Structure and Stratigraphy of Upper Cretaceous and Paleogene Strata (North Horn Formation), Eastern San Pitch Mountains, Utah—Sedimentation at the Front of the Sevier Orogenic Belt

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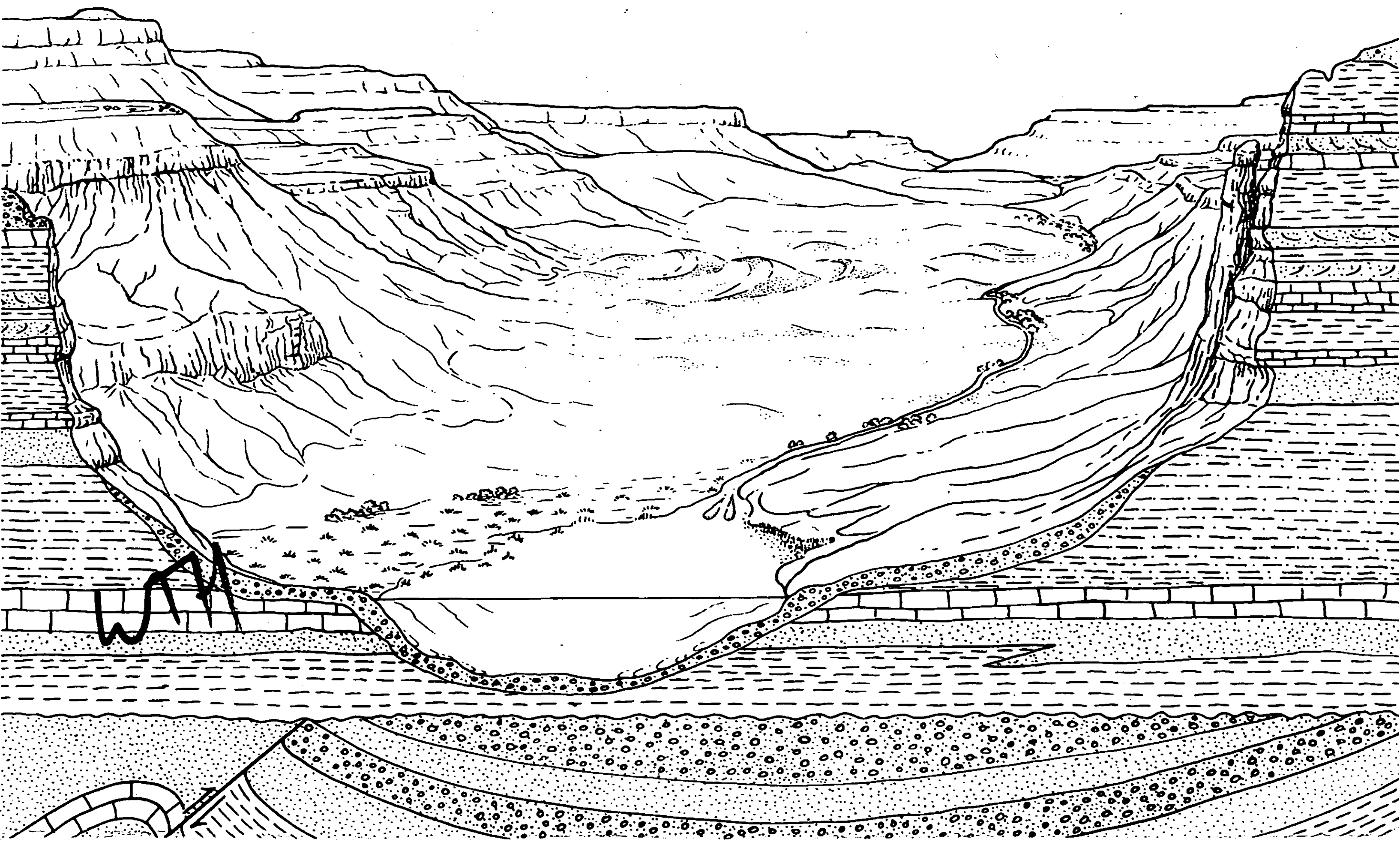

Lawton and others—UPPER CRETACEOUS AND PALEOGENE STRATA, EASTERN SAN PITCH MOUNTAINS, UTAH—U.S. Geological Survey Bulletin 1787–II

Chapter II

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By TIMOTHY F. LAWTON, PETER J. TALLING, ROBERT S. HOBBS, JAMES H. TREXLER, JR., MALCOLM P. WEISS, and DOUGLAS W. BURBANK

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

U.S. GEOLOGICAL SURVEY BULLETIN 1787

EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

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EVOLUTION OF SEDIMENTARY BASINS—UINTA AND PICEANCE BASINS

Structure and Stratigraphy of Upper Cretaceous and Paleogene Strata (North Horn Formation), Eastern San Pitch Mountains, Utah—Sedimentation at the Front of the Sevier Orogenic Belt

By Timothy F. Lawton,[1] Peter J. Talling,[2] Robert S. Hobbs,[3] James H. Trexler, Jr.,[4] Malcolm P. Weiss,[5] and Douglas W. Burbank[6]

Abstract

The North Horn Formation in the eastern part of the San Pitch Mountains of Utah was deposited in nonmarine environments that included alluvial fans, varied fluvial and overbank settings, and lacustrine settings. Exposed thicknesses of the unit range from 42 m (138 ft) where the North Horn laps onto thrust structures on the eastern flank of the range to more than 1,100 m (3,600 ft) in canyon exposures less than 2 km (1.2 mi) west of the eastern range flank. Limited age control indicates that the North Horn Formation in the eastern San Pitch Mountains ranges in age from Late Cretaceous (late Campanian) to early Eocene.

The North Horn Formation is herein subdivided into eight informal units that can be mapped along the eastern range front. In ascending order, they are (1) basal conglomerate, (2) lower redbed unit, (3) sheet sandstone unit, (4) coal-bearing unit, (5) Big Mountain unit, (6) Coal Canyon unit, (7) calcareous siltstone unit, equivalent in its lower part of the Big Mountain and Coal Canyon units, and (8) upper redbed unit. The basal conglomerate as described herein was considered Price River Formation by most previous workers, but the name Price River Formation is herein not used for conglomerate units in the San Pitch Mountains. A dominantly carbonate and shale section between the calcareous siltstone and upper redbed units of the North Horn is named the Wales Tongue of the Flagstaff Limestone. It was deposited in open-lacustrine and lake-margin environments. The Wales Tongue was previously mapped with the North Horn.

West-vergent thrust faults exposed low on the eastern flank of the San Pitch Mountains were active prior to and during deposition of the North Horn Formation. Thrust shortening prior to North Horn deposition resulted in tight folding and overturning of older strata. Basal beds of the North Horn subsequently onlapped these folded strata and were themselves syndepositionally deformed by continued uplift. At times thrust uplift influenced sedimentation patterns within the North Horn and resulted in westward and northwestward clastic dispersal off the uplift into a structural basin developed on the hanging wall of the thrust system. At other times, North Horn rivers flowed across the nascent uplift to intermontane basins that lay to the east. The interaction of thrust deformation and sedimentation indicates that thrust faulting in the vicinity of the Sanpete Valley, immediately east of the San Pitch Mountains, occurred intermittently from approximately middle to late Campanian time until early Eocene time.

INTRODUCTION

Uppermost Cretaceous and Paleogene strata exposed on the eastern flank of the San Pitch Mountains in central

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Utah provide an excellent opportunity to study sedimentation in the proximal part of the Cordilleran foreland basin and in a piggyback basin above the frontal thrust sheet. A piggyback basin is defined as a sedimentary basin that forms on the hanging wall of an active thrust fault (Ori and Friend, 1984). The strata are well exposed along the north-trending range front and in canyons cut westward into the range. West-verging thrust and reverse faults that cut Jurassic and Lower Cretaceous strata are exposed discontinuously along the lower part of the range front. The resulting three-dimensional view of stratigraphic and structural features reveals that the structural evolution of the thrust system affected deposition of Upper Cretaceous and Paleogene strata, which are included in the North Horn Formation. The geologic relationships along the east flank of the San Pitch Mountains are thus key to a basic understanding of sedimentation processes along the thrusted margin of a foreland basin.

Dramatic thickness variations and facies changes characterize the North Horn Formation of the eastern San Pitch Mountains (Spieker, 1949a; Birsa, 1973). A thick interval of sandstone and conglomerate in the central and southern part of the study area is equivalent to a stratigraphic interval dominated by siltstone in the northern part of the area. A number of angular unconformities are present locally in the basal part of the formation, as well as higher in the section. As a result of the geologic complexity, unit identifications and geologic interpretations have differed among different workers (for example, Spieker, 1949a; Birsa, 1973; Weiss, 1982; Lawton, 1985). We attempt herein to document the geologic relationships exposed on the eastern range front in the form of a detailed map and measured sections. Our objectives are (1) to establish lateral relationships of strata within the North Horn Formation along the east flank of the San Pitch Mountains and (2) to demonstrate concurrence of deposition of North Horn strata and development of the thrust system exposed along the range front.

Acknowledgments.—We thank the U.S. Geological Survey Evolution of Sedimentary Basins Program for partial support of this project. Burbank, Lawton, and Talling acknowledge support from the National Science Foundation (grant EAR–8904835 to Lawton and grant EAR–8905053 to Burbank). In particular, we thank T.D. Fouch and K.J. Franczyk for discussions in the field and continued interest in the North Horn Formation. D.A. Sprinkel, Utah Geological Survey, improved our understanding of Indianola stratigraphy and structure along the eastern flank of the San Pitch Mountains. K.F. Downing, University of Arizona, collected and analyzed dinosaur bones from the Deer Gulch section. Reviews by Franczyk, Sprinkel, Marjorie MacLachlan, and Judy Stoeser improved the text and illustrations.

LOCATION AND METHODS

The San Pitch Mountains, known in the geologic literature as the Gunnison Plateau (Spieker, 1946), extend southward from the Wasatch Mountains (fig. 1). They are at the eastern edge of the Sevier orogenic belt (Armstrong, 1968). At this approximate longitude, thrust-deformed strata of the Cordilleran foreland basin give way to mostly undisturbed equivalent strata of the Colorado Plateau (Lawton, 1985). The present-day physiography of the San Pitch Mountains is the result of Neogene extension (Smith and Bruhn, 1984). Normal faults delineate both the eastern and western margins of the range (fig. 2) (Witkind and others, 1987). The normal faults cut across and expose older structures and have resulted in approximately 730 m (2,400 ft) of topographic relief between Sanpete Valley, immediately east of the range, and the top of Big Mountain in the central part of the study area.

Using a Jacobs staff, eight stratigraphic sections were measured in the North Horn Formation along the eastern range front at Dry Canyon, Axhandle Canyon, Coal Canyon, Blind Canyon (immediately north of Coal Canyon), Big Mountain, an unnamed locality between Big Mountain and Petes Canyon, Petes Canyon, and Deer Gulch, an informal name (Weiss, 1982) for a locality south of Wales Canyon. Of these, only four (Dry Canyon, Coal Canyon, Big Mountain, and Petes Canyon) are complete from the unconformity at the base of the section to the base of the overlying Flagstaff Limestone. A section at Horse Mountain was taken from a description by Birsa (1973). The stratigraphic sections are shown on plate 1. On plate 1, section offsets are shown where overlap is present at the base of the Petes Canyon and Deer Gulch sections. These offsets were required by structural complexity in the lower part of the North Horn section. The traces of the measured sections are illustrated on plate 2, with the exception of the Horse Canyon and Dry Canyon sections, which are south of the mapped area.

To best illustrate the lateral facies changes in the middle part of the section, datum for most sections is taken as the top of a limestone-clast conglomerate within the conglomerate- and sandstone-dominated part of the section. Stratigraphic ties were made by walking units laterally. North of the pinchout of the conglomeratic section, a distinctive interval of interbedded coal and limestone is used as datum. Southward, where the conglomerate is in the subsurface or is not present in the section, the datum is the base of the main body of the Flagstaff Limestone.

Paleocurrent measurements were made on appropriate horizons. Crossbedded sandstones were analyzed using the trough-limb technique of DeCelles and others (1983). Linear flute marks and impressions of logs aligned parallel with the paleocurrent direction, as indicated by crossbeds, were utilized as paleocurrent indicators in a few instances.

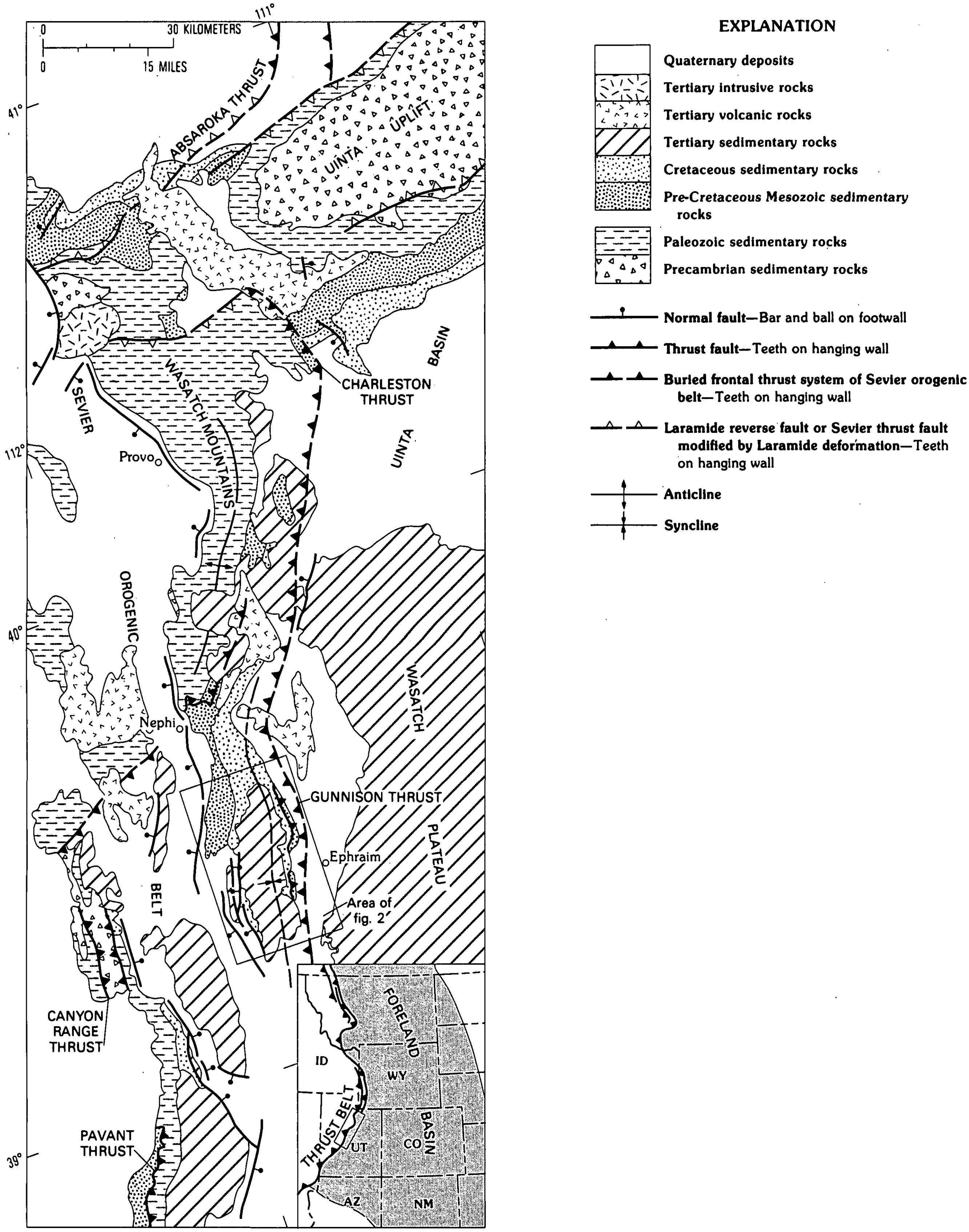


Figure 1. Geology of the region of study, east-central Utah. Geology modified from Hintze (1975).

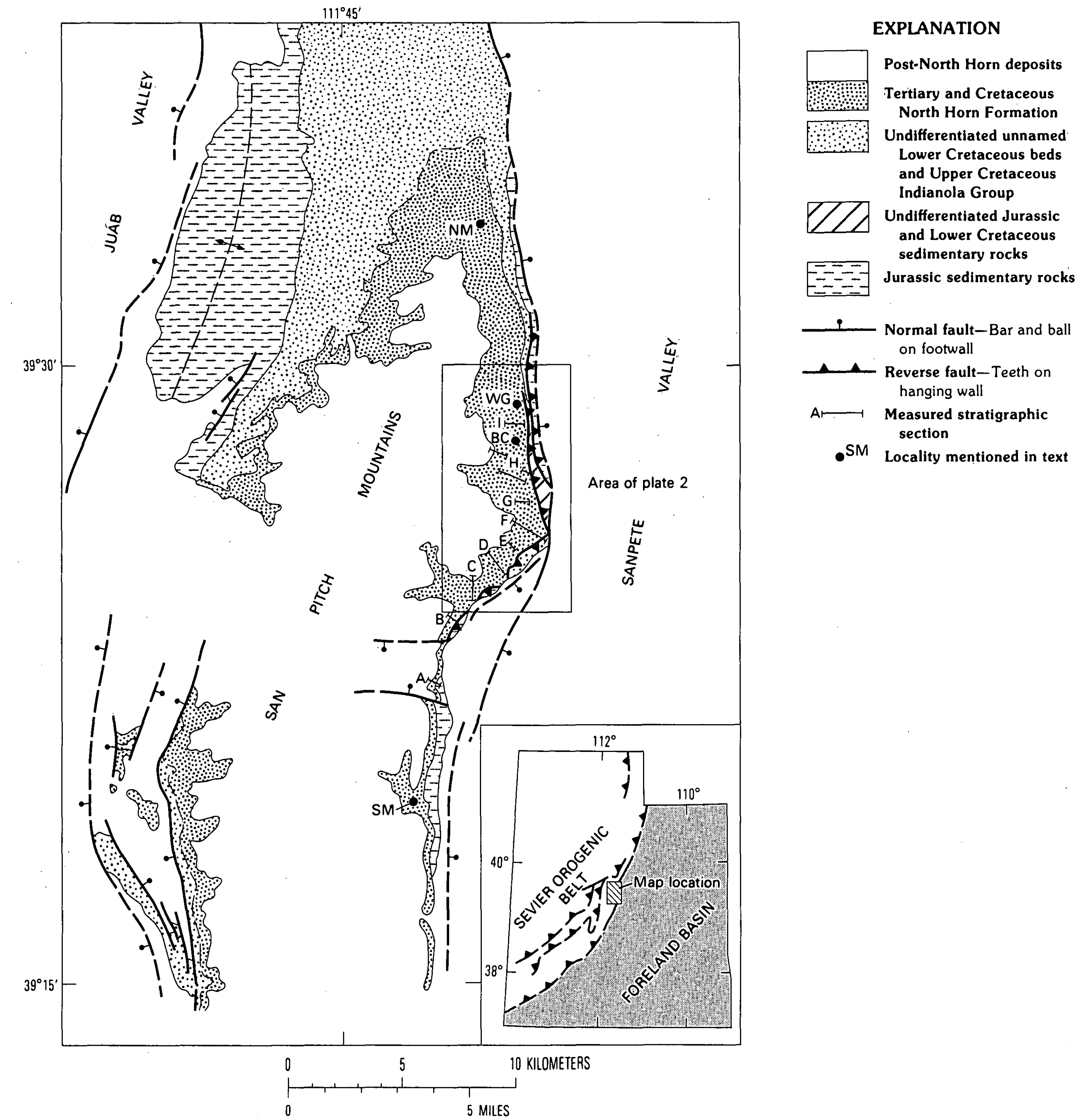


Figure 2. Geology of the San Pitch Mountains, Utah. Locations of measured sections of this study are also shown. The North Horn Formation occupies a small sedimentary basin between an anticline in Jurassic and Cretaceous strata on the west flank of the range and a system of west-verging thrust faults on the east flank of the range. Inset rectangle indicates area of geologic map (plate 2). Measured sections of plate 1: A, Dry Canyon; B, Horse Mountain (from Birsa, 1973); C, Axhandle Canyon; D, Coal Canyon; E, Blind Canyon; F, Big Mountain; G, Unnamed canyon; H, Petes Canyon; I, Deer Gulch. Asterisks indicate key locations mentioned in text: NM, North Maple Canyon; WG, Wales Gap; BC, Boiler Canyon; SM, South Maple Canyon. Geology modified from Witkind and Weiss (1985), Mattox (1987), and Witkind and others (1987).

These data were recorded as trend and plunge, and mean vectors were calculated from the individual measurements. Pebble and cobble imbrication measurements were collected in suitable conglomerate beds. Imbrication is typically uncommon within quartzite-pebble units in these strata because of the spheroidal shape of most of the clasts; however, many limestone and dolomite clasts have platy, oblate shapes, and thus conglomerate beds containing abundant carbonate clasts provided the most reliable and consistent paleocurrent data collected in the course of the study. Poles to the planes defined by platy clasts were plotted and structural dips were rotated to the paleohorizontal using a Schmidt equal-area stereonet. In the case of linear types of data, trend and plunge values were also rotated about the structural dip.

A magnetostratigraphic analysis of the North Horn Formation was undertaken as part of this study. The results of the paleomagnetic study are presented more completely elsewhere (Hobbs, 1989; Talling, 1992) and are described only briefly here. Oriented samples were collected for magnetostratigraphic analysis concurrent with measurement of sections at Axhandle Canyon, Petes Canyon, and Deer Gulch. The Axhandle and Petes Canyon sections were collected twice subsequently to fill gaps in the magnetic polarity stratigraphy, whereas the Deer Gulch section was collected only once. Samples were demagnetized at the paleomagnetic laboratory at the University of Southern California. The measured magnetic field directions were corrected by rotating bedding dip to the horizontal and averaged over 3 or 4 replicate samples per collecting site. Fisher k statistics were computed for the replicate samples at each site to quantify grouping of measured field directions (Fisher, 1953). Sites having a Fisher k statistic greater than 10 are termed class 1; those having a k statistic less than 10, but with recognizable normal or reversed polarity directions, are termed class 2. Sites having low k statistics and unrecognizable or transitional field directions were rejected. The positions of the sample sites are shown adjacent to the measured sections of plate 1.

Magnetic polarity intervals within the North Horn are defined from the polarity of the sample sites. Single class 1 sites may define a magnetic polarity interval, but single class 2 sites may not, except where a single class 2 site correlates with an independently defined magnetic polarity interval on the closely spaced Petes Canyon and Deer Gulch sections.

In concurrence with the work on the stratigraphy, the bedrock geology of the eastern range front was mapped at a scale of 1:12,000 (plate 2). In the field, geology was plotted directly on topographic bluelines; these data were transferred later to the final map. Quaternary units are not differentiated on plate 2, and the normal faults that delineate the San Pitch Mountains are not depicted on the map.

NOMENCLATURE AND AGE

The sedimentary rocks of this study have previously been assigned to the Price River and North Horn Formations (Spieker, 1949a). The name Price River has been applied to cobble and boulder conglomerate units at the base of the section. The basal conglomeratic sequence in the Big Mountain section (plate 1) represents an example of the Price River Formation as defined by Spieker (1949b) in the San Pitch Mountains. A thick-bedded cobble and boulder conglomerate exposed in the hogback at Wales Canyon (Wales Gap locality, fig. 2) has long been considered as Price River Formation (Spieker, 1946, 1949b; Hunt, 1950; Burma and Hardy, 1953; Weiss, 1982). This conglomerate is equivalent to the basal conglomeratic interval in the Deer Gulch section (plate 1).

The name Price River is not used here for conglomerate units of the San Pitch Mountains; rather, these conglomerates are included in the North Horn Formation. This convention marks a major break with previous nomenclature (for example, Spieker, 1949a, b; Hardy and Zeller, 1953; Weiss 1982; Weiss and Roche, 1988). Our reasons for this change are several: (1) the lithology of conglomerates previously designated Price River in the San Pitch Mountains is dissimilar to the sandstone and siltstone of type exposures of the Price River Formation (Spieker and Reeside, 1925) in the northeastern Wasatch Plateau; (2) the outcrops of the San Pitch Mountains are not continuous with those in the type area to allow direct tracing of units; and (3) conglomerate units designated as Price River by Hardy and Zeller (1953) in the southwestern part of the San Pitch Mountains are not demonstrably continuous with basal conglomerate units of the North Horn along the eastern range front (Lawton and Trexler, 1991). The inconsistency of Price River usage in the San Pitch Mountains was also recognized by Mattox (1987), who did not apply the Price River nomenclature in the southwestern part of the range.

Quartzite-dominated conglomerate inferred to lie above an angular unconformity of regional extent was assigned by Spieker (1949a) to the Price River Formation in the San Pitch Mountains. The unit was interpreted to grade upsection into the North Horn (Spieker, 1949a). Recognition that several unconformities are present in the North Horn above the base of the conglomerate indicates that stratigraphic relations are somewhat more complicated than envisioned by Spieker and suggests that the lower conglomeratic facies is better considered part of the overlying stratigraphic succession.

Strata above the basal conglomerate, which is not always present in outcrop, have been designated North Horn Formation in the San Pitch Mountains (Spieker, 1949a; Hunt, 1950). In the vicinity of Wales Canyon, Hunt (1950) designated three members in the North Horn. The lower member includes conglomerate, sandstone, and siltstone of various colors. The overlying middle member in Wales Canyon includes 98 m (320 ft) of coal-bearing shale and limestone. The upper member is dominantly gray limestone and shale and uncommon lenticular sandstone beds. These members are useful for subdividing the North Horn between Wales Canyon and Petes Canyon in the study area, but they lose their utility south of Petes Canyon.

The North Horn Formation ranges in age from late Campanian to early Eocene (fig. 3). Dinosaur bones are present within the North Horn section to a point at least 300 m (984 ft) above the base of our northernmost measured section (plate 1). A Maastrichtian palynomorph assemblage collected 213 m (698 ft) above the base of the North Horn Formation, in the sheet sandstone unit at Petes Canyon (plate 1), includes the forms *Balmeisporites canadensis*, *B. longiramosus*, *B. rarus*, and *B. rigidus* (G. Waanders, Waanders Palynology Consulting, Inc., written commun., 1992). A microfossil locality 346 m (1,135 ft) above the base of the section at Petes Canyon has yielded a collection of sparse charophytes and ostracodes. Based on the presence of *Retusochara* and the absence of *Platychara*, this collection is interpreted as late Campanian to early Maastrichtian in age (R.M. Forester, U.S. Geological Survey, written commun., 1988). This age assessment is consistent with the palynomorph data and with the only other published age determination pertinent to this part of the section in the San Pitch Mountains. In the northwestern part of the range (SW1/4 sec. 17, T. 14 S., R. 2 E.), a coal bed in the South Flat Formation of Hunt (1954) has yielded palynomorphs of late Santonian to early Campanian age (Hays, 1960; Fouch and others, 1983). The sample was collected approximately 311 m (1,020 ft) beneath massive boulder and cobble conglomerate exposed in North Maple Canyon, to the north of the study area (Thomas, 1960). The boulder conglomerate is equivalent to the basal conglomerate and lower redbed unit of the North Horn at Wales Canyon (Spieker, 1949a; Hunt, 1950); it is approximately 305 m (1,000 ft) thick in North Maple Canyon, where it is overlain by rocks probably equivalent to the coal-bearing unit of the North Horn Formation. Thus, the reported late Santonian to early Campanian palynomorphs are about 600 m (1,970 ft) downsection of the late Campanian to early Maastrichtian charophytes in the North Horn.

The lower parts of the Big Mountain unit and calcareous siltstone unit are probably Maastrichtian in age. Palynomorphs collected from a mudstone lens at the base of the Big Mountain unit in the Manti quadrangle, 6.5 km (4 mi) south of the study area, include the Late Cretaceous forms *Classopollis classoides*, *Polypodiidites inhangahuensis*, and ?*Proteacidites retusus* (G. Waanders, Waanders Palynology Consulting, Inc., written commun., 1992). *P. retusus* is found in strata ranging in age from Santonian through Maastrichtian in the thrust belt of Wyoming (Nichols and others, 1982). Alternatively, the palynomorphs in the Big Mountain unit may be reworked from older Cretaceous strata, but our interpretation is that the Cretaceous-Tertiary boundary lies within the Big Mountain unit and laterally equivalent calcareous siltstone unit (fig. 3).

The Flagstaff Limestone ranges in age from Late Paleocene to Eocene in the San Pitch Mountains. The Wales Tongue of the Flagstaff is late Paleocene in age based on magnetostratigraphy (Hobbs, 1989; Talling, 1992). The main body of the Flagstaff Limestone, which unconformably overlies the North Horn Formation in Petes, Coal, and Axhandle Canyons, is at least in part early Eocene in age in the San Pitch Mountains. This age assignment derives from three independent lines of biostratigraphic evidence.

1. In the Wasatch Plateau, La Rocque (1960) recognized three units within the Flagstaff Limestone. He assigned a Paleocene age to unit 1 and an Eocene age to unit 3, based on freshwater molluscan content. He considered the basal part of the main body of the Flagstaff in the San Pitch Mountains as equivalent to his unit 2 and therefore Paleocene to early Eocene in age.

2. Seven kilometers south of the study area, in South Maple Canyon, palynomorphs collected 78.25 m (256 ft) above the North Horn–Flagstaff contact are interpreted as early Eocene in age by the presence of *Platycarya platycaryoides* (Jacobson and Nichols, 1982; Fouch and others, 1983).

3. Also in South Maple Canyon, *Vulpavis australis*, a carnivore from the Wasatchian land mammal zone (early Eocene; Archibald and others, 1988), was found in float believed to be from the upper part of the Flagstaff Limestone (Rich and Collinson, 1973).

The magnetostratigraphic data shown on plate 1 do not independently confirm the Campanian-Eocene age range of the North Horn Formation, but they are consistent with such an interpretation (fig. 3). The dominantly normal polarity of the Deer Gulch section is consistent with a late Campanian to early Maastrichtian age for the section. The dinosaur fossils, palynomorph data, and charophyte data permit correlation of the initial normal-polarity interval at Deer Gulch with the normal event in chron 33 and the subsequent normal intervals with normal events in chron 32 (fig. 3). As interpreted here, the coal-bearing unit of the North Horn was deposited dominantly during the reversed-polarity part of chron 31, consistent with the presence of Maastrichtian charophytes in the unit. An unconformity at the top of the coal-bearing unit or within the lower part of the calcareous siltstone unit at Petes Canyon is necessary to eliminate dominantly normal-polarity strata expected if rocks representative of the reversed part of chron 31 or of chron 30 were present. Figure 3 illustrates this hiatus as occurring after deposition of the coal-bearing unit. Figure 3 also illustrates the tentative positions of the Late Cretaceous, Paleocene, and Eocene boundaries relative to units of the North Horn Formation.

The oldest strata of Paleocene age probably are within the Big Mountain unit and certainly within the calcareous siltstone unit. *Microcodium*, abundant in Paleocene rocks in Europe, has been recovered from the lower part of the calcareous siltstone unit at Axhandle Canyon (m 125; M. Feist, Université de Montpellier II, written commun., 1991). A

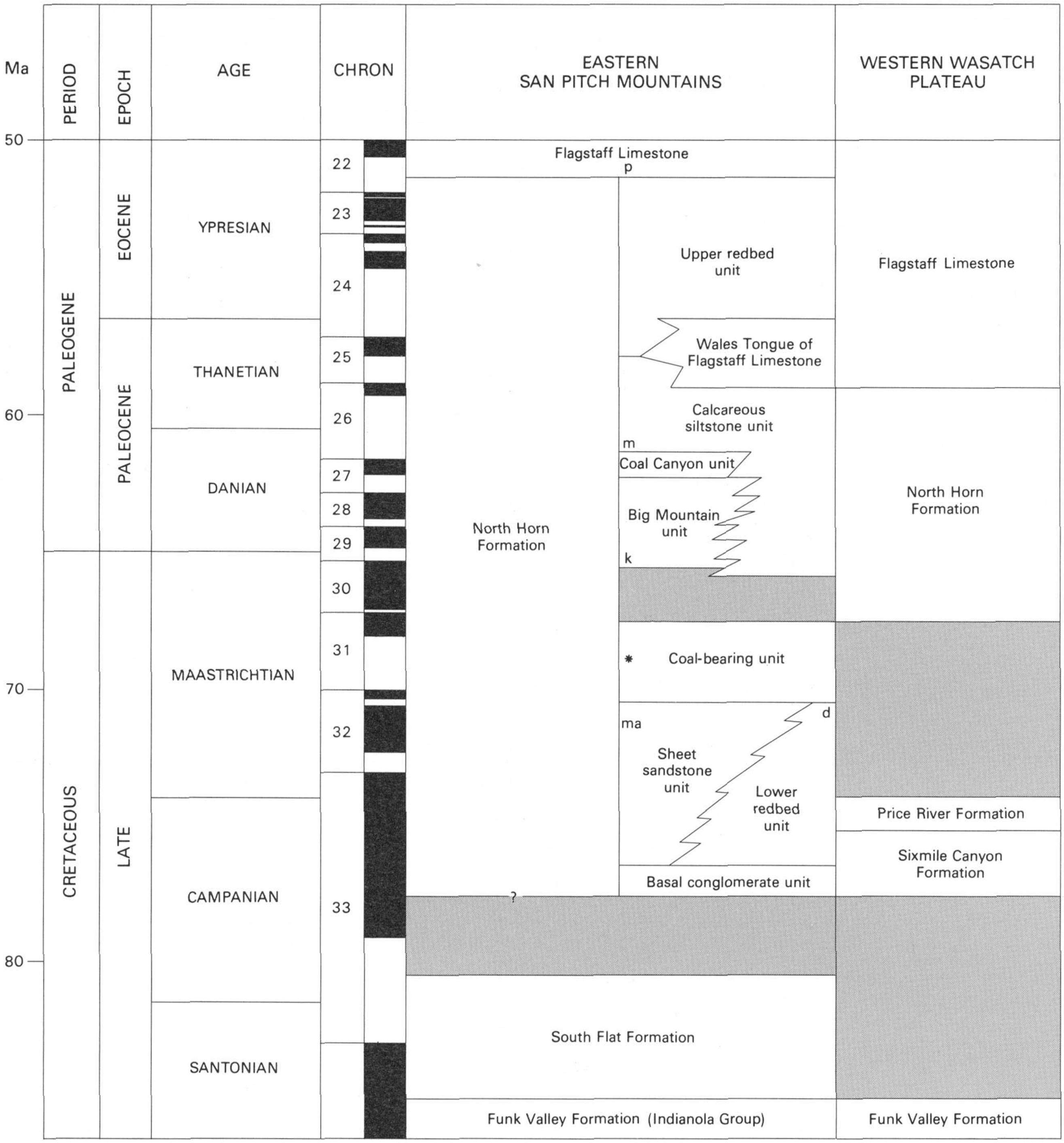


Figure 3. Age and nomenclature of the North Horn Formation and its informal members within the San Pitch Mountains, Utah, designated in this report and correlation with strata exposed in Sixmile Canyon in the western part of the Wasatch Plateau. Time scale from Harland and others (1990). Normal polarity events are shown in black on magnetic polarity time scale. Explanation of symbols: d, uppermost known occurrence of dinosaur bones in lower redbed unit; ma, Maastrichtian palynomorphs in sheet sandstone unit; *, late Campanian to early Maastrichtian charophytes in coal-bearing unit; k, Late Cretaceous palynomorphs at base of Big Mountain unit; m, *Microcodium* in calcareous siltstone unit, immediately above Coal Canyon unit; p, early Eocene palynomorphs in lower part of Flagstaff Limestone. The basal conglomerate of the North Horn Formation was considered Price River Formation by Spieker (1949a). The South Flat Formation is present beneath Sanpete Valley as shown by several oil tests, cuttings from one of which yielded Santonian palynomorphs (Hanson & True Oil No. 1-A-X Moroni, sec. 14, T. 15 S., R. 3 E.; D.A. Sprinkel, written commun., 1990). The unconformity beneath the North Horn and Sixmile Canyon Formations marks onset of thrust-generated uplift in the vicinity of the present Sanpete Valley. See text for additional explanation and references.

thick interval of reversed polarity rocks in the calcareous siltstone unit of both the Axhandle and Petes Canyon sections is inferred to correlate with the reversed-polarity part of chron 26 of the Paleocene.

Exact correlation of the established Paleogene magnetic polarity time scale (Harland and others, 1990) with the reversal sequence of the North Horn Formation in the San Pitch Mountains remains uncertain, mostly because expected normal-polarity intervals are missing in the calcareous siltstone unit beneath the reversed-polarity part of chron 26 and there are too many normal intervals above the reversed-polarity part of chron 26. The pattern of thin normal intervals in the upper North Horn of the Axhandle Canyon section correlates well with the expected normal events of chron 23 (Harland and others, 1989); however, this pattern matches poorly with the documented magnetic reversal stratigraphy of the Petes Canyon section. The reasons for the mismatch may include one or more of the following.

1. An unconformity at the base of the Flagstaff Limestone results in the absence of some magnetic-polarity intervals. Both map relations and the correlated stratigraphic sections permit interpretation of truncation of the upper redbed unit beneath the Flagstaff Limestone. This possibility is strengthened by the different heights above the base of the Flagstaff of a well-documented normal-polarity interval correlated with the normal part of chron 22 (Talling, 1992). The fact that the Flagstaff rests with angular discordance upon rocks as old as Late Cretaceous (Turonian) elsewhere in the Sanpete Valley region (Spieker, 1946) indicates the strong possibility of a pre-Flagstaff hiatus anywhere that strata were uplifted prior to Flagstaff deposition.

2. Westward thickening of the upper redbed unit observable in the western reaches of Petes Canyon (plate 2) and Axhandle Canyon, coupled with resultant increased accumulation rates, resulted in greater thickness of the reversal sequence, making it difficult to match with that at Axhandle Canyon.

3. Westward thickening of the upper redbed unit, combined with sampling gaps in the upper redbed unit at Petes Canyon, may conceal the presence of normal-polarity intervals correlative with normal intervals at Axhandle Canyon.

4. The upper redbed unit contains a dominantly reversed-polarity overprint caused by formation of authigenic hematite long after deposition of the unit (Talling, 1992). The red coloration and magnetic characteristics (Talling, 1992) of the unit indicate the presence of abundant hematite, but the general absence of ferromagnesian minerals in sediment derived from the Sevier orogenic belt (for example, Lawton, 1986a) suggests that detrital heavy minerals were not the source of the pervasive hematite. The hematite is more likely related to early pedogenesis.

The unconformity at the top of the North Horn Formation is localized in the vicinity of pre-Flagstaff uplifts (Spieker, 1946; Weiss, 1969). The contact appears to be conformable elsewhere in central Utah; for example, the Wasatch Plateau (Spieker, 1946; La Rocque, 1960; Fouch and others, 1987) and the Uinta basin (Fouch, 1976). The pre-Flagstaff uplifts are attributable to thrust deformation within and at the front of the Sevier orogenic belt (Standlee, 1982; Lawton, 1985).

The age range indicated for the North Horn in the San Pitch Mountains is generally consistent with regional ages for the North Horn, but the new data discussed above indicate an older age for the base of the formation relative to previously published reports. The basal part of the North Horn Formation is Maastrichtian in age in the northern part of the Wasatch Plateau at Price Canyon (Fouch and others, 1987), as well as in the southern part of the plateau (Spieker, 1946). Because the Maastrichtian palynomorphs are present 213 m (698 ft) above the base of the formation at Petes Canyon and thus, by correlation, approximately 500 m (1,640 ft) above the base of the section at Big Mountain, it is likely that the lowermost part of the formation may extend well into the Campanian.

The presence of upper Campanian strata in the North Horn Formation of the San Pitch Mountains indicates that the North Horn is at least in part equivalent with the Sixmile Canyon Formation (fig. 3). The Sixmile Canyon Formation is the uppermost unit of the Indianola Group exposed in Sixmile Canyon on the western flank of the Wasatch Plateau. Campanian palynomorphs have been reported from the middle member of the Sixmile Canyon Formation (Schwans, 1988). The Price River Formation, unconformable above the Sixmile Canyon Formation, has yielded late Campanian palynomorphs (Fouch and others, 1983). Fluvial strata of the sheet sandstone unit defined herein are similar in appearance to fluvial rocks of the Sixmile Canyon Formation. Moreover, rapid lateral thickness and facies changes of the type documented herein demonstrate the scant likelihood that the Sixmile Canyon Formation will have identical stratigraphic attributes beyond the small window of exposure that characterizes the formation in Sixmile Canyon. In the absence of contradictory data, we regard the lower part of the North Horn Formation of the study area as equivalent to the Campanian Sixmile Canyon Formation (Fouch and others, 1983).

STRATIGRAPHY

The North Horn Formation of the eastern San Pitch Mountains varies greatly in thickness and lithology. Although its base is typically structurally complicated, the formation can be identified from bracketing relationships. The section overlies older rocks on an angular unconformity. In most cases, subjacent strata are overturned and remain overturned when basal North Horn strata are restored to a horizontal attitude. Uppermost North Horn beds are overlain by the Flagstaff Limestone, which is lithologically distinctive, resistant to erosion, and thus readily identifiable. The North Horn Formation ranges in thickness from 42 m (138 ft) to more than 1,100 m (3,606 ft) in the measured sections in the study area. The maximum thickness of the formation is not known exactly because a thrust fault omits part of the section at Big Mountain (plate 1), the location of the thickest stratigraphic section; however, the North Horn is known to pinch out completely both east and west of the study area. In the subsurface to the east, the North Horn thins onto a thrusted structure beneath Sanpete Valley (Standlee, 1982; Lawton, 1985); westward, it thins above tilted older Cretaceous strata overlain by the Flagstaff Limestone on the west side of the range (Hardy and Zeller, 1953; Lawton, 1985).

The stratigraphy of the North Horn Formation can be described in terms of eight lithologically distinct units. The geometry and stratigraphic relationships of these units are summarized in figure 4. The units are described in the following sections in ascending order, in so far as possible.

Basal Contact

Strata described herein rest unconformably on older rocks. Subjacent strata in the northern part of the study area from Wales Canyon to Petes Canyon include the Middle Jurassic Twist Gulch Formation and the Lower Cretaceous Cedar Mountain Formation. The basal contact is best exposed in an unnamed canyon (SE¼NW¼ sec. 36, T. 15 S., R. 2 E.) where conglomeratic sandstone beds of the North Horn having 20° W. dips overlie Twist Gulch beds (fig. 5). Here, the Twist Gulch is overturned and dips 55° E. The conglomeratic sandstone beds of the North Horn are 2–5 m (6.5–16 ft) thick and interbedded with red siltstone. To the north, the basal contact is exposed for a short distance on the north side of the next major drainage (Boiler Canyon of Doelling, 1972). There, lower North Horn beds consist of brown siltstone overlying steeply dipping, overturned Twist Gulch strata. The brown siltstone overlies boulder conglomerate of the basal unit in the next drainage to the north (locally known as Deer Gulch; for example, Weiss, 1982; S½ sec. 25, T. 15 S., R. 2 E.). At this locality the basal conglomerate probably is unconformable beneath the siltstone. This contact is regarded as an intraformational unconformity separating the basal conglomerate and the lower redbed unit.

At Big Mountain and southward from there, the North Horn rests on overturned quartzite-clast conglomerate of an unnamed Lower Cretaceous Formation and pebbly sandstone of the Indianola Group (Spieker, 1949a, b). The subjacent conglomerate ranges in caliber from pebble to boulder. At Big Mountain (NW¼NE¼ sec. 13, T. 16 S., R. 2 E.), basal conglomerate of the North Horn section dips steeply to the west and overlies overturned east-dipping conglomeratic sandstone of the Indianola Group (fig. 6)(Spieker, 1949b). In Coal Canyon (NW¼NE¼ sec. 23, T. 16 S., R. 2 E.), basal North Horn beds are steep and upright to overturned; they rest on overturned west-dipping boulder conglomerate of the unnamed formation. The erosional and unconformable nature of the contact at this locality is evidenced by several features: (1) individual clasts and conglomeratic clasts of the underlying beds are present in the basal sandstone of the North Horn; (2) the contact is not precisely planar but rather contains gravel- and boulder-filled swales cut into the underlying rocks; and (3) pervasive fracturing and mineral-filled cracks present in the underlying thrusted rocks are not present in the North Horn beds.

The basal North Horn beds demonstrate eastward onlap onto the subjacent section at Coal Canyon (fig. 7). The lowermost bed (unit Kns in fig. 7) exposed immediately above the canyon bottom pinches out against subjacent strata about halfway up the hillside of the north canyon wall. A sandstone bed 10 m (33 ft) upsection (also unit Kns) rests directly on the unconformity at the top of the hill. Thus, 10 m (33 ft) of thinning occurs in a lateral distance of no more than 200 m (656 ft).

Basal Conglomerate Units

Within the study area, the conglomerate lying above the basal unconformity forms two discontinuous units at the base of the North Horn Formation. At Big Mountain this unit consists of approximately 100 m (330 ft) of conglomerate and sandstone and no siltstone interbeds. Although the basal unit is separated from overlying North Horn beds by two thrust faults within red siltstone at this locality, it is here designated as the reference section because of its continuous exposures. The basal conglomerate at Wales Gap is equivalent to this unit. An angular unconformity between the basal conglomerate and overlying red siltstone unit causes the conglomerate to be absent between Wales Gap and Big Mountain. Although the two conglomerate exposures are demonstrably discontinuous in outcrop, they may be contiguous in the subsurface.

The basal unit at Big Mountain forms a series of upward-fining conglomerate and sandstone sequences, each of which is separated from the next by an angular unconformity. The upward-fining sequences are about 20 m (66 ft) thick where the section was measured in the canyon, but each sequence thins erosionally updip to the east as the unconformities converge (fig. 8). The lower two truncations are exposed in the lower reach of Lambs Canyon in the northernmost part of section 13 (the location of the measured section). Four additional truncations can be inferred from dip changes and eastward thinning of

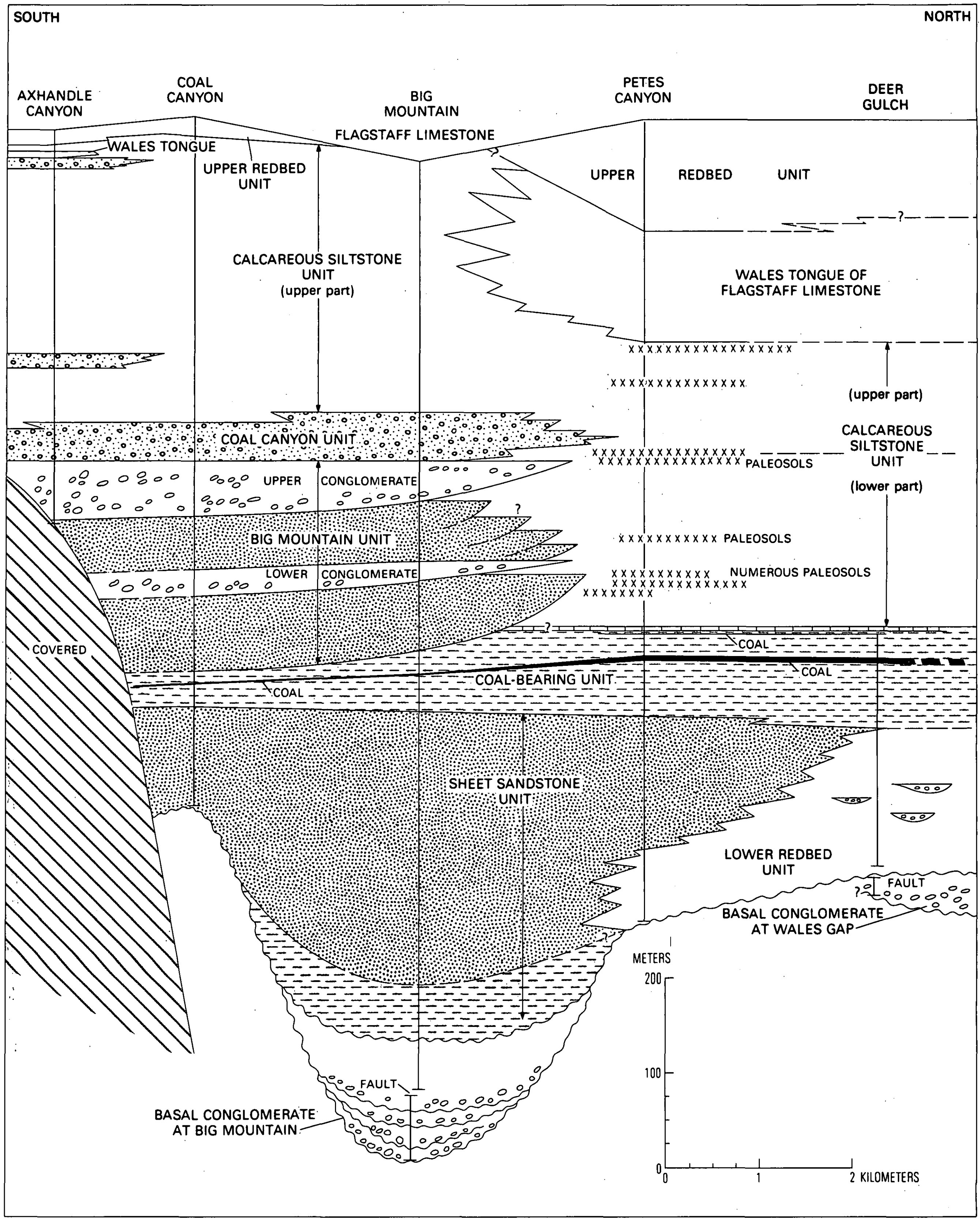


Figure 4. Stratigraphic nomenclature and geometry of the informal members of the North Horn Formation and the Wales Tongue of the Flagstaff Limestone on the eastern front of the San Pitch Mountains, Utah. Location of measured sections shown in figure 2.

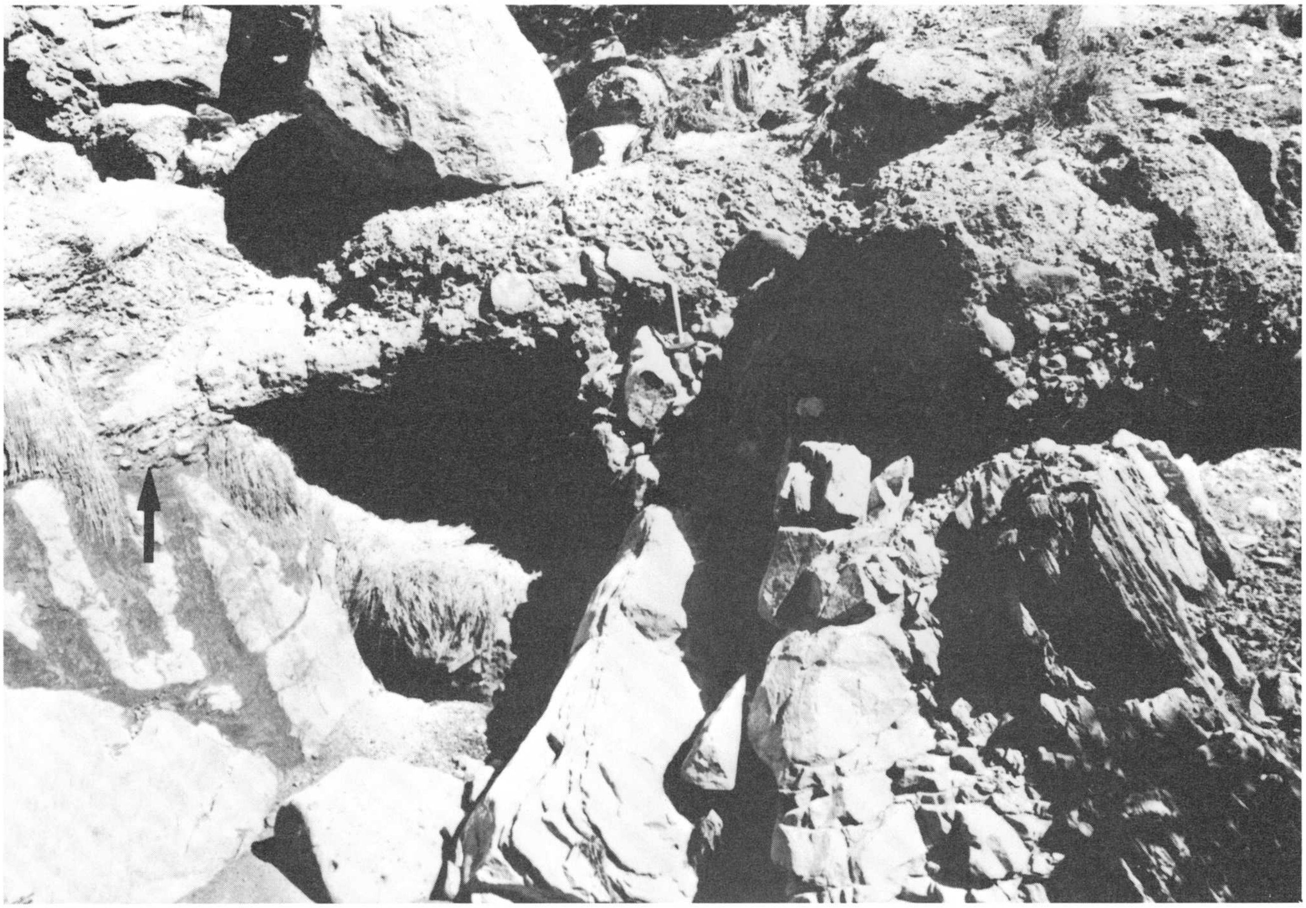


Figure 5. Basal contact of the North Horn Formation in unnamed canyon between Petes Canyon and Boiler Canyon, Utah (SE1/4NW1/4 sec. 36, T. 15 S., R. 2 E.)(fig. 2). Overturned strata of the Middle Jurassic Twist Gulch Formation beneath contact (indicated by arrow) dip eastward. Hammer handle in center of photo is 35 cm (14 in.) long. Angular Twist Gulch clasts are visible in vicinity of hammer; a block having a diameter in excess of 1.5 m (5 ft) was observed 20 m (66 ft) upsection of this locality. Paleocurrent measurements on clast imbrication in lowermost North Horn beds here indicate southwestward dispersal (plate 1). The basal North Horn here is considered lower redbed unit rather than basal conglomerate (plate 1).

sequences. The lowermost conglomeratic bed (fig. 6) was considered Price River Formation in the San Pitch Mountains by Spieker (1949b, plate 3).

Conglomerate at Big Mountain is present in thick (as much as 2.5 m), clast-supported beds. Clasts are generally well rounded. The matrix consists of fine- to coarse-grained sandstone that contains meniscoid laminae between the clasts; the sandstone is absent beneath some clasts. The sandstone thus may have infiltrated following clast deposition. Sandstone beds are lenticular, 0.5–2 m (1.6–6.6 ft) thick, and rest on erosive bases. Sandstone is moderately to poorly sorted, fine to coarse grained, and dominated by trough crossbeds. Pebble content in the sandstone ranges from a few percent to clast-supported pebble conglomerate in lenses as much as 1 m (3.3 ft) thick. Typically, conglomerate beds at the base of the upward-fining cycles grade upward through pebbly sandstone into sandstone containing trough crossbeds.

Clast populations within conglomerate of the basal unit are variable (fig. 9). Quartzite-clast abundances and abundances of Paleozoic limestone and dolomite clasts decrease upsection. Tan quartzarenite pebbles and cobbles, litharenite clasts, boulders of oncolitic limestone, and boulders of limestone- and quartzite-clast conglomerate first are present 76 m (250 ft) above the base of the section. The quartzarenite clasts are interpreted to have been derived from the upper part of the Funk Valley Formation (Indianola Group), litharenite clasts were derived from various units of the Indianola Group, and the larger clasts of conglomerate and limestone were probably derived from the Cedar Mountain Formation or unnamed conglomerate and siltstone beds above the Cedar Mountain. Clast imbrication measured at meter 55 of the section indicates eastward transport of clasts within that part of the unit (fig. 9).

In the measured section at Deer Gulch, the conglomerate is separated from the lower redbed unit above it by an

Figure 6. Basal contact (at end of hammer handle) of the North Horn Formation at Big Mountain, Utah (NW¼NE¼ sec. 13, T. 16 S., R. 2 E.)(fig. 2). Hammer handle is 35 cm (14 in.) long. Overturned strata of the Sanpete Formation (Indianola Group) beneath the unconformity dip eastward; conglomerate dips westward into hill. This contact forms the base of sequence 1 in the progressive unconformity at Big Mountain depicted in figure 8. E.M. Spieker (1949b, plate 3) considered this conglomerate to be Price River Formation.

angular unconformity. The lowermost part of the unit consists of 34 m (111 ft) of clast-supported boulder and cobble conglomerate containing well-rounded clasts. The middle part of the conglomerate contains 10 m (33 ft) of coarse sandstone containing trough crossbeds. An angular unconformity is present within the sandstone (plate 1). Discontinuous tabular sandstone beds 25–30 cm (10–12 in.) thick and containing horizontal laminae, present at intervals of 1.5–2 m (5–6.6 ft) in the upper 10 m (33 ft) of the conglomerate, probably represent bar-top sandstones (for example, DeCelles and others, 1991); their vertical spacing thus indicates the thickness of gravel bars within the fluvial system that deposited the conglomerate.

In the vicinity of Deer Gulch, the style of deposition changes abruptly within the upper part of the basal conglomerate unit. Nine meters (30 ft) of apparently structureless gray sandy siltstone sharply overlies the basal conglomerate facies at Deer Gulch. Above the siltstone, a 2-m-thick (6.6 ft) bed of coarse to very coarse grained sandstone grades upward, through several half-meter-thick (1.6 ft) tabular beds of medium-grained sandstone that have burrowed tops, into mottled fine-grained silty sandstone. Above the mottled silty sandstone is 28 m (92 ft) of graded 2–3-m (6.6–10 ft)-thick beds of sandstone and pebbly sandstone interbedded with olive-gray sandy siltstone. Because the interbedded siltstone is olive gray and carbonaceous rather than red, these pebbly sandstone beds are included in the basal conglomerate unit rather than in the overlying redbed unit.

The lower conglomeratic units were deposited by gravelly braided rivers that flowed eastward. The rivers transported quartzite cobbles and boulders derived from Precambrian units presently exposed only to the west in the Canyon, Sheeprock, and Tintic Ranges (Hintze, 1988). These quartzites also are present as clasts in Indianola conglomerates on the western flank of the basin that contains the North Horn Formation (Lawton, 1985) and thus may have also come from more proximal western sources. The possibility that subjacent conglomerates, such as those beneath the North Horn at Coal Canyon, provided clasts

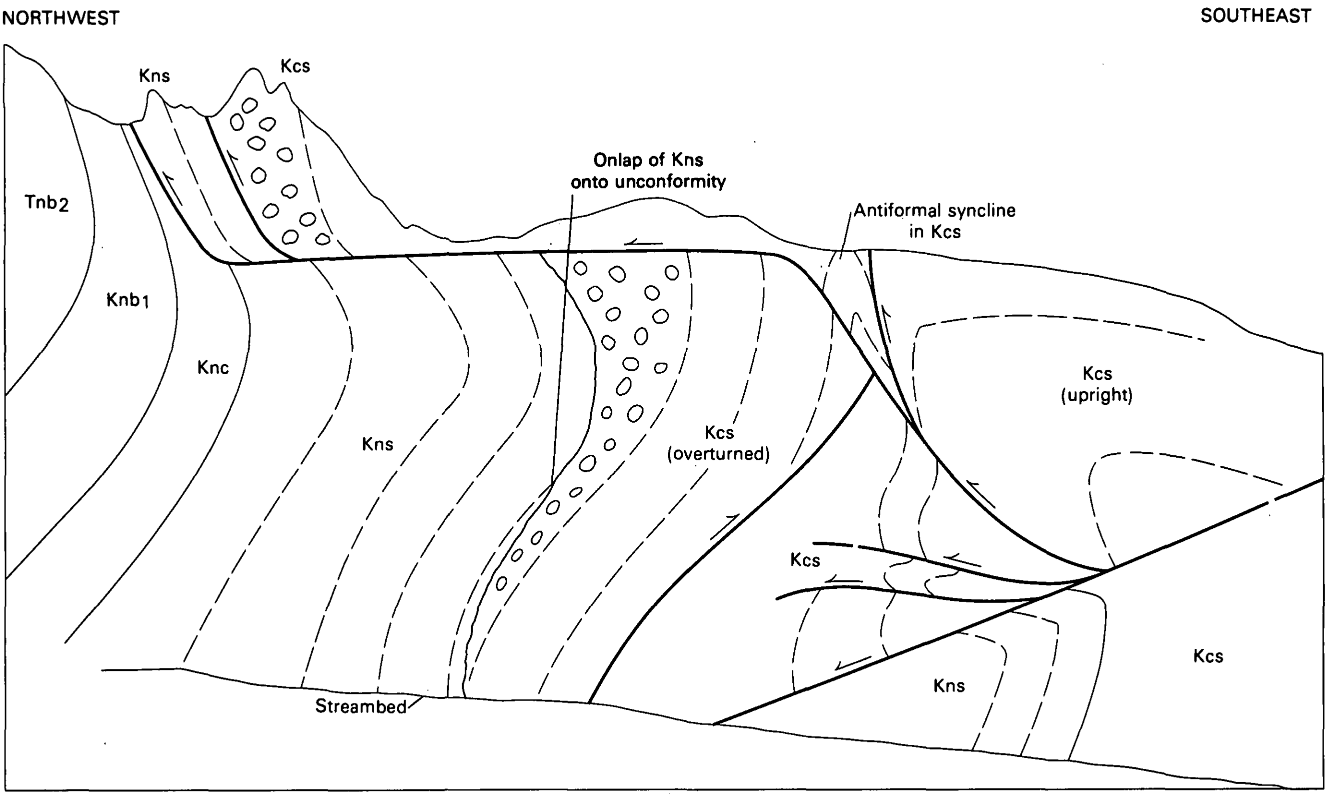


Figure 7. Sketch of geologic relations exposed on the north wall of Coal Canyon, Utah (NE1/4 sec. 23, T. 16 S., R. 2 E.)(fig. 2). Bedding lines in the North Horn Formation (Kns, sheet sandstone unit) depict onlap of basal beds onto overturned conglomerate (Kcs, unnamed conglomerate and siltstone unit). Conglomerate pattern depicts a boulder conglomerate unit in the unnamed conglomerate and siltstone unit. Also shown is system of thrust faults that forms duplex in unnamed conglomerate and siltstone unit and North Horn beds. Rock units: Kcs, unnamed conglomerate and siltstone unit; Kns, sheet sandstone unit of North Horn Formation; Knc, coal-bearing unit of North Horn Formation; Knb_1, lower sandstone of Big Mountain unit, North Horn Formation; Tnb_2, lower conglomerate of Big Mountain unit, North Horn Formation. Relief between canyon bottom and pinnacles of unnamed conglomerate in upper plate of duplex is 140 m (450 ft).

from uplifted strata east of present exposures is precluded by the east-directed paleocurrent indicators and by the huge volume of quartzite clasts in the basal unit. The latter point is particularly evident when the equivalent thick conglomerate of North Maple Canyon, north of the study area, is considered. The thickening of the basal conglomerate interval both north and south away from Petes Canyon, where no comparable conglomerate is present, indicates that the lowermost strata were deposited in valleys cut into older strata. The minimum relief of these initial paleovalleys, considering the thickness of the basal unit at both Big Mountain and Deer Gulch, was at least 100 m (330 ft). At Big Mountain, the easterly flowing rivers were succeeded by short-headed, west-directed streams flowing off uplifted strata east of the present range front, apparently when drainage was blocked by the uplift. The uplift resulted in the formation of a series of angular unconformities. Indianola clasts in the upper conglomerates of the basal unit were derived from the uplift. Moreover, an unroofing sequence is present in the succession of conglomerates, marked by the appearance of Coniacian clasts followed by Albian clasts (fig. 8). At Deer Gulch, it is not likely that the drainage direction was so quickly reversed by uplift but rather that fluvial deposition was abruptly altered in style and grain size from braided and gravelly to meandering and sandy.

Lower Redbed Unit

Overlying the basal contact at Petes Canyon and northward is a unit composed of dominant red sandy siltstone and subordinate conglomerate and pebbly sandstone. The lower redbed unit ranges in thickness from 138 m (450 ft) at Petes Canyon to about 240 m (785 ft) at Deer Gulch. At Petes Canyon the unit rests directly on the Twist Gulch Formation, whereas at Deer Gulch it overlies the basal conglomerate unit of the North Horn Formation. It grades upsection into the coal-bearing unit and southward into the sheet sandstone unit. Northward thickening of the lower redbed unit is due to both relief on the basal unconformity and northward pinchout of individual sandstone beds within the laterally equivalent sheet sandstone unit. The

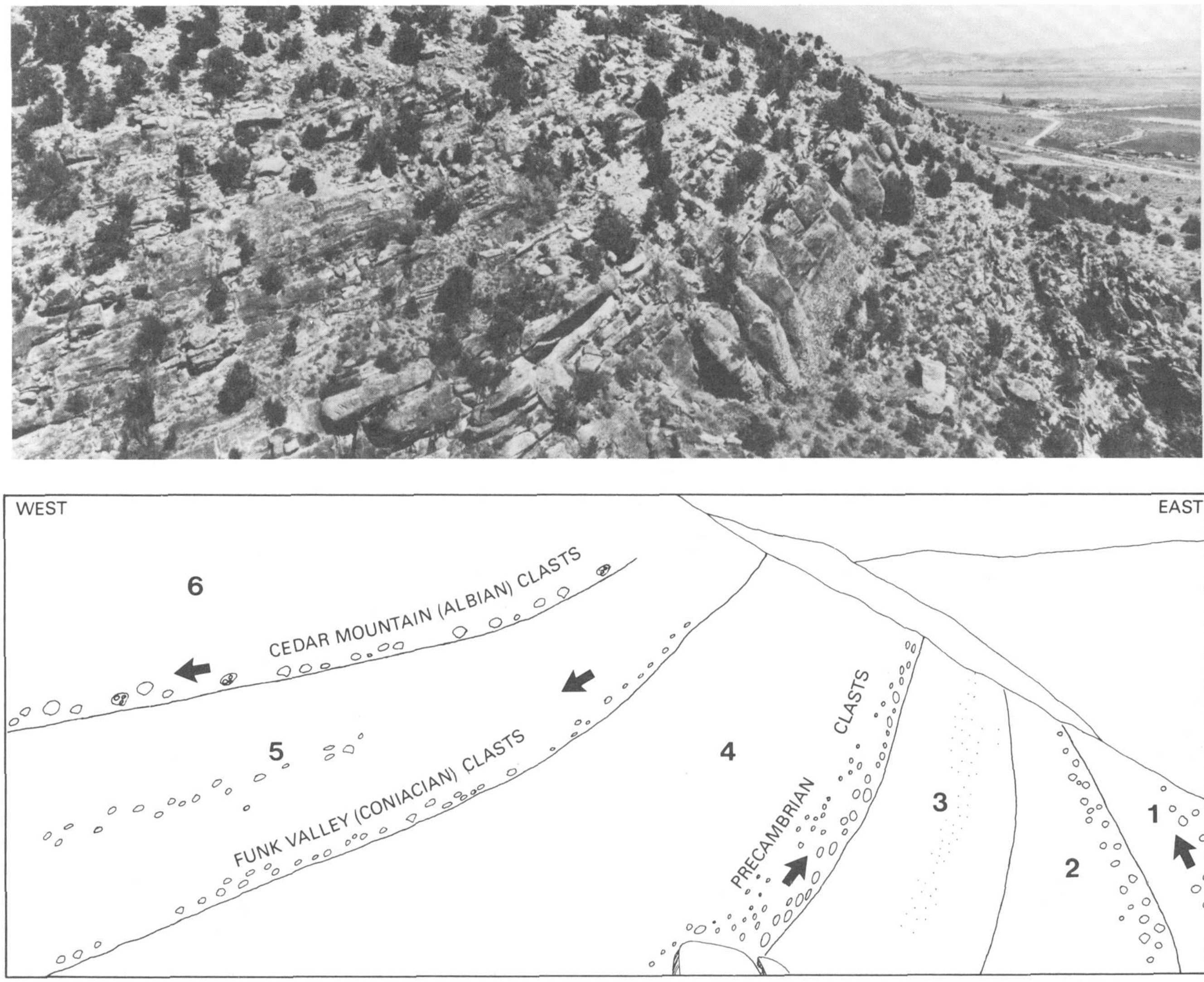


Figure 8. Intraformational unconformities in basal conglomerate unit of the North Horn Formation, north flank of Lambs Canyon, Big Mountain, Utah (N½ sec. 13, T. 16 S., R. 2 E.) (fig. 2). Sequences 1 through 6 overlie unconformities depicted by contacts. Sequences 1 and 2 are overturned. All sequences thin eastward. Arrows schematically depict paleocurrent directions inferred from clast compositions; arrows oriented upward indicate original eastward dispersal, arrows oriented downward indicate westward to northwestward dispersal. Sequence 4 paleocurrents are from clast imbrication measurements (fig. 9). Base of sequence 4 is mapped on plate 2. A reversal of dispersal is indicated between sequences 4 and 5. Both geometry and sedimentology of sequences indicate coeval uplift and deposition. Similar sets of unconformity-bounded conglomerates in the Ebro Basin of Spain have been termed progressive unconformities (Riba, 1976).

lower redbed unit is present to the south at Big Mountain, but its thickness there is obscured by faulting.

Tabular beds of conglomerate and pebbly sandstone are present in the lower part of the redbed unit. The beds contain crude horizontal laminae defined by pebbles and coarse sandstone. Graded beds 10–20 cm (4–8 in.) thick are also present; these form stacked sets as much as 1 m (3.3 ft) thick. This conglomeratic facies is most common in the lower 30 m (100 ft) of the redbed unit.

At Petes Canyon, graded conglomerate beds near the base of the redbed unit are in several instances overlain by matrix-supported conglomerate. The matrix is red sandy siltstone; the enclosed clasts are angular and poorly sorted. In the area between Petes Canyon and Deer Gulch, Twist Gulch clasts and brown sandstone clasts attributable to the Cedar Mountain Formation or to the Indianola Group are common in the lower conglomerate beds. A 1.5-m (5 ft) block of Twist Gulch was observed 10 m (33 ft) above the base of the section at the unnamed canyon in NW¼ sec. 36, T. 15 S., R. 2 E. Clast imbrication measured in the lowermost conglomerate beds at this locality indicates southwestward dispersal (plate 1).

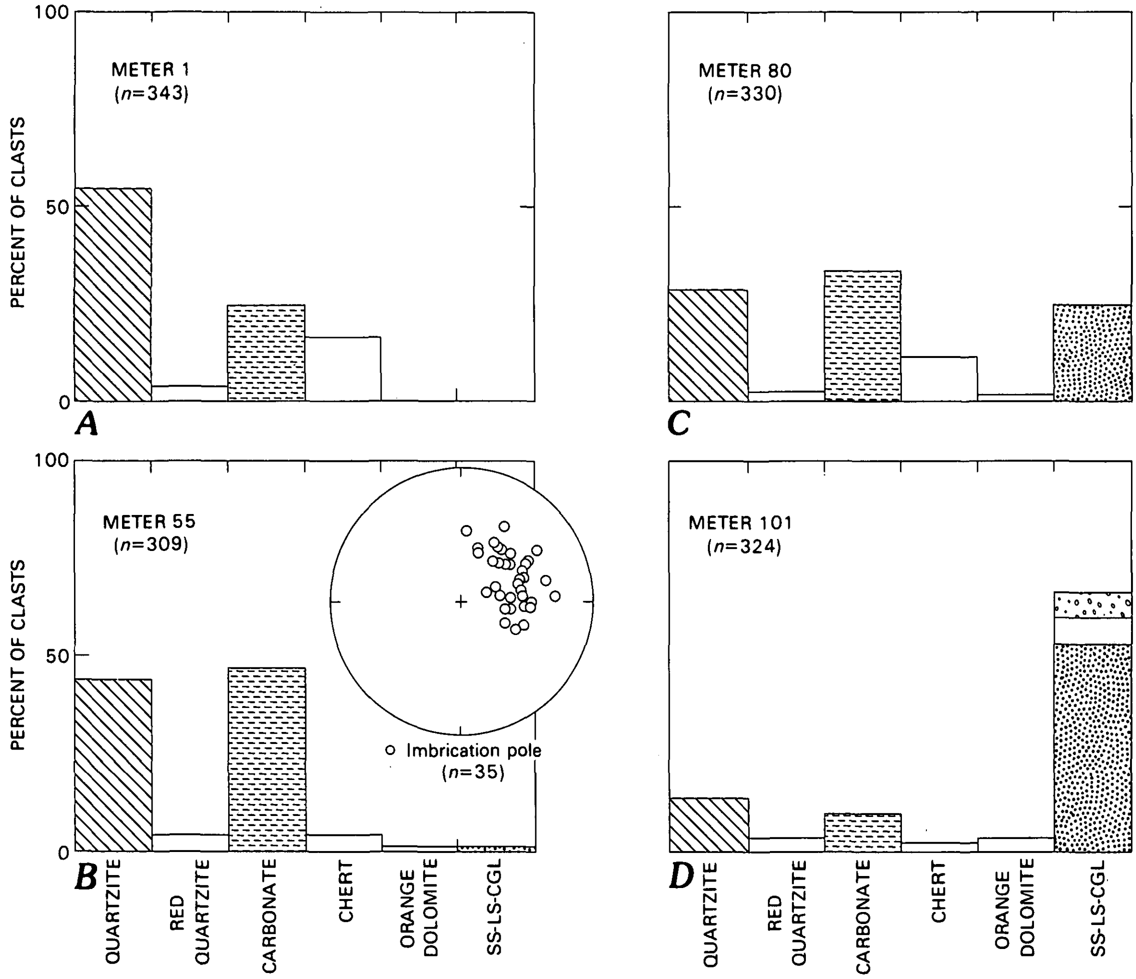


Figure 9. Histograms of clast counts, lower part of Big Mountain section (fig. 2). Clasts were counted using a 7.5 cm by 7.5 cm (3 in. by 3 in.) grid. Elevation in section and number of clasts counted (*n*) are indicated for each histogram. Stereogram *B* is plot of poles to clast imbrication and indicates northeasterly dispersal at meter 55 (sequence 4 of fig. 8). Clast categories are defined as follows: quartzite includes white, tan, and pale-green quartzite, mostly of Precambrian and Cambrian age; red quartzite includes red or purple quartzite clasts inferred to have been derived from the Precambrian Mutual Formation; carbonate includes limestone and dolomite clasts of various colors; chert includes chert and some cherty carbonate clasts; orange dolomite includes orange- to orange-brown-weathering dolomite of uncertain origin; SS–LS–CGL includes lithic and quartzose sandstone clasts, clasts of oncolitic limestone, and clasts composed of quartzite and carbonate pebbles. Clasts of the SS–LS–CGL category are inferred to have been derived from Cretaceous strata of the west-vergent thrust system exposed along the range flank. The conglomerate beds of this stratigraphic interval are in unconformity-bounded sequences and record a transition from early thrust belt derivation to later derivation from both the thrust belt and the west-vergent thrust system in the vicinity of the present-day Sanpete Valley. The percentage of clasts derived from immediately to the east increases upsection from 0 to 67 percent. A sequential upsection appearance of clasts from older units in the west-vergent thrust system represents progressive unroofing of the uplift.

Lenticular beds of clast-supported boulder and cobble conglomerate are common in the middle part of the lower redbed unit. The conglomerate beds are from 1 to 2.5 m (3.3–8 ft) in thickness but have proportionately small widths, some less than 10 m (33 ft). One example of a channel complex was observed at meter 156 of the Deer Gulch section. The complex consists of a 2.5 m by 20 m (8 ft by 66 ft) lenticular channel cut into red nodular siltstone. The channel is filled with at least five conglomerate lenses measuring about 1 m by 7 m (3.3 ft by 23 ft). Cross-bedded sandstone forms lenses within the conglomerate and caps many conglomerate beds. Clasts within the conglomerate beds are rounded quartzite cobbles and boulders that are as long as 28 cm (11 in.).

The conglomerate lenses are present within thick sections of red siltstone. The very poor sorting and general lack of primary bedding features in the siltstone suggests that the siltstone is bioturbated. Thin (5–20 cm, 2–8 in.) beds of very fine to coarse grained, very light gray sandstone within the siltstone may exhibit trough crossbedding but more commonly are mottled and contain rootlet traces. The siltstone contains discrete nodular intervals 1.5–2 m (5–6.6 ft) thick. The nodules are subspheroidal and have dimensions of 1–2 cm (0.5–1 in.), but they also are present as vertical tubes having diameters of as much as 3 cm (1.5 in.). They are composed of warty gray micrite containing as much as a few percent quartz sand grains. Although these nodular intervals are not always well exposed, they produce abundant micrite float and are thus easily recognized.

Sediment dispersal within the middle part of the lower redbed unit was southerly to easterly. Imbrication measured at two locations, 168 and 199 m (550 and 650 ft) above the base of the North Horn at Deer Gulch, indicates southerly to southeasterly paleoflow directions. At meter 276, the margin of the composite channel described above has an orientation of 080°, with flow toward the east.

The lower redbed unit grades upward into the overlying coal-bearing unit by loss of red siltstone beds, disappearance of conglomeratic lenses, and a change to gray siltstone and mudstone. It grades southward into the sheet sandstone unit by the appearance of tan medium-grained sandstone beds.

The lower part of the lower redbed unit consists of alternating sheetflood deposits marked by thin tabular beds of conglomeratic sandstone and oxidized overbank deposits. Channelized conglomerate represents minor fluvial channels. Matrix-supported conglomerate overlying the clast-supported conglomerate indicates that debris flows exploited pre-existing channels. The presence of debris-flow deposits suggests an alluvial-fan origin for the lower part of the unit (Rust and Koster, 1984). These fans were formed adjacent to the rising thrust uplift east of the range front, as evidenced by the westward dispersal and presence of locally derived Twist Gulch and Cedar Mountain clasts.

The depositional environment of the upper part of the lower redbed unit consisted of well-drained interfluve areas incised by deep narrow channels, probably of ephemeral flow. The nodular siltstone intervals are interpreted as aridisols with micrite-enriched B horizons, based on comparison with descriptions by Retallack (1988). The conglomerate bodies have similarities with ribbon channels in the Ebro Basin described from environments interpreted as distal alluvial fans by Allen and others (1983). These channels have composite fill as indicated by the geometry of the conglomerate and sandstone beds within them. Paleoflow directions were southerly, parallel with the trend of the thrust uplift to the east, to easterly.

Sheet Sandstone Unit

The sheet sandstone unit includes sheetlike sandstone beds interbedded with siltstone that is generally gray and carbonaceous. Limestone beds are present but uncommon. Light-brown, ledge-forming sandstone beds dominate the unit (fig. 10). The sandstone is fine to coarse grained and in beds 20–50 cm (8–20 in.) thick separated by thin silty sandstone beds. In some cases, these bedsets are gently inclined and broadly wedge shaped, generally thinning down the dip of the beds. The inclined bedsets are interpreted as lateral accretion bedding. Trough crossbeds are the most abundant structure, but convolute laminae are also present and are particularly common within the inclined bedsets. The sandstone beds grade by thinning and fining into overlying siltstone and sandstone. Bed tops at the sandstone-siltstone transition are typically mottled by root traces.

Individual upward-fining sandstone sequences have typical thicknesses of 4 m (13 ft). Sequences commonly form stacks of two or three sandstone bodies and little or no intervening siltstone to form a multistory architecture. Sandstone beds are sheetlike and terminate laterally by thinning to a pinchout in the adjacent siltstone. Paleocurrent measurements within the sandstone beds indicate northeast and east dispersal. The abundance of sandstone beds decreases within the upper part of the unit. Here, sandstone beds coarsen upward in a few cases and have tabular continuous geometry.

Interbedded siltstone intervals are from less than a meter to 16 m (3.3–50 ft) in thickness. The siltstone is gray to olive gray, mottled, and generally without distinct bedding. Thin, very fine grained sandstone beds a few centimeters thick are present within the siltstone. Plant fragments are present throughout the siltstone; gastropods and their shell fragments are present but uncommon. An uncommon but characteristic lithology of the unit is brown-weathering, dark-gray micrite in beds as much as 80 cm (30 in.) thick. Typically mottled, some of the micrite beds contain several percent charophyte fragments and gyrogonites, gastropods, and ostracodes. A rich petroliferous odor issues from freshly broken surfaces. These micrite beds are associated with thin beds of brown shale and light-gray claystone, the former containing abundant small plant fragments and impressions.

The sheet sandstone unit represents meanderbelt and floodplain deposits in its lower part. The northward change from meandering-fluvial system to well-drained interfluves and gravel-floored channels of the lower redbed unit apparently marks a paleogeographic transition between a perennial drainage system, flowing east, and an ephemeral system, flowing southeast.

An increase in the sandstone content and the thickness of the sheet sandstone unit is pronounced at Big Mountain. Southward from Big Mountain the unit thins, as indicated

Figure 10. Alternating sandstone and shale of sheet sandstone unit of the North Horn Formation (Kns), Petes Canyon, Utah (fig. 2). The North Horn Formation is separated from the Middle Jurassic Twist Gulch Formation (Jt) by a thrust fault. The contact between the lower redbed unit (Knl) and the sheet sandstone unit (Kns) is indicated by the lower dashed line; the contact between the sheet sandstone unit and the overlying coal-bearing unit (Knc) is indicated by the upper dashed line. The top of the coal-bearing unit is a sandstone ledge that forms the cuesta in the upper left part of the photograph. Maximum relief of cuesta is 122 m (400 ft). View to the northwest.

by its measured thickness at Coal Canyon. These observations, in combination with the northward disappearance of sandstone, indicate that the axis of the meandering-fluvial system was in the vicinity of Big Mountain.

Coal-Bearing Unit

The coal-bearing unit overlies the sheet sandstone and lower redbed units. The sheet sandstone unit grades upward into the coal-bearing unit by a loss of sandstone beds and an increase in abundance and thickness of siltstone intervals. The lower redbed unit grades upward into the coal-bearing unit through an alternation of redbeds containing caliche nodules and mottled olive and gray siltstone that finally gives way to drab-gray carbonaceous siltstone and shale. Coal beds and coal-streaked siltstone characterize the fine-grained rocks of this interval. The coal-bearing unit is 40 m (131 ft) thick in Coal Canyon and thickens northward to 114 m (374 ft) at Deer Gulch. At Coal Canyon, 20 m (66 ft) beneath the major coal bed, a sandstone bed containing abundant intraclasts of North Horn sandstone is included in the coal-bearing unit. It overlies the sheet sandstone unit with slight angular discordance (4°) that is particularly visible near the coal mine at SW1/4NW1/4 sec. 23, T. 16 S., R. 2 E. The angular discordance is correlative with the gradational change in color of the siltstone at Deer Gulch.

Gray to brown micrite beds are abundant near the top of the unit and form a laterally continuous hogback in the vicinity of Wales Canyon. The micrite beds contain abundant ostracodes, gastropods, and charophyte material. Interbedded coal beds are as much as 2 m (6.6 ft) thick. Although the coal beds of the southern part of the study area are more intimately associated with fluvial sandstone beds, similar thin beds of fossiliferous micrite are nevertheless present in association with the coal.

The limestone and coal of the coal-bearing unit represent deposits of marshy bogs or poorly drained floodplains and lakes. The northward transition from coal associated with meanderbelt sandstone to coal associated with marsh deposits is marked by thick siltstone beds and tabular sandstone bodies that have upward-coarsening profiles. The sandstone beds here may represent splay or lacustrine-delta deposits.

Calcareous Siltstone Unit

The calcareous siltstone unit overlies the coal-bearing unit at Petes Canyon (fig. 11), where it is 254 m (833 ft) thick. The contact is above a prominent sandstone ledge that forms a dip slope immediately upstream from the abandoned coal mine (NE¼SE¼ sec. 2, T. 16 S., R. 2 E.). The lower 164 m (540 ft) of the unit at Petes Canyon is equivalent to coarse-grained sandstone and conglomerate in sections measured to the south; the upper 90 m (295 ft) continues southward as a siltstone-dominated unit but is enriched in sandstone and conglomerate relative to the section at Petes Canyon (fig. 4). The Petes Canyon section is designated the reference section for the calcareous siltstone unit, where it is best exposed in the northern part of section 2, T. 16 S., R. 2 E. The unit is extremely prone to slumping and other mass-wasting processes; northward along the range front from Petes Canyon it is poorly exposed and forms hummocky topography underlain by beds that have chaotic attitudes.

The calcareous siltstone unit is concordant with underlying strata at Petes Canyon; however, the change in lithology at this point is abrupt and striking. The dominant lithology of the unit is calcareous siltstone and mudstone that have blocky to massive structure. The blocky structure is particularly associated with gray to olive-gray calcareous siltstone. Sand grains are present in the siltstone in variable quantities of as much as a few percent, and gastropod shell fragments are locally present. These features suggest that the calcareous siltstone and mudstone experienced significant bioturbation. Massive siltstone is also sandy and is more brightly colored than blocky siltstone; colors include red and purple. The colored horizons probably are stratigraphic and are commonly associated with discrete horizons of warty micrite nodules. The nodules range from equant (3 cm (1.5 in.) diameter) to vertical tubes as much as 5 cm (2 in.) in diameter.

Sandstone beds form a subordinate lithology within the siltstone. Sandstone beds associated with blocky siltstone are typically tabular and 20–75 cm (8–30 in.) thick. They form upward-thickening and upward-coarsening sequences as much as 2 m (6.6 ft) thick. The calcareous sandstone is very fine to medium grained and generally burrowed and bioturbated and contains gastropods, ostracodes, and algal fragments. Sandstone beds associated with the brightly colored siltstone are broadly lenticular to tabular and as much as 2 m (6.6 ft) thick. Sandstone ranges from very coarse to fine grained and fines upward within the beds.

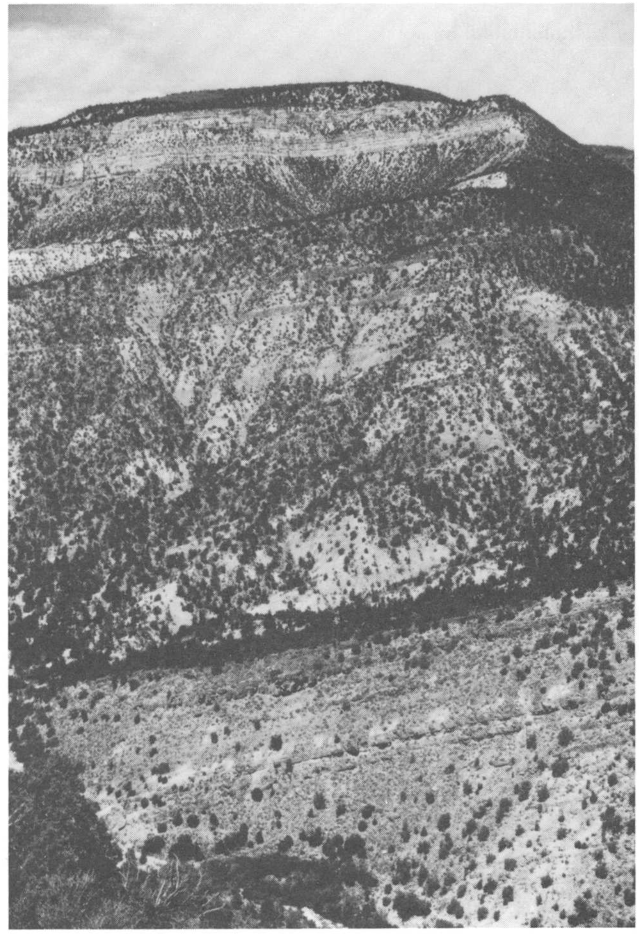


Figure 11. Calcareous siltstone unit of the North Horn Formation (center foreground) in Petes Canyon, Utah (fig. 2). The lower foreground up to the densely forested ledge is the coal-bearing unit (see also fig. 10). The ledges near the skyline are the main body of the Flagstaff Limestone. Total relief in photo is 366 m (1,200 ft).

Limestone and quartzite pebbles are present in lags and lenses at the bases of the thickest parts of the beds. Individual sandstone beds thin laterally and pinch out by loss of their upper parts. They thus terminate against the basal scour surface and are laterally equivalent to blocky, burrowed siltstone that is drab olive rather than bright red. Paleocurrent measurements indicate easterly to southeasterly sediment dispersal. The brightly colored siltstone beds also contain thinner (as much as 0.5 m (1.5 ft) thick), tabular sandstone beds that have diffuse contacts with the siltstone. Rootlet penetration marks are abundant in these sandstone beds, which otherwise have a mottled texture. A single channelform body was observed in siltstone associated with these tabular sandstone beds (fig. 12).

The calcareous siltstone unit formed in depositional environments that fluctuated between shallow lacustrine conditions and well-drained floodplains crossed by sinuous

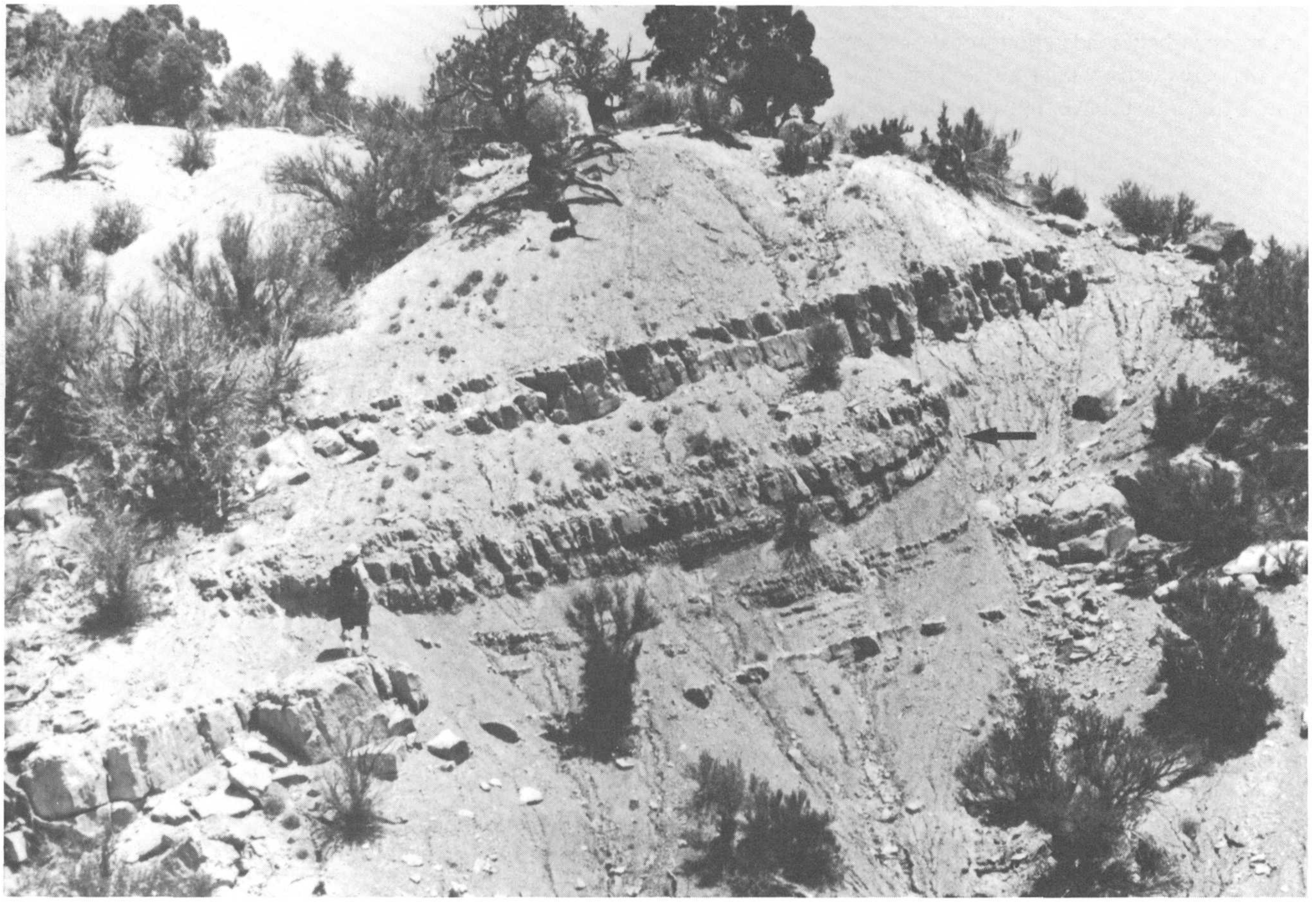


Figure 12. Channelform siltstone (arrow) of abandoned channel, calcareous siltstone unit of the North Horn Formation (meter 460 of Petes Canyon section, Utah) (fig. 2). *Note geologist on left side of channel.*

rivers. Blocky, bioturbated calcareous siltstone beds probably represent lacustrine sediments that were extensively burrowed. Associated upward-coarsening sandstone beds represent lake-margin deposits, possibly of deltaic origin. Brightly colored siltstone beds are floodplain deposits modified by pedogenic processes. Bright-red units closely associated with micrite nodules are interpreted as aridisols and thus represent gaps in sedimentation. Thick discrete sandstone beds are interpreted as deposits of meandering streams; their tapered tips represent preserved point-bar forms, and laterally adjacent siltstone plugs represent abandoned-channel deposits. Individual channelform bodies of siltstone are also interpreted as abandoned-channel deposits. Tabular mottled sandstone beds probably represent vegetated splay deposits on the floodplain.

Above the Coal Canyon unit, the calcareous siltstone unit (labeled upper part on plate 1) is laterally equivalent to the Wales Tongue of the Flagstaff Limestone in the northern part of the study area. It contains interbeds of coarse-grained sandstone and conglomerate that pinch out westward into siltstone. Sandstone beds are lenticular, commonly on a lateral scale of hundreds of meters. The beds contain lenses of oncolites, both whole and fragmental, and cobbles and pebbles that have concentrically laminated micrite rims as much as a centimeter thick. Laminated to stromatolitic micrite caps these lenses and is overlain by blocky calcareous siltstone or another sandstone bed. Conglomerate beds contain large foresets extending from the top to the base of the entire bed; the foresets are as much as 4 m (13 ft) thick. Pinchout directions of sandstone beds and foreset orientations within conglomerate beds indicate westward to northwestward dispersal. Brightly colored siltstone is absent from the southern sections.

The coarse-grained lithofacies association of the blocky calcareous siltstone of the southern sections is interpreted as deposits of lacustrine deltas and fluvial systems on a plain adjacent to a lake. Oncolites in the North Horn previously have been interpreted to represent nearshore lacustrine facies (Weiss, 1969). They also may have formed in channels, perhaps intermittently active, adjacent to the lake. The sediment source for these lacustrine deltas was nearby and was to the east and southeast rather than to the west in the thrust belt.

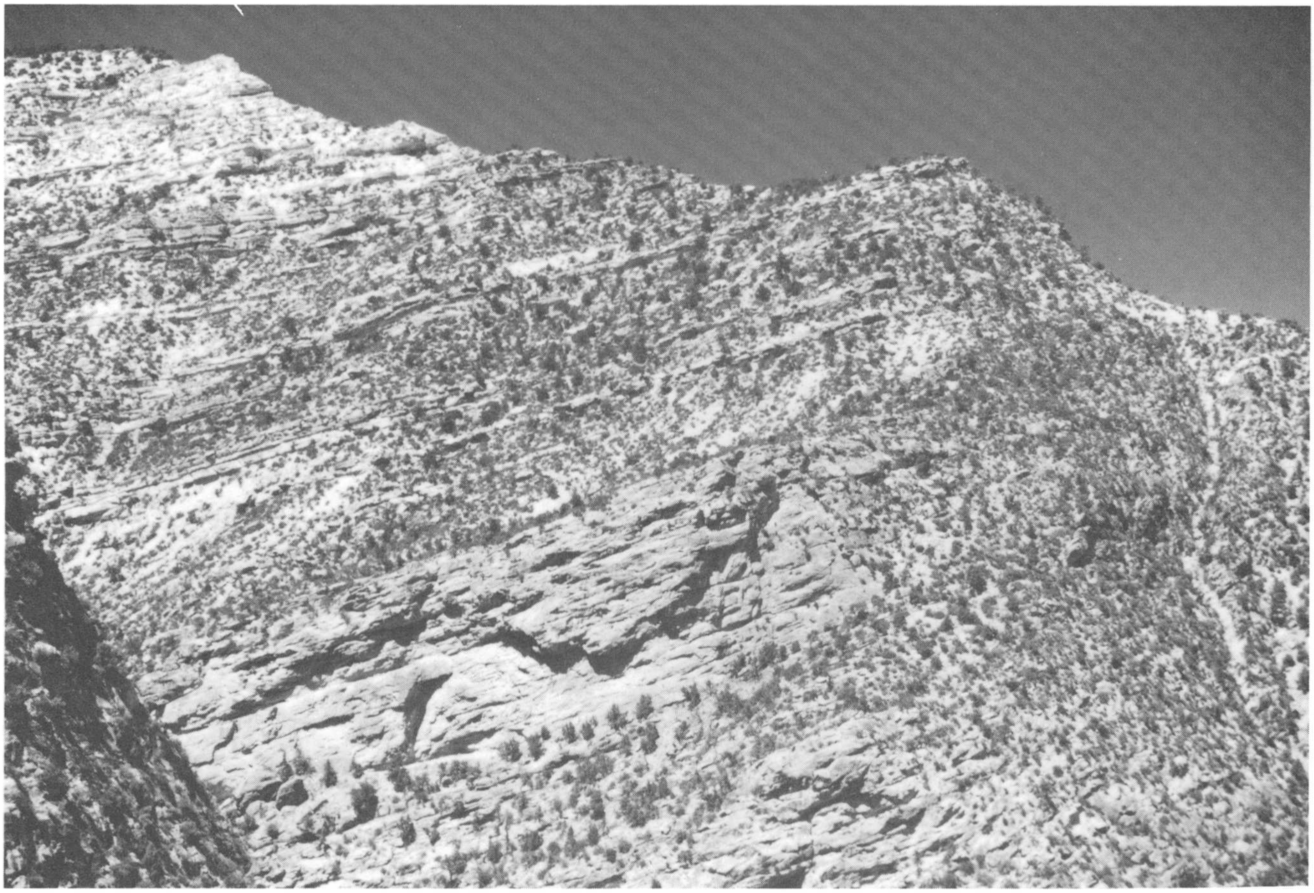


Figure 13. Big Mountain unit (cliff) and overlying upper part of the calcareous siltstone unit, both of the North Horn Formation, on the north wall of Blind Canyon, Utah (NE¼ sec. 14, T. 16 S., R. 2 E.) (fig. 2). Height of unvegetated cliff is 75 m (240 ft).

Big Mountain Unit

Immediately south of Petes Canyon, strata equivalent to the lower part of the calcareous siltstone unit form a thick section of coarse clastic deposits (fig. 4). These deposits consist of interbedded conglomerate and sandstone that have a maximum thickness of almost 230 m (754 ft) at Big Mountain and Coal Canyon (fig. 13). In ascending order, the unit may be subdivided into a lower sandstone, a lower conglomerate, an upper sandstone, and an upper conglomerate.

The lower and upper sandstone intervals form thick amalgamated sequences of medium- to coarse-grained sandstone dominated by trough crossbeds. Tabular beds as much as 3 m (10 ft) thick are visible in places; the sandstone may have formed by stacking of channel deposits having high width to depth ratios. Pebbles and intraclasts are common as lags above scour surfaces and as lenses within sandstone. Trough crossbeds decrease upward in scale from more than a meter to 10 cm (3.3 ft–4 in.) within some sandstone beds. Log impressions are present within some lags. Tabular crossbed sets are present but uncommon; these are as high as 1.5 m (5 ft). Convolute laminae and contorted trough crossbeds are present in some beds.

The lower and upper conglomerates form discrete, compositionally distinct lithosomes. The lower conglomerate interval rests erosionally on the lower sandstone of the Big Mountain unit, at least in the vicinity of Coal Canyon. The upper conglomerate interval pinches out on the ridge south of Petes Canyon; in thickening southward, its base cuts downward across a calcareous paleosol that can be traced northward to Petes Canyon. The lateral transition from conglomerate and sandstone to the calcareous siltstone unit is thus erosional, although it appears to be intertonguing on the map (plate 2).

The conglomerate is clast supported; its sandstone matrix increases upward in beds 2–3 m (6.6–10 ft) thick. Imbrication is present in basal lenses and at the top of the conglomerate beds where the beds are overlain on sharp contacts by sandstone. Imbrication is generally lacking within the middle of the conglomerate beds, where crude foresets may be distinguished in some places.

The upper and lower conglomerate intervals have distinctive and consistent clast compositions (fig. 14). Approximately 50 percent of the clast population in the lower conglomerate consists of limestone and dolomite, whereas 80 percent of the clast population in the upper conglomerate consists of carbonate rock types. Easterly and southeasterly paleocurrents determined from imbrication measurements are consistent along the range front.

The sandstone and conglomerate of the Big Mountain unit were deposited by braided rivers that flowed eastward. Bedforms within the sandy rivers consisted dominantly of dunes; subordinate transverse bars are recorded by uncommon planar foresets. Bedforms within the pebbly rivers consisted of gravelly bars as much as 2 m (6.6 ft) high. Bar tops were apparently sandy. These river systems were probably incised into adjacent deposits, at least immediately before deposition of the upper conglomerate interval, and are thus not precise chronostratigraphic equivalents of the finer grained section to the north. The siltstone section, in which calcareous paleosols are abundant, is laterally adjacent to this coarse-grained section. Periods of nondeposition within the fine-grained section thus probably coincided with periods of fluvial incision at Big Mountain.

Coal Canyon Unit

Above the limestone-clast conglomerate at Big Mountain is a 60-m (200 ft)-thick section of sandstone, pebbly sandstone, and conglomerate that contrasts with the underlying conglomerate and sandstone in terms of depositional style and dispersal direction. These differences indicate the probable presence of an unconformity and the need for establishing the upper interval as a separate unit. The Coal Canyon unit grades vertically and laterally into the calcareous siltstone unit described previously. It consists of stacked tabular beds of conglomerate and sandstone arranged in foresets as much as 2 m (6.6 ft) thick. The foresets include tabular to broadly trough shaped geometries and range from aggradational, apparently without erosive bases, to complexly erosive; abundant scours and reactivation surfaces are present between sets. Foresets terminate laterally into burrowed sandstone, and the terminal foresets are onlapped by sandstone and calcareous siltstone (fig. 15). The foreset beds are generally capped by thin sequences of trough-crossbedded sandstone, which are overlain in turn by mottled calcareous siltstone. Foreset orientations indicate westward and northwestward dispersal.

The large-scale foresets and termination into burrowed sandstone and siltstone indicate that the upper pebbly sandstone unit was deposited dominantly as lacustrine deltas that prograded west and northwest. The unit represents a dramatic change from the underlying conglomerate in terms of both depositional style and direction. The upper part of the Coal Canyon unit is laterally equivalent to a fossiliferous, tabular, upward-coarsening sandstone interval at Petes Canyon. The Coal Canyon unit thus interfingers depositionally with the adjacent fine-grained section rather than being incised into it.

Upper Redbed Unit

The upper redbed unit is the uppermost unit within the North Horn Formation. It is 120 m (390 ft) thick at Petes Canyon and thins eastward and southward to disappear between Petes Canyon and Big Mountain. At Coal Canyon and Axhandle Canyon, it is thin, on the order of 10 m (33 ft), and poorly expressed. It thickens rapidly westward on the north side of Axhandle Canyon.

At Petes Canyon, the unit consists dominantly of red-brown mottled siltstone and sandy siltstone. A few sandstone beds as much as 2 m (6.6 ft) thick are present in the upper redbed unit. These are lenticular and grade vertically from medium-grained sandstone above sharp bases to fine-grained sandstone that is mottled and burrowed. Thin (0.25 m, 0.8 ft) beds of medium-grained fossiliferous micrite also are present in the siltstone. Gastropods are dominant, although charophytes were also observed in the micrite. The thin intervals assigned to this unit at Coal and Axhandle Canyons consist mainly of mottled tan and red calcareous siltstone and sandstone. The sandstone is locally brecciated and contains vertical fractures filled with dark-red mudstone. The upper redbed unit is overlain with sharp contact by thick-bedded dolomicrite of the main body of the Flagstaff Limestone.

A distinctive feature of the uppermost siltstone beds of the North Horn Formation and the lowermost dolomicrite beds of the Flagstaff Limestone is the presence in the siltstone of thin-shelled plant nuts. These are spheroidal, 2–3 mm in diameter, and have a 0.5-mm-thick shell whose outer surface is dimpled with shallow circular depressions. The nuts are typically filled with calcite spar. They are morphologically identical to nuts of the contemporary hackberry (*Celtis* spp.), common in arroyos and riparian habitats of the southwestern United States.

The upper redbed unit was deposited on a low-gradient subaerial plain that was adjacent to an open-lacustrine environment to the north, as indicated by the equivalent Flagstaff beds north of the study area. Equivalent sand- and gravel-rich sediment was deposited in the eastern part of the depositional area, such as at Big Mountain. Lenticular sandstone beds represent deposits of sinuous channels cut into well-drained and oxidized floodplains represented by siltstone. Fossiliferous micrite probably represents deposits of ponds on the floodplain. A transition to lake-margin mudflat deposition of the Flagstaff occurred as the lake expanded across the low-gradient fluvial plain. The riparian margins and lake margin were vegetated by stands

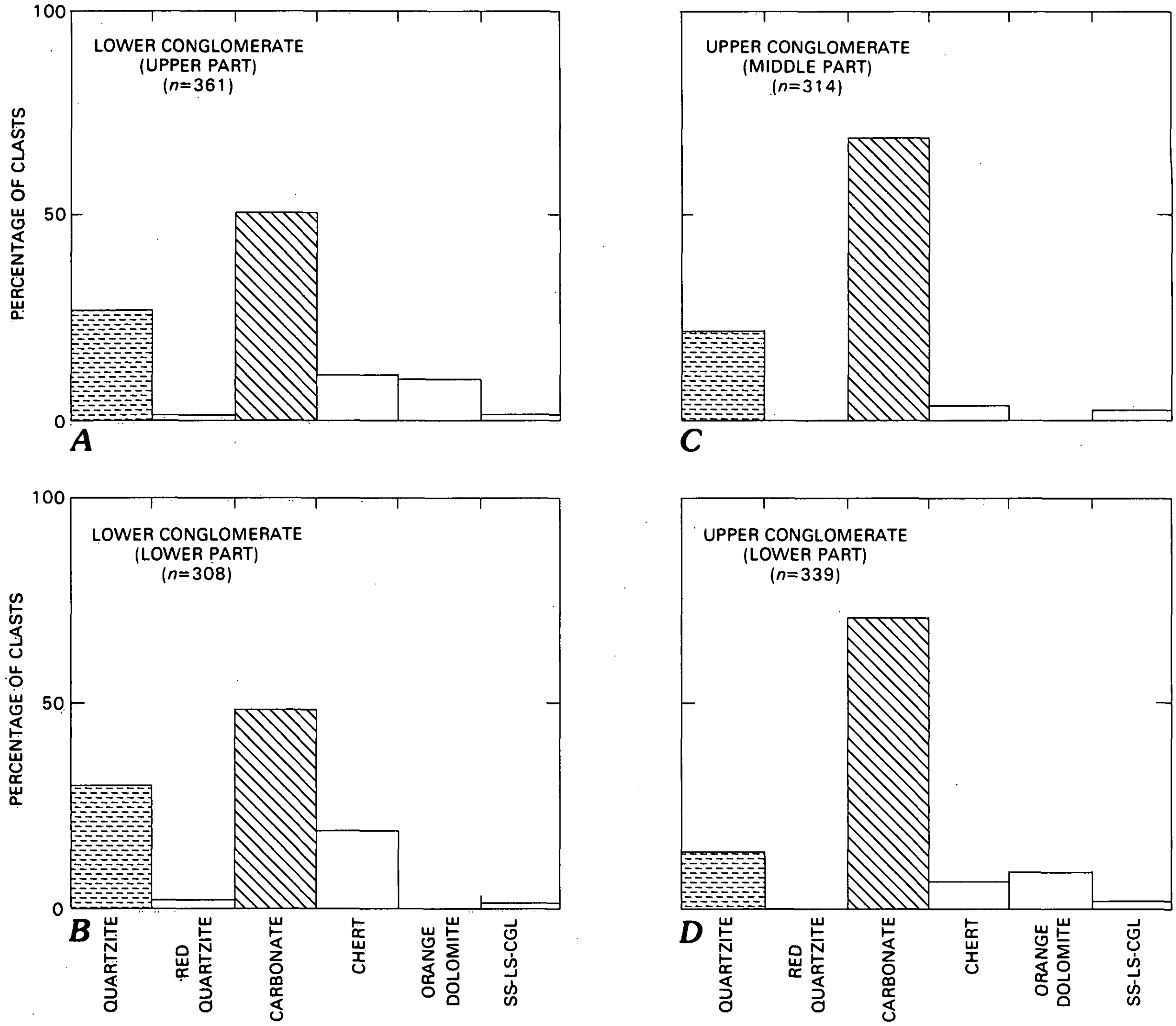
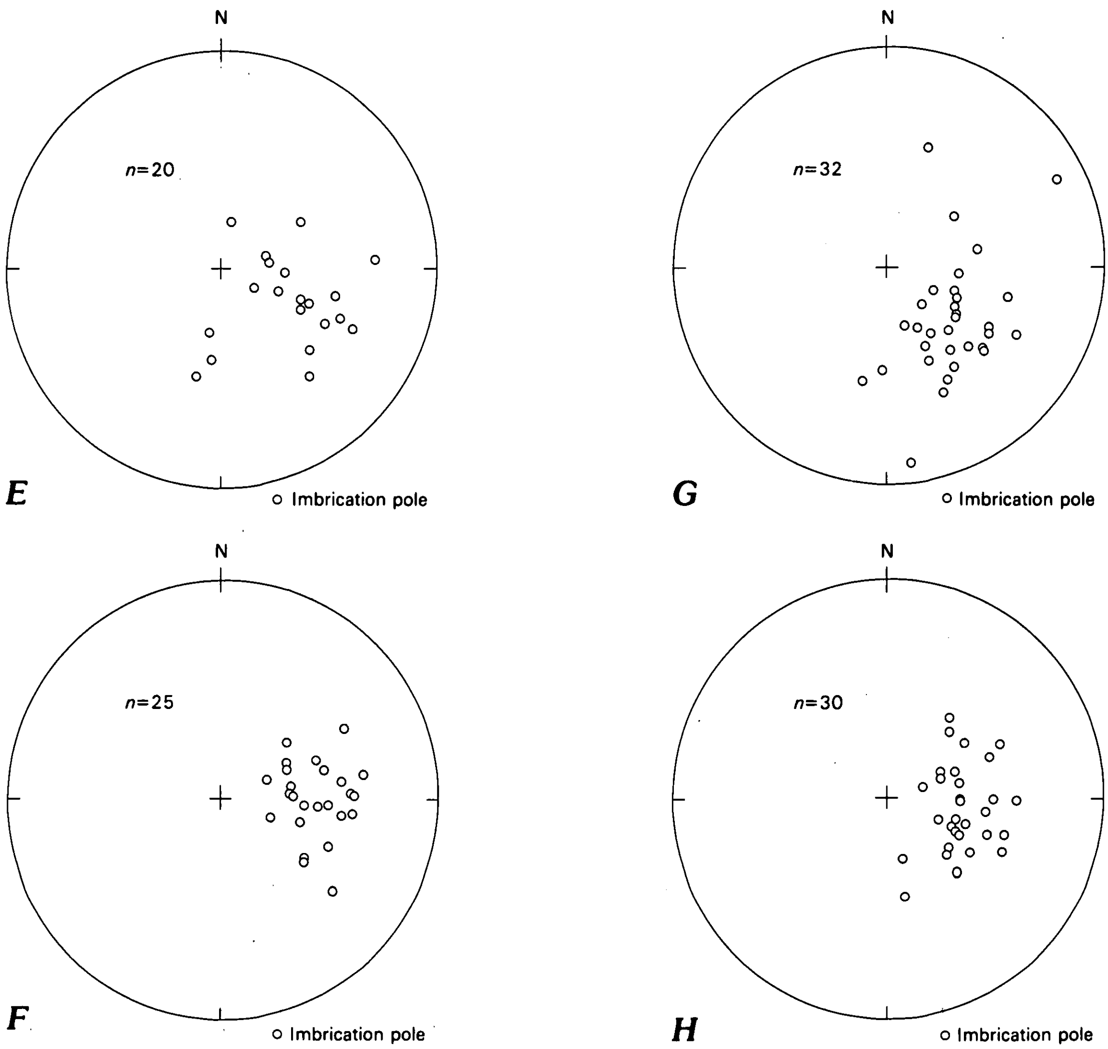


Figure 14 (above and facing page). Histograms of clast counts (*A–D*) and imbrication stereograms (*E–H*) of the lower and upper conglomerate beds, Big Mountain unit of the North Horn Formation. Clast categories and counting procedures as in figure 9. Imbrication measurements are rotated about present bedding attitudes. Data presented in stereograms *E* and *G* were collected in Coal Canyon; data in stereograms *F* and *H* were collected on partial section in unnamed canyon between Big Mountain and Petes Canyon (fig. 2), 3.4 km (2 mi) to north. All data are poles to clast imbrication (Schmidt equal-area stereonet).

of trees, possibly hackberries, as indicated by the localization of nuts in this facies association.

Wales Tongue of the Flagstaff Limestone

The Wales Tongue of the Flagstaff Limestone, named here, gradationally overlies the calcareous siltstone unit of the North Horn Formation at Petes Canyon. Although named for exposures in Wales Canyon to the north, it is better exposed on the ridge north of Petes Canyon. Therefore, the type locality is designated in SW¼ sec. 35, T. 15 S., R. 2 E., and N½ sec. 2, T. 16 S., R. 2 E., in Petes Canyon where the Wales Tongue lies between the calcareous siltstone and upper redbed units of the North Horn. Hunt (1950) included the Wales Tongue in the North Horn Formation; Birsa (1973) noted that it might be a member of the Flagstaff Limestone. At the type exposure, the Wales Tongue is 120 m (390 ft) thick. It thickens northward from Wales Canyon, where it is approximately 115 m (376 ft) thick (Hunt, 1950), and merges with the overlying Flagstaff Limestone 4.5 km (2.7 mi) north of Wales Canyon through disappearance of the intervening upper redbed unit (fig. 4) described above. The Wales Tongue interfingers southward with the calcareous siltstone unit. South of the map area of plate 2, at Horse



Mountain, the Wales Tongue is clearly recognizable above the calcareous siltstone unit, although the upper redbed unit is absent between it and the main body of the Flagstaff Limestone. The Wales Tongue rests directly on the Twist Gulch Formation at Dry Canyon but is not present in the section south of Dry Canyon. A carbonate unit believed to be equivalent to the Wales Tongue is present in Timber Canyon in the southwestern San Pitch Mountains (sections 4 and 5, T. 17 S., R. 1 E.; Mattox, 1987). There, an interval of micrite and oncoidal rudstone within the North Horn Formation is 51 m (167 ft) thick and resembles the upper part of the Wales Tongue described below. This interval overlies limestone-clast conglomerate and underlies calcareous red siltstone. Thus, the Wales Tongue of the Flagstaff is widely distributed in the central and southern San Pitch Mountains. In Petes Canyon, the base of the Wales Tongue is picked above a 4-m (13 ft)-thick interval of sandstone beds that overlies a conspicuous bed of red siltstone. The Wales Tongue forms two distinct subunits of distinctive lithology at Petes Canyon. The lower part is 40 m (131 ft) thick. It consists of dark-gray micrite beds 0.5–1 m (1.6–3.3 ft) thick interbedded with light-olive-gray claystone intervals several meters thick. The micrite beds contain abundant gastropods and their fragments. A few sandstone beds as much as 2 m (6.6 ft) thick are present in the lower part; they are extensively burrowed and contain gastropod fragments. An interval of brick-red claystone containing warty sandy micrite nodules is present at the top of the lower part (between meters 650 and 660 in the Petes Canyon section, plate 1) of the Wales Tongue. The lower part was measured only in the Petes Canyon section, but it continues northward beyond Wales Canyon.

The upper part of the Wales Tongue is 80 m (262 ft) thick and forms a distinctive succession of ledge-forming dolomite, limestone, and subordinate claystone that weathers white to orange (fig. 16). This distinctive succession continues southward and is present along the mountain front throughout the map area but is only a few meters thick and thus is not shown on the map of plate 2. The dominant lithology is very light brownish gray dolomicrite containing 2–10 percent fine to medium quartz sand

Figure 15. Lacustrine delta at the top of the Coal Canyon unit of the North Horn Formation, Blind Canyon, Utah (NE1/4 sec. 14, T. 16 S., R. 2 E.) (fig. 2). The base of the foresets is indicated by the lower arrow; the onlap of the foresets by the burrowed sandstone bed is indicated by the upper arrow. Thickness of delta between arrows is 4 m (13 ft).

grains. The dolomicrite is in beds 0.5–3 m (1.5–10 ft) thick that contain sparse gastropods and sparry algal fragments. The dolomicrite beds are separated by thin partings of dark-olive-gray claystone as much as 10 cm (4 in.) thick. The claystone beds are continuous for tens of meters laterally. The uppermost 30 m (100 ft) of the section grades to silty dolomicrite or calcareous siltstone by a gradual increase in the detrital silt content of the dolomicrite. Gastropods and algal fragments are present to the top of the Wales Tongue. Vertical rootlet traces penetrate 2 m (6.6 ft) down into the uppermost micrite bed.

In Coal Canyon, strata equivalent to the Wales Tongue are sufficiently different that they are included in the calcareous siltstone unit. They contain abundant intervals of mottled gray micrite and tan, purple, and gray dolomicrite. Some dolomite is dismicritic and has irregular cavities filled with calcite spar. Micrites commonly contain micritic intraclasts; in situ nodule development is also common. Sandstone beds are abundant in Coal Canyon. They are as thick as 4 m (13 ft) and are extensively burrowed and locally rippled and contain abundant shell fragments. This facies association grades laterally to a section dominated by nodular siltstone and approximately 30 percent sandstone at Axhandle Canyon. Sandstone beds there are as much as 4 m (13 ft) thick and fine upward from coarse- to medium-grained sandstone. Oncolites are present in lags at the bases of the beds; the overlying sandstone beds contain trough crossbeds. A 10-m (33 ft)-thick conglomerate is also present in this section. It thins and pinches out westward from the Axhandle Canyon section. At Horse Mountain, a matrix-supported cobble and pebble bed 1 m (3.3 ft) thick is interbedded in micrite. Its base is sharp, and the clast-rich interval grades upward through medium-grained sandstone into micrite.

The Wales Tongue of the Flagstaff was deposited within a lake of substantial size. Fossiliferous, burrowed dolomicrite beds are interpreted as shallow-water, open-lacustrine deposits. Dolomite and the higher sandstone content of equivalent strata in the Coal Canyon section represent lake margins, including both intermittently exposed carbonate mudflats and sandy shorelines or shoals. A similar association of facies constitutes the marginal-lacustrine

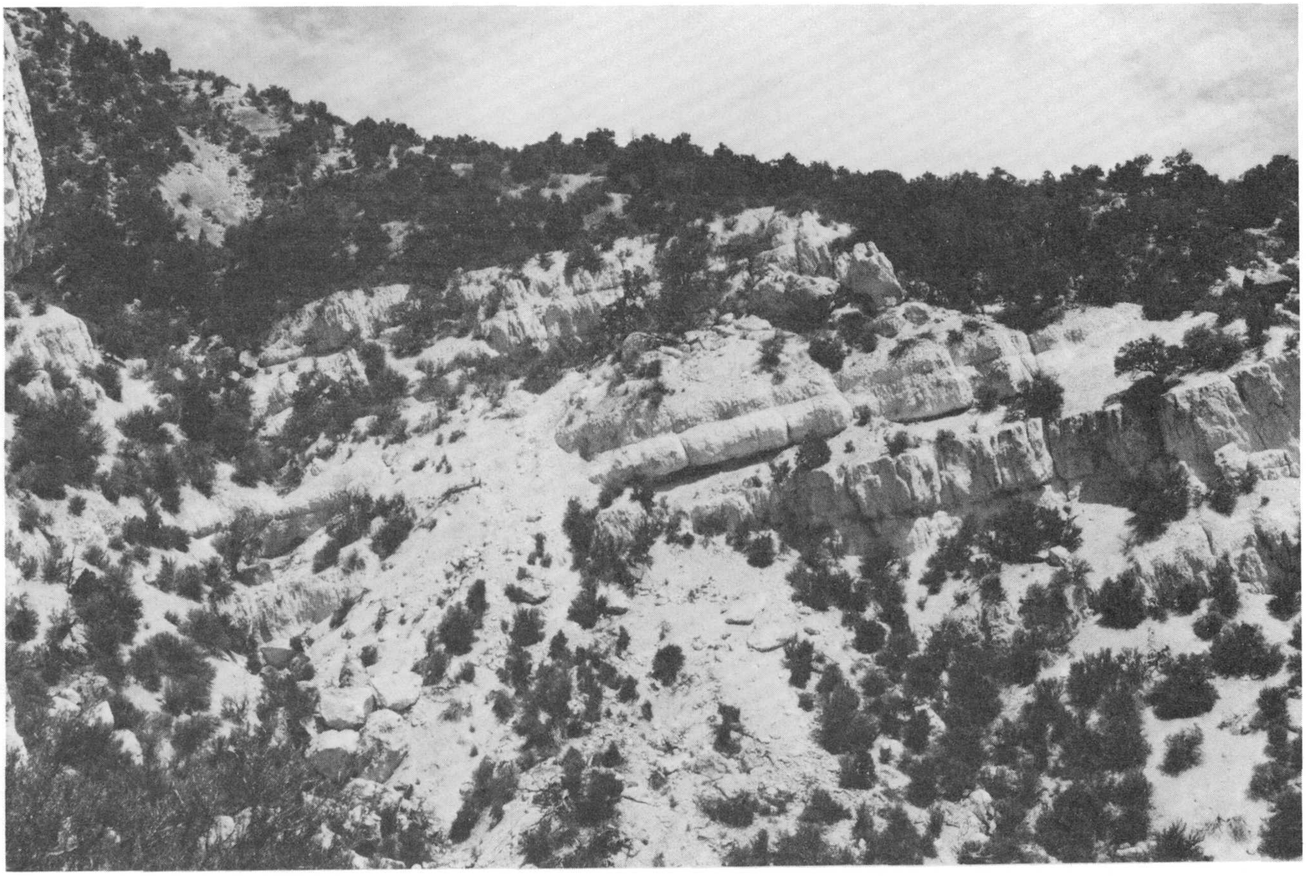


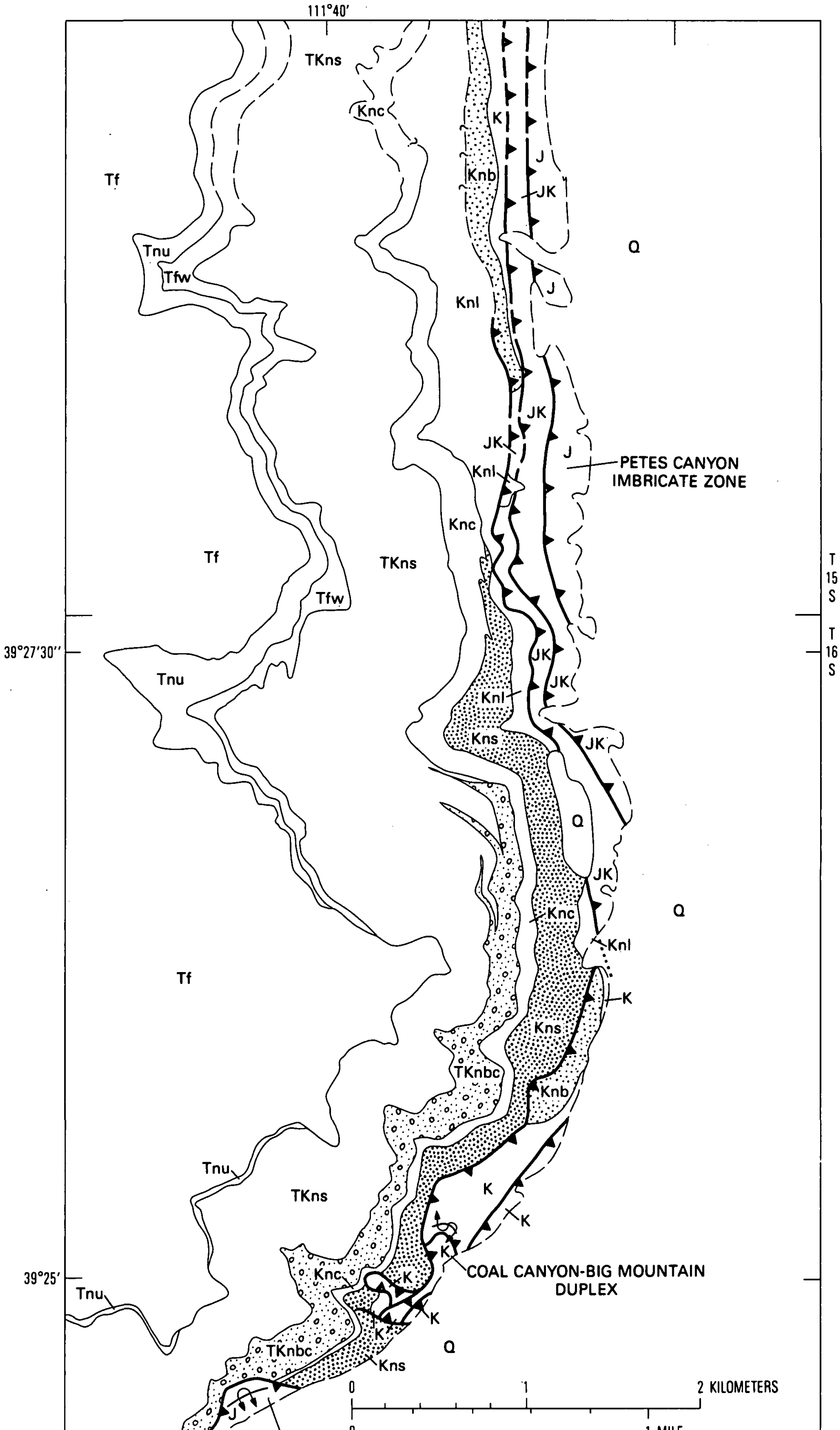
Figure 16. Ledge-forming micrite beds of the upper part of the Wales Tongue of the Flagstaff Limestone, Petes Canyon section, Utah (fig. 2). Upper ledge is approximately 10 m (33 ft) high.

facies of Ryder and others (1976) in the Flagstaff Member of the Green River Formation in the Uinta basin. Dismicritic dolomite suggests desiccation; nodule development suggests pedogenic modification of previously deposited carbonate mud. Stanley and Collinson (1979) noted similar features in strata interpreted as representing exposure modification of lacustrine facies of the Flagstaff Limestone in the Wasatch Plateau. The lacustrine deposits grade eastward and southward into fluvial and possible deltaic deposits, represented by the sandstone beds and thick conglomerate bed at Axhandle Canyon in the upper part of the calcareous siltstone unit. Matrix-supported conglomerate at Horse Mountain is interpreted to represent a subaqueous debris flow at the toe of one of these deltas. Nodular siltstone may represent pedogenically altered lacustrine deposits, but the sandstone probably represents channels peripheral to the lacustrine setting. Oncolites are an important indicator of the distributary channel system adjacent to and traversing the lake-margin flats. Their abundance at the base of channelform sandstone beds adjacent to lacustrine deposits indicates that the oncolites formed in stream environments, as well as in the lake itself, or that they were eroded from lacustrine beds by streams traversing lake-margin deposits.

Based on magnetostratigraphic evidence, the Wales Tongue is late Paleocene in age (fig. 3). Its position and age indicate equivalence with unit 1 of the Flagstaff Limestone of LaRocque (1960) in the Wasatch Plateau and thus with the Ferron Mountain Member and lower part of the Cove Mountain Member of the Flagstaff Limestone in the Wasatch Plateau (Stanley and Collinson, 1979).

STRUCTURAL GEOLOGY

The eastern flank of the central part of the San Pitch Mountains is characterized by thrust faults and folds that involve the North Horn Formation and older strata (Spieker, 1946; Lawton and Trexler, 1991). Three exposures of thrust-faulted strata, each exhibiting distinctive structural trends and styles, are present along the range front (fig. 17). These structural domains have strike lengths from 1.6 km to more than 6.5 km (1–4 mi) and form panels of imbricated and folded strata.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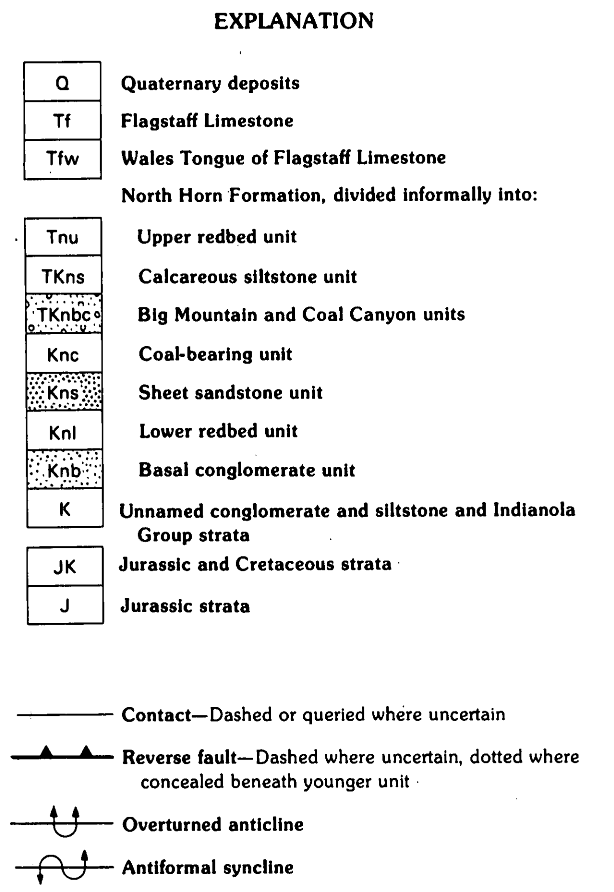

Figure 17 (above and facing page). Simplified tectonic map of study area, eastern San Pitch Mountains, Utah, showing locations of structural features discussed in text. Location of study area is shown in figure 1.

Petes Canyon Imbricate Zone

The Petes Canyon imbricate zone consists of several panels of east-dipping Middle Jurassic and Lower Cretaceous strata. These panels are separated by thrust faults or reverse faults of moderate dip, some of which may be traced the length of the zone within the map area. The zone of deformation extends from just north of Wales Canyon, where it disappears beneath landslide deposits, southward to SE¼ sec. 12, T. 16 S., R. 2 E., where it continues beneath alluvium of Sanpete Valley.

Within the deformed strata, thrust faults trend due north to N. 10° W. Strata of the easternmost thrust plate are upright; however, strata in most of the other plates are overturned. Dips of the major fault planes are consistently 50°–55° E. Minor faults of similar strike dip more steeply or shallowly and probably connect major faults, partitioning the larger plates into horses. North Horn strata overlap, and thus postdate, a thrust fault within the imbricate zone (NW¼ sec. 36, T. 15 S., R. 2 E.), but the westernmost fault of the imbricate zone cuts North Horn beds. Adjacent to this western thrust, the North Horn of the footwall is folded into a west-verging syncline (fig. 18). The observed relations suggest that faulting broke sequentially westward.

The western thrust fault is difficult to follow in the vicinity of Deer Gulch, where both the footwall and hanging wall consist of North Horn strata. Minor faulting and folding within the North Horn indicate that the western thrust fault probably follows the north-south drainage west of the ridge of basal conglomerate of the North Horn between Deer Gulch and Wales Canyon. Displacement on the fault may decrease northward, and the fault may die out where the conglomerate beds lose their steep attitudes and have shallow westerly dips near the northern map boundary. An intermediate plate within the imbricate zone is interpreted to terminate at a lateral ramp beneath Quaternary terrace deposits in the drainage south of Deer Gulch.

Coal Canyon–Big Mountain Duplex

The Coal Canyon–Big Mountain duplex extends from the foot of Big Mountain to the mouth of Coal Canyon. Strata in the hanging wall comprise interbedded cobble and boulder conglomerate and red siltstone of the unnamed Lower Cretaceous formation and pebbly sandstone of the overlying Sanpete Formation (plate 2). The western margin of the duplex is a thrust fault that separates Indianola strata in the hanging wall from the sheet sandstone unit of the North Horn in the footwall. In the northern part of the duplex, this fault enters the red siltstone unit of the North Horn Formation and separates basal North Horn of the hanging wall from the rest of the North Horn in the footwall.

The style of deformation within the duplex is different from that in the imbricate zone to the north. Strata and faults trend northeast rather than north. Slickensides associated with the thrust faults consistently indicate a strong component of oblique slip offset. The duplex consists of southeastern and northwestern panels. The southeastern panel is folded beds of unnamed conglomerate and siltstone thrust over a northwestern panel of younger, southeast-dipping, and mostly overturned Indianola beds. Rocks of the northwest panel are folded complexly. Between Coal and Blind Canyons, upright Sanpete beds within the northwest panel are folded into an anticline (interpreted as inverted by Birsa, 1973). A thrust fault that emplaced overturned unnamed sandstone beds over the upright Sanpete beds of the anticline is folded congruently with beds of the anticline.

A characteristic of the Coal Canyon–Big Mountain duplex is the presence of antiformal synclines associated with thrust faults. Such a syncline is adjacent to the folded thrust described above (plate 2). The synclinal axis is folded about the same axis as the thrust fault and upright

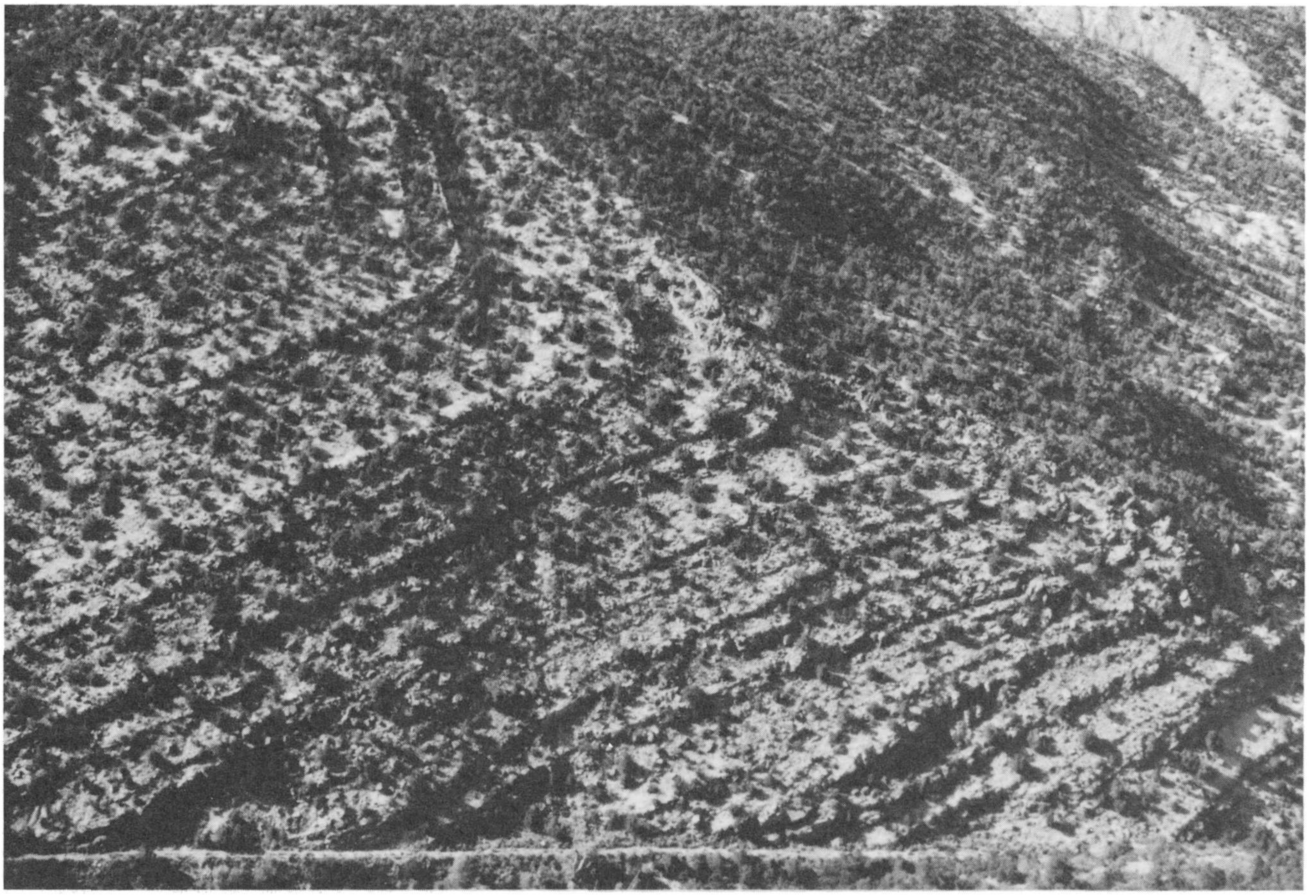

Figure 18. Footwall syncline in the sheet sandstone unit of the North Horn Formation, north wall of Petes Canyon, Utah (fig. 2). Fold lies immediately west of the Petes Canyon duplex and was formed beneath a west-vergent thrust fault. Relief on left edge of photograph is 120 m (400 ft).

anticline of the northwestern panel. A small antiformal syncline is present within a complexly faulted zone on the north wall of Coal Canyon (fig. 7).

The Coal Canyon–Big Mountain duplex ends abruptly at a lateral ramp at the mouth of Coal Canyon. The southern part of the duplex is floored by a blind thrust fault of moderate northwest dip that emplaced the unnamed formation and North Horn beds above North Horn strata of the footwall (fig. 7). A low-angle, northwest-dipping thrust fault is subparallel with and above the floor thrust fault. North Horn and unnamed strata were displaced westward above the upper thrust fault, which forms the roof of the duplex. Steeper east- and west-dipping faults cut between the low-angle thrust faults to form a small triangular zone of faulted unnamed formation strata (figs. 7, 19).

North Horn strata of the footwall are strongly deformed adjacent to the duplex. The lowermost part of the section is almost vertical beneath the duplex, but the North Horn beds have experienced only a small part of the shortening that affected the unnamed formation. The strata beneath the basal North Horn unconformity are overturned but dip to the west in apparent contradiction to the dominant west vergence observed elsewhere along the range front. The Big Mountain unit of the footwall is overturned and folded to conform to the margin of the duplex. Also within the Big Mountain unit the lower sandstone bed thins toward the duplex and is rotated to steep attitudes adjacent to the upper plate rocks (plate 2) to form a progressive unconformity (Riba, 1976), indicating a syndepositional response to early deformation of the duplex.

Immediately south of Coal Canyon, basal North Horn beds rest depositionally upon deformed beds of the unnamed formation and dip northwest at a low angle. Rotation of the North Horn beds counterclockwise about an almost vertical axis in proximity to the southern boundary of the duplex indicates a localized structural response to duplex development.

Structural and depositional relations of the Coal Canyon–Big Mountain duplex record repeated deformational episodes not as clearly demonstrated in blocks to the north and south. Major shortening caused thrust faulting and overturning of the unnamed formation and Sanpete

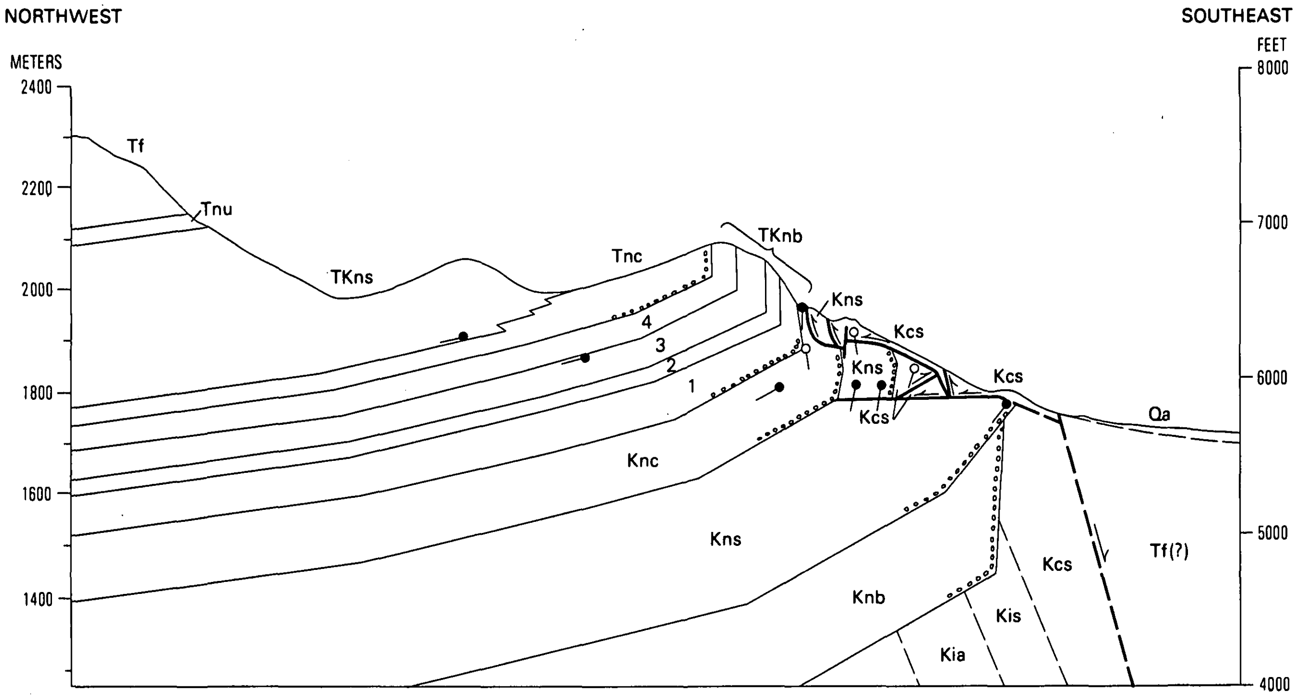

Figure 19. Cross section of eastern range front at Coal Canyon, Utah, through the Coal Canyon duplex (see also fig. 7) and North Horn Formation. Pebble symbol depicts the base of units deposited during uplift associated with the thrust system on the eastern flank of the San Pitch Mountains. Solid dip symbols indicate upright to vertical strata; open dip symbols indicate overturned strata. Rock units (from oldest to youngest) are as follows: Kcs, unnamed conglomerate and siltstone; Kis, Sanpete Formation of the Indianola Group; Kia, Allen Valley Shale of the Indianola Group; North Horn Formation—Knb, basal conglomerate; Kns, sheet sandstone unit; Knc, coal-bearing unit; TKnb, Big Mountain unit (1, lower sandstone; 2, lower conglomerate; 3, upper sandstone; 4, upper conglomerate); Tnc, Coal Canyon unit; TKns, calcareous siltstone unit; Tnu, upper redbed unit; Tf, Flagstaff Limestone (main body); Qa, alluvium.

beds prior to deposition of the North Horn. Thrust faulting following deposition of North Horn strata resulted emplacement of previously thrusted and folded beds of the unnamed formation over the North Horn. During this later shortening, earlier footwall synclines were overturned and previously formed thrust faults folded.

Axhandle Block

The Axhandle block consists of Middle Jurassic Twist Gulch Formation strata thrust over the coal-bearing unit and lower sandstone and conglomerate of the Big Mountain unit. Twist Gulch beds adjacent to the bounding thrust fault are overturned, but the bulk of the hanging wall is composed of upright beds dipping to the southeast. North Horn strata are steeply upturned adjacent to the fault.

Although the hanging wall of the Axhandle block disappears beneath alluvium north of Axhandle Canyon, it reappears along the eastern front of Horse Mountain, south of the map area (fig. 2). There, upright Twist Gulch beds are thrust over North Horn beds, which are overturned adjacent to the thrust. Footwall deformation involves beds as young as the lower part of the main body of the Flagstaff. The thrust fault flooring the Axhandle block continues southward to Dry Canyon, where it is manifested as a sharp, west-vergent fold in the Wales Tongue and the main body of the Flagstaff. Thus, the Axhandle block was emplaced to its current position following deposition of the Flagstaff Limestone.

TIMING OF THRUST FAULTING RELATIVE TO NORTH HORN DEPOSITION

Relations of structural features and North Horn stratigraphy in the east-central San Pitch Mountains demonstrate that thrust deformation continued episodically throughout deposition of the North Horn Formation (Lawton and Trexler, 1991). In addition, significant thrust shortening predated deposition of the North Horn Formation. These findings are significant in that they indicate episodic thrust deformation on the same system from approximately late Campanian until early Eocene time.

The unconformity beneath the basal conglomerate unit is evidence for significant pre-North Horn shortening. This deformation consisted of west-vergent thrust faulting that resulted in folding and overturning of Jurassic through Cretaceous strata. Within the Petes Canyon imbricate zone, the thrusted beds dip moderately eastward and are overlain by North Horn rocks that have low westward dips. At Coal Canyon, the angular relationship of basal North Horn beds and subjacent strata is the same as in the Petes Canyon imbricate zone, but subsequent shortening rotated the unconformity to a vertical attitude (fig. 7).

Thrust faulting proceeded intermittently during initial deposition of the North Horn Formation, as is best demonstrated by the progressive unconformity within the basal conglomerate at Big Mountain (figs. 4, 8). There, ongoing deformation rotated older beds that were subsequently beveled beneath younger beds to create a series of eastward-thinning, unconformity-bounded units. Similar unconformity-bounded conglomerate beds have been interpreted to represent the interaction of concurrent sedimentation and deformation on the northern margin of the Ebro Basin in Spain (Riba, 1976). The unconformities within the lower part of the North Horn section at Deer Gulch likewise create a fan-shaped wedge of conglomerate, sandstone, and siltstone, probably within a paleovalley cut into older strata.

Thrust deformation also accompanied later deposition of the North Horn. Thinning and progressive rotation of the lower sandstone of the Big Mountain unit adjacent to the Coal Canyon–Big Mountain duplex indicate that thrust structures along the range front were active during deposition of that unit. Moreover, subsequent deformation of all sandstone and conglomerate beds of the Big Mountain unit during continued development of the Coal Canyon–Big Mountain duplex indicates that deformation also postdated deposition of the Big Mountain unit. Similar evidence for late North Horn shortening is shown by folding of the sheet sandstone and coal-bearing units beneath the westernmost thrust fault of the Petes Canyon imbricate zone (fig. 18) and thrust faulting of the basal part of the formation. This younger shortening probably resulted in paleocurrent reversal to west- and northwest-directed deltaic sedimentation of the Coal Canyon unit. Deltaic conglomerate and sandstone of the Coal Canyon unit that interfinger with the calcareous siltstone unit along the face of Big Mountain were probably derived from the North Horn Formation of the footwall and thrusted hanging-wall strata of the west-vergent thrust plates. The increased percentage of conglomerate and sandstone in the calcareous siltstone unit of the Axhandle Canyon and Big Mountain sections suggests derivation of clastic material from thrust uplift to the east. A gradual upsection decrease in dip through the upper part of the North Horn section along the mountain front indicates that deformation continued during deposition of the uppermost part of the North Horn.

It is difficult to precisely constrain the end of deformation, but the Flagstaff Limestone is deformed by the episode of shortening that emplaced the Axhandle block. In contrast, the Flagstaff Limestone rests unconformably on upturned Indianola beds elsewhere in the vicinity of Sanpete Valley, such as at Sixmile Canyon, southeast of the study area, and in the vicinity of Indianola, northeast of the study area (Spieker, 1946). At those localities, there is no evidence of folding of the Flagstaff. However, both the possibility of a sub-Flagstaff unconformity at Axhandle Canyon, as indicated by the magnetic reversal stratigraphy, and significant amounts of sandstone in the Flagstaff at Axhandle Canyon suggest that thrust uplift immediately preceded and even accompanied deposition of the Flagstaff.

Crosscutting structural relations indicate that west-directed thrust faulting and structural uplift (Sanpete Valley anticline of Gilliland, 1963) in the vicinity of the eastern range front of the San Pitch Mountains preceded deposition of the North Horn and continued intermittently through deposition of the main body of the Flagstaff Limestone of early Eocene age (Fouch and others, 1983). The timing constraints are significant in that they firmly document long-lived, intermittent activity on a single thrust system. The west-verging thrust faults of the San Pitch Mountains represent the core of a fault-propagation fold, antithetic to the dominant east vergence of the thrust belt, that formed above the approximate eastern extent of the Gunnison thrust system of Villien and Kligfield (1986). The Gunnison thrust system terminates eastward into a complex of thrust faults in the shale and evaporites of the Middle Jurassic Arapien Formation, which underlies Sanpete Valley (Standlee, 1982; Lawton, 1985). The history of the Gunnison thrust fault is thus well documented by the deposits of the North Horn Formation on the eastern flank of the San Pitch Mountains. It is worth noting that the deformational history of the Gunnison thrust fault spans most of the temporal range of Laramide deformation (late Campanian to approximately late middle Eocene) that affected the Colorado Plateau and Rocky Mountain region east of the Colorado Plateau (Dickinson and others, 1986, 1988; Lawton, 1986b).

CONCLUSIONS

The North Horn Formation of the eastern San Pitch Mountains ranges from 42 to more than 1,100 m (137–3,600 ft) in thickness. The basal contact is an angular unconformity; the upper contact with the Flagstaff Limestone may also be unconformable along the eastern range front. The basal contact of the main body of the Flagstaff is probably an angular unconformity in the vicinity of the thrust uplift of Sanpete Valley, but these relations are there eroded or in the subsurface. The contact becomes conformable with North Horn beds westward into the range away from the thrust uplift. The gradational contact within the range is demonstrated by intertonguing of

North Horn and Flagstaff strata north of Wales Canyon. The North Horn was deposited between thrust-generated structures along the present eastern and western range flanks. The resulting sedimentary basin, developed on the hanging wall of the Gunnison thrust system, is a piggyback basin.

Biostratigraphic evidence from the eastern side of the San Pitch Mountains indicates that the North Horn there ranges in age from late Campanian to early Eocene. Magnetostratigraphic data are permissive of this conclusion. The age constraints indicate that onset of North Horn deposition in the San Pitch Mountains predated that in the Wasatch Plateau.

The North Horn Formation is here subdivided into eight informal units that can be mapped along the eastern range front. In ascending order, they are (1) basal conglomerate unit (formerly Price River Formation), (2) lower redbed unit, (3) coal-bearing unit, (4) sheet sandstone unit, (5) Big Mountain unit, (6) Coal Canyon unit, (7) calcareous siltstone unit, equivalent in its lower part to the Big Mountain and Coal Canyon units, and (8) upper redbed unit. The term Price River Formation is not used for conglomerate units exposed in the San Pitch Mountains. A member of the Flagstaff Limestone, named here the Wales Tongue, is present between the calcareous siltstone and upper redbed units of the North Horn.

The North Horn Formation was deposited in nonmarine environments that ranged from alluvial fans (lower redbed unit) and incised valleys with braided streams (basal conglomerate unit) to open-lacustrine conditions (carbonates of the Wales Tongue). Transport of clastic detritus was dominantly from the west, but sediment was shed from the rising thrust structure of Sanpete Valley early (upper part of basal conglomerate unit and lower redbed unit) and later (Coal Canyon unit and upper part of calcareous siltstone unit) in the deposition of the North Horn.

Abrupt lateral changes of depositional environment were the rule, rather than the exception, during North Horn deposition. A major fluvial axis occupied a position coincident with the present location of Big Mountain during deposition of the lower two-thirds of the section. Eastward-flowing rivers of the Big Mountain unit were restricted by incision into adjacent fine-grained interfluve areas that developed numerous calcareous paleosols (Talling, 1992). The overlying Coal Canyon unit, which was shed westward and northwestward from the thrust uplift, grades laterally into lacustrine deposits of the calcareous siltstone unit.

Thrust deformation, which preceded and accompanied deposition of the entire North Horn section, strongly controlled depositional patterns of the North Horn Formation. Deformation took the form of west-vergent thrusts and folds at the eastern extent of the Gunnison thrust system of the Sevier orogenic belt. The thrust uplift that resulted was at times a sediment source (upper part of basal conglomerate unit, Coal Canyon unit, upper part of calcareous siltstone unit) and at other times breached by eastward-flowing rivers (lower part of basal conglomerate unit, sheet sandstone unit, Big Mountain unit). Structural containment of drainage may have resulted in the lacustrine conditions that developed concurrent with and following deposition of the Coal Canyon unit.

Interaction between the thrust system of Sanpete Valley and North Horn deposition indicates that the thrust system likewise persisted from late Campanian until early Eocene time.

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SAMUEL Y. JOHNSON, Project Coordinator

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