves and gastropods occur in Rifle Gap and the Haas mine area. Assemblages identified by W.A. Cobban (written commun., 1982) are listed below in ascending stratigraphic order above the Trout Creek Sandstone Member: (1) *Anomia micronema* Meek, *Corbula subtrigonalis* Meek and Hayden, and *Melania* sp., 30 ft (9.2 m), Rifle Gap; (2) *Corbula subtrigonalis* alone, 40 ft (12.2 m), Rifle Gap; (3) *Corbula* n. sp., *Leptesthes berthoudi* (White) (="*Corbicula*" *berthoudi*), and *Goniobasis*(?) sp., 160 ft (49 m), Haas mine area; and (4) poorly preserved *Corbula* sp., 200 ft (61 m) and 206 ft (63 m), Rifle Gap.

Small and poorly preserved fresh-water gastropods occur in brown siltstone lying 252 ft (77.5 m) above the Trout Creek Sandstone Member in Rifle Gap.

A limited variety of fossil plants are preserved in siltstone. The fossil-plant collections consist of compressions and impressions of broken stems and needles of conifers. Araucarian-like conifer dominates the assemblage, and fragments of cupressaceous-like conifer are far less abundant in the assemblage (J.A. Wolfe, oral commun., 1982). These are detrital plant fragments which vary in size due to varying conditions of transport and distances of transport from their source. They do not necessarily reflect a local flora; rather, they probably originated higher up on the ancient delta plain. In addition to the conifers, fragments of a fan-palm leaf impression occur. Further identification of the form genus is impossible because the incomplete sample lacks the petiole (J.A. Wolfe, oral commun., 1982).

Palynomorphs include miospores named by Newman (1965b): *Kuylisporites scutatus* (spore), *Myrtaceoipollenites peritus* (pollen), *Trudopollis meekeri* (pollen), *Pseudoplicapollis* (*Sporopollis*) *laqueaeformis*, *Vacuopollis* (*Conclavipollis*) *wolfcreekensis*, and a species of *Plicapollis* (Madden-McGuire and Newman, 1988). The latter four pollens have restricted time ranges and are important tools in the biostratigraphic correlation of nonmarine strata.

DEPOSITIONAL CONDITIONS

The shoreline of the Trout Creek Sandstone Member passed seaward and a delta plain covered the area of the central Grand Hogback. At its outer margin, beach ridges fringed this delta. Tidal channels and sparse, widely spaced, distributary channels cut the beach ridges; and washover fans overlapped the ridges during storms. Landward, brackish-water bays and peaty marshes extended their seaward margins to the beach. These bay and marshy areas of the lower delta plain filled with sediment delivered by small streams, and with crevasse-splay and overbank deposits from the large distributary channels. Further landward, in central areas of the upper delta, vast tracts of poorly drained and permanently waterlogged swamps produced peat in fresh-water environments.

Fresh-water deposits of the upper delta plain compose most of the Songer coal-bearing unit. Sandstone in this unit formed in fluvial-channel, levee, and overbank environments. For example, a thick-bedded, 30-ft (9.1-m) sandstone enclosing horizons of claystone clasts and interpreted as upper delta-plain, active, distributary-channel fill is exposed in Rifle Gap. This sandstone lies 180 ft (84 m) above the Trout Creek Sandstone Member. Two lower, channel-fill sequences lie between 70 ft and 120 ft (21–36 m) above the Trout Creek Sandstone Member. More thinly bedded sandstone, arranged in coarsening-upward sequences, formed as crevasse splays and levees. The finest grained deposits of silt and shale, beneath and within coal beds, are back-levee and flood-basin deposits of distal splays. Sandstone beds show predominantly southeastward sediment-transport directions, toward the sea and normal to the shoreline. Overbank deposits contain fresh-water gastropods in a faunal assemblage comprised of many individuals of a limited number of taxa. Coal beds formed in fresh-water swamps located between distributary channels, and lower on the delta in marshes.

Brackish-water-bay deposits compose only 10–15 percent of the unit. These consist of oxidized, burrow-mottled siltstone and sandstone, and structureless gray mudstone bearing brackish-water pelecypods and gastropods. The fossil assemblages suggest that deposition occurred in low-salinity environments such as brackish-water, back-bay areas subject to fresh-water runoff.

The low-salinity, brackish-water fauna contrasts with a higher salinity, brackish-water fauna from the same stratigraphic interval exposed more than 60 miles (97 km) to the northeast near Oak Creek in Routt County (W.A. Cobban, oral commun., 1982). Gaffke (1979) described onshore, bay-fill sequences containing *Corbula undiffera*, a time-restricted brackish-water pelecypod, and *Lingula* sp., a shallow-marine to brackish-water brachiopod. The fossil assemblage suggests a wider connection between the bay environment in the Oak Creek area and the Cretaceous sea than existed between bays and the sea in the Grand Hogback area.

Sandstone beds deposited in the lower delta plain contain casts of *Teredolites* associated with carbonized wood compressions on the undersides of beds. *Teredolites* occur elsewhere in Upper Cretaceous brackish-swamp deposits, nearshore high-energy deposits, and tidal-zone and flood-plain deposits (Chamberlain, 1976; Frey and Howard, 1982; Maberry, 1968). In the Grand Hogback, *Teredolites* are in brackish-water bay-fill deposits and in redeposited fragments of wood in channel and shoreface sandstone.

The thin-bedded sandstone above the lowest coal bed in Rifle Gap is interpreted as a distal washover fan, which formed over a period of years. After a major storm scoured a channel through beach and dune deposits, beach sandstone that was well sorted and upper fine in grain size was transported landward through the storm channel during times of high storm surge. Upon waning of landward-directed storm surge, sand covered low-lying, marginal peat swamps. In a modern example, in the Gulf of Mexico, Hurricane Frederic (1979) left washover-fan deposits fringing portions of Chandeleur Sound and covering marshy areas southeast of the Mississippi Delta plain. These modern fans were deposited in thin sheets a few centimeters thick (Kahn and Roberts, 1982, p. 142), similar to the thin beds making up sandstone above the lowest coal bed in Rifle Gap.

SANDSTONE UNITS, LOWER PART OF THE WILLIAMS FORK FORMATION

Four sandstone units, comprising nearshore-marine deposits, occur in the lower part of the Williams Fork Formation: the Doll, Haas, Harvey, and Henry sandstone units. All are named after local mines. These units form thick, prominent, massive-weathering sandstone bodies with white-weathered tops similar to the Trout Creek Sandstone Member.

Only the Haas sandstone unit (fig. 13) extends throughout the central Grand Hogback. The Doll sandstone unit occurs only in the eastern portion of the area; and the Harvey and Henry sandstone units occur only in the central portion, near Harvey Gap. The Henry sandstone unit is the highest marine-shoreface deposit found. It lies more than 800 ft (244 m) above the Trout Creek Sandstone Member in Harvey Gap (fig. 14).

The four sandstones show several characteristics which are different from the Trout Creek Sandstone Member: (1) absence of underlying, thick offshore

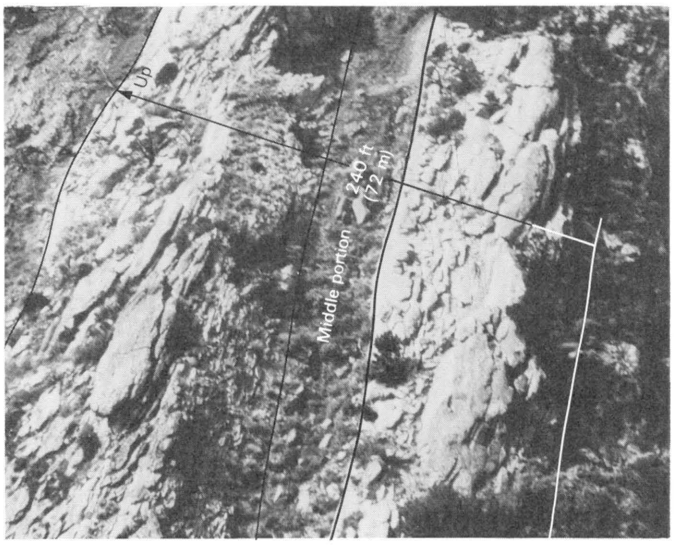

FIGURE 13.—The Haas sandstone unit (240 ft, 72 m thick) on the west side of Harvey Gap. Note well-developed upper and lower sandstones in this unit. Stratigraphic thickness serves as scale.

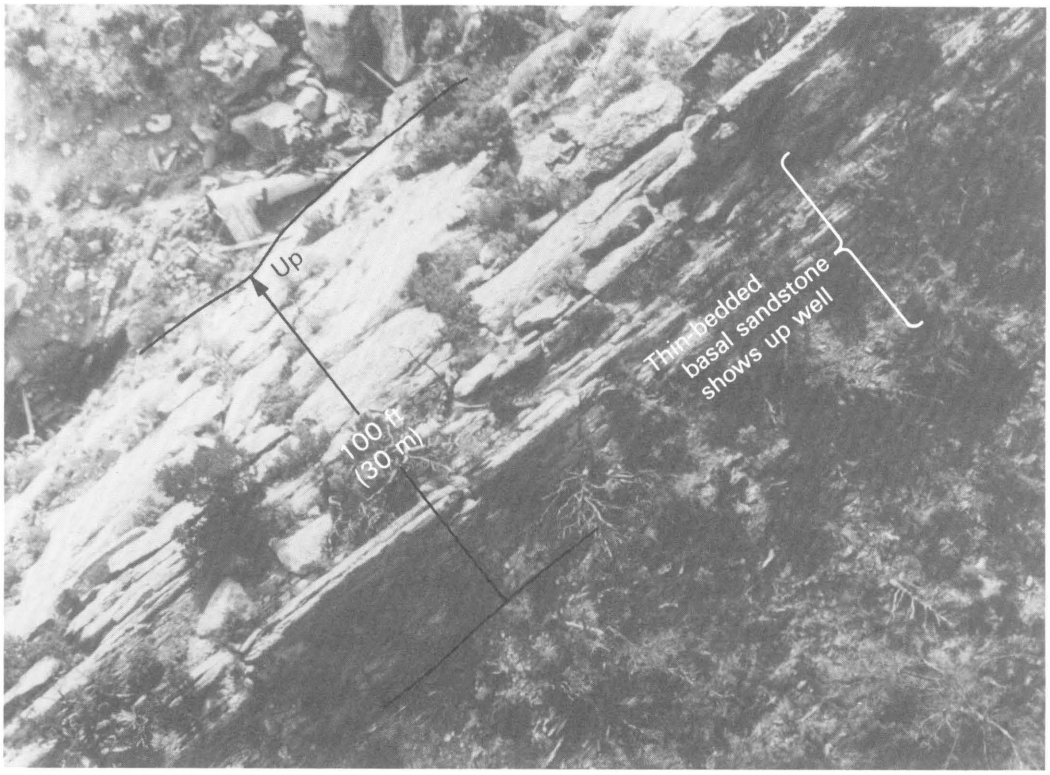

FIGURE 14.—The Henry sandstone unit (100 ft, 30.5 m thick) on west side of Harvey Gap. Note mine entrance on left side of photo. Stratigraphic thickness serves as scale.

sequences analogous to the Rifle shale unit; (2) local presence of coarse-grained, basal sandstone; and (3) variety of predominant sediment-transport directions that are different from the Trout Creek and that differ among the four sandstones. The lower part of the Williams Fork Formation is sandier than the upper part of Iles Formation. No thick shale sequences occur in the lower Williams Fork, and relatively coarse material was available below these marine units to facilitate accumulation of coarse basal lag deposits. The differences in directions of sediment transport may reflect slightly different shoreline orientations between and even within units. For example, some paleocurrent data suggest that local shoreline orientation changed during deposition of the Haas sandstone unit.

DOLL SANDSTONE UNIT

The Doll sandstone unit is an eastward-thickening tongue of massive-weathering, nearshore-marine sandstone. It splits the Songer coal-bearing unit into two nonmarine tongues. The western limit of the Doll sandstone unit, near Harvey Gap, is concealed beneath slope wash. To the east, the unit thickens from 140 ft (43 m) near the Doll mine to 240 ft (73 m) at New Castle. Near Doll mine, the sandstone consists of three subunits: (1) a fine-grained basal, transgressive(?) sandstone (8 ft, 2.4 m thick) overlain by (2) a finer grained, thinner bedded, offshore sequence (35 ft, 10.7 m thick) resembling the upper part of the Rifle shale unit, topped by (3) a thick (105 ft, 32 m), massive-weathering, shoreface sandstone with a white-weathered top. Five paleocurrent measurements were taken from this unit. Their vector mean is 181° and the standard deviation is 32°.

HAAS SANDSTONE UNIT

The Haas sandstone unit overlies the Songer coal-bearing unit and underlies the Silt coal-bearing unit (Madden, 1985). The sandstone generally consists of three subunits: the lowest is shoreface sandstone; the middle is a less resistant, thin-bedded interval of offshore sandstone and minor mudstone; and the highest is shoreface sandstone. Thicknesses of these subunits vary considerably along the outcrop, and their contacts vary from sharp to transitional. Thickness of the whole Haas sandstone unit ranges from only 70 ft (21.3 m) in

Rifle Gap to 300 ft (91 m) eastward near the abandoned Doll coal mine.

The basal contact of the lower sandstone is sharp, locally overlying coal and clinker. Where the sandstone overlies unburned coal, the basal several feet (approximately 1 m) consist of detrital carbonaceous and coaly debris interbedded with sandstone. The basal portion (approximately 10 ft, 3 m) of the lower sandstone is coarser grained (lower to upper fine grained (3.0–2.0ϕ)) than overlying sandstone.

The lowest shoreface sandstone contains a marine trace-fossil assemblage of *Ophiomorpha*, *Thalassinoides*, *Rhizocorallium*(?), and *Diplocraterion*. *Ophiomorpha* is the most common trace fossil, occurring in localized burrow mazes scattered throughout the sandstone. *Thalassinoides* occur in sparse shalier intervals. Horseshoe-shaped, horizontally oriented, unlined burrows, cf. *Rhizocorallium* without spreite, occur on bedding surfaces near the base of the lower sandstone.

The middle portion of the unit forms a continuous outcrop, 10–37 ft (3.1–11.3 m) thick, extending along the central hogback. This is an offshore deposit containing hummocky cross-stratified and wave-rippled, lower very fine grained sandstone interbedded with silty mudstone. These strata contain transported *Inoceramus* sp., *Didymoceras cheyennense*, and *Oxytoma* sp. The presence of *Didymoceras cheyennense* is useful in correlation. Also, this is the first occurrence of an ammonite in the Williams Fork Formation and the westernmost occurrence of *Didymoceras cheyennense* (W.A. Cobban, oral commun., 1983).

The trace-fossil assemblage of the middle portion of the unit is the most diverse of all units. It includes short, thick-lined, cylindrical, vertical burrows (7.0–8.8 mm wide) (fig. 15) in sandstone; bilobate (gastropod?) trails resembling *Aulichnites*; smooth, unwalled, horizontal burrows on bedding planes cf. *Thalassinoides*?; ?*Isopodichnus* (large, 15–18 mm wide; small, 4–5 mm wide) (fig. 16); *Asteriacites* (fig. 17); a meniscate, horizontal burrow; concentrations of *Rhizocorallium jenense* causing local bioturbation of bedding surfaces; bulbous impressions on bedding bases cf. *Pseudobilobites* sp. (up to 66 mm long, 32.5 mm wide, and 13.8 mm thick with poorly preserved, chevron-shaped scratch marks(?)) (fig. 18); mazes of horizontally oriented, irregular burrows on bedding bases; and sparse *Ophiomorpha* and *Diplocraterion*.

The highest shoreface sandstone is a massive-weathering deposit with a white-weathered top similar to the Trout Creek Sandstone Member. Its thickness ranges from 25 ft (7.6 m) to 130 ft (40 m).

Paleocurrent directions in the lower part of the Haas sandstone unit are predominantly to the south. The vector mean of 29 observations is 181°, and the standard

FIGURE 15.—Unnamed, thick-walled, vertical burrows in sandstone, in middle portion of the Haas sandstone unit. View of upper bedding surface.

deviation is 61°. Directions of the larger features, such as low-angle trough crossbeds, are most likely to show the main sediment-transport directions. Directions of 14 low-angle crossbeds in the lower sandstone have a vector mean to the south-southwest of 189° and a standard deviation of 37°. In contrast, in the upper part of the Haas sandstone unit, directions of all features are predominantly to the southeast, based on 26 measurements. The vector mean is 165°, and the standard deviation is 68°. The subpopulation of larger scale features in the upper sandstone is the most significant. Directions indicated by 11 large trough crossbeds have a vector mean to the southwest of 216° and a standard deviation of 57°.

DEPOSITIONAL CONDITIONS OF THE MIDDLE PORTION

The middle portion of the unit contains marine fossils and hummocky cross-stratification. It formed in the

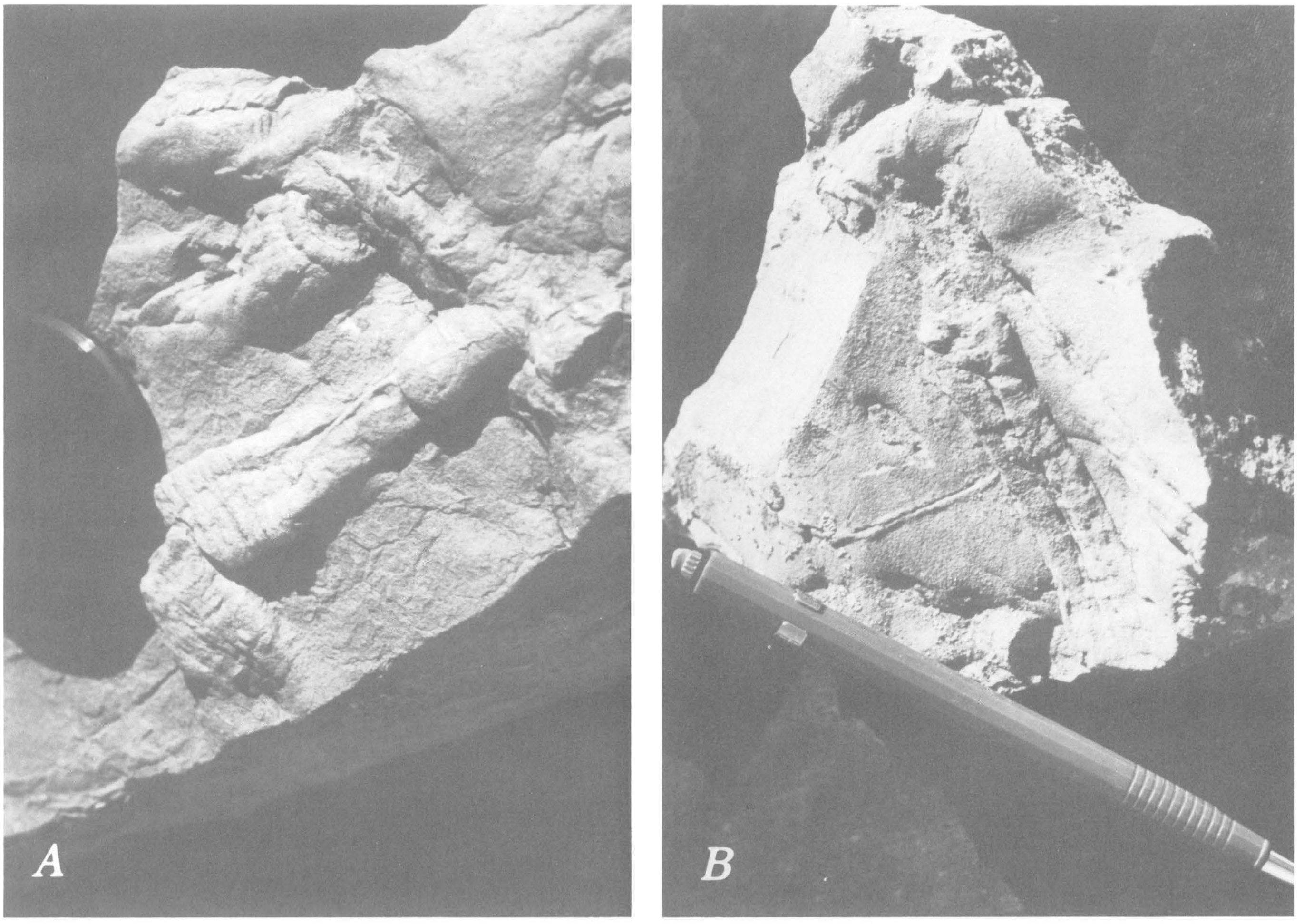

FIGURE 16.—*Isopodichnus* sp., from middle portion of the Haas sandstone unit. Views of upper bedding surfaces. *A*, ribbon trace with transverse appendage marks (lens cap for scale); *B*, pronounced medial groove.

inner offshore to lower shoreface below fair-weather wave base.

These inner-offshore deposits contain diverse trace-fossil taxa. The assemblage suggests that mobile, deposit-feeding organisms were more abundant than immobile, suspension-feeding organisms. The diversity of trace fossils suggests some diversity of benthic activities and fauna. This diversity, together with *Asteriacites*, a marine-echinoid resting trace, suggests normal marine salinity of bottom waters and a plentiful food supply. The mobile, deposit-feeding, benthic organisms made *Asteriacites*, bilobate trails, and *Isopodichnus*; whereas the immobile, suspension feeders made the sparser *Ophiomorpha* and *Diplocraterion*. The abundance of mobile deposit feeders may reflect the presence of a firm substrate during calm intervals below fair-weather wave base. The scarcity of immobile suspension feeders may reflect abundant suspended clay and silt which choked feeding apparatuses, low current activity, or merely poor preservation of trace fossils made by suspension feeders.

HARVEY SANDSTONE UNIT

The Harvey sandstone unit, 165 ft (50.3 m) thick, is within the Silt coal-bearing unit. Three subunits compose this sandstone near the Haas mine: a basal series of massive sandstone and interbedded, shaly intervals (100 ft, 30.5 m); a middle interval of more thinly bedded offshore deposits (20 ft, 6.1 m); and an overlying massive-weathering, shoreface sandstone (45 ft, 14 m).

The lower and upper sandstone-rich subunits resemble the Trout Creek Sandstone Member in some characteristics: the presence of low-angle cross-stratification, scour surfaces littered with claystone clasts, and *Ophiomorpha* and *Terebellina*. *Inoceramus* sp. occurs in the lower sandstone. The middle portion of the unit resembles the middle portion of the Haas sandstone

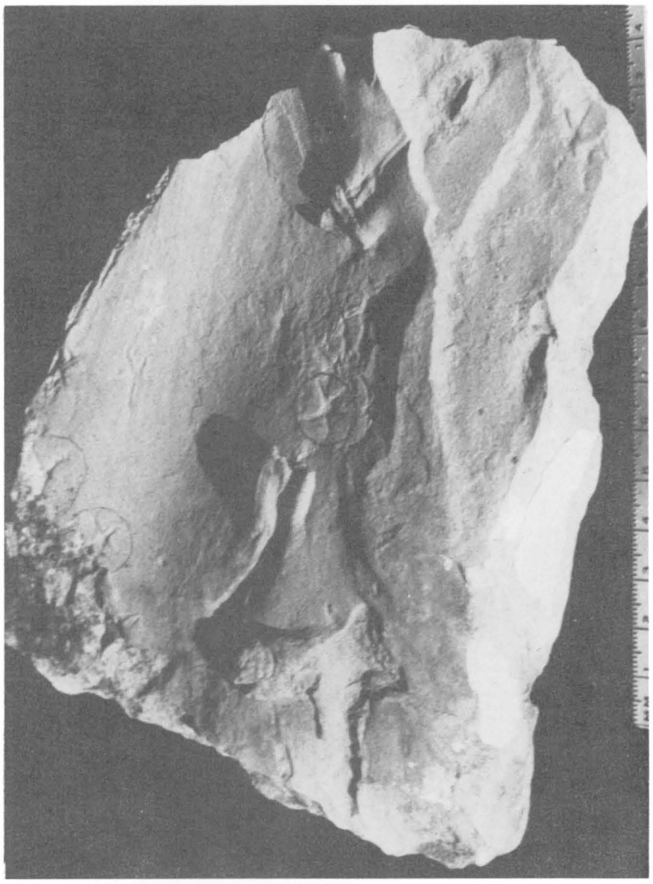

FIGURE 17.—Horizontal *Asteriacites* and oblique *Isopodichnus* sp. on same bedding plane, from middle portion of the Haas sandstone unit.

unit. It consists of silty mudstone, interlayered with lenticular beds of hummocky cross-stratified sandstone overlying shallow erosional surfaces (fig. 19). Locally, the base of the middle portion of the unit is a coarse, poorly sorted lag deposit of broken bivalve shells in a lower fine grained (3.0–2.5ϕ) sandstone matrix. Shrinkage cracks are exposed on one sandstone bedding surface.

Burrow mottling on bedding surfaces is abundant in the middle portion of the unit, as it is in the middle portion of the Haas sandstone unit. The following trace fossils occur: (1) *Rosselia*(?); (2) sand-filled *Thalassinoides*; (3) large (1–1.5 cm diameter), horizontally oriented, sand-filled, unbranched burrows in siltstone, cf. *Planolites*; (4) thick-walled, cylindrical, vertical burrows; (5) bulbous impressions on sandstone bedding bases, cf. *Pseudobilobites*; (6) horizontal, U-shaped burrow casts, cf. *Rhizocorallium* without spreite; and (7) poorly preserved *Isopodichnus*(?).

Axes of trough crossbeds in the upper sandstone are oriented to the south-southeast. The vector mean of eight trough-crossbed axes is 164° and the standard deviation is 43°.

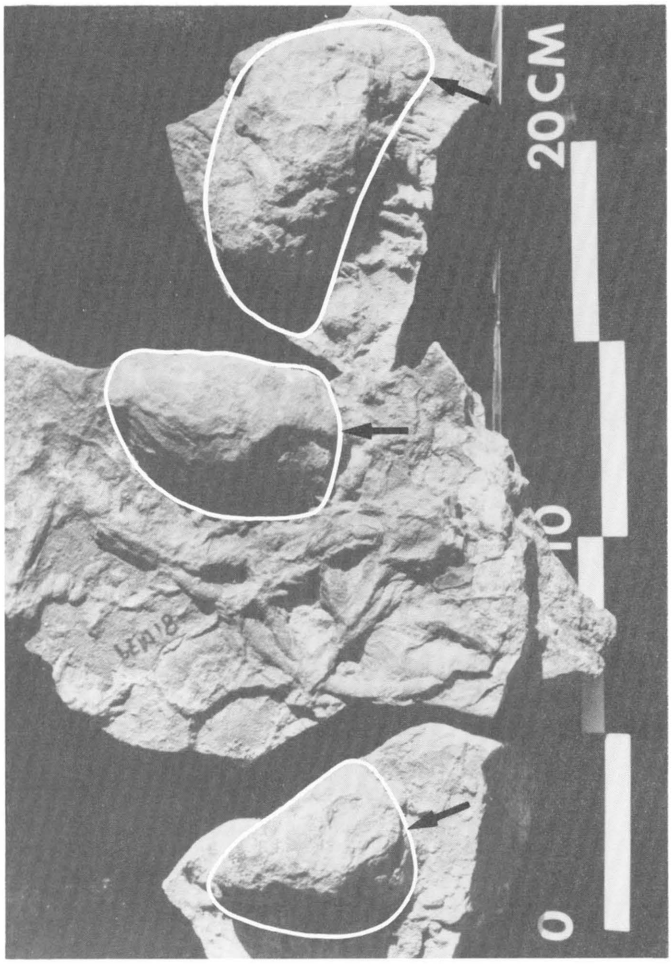

FIGURE 18.—*Pseudobilobites* sp. on a basal bedding surface, middle portion of the Haas sandstone unit. Identification by A. Rindsberg, Colorado School of Mines.

DEPOSITIONAL CONDITIONS OF THE MIDDLE PORTION

The middle portion of the unit formed in the inner offshore, as did the middle portion of the Haas sandstone unit. This is indicated by its similar stratigraphic position between two shoreface sequences; preservation of hummocky cross-stratified sandstone; diverse trace-fossil assemblage; and the basal lag deposits of marine-shell debris. Shrinkage cracks occur, but it is not known how they formed. Formation by partial emergence is improbable because the other evidence indicates that this is an offshore deposit.

HENRY SANDSTONE UNIT

The Henry sandstone unit is the highest marine-shoreface sandstone in the section. Like the Harvey sandstone unit, it is enclosed within the Silt coal-bearing

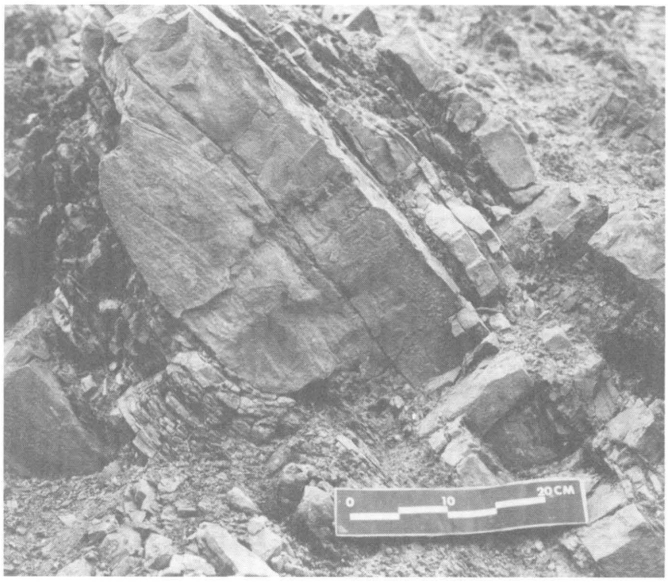

FIGURE 19.—Lenticular beds of hummocky cross-stratified sandstone overlying shallow erosional surface, middle portion of the Harvey sandstone unit. Outcrop up is at top of photograph; stratigraphic up toward top right corner.

unit. The Henry sandstone unit is thickest (130 ft, 39.6 m) in Harvey Gap (fig. 14), and it pinches out into nonmarine strata within a mile and a half (2 km) east and west of Harvey Gap. Contacts with the Silt coal-bearing unit are sharp. Bedding thickness increases upward, and the style of cross-stratification changes upward from hummocky bedding in the lower portion to low-angle trough or tabular cross-stratification in the upper portion.

Ophiomorpha is locally abundant on several bedding surfaces within the middle and top portions of the massive sandstone. Approximately 20 ft (6.1 m) below the top, *Ophiomorpha* occurs as a maze on a bedding surface, where burrows grade laterally to *Thalassinoides*.

SILT COAL-BEARING UNIT, WILLIAMS FORK FORMATION

The Silt coal-bearing unit forms the upper portion of the coal-rich interval in the central Grand Hogback. The unit is vertically continuous at Rifle Gap and New Castle, but it splits into several tongues separated by marine sandstone units in Harvey Gap. Where it is continuous, the Silt coal-bearing unit ranges from 500 ft (152 m) to 800 ft (244 m) in thickness.

Comparing the Silt and Songer coal-bearing units, one finds both similarities and differences. The units are similar in lithologies and sedimentary structures, and both contain fresh-water and sparse brackish-water deposits in their lower portions. However, several differences are notable as well: (1) biogenic structures made by benthic organisms are rare in the Silt coal-bearing unit, whereas in certain portions of the Songer coal-bearing unit such structures are abundant; (2) coal beds are sparser and thinner in the Silt coal-bearing unit; and (3) the top of the Silt coal-bearing unit is not a clear-cut contact overlain by marine sandstone, but is gradational upward into non-coal-bearing, nonmarine strata. Two types of shells occur in the Silt coal-bearing unit but not in the Songer coal-bearing unit: low-salinity brackish-water bivalve *Anomia micronema* Meek occurs on the Rifle Gap roadcut and oyster shells occur in float at New Castle.

Paleocurrent directions in the Silt coal-bearing unit have a mean to the south-southeast. The vector mean of 11 observations is 152°, the standard deviation is 80°, and the mode is 105°.

DEPOSITIONAL CONDITIONS

Most of the Silt coal-bearing unit formed in an upper delta-plain area, which was sandier than that of the Songer coal-bearing unit and contained only sparse peat swamps. The presence of a sandy upper delta plain probably was due to the wide influence of clastic deposition which limited the extent of sediment-starved, waterlogged areas.

PALEOGEOGRAPHY

During the Campanian Stage of Late Cretaceous time, North America consisted of a high, narrow Cordilleran land mass to the west and a large, low-lying land mass to the east. These were separated by a north-trending seaway covering the center of the continent. The coal-rich strata of the central Grand Hogback formed on the eastern flank of the Cordillera, and on the southern flank of a seaward bulge in that shoreline (McGookey and others, 1972, figs. 45 and 49). This bulge was a Campanian deltaic center now preserved as a thickened wedge of Upper Cretaceous strata in northwestern Colorado and southwestern Wyoming (Weimer, 1961, 1970).

PALEOGEOGRAPHIC RECONSTRUCTIONS

The sketches that follow are based mostly on data I collected in the central Grand Hogback. Additional data sources are listed in figure captions. The paleocurrent data from the hogback form the basis for the shoreline orientations shown in the sketches. These paleocurrent measurements were taken from: (1) low-angle, cross-bedded, upper-shoreface sandstone; (2) shallow, elongate, erosional surfaces associated with hummocky-bedded sandstone sequences; and (3) structures in fluvial delta-plain sandstone.

Other sources of information for these sketches are regional paleogeographic reconstructions from McGookey and others (1972), the geography of modern wave-dominated coasts, and the dimensions of Late Cretaceous delta plains determined from the well-exposed, Campanian Blackhawk Formation of east-central Utah (Balsley, 1980, p. 19).

Before deposition of the Cozzette Sandstone Member, earlier shorelines swept through northwestern Colorado. Boyles determined the orientations of these earlier shorelines and positions of their major distributary channels in a study of the lower part of the Iles Formation (Boyles and others, 1981).

COZZETTE SANDSTONE MEMBER, ILES FORMATION

An embayment containing oyster reefs is shown along this paleoshoreline (fig. 20) because of the abundant oyster fragments which occur in outcrop above the Cozzette Sandstone Member of Warner (1964) in Rifle Gap. The approximate maximum seaward extent of the Cozzette delta plain is based upon the maximum southeastward extent of the Wheeler coal bed along the Grand Hogback (Gill and Freeman, 1978) and the occurrence of *E. jenneyi* above the Cozzette Sandstone Member of Warner (1964) in North Thompson Creek.

The lateral transitions of facies are abrupt and the lateral distribution of facies in some marine intervals (pl. 1) is reversed from what is more usual. In intervals such as the Cozzette of Rifle Gap, coal-bearing strata are distributed laterally seaward from marine shale as a result of shoreline embayments. These odd lateral facies distributions are not too surprising when one considers that these strata formed on an ancient structural boundary between the Colorado Plateau and the Rocky Mountains tectonic province. This boundary has repeatedly been tectonically active since at least the Pennsylvanian to Permian ancestral Rocky Mountain orogeny (Haun and Kent, 1965). Only small-scale, synsedimentary movement along this boundary would be required to complicate sedimentation patterns along the Late Cretaceous shoreline.

RIFLE SHALE UNIT, ILES FORMATION

The approximate maximum landward extent of the Rifle shale unit (fig. 21) is based upon measured sections in Bass and others (1955), Warner (1962, 1964), Izett and others (1971), and Gill and Hail (1975). An irregular shoreline is indicated by the landward occurrence of Foraminifera (Newman, 1964, fig. 3) at Wolf Creek, suggesting the presence of embayments.

TROUT CREEK SANDSTONE MEMBER, ILES FORMATION

The paleoshoreline of the Trout Creek Sandstone Member is interpreted as a north-northeast-trending, embayed delta plain and strand line (fig. 22). Along this strand line, restricted, low-salinity, brackish-water bays lay behind sandy beach ridges locally cut by tidal inlets as indicated by deposits exposed in Rifle Gap and near Haas mine. A more saline bay is shown 60 mi (97 km) to the northeast (Gaffke, 1979). In the hogback, distal splays from distributary channels and storm washovers carried up from the beach provided brackish-water bay-fill sediments preserved in Rifle Gap. Away from major distributary channels, peat swamps developed on the lower delta plain. These swamps were elongate parallel to the shoreline and formed on crevasse-splay deltas built out into bays. The shapes of these swamps were influenced by beach-ridge topography on the lower delta plain. Such topography was progressively covered by more crevasse-splay deposits as the shoreline prograded southeastward and, therefore, the beach-ridge topography was less prominent on the upper delta plain. The maximum seaward extent of the Trout Creek coastal plain is placed near New Castle, based upon east-southeastward thinning of fresh-water deposits and disappearance of coal above the Trout Creek Sandstone Member. In addition, the Trout Creek Sandstone Member itself has a more marine and a less nearshore appearance at New Castle, where it is thinner than to the west, has lost its white cap, and contains few if any shell and claystone lag deposits and horizons littered with plant fragments that are typical of western exposures.

DOLL SANDSTONE UNIT, WILLIAMS FORK FORMATION

A slight change in shoreline orientation is suggested by paleocurrent data from the Doll sandstone unit (fig. 23). The reorientation may have been a result of increased sedimentation rates to the south, extending the shoreline farther seaward in areas to the south. The maximum seaward extent of the Doll coastal plain is not known.

LOWER PART OF HAAS SANDSTONE UNIT, WILLIAMS FORK FORMATION

During deposition of the lower part of the Haas sandstone, the shoreline was oriented north-northeast (fig. 24). This is similar to the orientation of the shoreline during deposition of the Trout Creek Sandstone Member. This orientation is based on paleocurrent directions. The maximum seaward extent of the fresh-water delta plain lay somewhere to the northwest of the

FIGURE 20.—Schematic sketch of coastal paleogeography during deposition of the Cozzette Sandstone Member and the Wheeler coal bed, before or during the time represented by range zone of *E. jenneyi*, based on data from Grand Hogback (this report; Collins, 1976; Gill

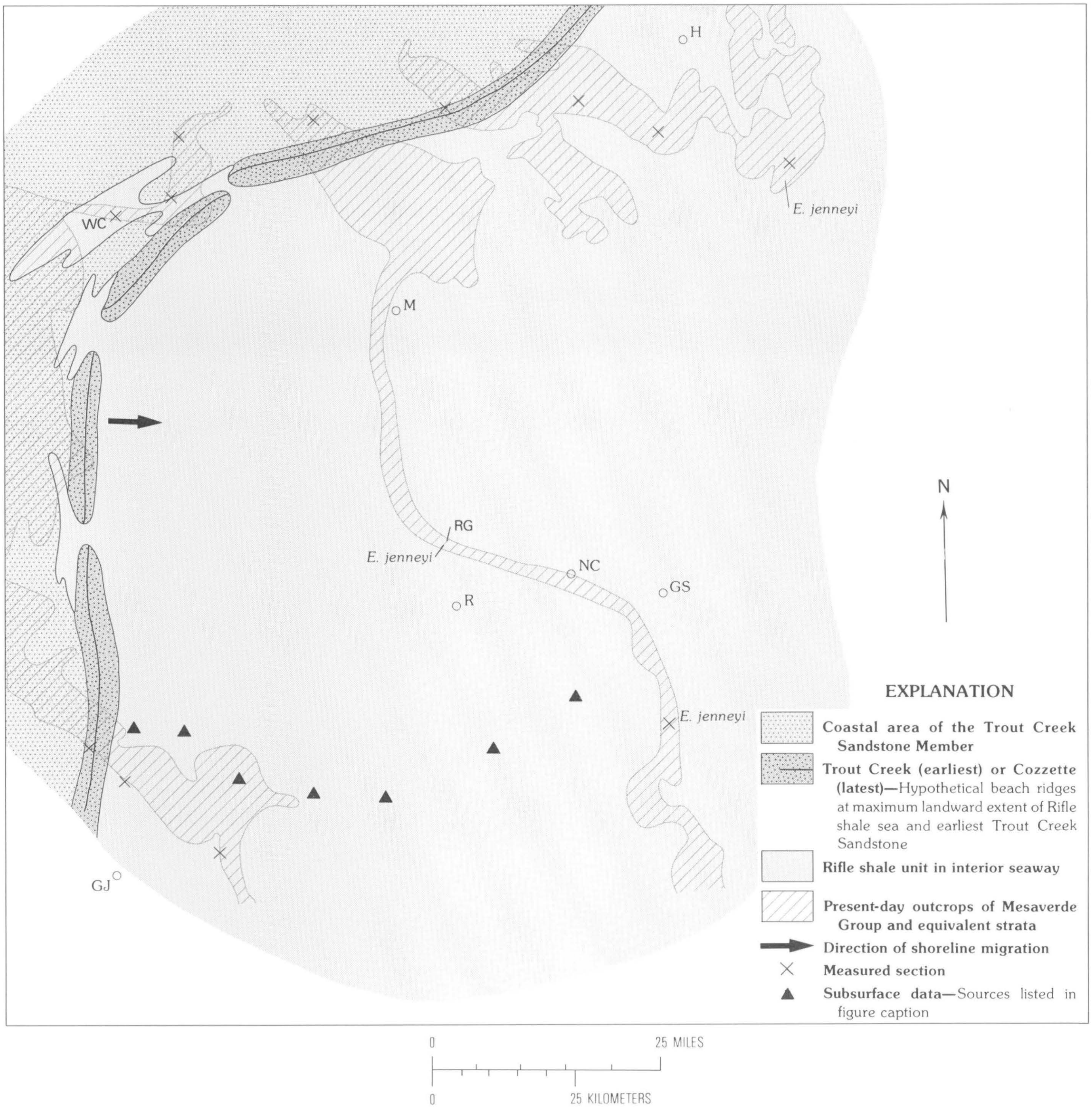

FIGURE 21.—Schematic sketch of coastal paleogeography during maximum(?) landward extent of the Rifle shale unit, during time of *Exiteloceras jenneyi*, which occurs in the basal Rifle shale unit. Approximate position of coastline is based on data from Bass and others (1955), Warner (1962, 1964), Izett and others (1971), Gill and Hail (1975), and Newman (1964, fig. 3). Newman (1964) found arenaceous Foraminifera at Wolf Creek (WC), just above a unit equivalent to the Trout Creek Sandstone Member, indicating that brackish-water or marine embayments existed and that this coastline was irregular as is shown. Outline of present outcrops of the Mesaverde Group/Formation from Tweto (1979). H, Hayden; M, Meeker; RG, Rifle Gap; R, Rifle; NC, New Castle; GS, Glenwood Springs; GJ, Grand Junction. North arrow represents modern north.

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and Freeman, 1978) and adjacent areas (Bass and others, 1955; Warner, 1962, 1964; Gill and Hail, 1975; Johnson and others, 1979a, b, c; Tweto, 1979). Outline of present outcrops of the Mesaverde Group/Formation from Tweto (1979). GS, Glenwood Springs; M, Meeker; NC, New Castle; PC, Piceance Creek; R, Rifle; H, Hayden; GJ, Grand Junction. North arrow represents modern north.

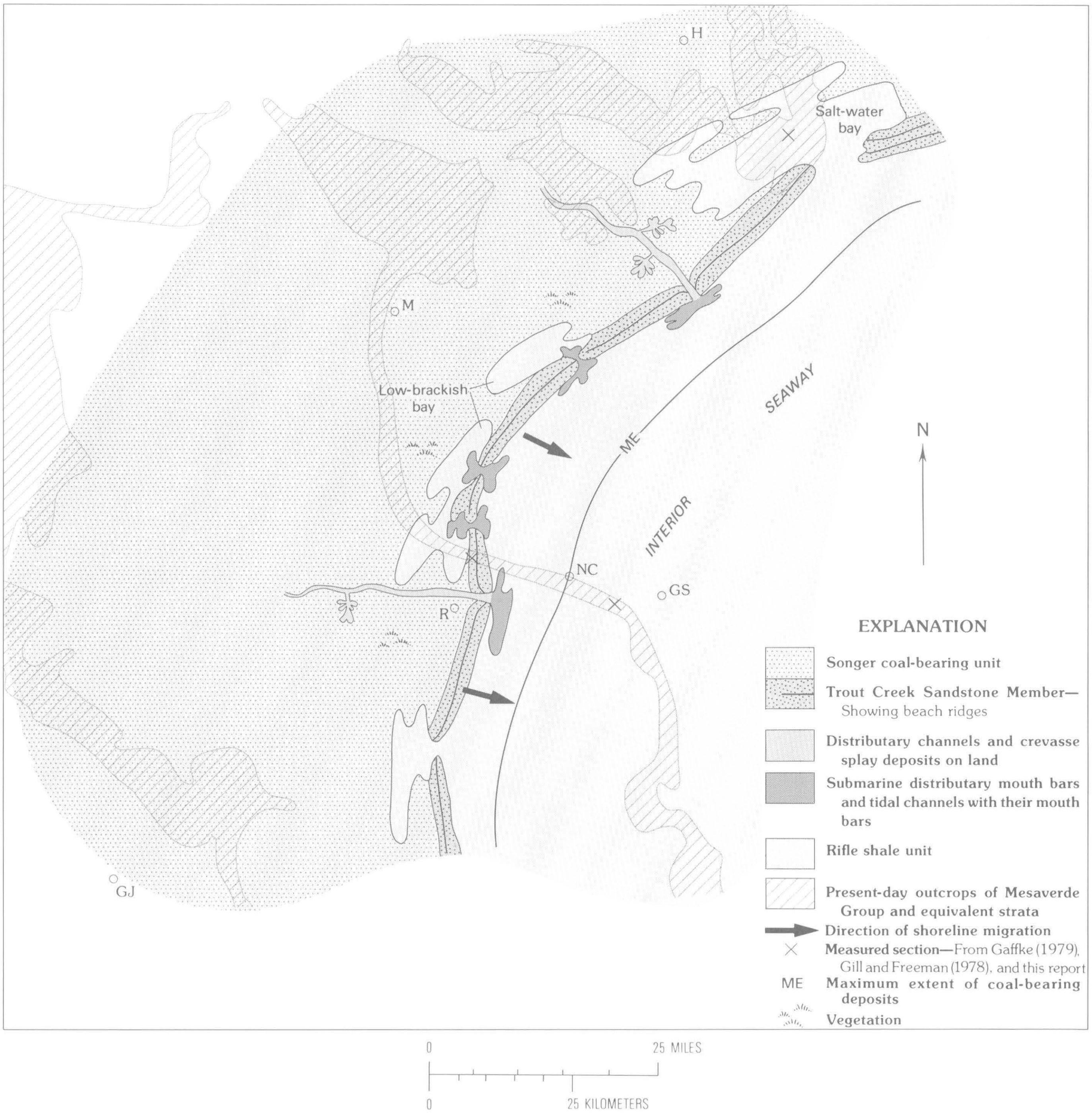

FIGURE 22.—Schematic sketch of coastal paleogeography during deposition of Trout Creek Sandstone Member, based on surface data from Grand Hogback (Madden, 1983 and this report) and Routt County (Gaffke, 1979) and extrapolated to adjacent areas of western and northwestern Colorado. Outline of coast is modified from Boyles and others (1981, fig. 5, pt. I–6). Outline of Mesaverde Group/Formation from Tweto (1979). H, Hayden; M, Meeker; R, Rifle; NC, New Castle; GS, Glenwood Springs; GJ, Grand Junction. North arrow represents modern north.

study area. The maximum east-southeastward extent of the shoreface environment lay somewhere east of New Castle, based upon eastward thinning of this unit through the study area from Haas mine to New Castle.

UPPER PART OF HAAS SANDSTONE UNIT, WILLIAMS FORK FORMATION

Paleocurrent data suggest reorientation of the

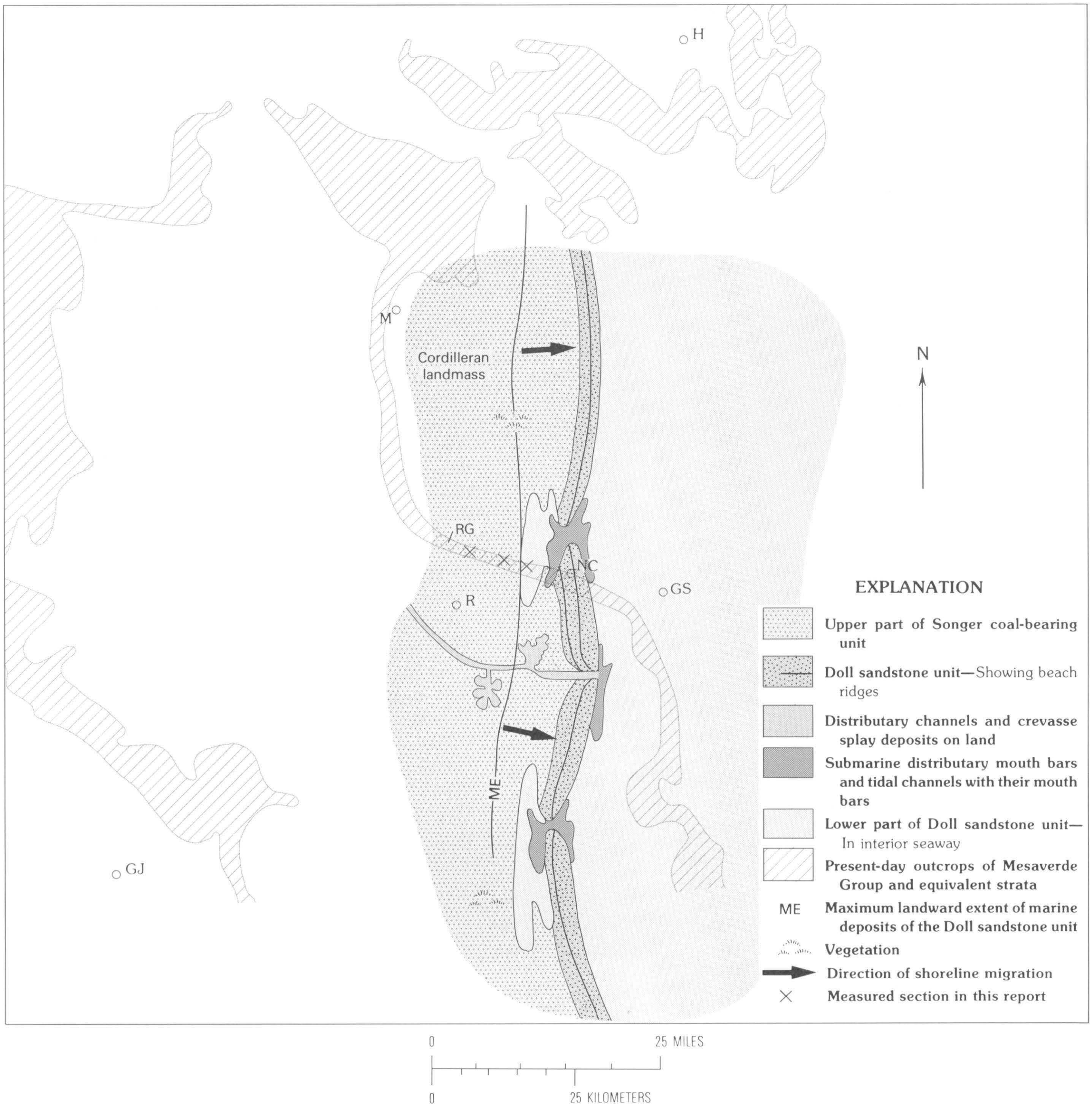

FIGURE 23.—Schematic sketch of coastal paleogeography during deposition of the Doll sandstone unit, based on surface data from the Grand Hogback and extrapolated to adjacent areas of western and northwestern Colorado. Outline of coast modified from Boyles and others (1981, fig. 5, pt. I-6). Outline of Mesaverde Group/Formation outcrops from Tweto (1979). H, Hayden; M, Meeker; RG, Rifle Gap; R, Rifle; NC, New Castle; GS, Glenwood Springs; GJ, Grand Junction. North arrow represents modern north.

shoreline (fig. 25) during deposition of the upper portion of the Haas sandstone unit. This reorientation probably was caused by increased rates of sedimentation and delta extension south of the present-day hogback.

HARVEY SANDSTONE UNIT, WILLIAMS FORK FORMATION

Lateral stratigraphic relationships along the central Grand Hogback indicate that marine sandstone of the Harvey sandstone unit was deposited landward from

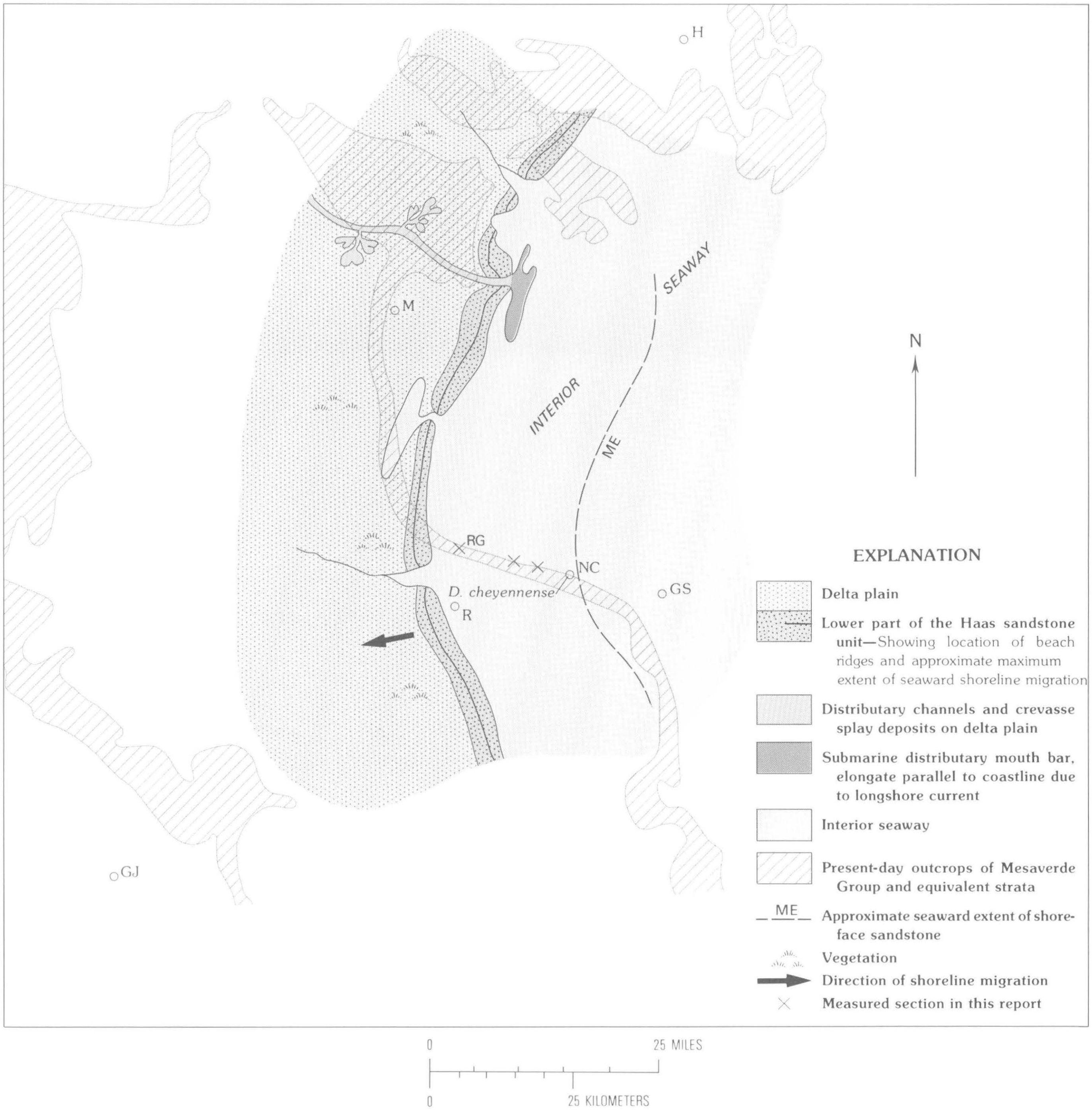

FIGURE 24.—Schematic sketch of coastal paleogeography during deposition of lower part of the Haas sandstone unit and during time of *Didymoceras cheyennense*. Sketch based upon surface data from Grand Hogback and extrapolated to adjacent areas of western and northwestern Colorado; outline of coast modified from Curray (1985, fig. 9). Outline of Mesaverde Group/Formation outcrops from Tweto (1979). H, Hayden; M, Meeker; RG, Rifle Gap; NC, New Castle; GS, Glenwood Springs; GJ, Grand Junction. North arrow represents modern north.

fresh-water delta-plain deposits. The local shoreline was embayed (fig. 26) because of distributary-channel abandonment which cut off the sediment supply to the area now extending from the Haas mine to Harvey Gap. The north-northwestward shoreline orientation is based upon paleocurrent data from the Harvey sandstone unit in the Haas mine area. The maximum seaward extent of this unit is unknown.

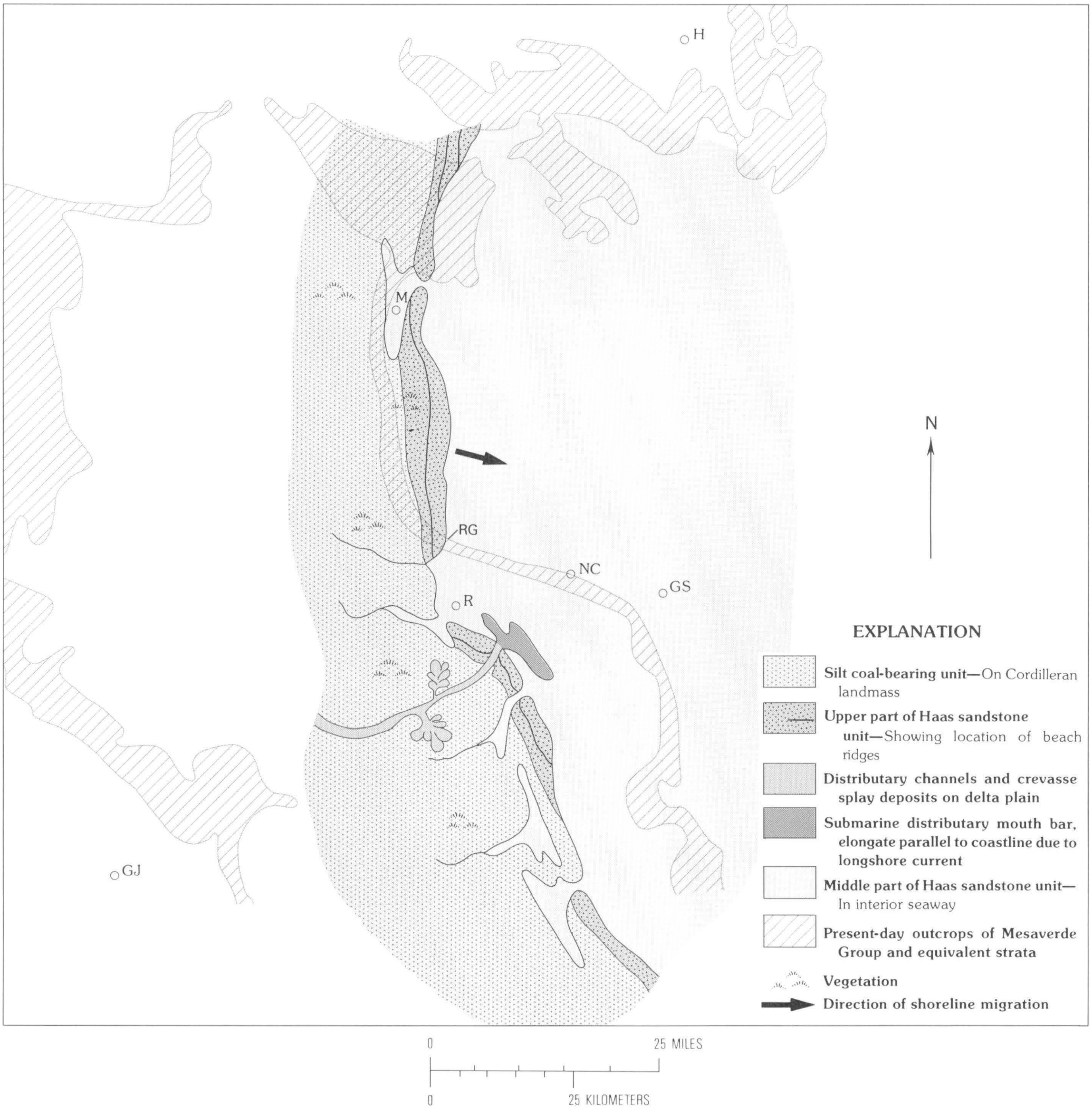

FIGURE 25.—Schematic sketch of coastal paleogeography during deposition of upper part of the Haas sandstone unit, based upon surface data from Grand Hogback and extrapolated to adjacent areas of western and northwestern Colorado. Outline of coast modified from Curray (1975, fig. 9); outline of the Mesaverde Group/Formation outcrops from Tweto (1979). Maximum seaward extent of coastal plain is unknown. H, Hayden; M, Meeker; RG, Rifle Gap; R, Rifle; NC, New Castle; GS, Glenwood Springs; GJ, Grand Junction. North arrow represents modern north.

HENRY SANDSTONE UNIT, WILLIAMS FORK FORMATION

Lateral stratigraphic relations indicate marine-sandstone deposition of the Henry sandstone unit in a more limited marine embayment, restricted to the Harvey Gap area (fig. 27). This unit records the final retreat of the seaway. Actual orientation of the shoreline is unknown owing to lack of paleocurrent data.

FIGURE 26.—Schematic sketch of coastal paleogeography during deposition of the Harvey sandstone unit, based upon surface data from Grand Hogback and extrapolated to adjacent areas of western and northwestern Colorado. Outline of Mesaverde Group/Formation outcrops from Tweto (1979). H, Hayden; M, Meeker; RG, Rifle Gap; R, Rifle; NC, New Castle; GS, Glenwood Springs; GJ, Grand Junction. North arrow represents modern north.

CONCLUSION

DEPOSITIONAL SETTING

The principal strata of interest in the central Grand Hogback formed on a deltaic coastline along which wave reworking and longshore transport of sediment were important processes. Deltaic sedimentation involved buildup of sand in bars at the mouths of distributaries. This sand was reworked by waves which eroded the bars,

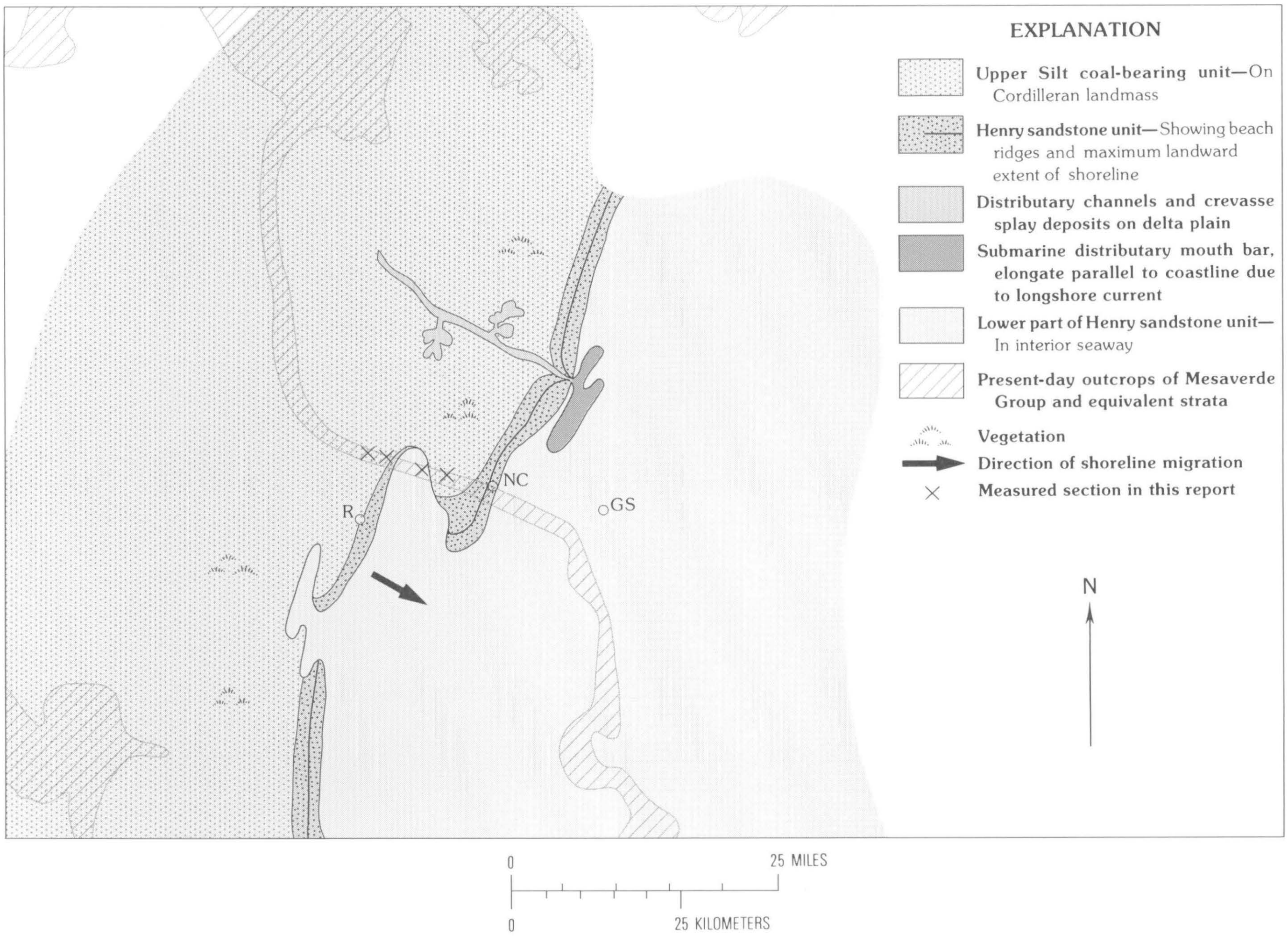

FIGURE 27.—Schematic sketch of coastal paleogeography during deposition of the Henry sandstone unit, based solely upon surface data from Grand Hogback and extrapolated to adjacent areas of western and northwestern Colorado. Outline of Mesaverde Group/Formation outcrops from Tweto (1979). R, Rifle; NC, New Castle; GS, Glenwood Springs. North arrow represents modern north.

moved the sand laterally in southwestward-migrating longshore bars and troughs, and left sand as deposits of longshore drift. Changes in location of the deltaic center northeast of the hogback (due to complete delta switching, or to channel switching or channel extension on the same delta) caused fluctuations in longshore-sediment supply. Decrease in sediment supply, together with continuing subsidence, led to local marine transgressions in the area of the present-day hogback. Conversely, increase in fluvial and longshore-sediment supply, and in local deposition of longshore drift, caused local coastal progradation.

Deltaic sedimentation and shoreline orientations were controlled by fluvial processes on the delta plain. Shoreline orientation is recorded in paleocurrent directions that are approximately parallel to the shoreline in shoreface deposits. Storm-scour surfaces in rocks below the shoreface deposits and fluvial paleocurrent directions from delta-plain strata above the shoreface deposits are oriented approximately perpendicular to the shoreline. All directions shift slightly from one sandstone unit to the next, recording shoreline realignment.

Delta-plain strata lying above the shore facies comprise fresh-water deposits and minor brackish-water deposits formed on a lower delta plain. Lagoonal-type strata which would form behind barrier islands are uncommon. Distributary-channel fill occurs, but channel-fill deposits are not numerous. Delta-plain strata of the Songer coal-bearing unit in Rifle Gap contain only one massive, sandy, distributary-channel deposit, and two thinly bedded channel deposits interlayered with lower delta-plain deposits. This suggests that the local delta plain was supported by only one to three distributaries. Some modern wave-dominated deltas also are fed by few distributary channels. For example, the San Francisco delta is fed by only one distributary channel (Balsley, 1980), and the Nile in its natural state, before human interference, was fed by only two (Coleman and others, 1981).

COMPARISON WITH MODERN NIGER DELTA

Previous workers have compared depositional settings of Upper Cretaceous strata in Colorado and Utah with the modern, wave-dominated Niger Delta, on the western coast of Africa. Van de Graaf (1972) studied the middle Campanian Castlegate Sandstone of central and eastern Utah and concluded that it formed in a setting similar to that of the Niger Delta. Then, Collins (1970, 1976) compared his late Campanian Piceance delta of southeastern Piceance Creek basin with the Niger Delta. In comparison to the Niger, he characterized the Piceance delta as (1) less wave dominated, resulting in less distinct beach-ridge, barrier-island facies; (2) more strongly dominated by fresh-water distributary systems; and (3) receiving a greater sediment load. Collins (1976) concluded that no delta described in the literature is a completely accurate model for the Piceance delta. Collins' (1976) conclusion is probably true: modern deltas are all different in one way or another, and each ancient delta was probably unique as well. The first two contrasts between the ancient Piceance delta and the modern Niger Delta are supported by information about the Piceance delta from the central Grand Hogback; the third one is not.

The ancient Piceance delta was less influenced by wave action than the modern Niger Delta because of differences in tectonic settings, size of receiving basins, wind patterns, and wave power. Set in an extensional tectonic setting, the Niger Delta is prograding seaward from the passive, trailing margin of the African craton. In contrast, the Piceance delta formed in a compressional tectonic setting as part of a clastic wedge shed from the eastward-advancing Sevier orogenic belt into a tectonically depressed foreland basin. The Niger Delta faces a large receiving basin, the Gulf of Guinea and the Atlantic Ocean, whereas the Piceance delta faced a shallower, narrower, epicontinental sea. The Nigerian coastline catches stronger winds because it faces westward against dominant south-southwesterly winds blowing onshore (Oomkens, 1974), whereas the Piceance delta faced southeastward where fair-weather northwesterly winds blew offshore (Dott and Batten, 1981, p. 431). The Nigerian coast is shaped by stronger wave action; the delta faces the Atlantic Ocean over which prevailing winds have a long ocean fetch and generate large-swell waves that generate high-intensity waves (Allen, 1965a, 1965b). The Late Cretaceous seaway east of the Piceance delta was relatively narrow, and prevailing offshore winds would not have generated such high-intensity waves on a leeward coast.

The Piceance delta plain was more strongly affected by fresh-water distributary processes than the Niger Delta. On the Niger Delta, tidal waters penetrate far inland and brackish-water mangrove swamps dominate the lower delta plain (Allen, 1965a, b; Oomkens, 1974). This great extent of brackish-water penetration probably inhibits peat development. In contrast, the lower delta plain of the Piceance delta contained only minor brackish-water swamps, and thick deposits of peat accumulated in fresh-water swamps: the 45-ft (14-m) Wheeler coal bed, which lies above the Cozzette Sandstone Member, represents the formation of 495 ft (149 m) of peat, and the 25-ft (7.6-m) coal bed above the later Trout Creek Sandstone Member represents 275 ft (84 m) of peat, according to compaction ratios of Ryer and Langer (1980). On the Niger Delta, tidal-channel sand makes up most of the coastal-sand deposits on the face. Although the Nigerian deltaic coast is barred, only minor, barrier-bar sandstone is preserved in core samples (Oomkens, 1974, p. 202). In contrast, the coastal sandstone bodies in the central Grand Hogback are dominantly shoreface deposits, and sandstone deposited as tidal-channel fill is minor in volume.

The Piceance delta did not necessarily receive a greater sediment load than the Niger Delta, as suggested by Collins (1976); in fact the reverse may be true. The modern Niger Delta has deposited only 98 ft (30 m) of sediment (Oomkens, 1974) during 5,000 to 7,000 years of relative stillstand in sea level. This is a depositional rate of approximately 16,300 ft (4,900 m) of sediment per million years, equivalent to a rock-accumulation rate of 2,700 ft (820 m) per million years, accounting for compaction of 6 ft (1.8 m) of sediment to 1 ft (0.3 m) of rock (Pettijohn, 1975, p. 276). In comparison, nearshore and delta-plain strata in the central Grand Hogback accumulated at 1,500 ft (460 m) to 3,000 ft (700 m) per million years based on thickness of strata between ammonite collections (Madden, 1983, p. 25). The difference is small, but because the Niger Delta is more influenced by wave action than the Piceance delta, the Niger may lose more sediment to longshore currents and seaward storm transport. Therefore, the Niger probably receives a greater sediment load than did the Piceance delta.

SANDSTONE-MEMBER CORRELATIONS

In order to reconstruct local coastal paleogeography, the marine-sandstone members of the Iles Formation must be correctly correlated along the Grand Hogback. Their correlation can be accomplished best by field mapping these sandstones. Mapping in the central Grand Hogback has shown that the Rollins Sandstone Member at New Castle (Warner, 1964) can be traced to the Cozzette Sandstone Member of Warner (1964) at Rifle Gap. Overlying this interval is the Trout Creek Sandstone Member, which is 300-450 ft (91-137 m) higher in the Iles Formation. These correlations are illustrated on plates 1 and 2, and on figure 28, and they differ from established correlation of the Rollins and Trout Creek Sandstone Members of Warner (1964),

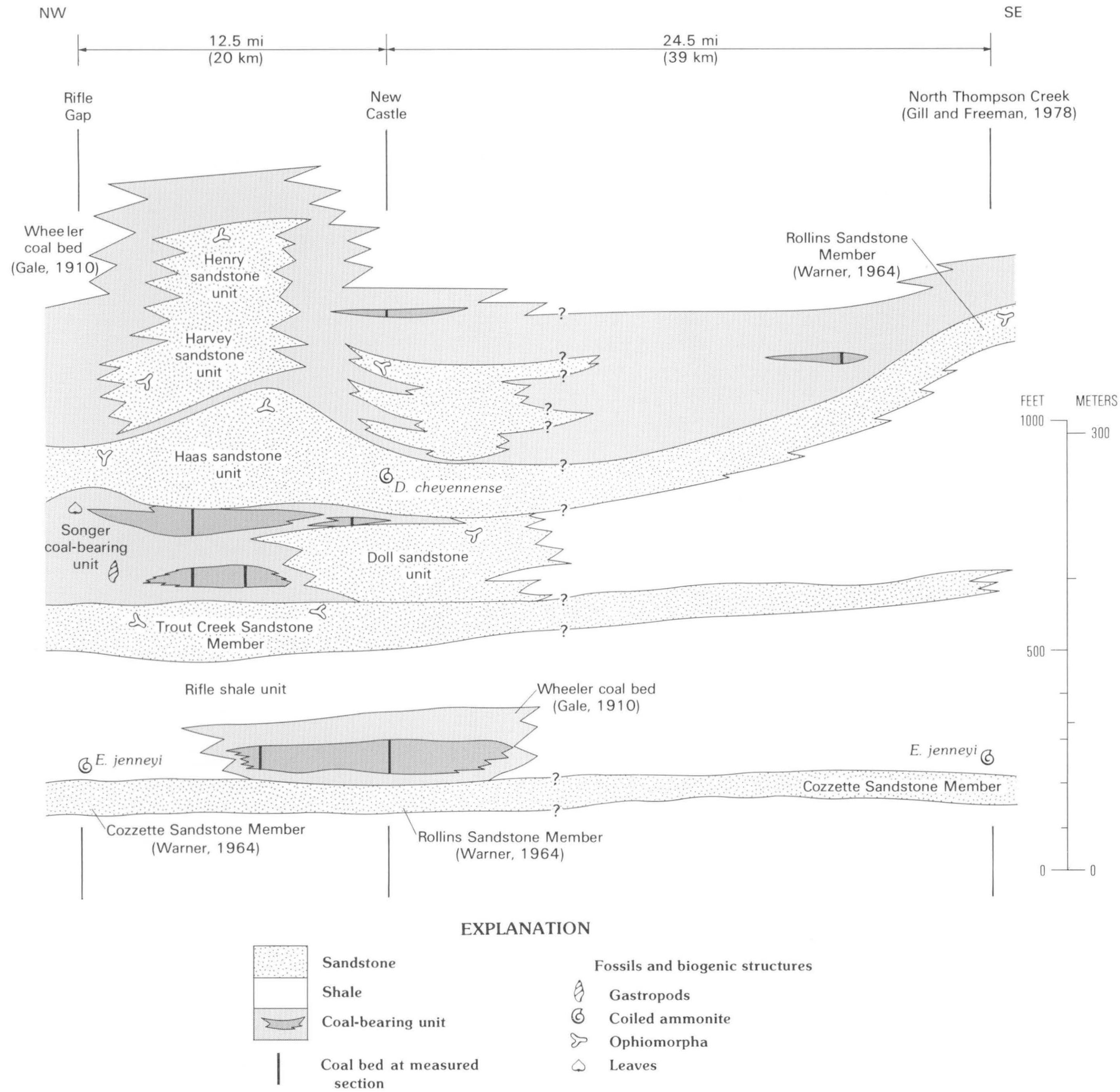

FIGURE 28.—Sketch of hypothetical rock-stratigraphic correlations along Grand Hogback, Rifle Gap to North Thompson Creek, between two measured sections containing *Exiteloceras jenneyi*. Correlations queried between New Castle and North Thompson Creek. Actual correlations can only be determined by systematic field mapping. Note *Didymoceras cheyennense* at New Castle. *E. jenneyi* range-zone thickness is unknown. Estimate of 115-210 ft (35-64 m) is based upon the known range-zone thickness in northwestern Wyoming (Gill and Cobban, 1966, pl. 2) and difference in thickness of Upper Cretaceous strata between that area and Grand Hogback area (McGookey and others, 1972, p. 207).

Johnson (1982), and Lorenz and Rutledge (1987). The new correlations have resulted in recognition of unusual lateral-facies relations of marine strata of the Rifle shale unit distributed west-northwest of, or inland from, thick coal deposits containing the Wheeler coal bed. This lateral-facies distribution suggests that localized abandonment and marine embayment of the shoreline took place in the area of Rifle Gap, during deposition of the Cozzette Sandstone Member. This resulted in the paleogeographic sketch of the shoreline of the Cozzette (fig. 20).

The recorrelation of units in the central Grand Hogback raises questions regarding correlation of the Rollins Sandstone Member to the south. The questions arise because of the relation of this sandstone to the fossil *E. jenneyi* and new correlations. Considering these, the section at New Castle is reinterpreted. At New Castle, the Rollins Sandstone Member of Warner (1964) lies beneath the horizon of *E. jenneyi* as it was traced from its collection site in Rifle Gap. In contrast, at North Thompson Creek the Rollins Sandstone Member of Warner (1964) lies 860-900 ft (262-274 m) above a collection of *E. jenneyi* in marine mudstone (fig. 28). The relations could result from a very rapid time-transgressive, seaward rise in section of the sandstone. Alternatively, the Rollins Sandstone Member at New Castle may trace in the field to a sandstone below the Rollins in North Thompson Creek. Figure 28 shows a possible relation in which the Trout Creek Sandstone Member pinches out into marine mudstone and the Haas sandstone unit climbs in section to the Rollins Sandstone Member. Alternatively, an even higher, informal, marine-sandstone unit in the Williams Fork Formation may extend southeastward to the Rollins Sandstone Member.

During local coastal progradation, the marine-sandstone units formed at the front of the windswept deltas. These deltas grew in pulses. Each pulse probably left a lens-shaped body of sandstone underlain by marine shale and overlain by coal-bearing delta-plain strata. Bodies of sandstone such as the Trout Creek are thus likely to be lens shaped rather than continuous blankets spread across the entire basin. It is thus unlikely that a single sandstone member can be followed from its type locality throughout the entire basin in the surface and subsurface.

COAL-RESOURCE POTENTIAL

Abundant coal remains in the central Grand Hogback (pl. 2), but this coal presently has relatively low economic potential for large-scale mining operations compared with other Rocky Mountain deposits. Coal beds in the Grand Hogback dip steeply, 50° to 80°, and are not minable by strip-mining methods. The coal is high-volatile C bituminous making subsurface hydraulic mining unlikely (Kent and Arndt, 1978). Many of the thick deposits are in remote areas of the steep hogback away from main, accessible canyons. More accessible deposits of horizontal to shallow-dipping, strippable, noncoking, bituminous coal are abundant in the Rocky Mountain region, and these have more economic potential than coal beds in the Grand Hogback. Coal deposits in the central hogback may be valuable only to small mining operations, supplying coal for local use.

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