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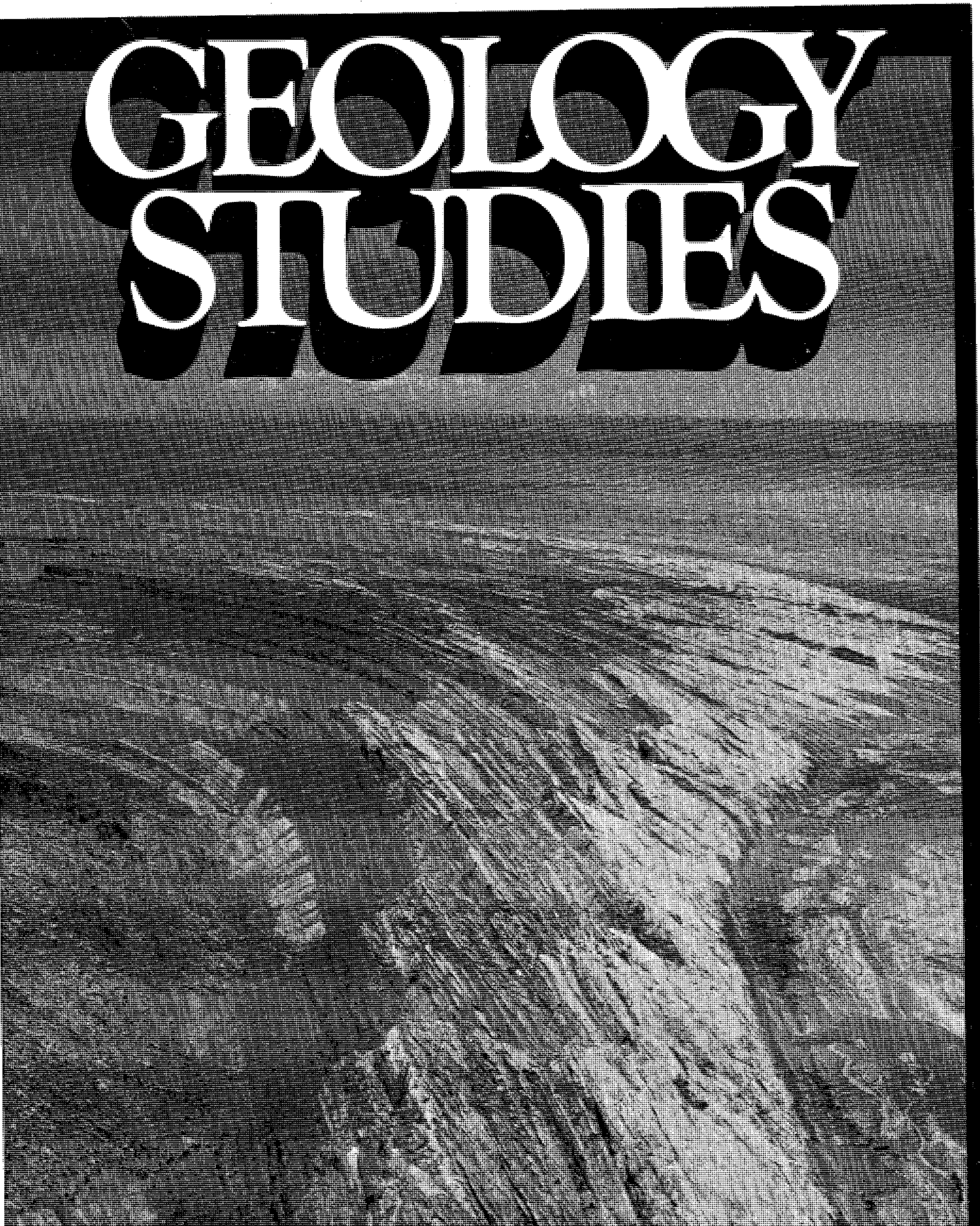
GEOLOGY STUDIES



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THE GLORY OF GOD IS INTELLIGENCE

Cover: East flank of San Rafael Swell, Emery County, Utah; looking north. Photo by W. K. Hamblin.

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Mesozoic and Cenozoic Sedimentary Environments of the Northern Colorado Plateau

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Abstract.– Mesozoic and Cenozoic sedimentary rocks of the northern Colorado Plateau display an unusually varied suite of sedimentary environments, including both marine and nonmarine sites of deposition. Eolian deposits are well shown in the Navajo, Wingate, and Entrada sandstones over much of the plateau, and particularly in the Canyonlands area in eastern Utah. Swamp and marsh sediments are well shown at the northwestern wedge-edge of the Colton Formation and are associated with the numerous coal beds of the Blackhawk Formation. Lacustrine deposits are represented in the Green River, Flagstaff, North Horn, and Morrison formations, with possible playa-type lacustrine deposits in carbonate lenses within the Navajo and Kayenta formations.

Fluvial beds are exposed in Morrison, Colton, and Cedar Mountain formations, and each includes deposits of meandering streams and alluvial plains. Braided-stream fluvial deposits are exposed in the extensive Castle Gate Sandstone, Price River, and North Horn formations in the High Plateaus and in the Kayenta and Chinle beds in the northwestern part of the Canyonlands section. Piedmont or alluvial fan deposits are well shown in the Red Narrows Conglomerate, as well as in some pediment-veneering gravel of probable Pleistocene age around the flanks of the San Rafael Swell.

Marginal marine or mixed sedimentary environments, including tidal flats, deltas, barrier-island complexes, and sabkha deposits and evaporite sequences, are represented by rocks in the Thaynes, Twin Creek, Summerville, Entrada, and Carmel formations in the High Plateaus and along the flanks of the San Rafael Swell. Rocks of low-energy, arid coastlines, which include evaporate accumulations, are well displayed in the Summerville, Carmel, Arapien, and Twin Creek formations in the San Rafael Swell and the High Plateaus, particularly in the Wasatch Plateau. Some of the carbonate deposits of the Jurassic Carmel Formation and the Twin Creek Formation may represent sabkha deposits. Deltaic sequences are well displayed in the Cretaceous Ferron Sandstone along the flanks of the San Rafael Swell and, to some degree, in the Blackhawk Formation, as that formation records distribution of clastic sediments along the down-current plain from a major delta. The Eocene Colton Formation is an excellent example of a lacustrian deltaic sequence, between the underlying Flagstaff and overlying Green River beds.

Barrier-island coastal deposits and rocks of associated marsh, shore-lagoon, and estuarine environments are represented in the Cretaceous Blackhawk–Mancos Shale sequence. They are particularly well shown in the Panther Sandstone, the Ferron Sandstone, and the Star Point Sandstone along the eastern margin of the Wasatch Plateau and the southern margin of the East and West Tavaputs Plateaus. Much of the coal of the Book Cliffs and Wasatch Plateau coalfields was deposited in coastal lagoons associated with the barrier-island sequence. Open marine to sabkha environments are represented in the Triassic Sinbad Limestone, which is extensively exposed in the central part of the San Rafael Swell. Similarly, the thick Cretaceous Mancos Shale represents marginal deltaic to open marine deposition.

Uppermost Paleozoic rocks in the northern part of the Colorado Plateau and the adjacent Wasatch Mountains display a variety of sedimentary environments, ranging from the moderately deep marine environments of the Oquirrh Basin to the interfingering shallow marine and nonmarine deposits of the Triassic Thaynes Limestone and the limestone-dominated environments of the Jurassic Twin Creek Formation. Cyclic marine and nonmarine interbedded rocks are also well exposed in the Hermosa–Rico–Cutler facies in the Canyonlands area near Moab and Potash.

INTRODUCTION

Late Paleozoic, Mesozoic, and Cenozoic rocks of the Colorado Plateau record one of the thickest, most persistent dominantly nonmarine sections in North America, and probably in the world. A great variety of sedimentary rocks are exposed in the High Plateaus and deep gorges of the Canyonlands sections of the Colorado Plateau (fig. 1) and represent sedimentary environments ranging from arid to humid nonmarine, and marginal marine to open marine. The classification of sedimentary environments utilized here is essentially that of Crosby (1972). This paper is not intended as a definitive study on any of the environments or rock units, but is an introduction to selected units, environments, and literature.

EOLIAN DEPOSITS

Eolian-dominated sedimentary environments were the site of accumulation of the Triassic(?) Wingate Sandstone and part of the overlying Jurassic(?) Kayenta Formation and the younger Jurassic Navajo Sandstone (fig. 2). Workers in the Colorado Plateau have long recognized the Navajo Sandstone as principally an eolian unit. Gregory (1915, p. 102) named the Navajo Sandstone and concluded (1917) that it was an eolian deposit because of its uniformity of grain size and cross-bedding and its red color, with the tangential persistent cross-bedding being diagnostic. Gregory also noted limestone and limestone conglomerate lenses and interbeds within the formation and suggested that they may be playa deposits or ephemeral lake accumulations. Gilluly and Reeside (1928), Gilluly (1929), and Baker, Dane, and Reeside (1936) followed the earlier interpretation by Gregory and concluded that the cross-bedded Navajo Sandstone was of eolian origin. More recently, however, Stanley, Jordan, and Dott (1971) proposed that much of the Navajo Sandstone may be the result of shallow-water deposition and marginal coastal dunes. Sanderson (1974) investigated the Navajo Sandstone along the western side of the San Rafael Swell (fig. 3) and interpreted the accumulation there as an extensive dune field, in which ground water may have played an important role in producing some of the irregular slumped bedding within the formation.

The Navajo Sandstone is truly one of the remarkable sheets of well-sorted clastic rocks that extends over much of the Colorado Plateau and is a remarkably homogeneous unit throughout much of its extent. Along the western part of its exposure belt it interfingers with the Carmel Formation, as interpreted by Stanley, Jordan, and Dott (1971). Wright and Dickey (1963) described the Thousand Pockets Tongue of the Navajo Sandstone, which wedges northwestward into the Carmel Formation in the southern Canyonlands section of the plateau. Thompson and Stokes (1970) described the Temple Cap Member of the Navajo Sandstone in the Zion Park area (fig. 4) in the southwestern part of the High Plateaus section. That member also wedges northwestward into the Carmel Formation. The basal part of the sequence also interfingers with the upper part of fluvial-dominated Kayenta Formation in the Cedar Mountain quadrangle in southwestern Utah (Averett 1962).

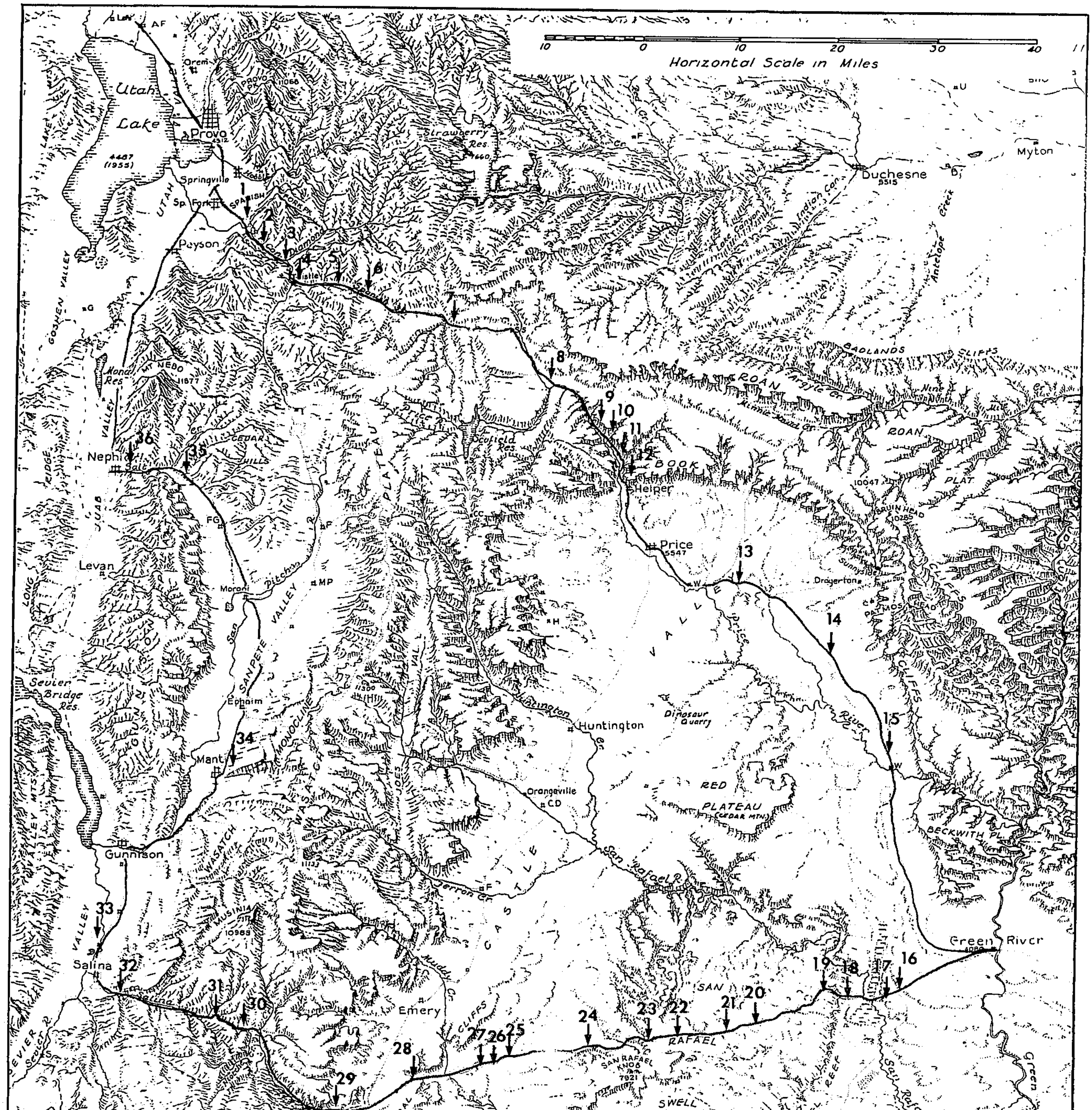

FIGURE 1.– Index map to localities which are particularly instructive and show facies relationships between Green River, Provo, and Salina, Utah, encompassing most of the northwestern corner of the Colorado Plateau and part of the Canyonlands. Some are cited in the text and accompanying illustrations. Localities 1–15 are along U.S. Highway 50–6. Localities 16–32 are along Interstate 70. Localities 33 and 34 are along U.S. Highway 89, and localities 35 and 36 are along Utah State Highway 132 (base map from Merrill Ridd).

Sedimentary structures and sedimentary petrology of the formation have been described by Kiersch (1950), Jordan (1965), Poole (1962), and Marzolf (1969). Marzolf (1969) noted the abundance of horizontal beds in the lower part of the Navajo Sandstone; a predominance of trough cross-beds, with tangential bedding, interbedded with contorted slumped or unbedded rocks in the middle part of the formation; and an abundance of planar cross-bedded sandstone in the upper part.

In general, Navajo Sandstone in the northern part of the

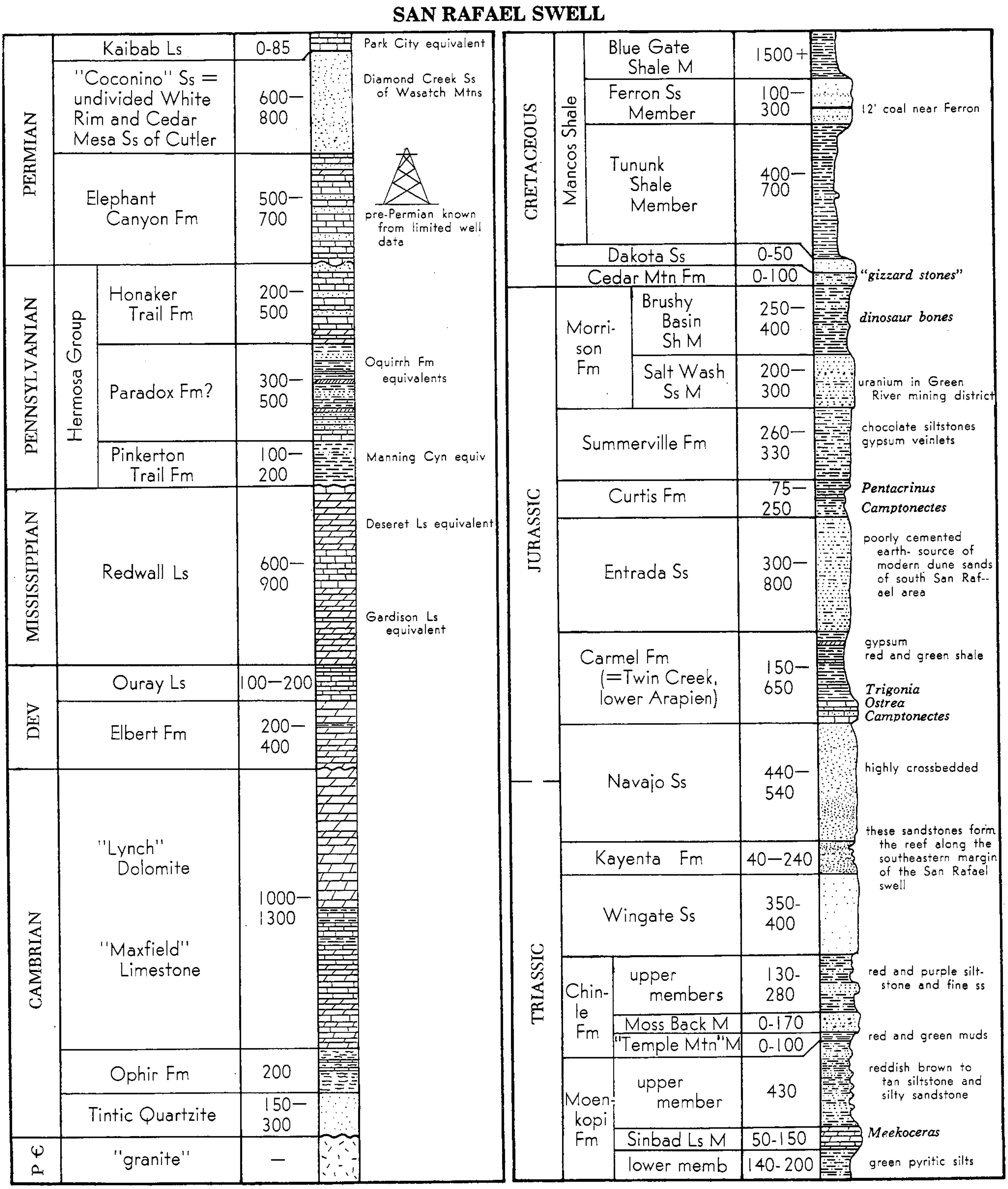

FIGURE 2.—Stratigraphic column of rocks exposed in the San Rafael Swell or encountered in the subsurface (from Hintze 1973).

Colorado Plateau appears to have been transported from the northwest, judging from the remarkably consistent cross-bed directions.

Few fossils have been found in the Navajo Sandstone. Jordan (1965) reported dinosaur footprints on some of the cross-bedded surfaces within the formation. Sanderson (1974, p. 234) reported three-toed dinosaur tracks, 5 to 6 inches long, occurring on some of the brown beds in the Navajo Sandstone in the western side of the San Rafael Swell, where he did his study. A few burrows of *Ophiomorpha*-like patterns occur in the lower part of the Navajo Sandstone in the same general area (Sanderson 1974, p. 234). A single reedlike plant fragment has been found in the margin of one of the calcareous units in the lower part of the Navajo Formation in the Moab area (Gilland 1977 pers. comm.).

Navajo Sandstone appears to represent a coastal dune sequence to a broad sand-sheet dune sequence in the Colorado Plateau, with the westernmost exposures of the formation interfingering, and perhaps intergrading, with the lower Carmel Formation. In this interfingering area, increase in carbonate content, increase in irregular slump bedding, and increase in horizontal bedding may indicate a transition zone. Over most of the Colorado Plateau, however, high cross-beds sets, some up to approximately 60 m high along the Colorado River, and the dominance of festoon or tangentially cross-bedded units indicate that much of the formation must have been deposited beyond the zone of dominance of the marine environment and must represent an accumulation in a desert environment as a sheet of loose, drifting sand.

The older Wingate Sandstone and the eastern massive Moab Tongue of the younger Entrada Sandstone both appear to be eolian deposits as well, but their internal sedimentary structures, grain size, and stratigraphic relationships with adjacent beds have been less intensely investigated than the more classic Navajo Sandstone.

The Entrada Formation contains eolian deposits, principally in its development in easternmost Utah. Toward the west, in the San Rafael Swell, the formation grades into a dominantly tidal plain deposit. The arches in Arches National Park, however, have been eroded into the massive upper Entrada Sandstone (fig. 5) and, locally, provide exposure of the low festoon cross-bedding within the remarkably uniform-sized clastic rocks.

The eolian origin of at least part of the Wingate Sandstone is indicated by exposures readily accessible from Interstate 70 (Rigby, Hintze, and Welsh 1974, p. 66–67). Here high, broad, sweeping cross-beds indicate a general transport direction from the northwest, similar to the overlying Navajo Sandstone. Grain size, general character of the bedding, and localized occurrence of irregular trace fossils are also similar to the overlying unit. Here the rocks have apparently been hydrothermally altered or have been bleached by hydrocarbons, so that the normally massive, angular-jointed, iron-stained cliff of the Wingate Sandstone is broken down, and the internal structure of the unit shows very well.

ALLUVIAL FAN–PIEDMONT DEPOSITS

Coarse conglomeratic alluvial fan–piedmont deposits are exposed in the older rocks of the Colorado Plateau, as well as on the younger, recently abandoned and incised pediment surfaces across the Mancos Shale in eastern Utah.

Young (1976, p. 220–26) defined the Red Narrows Conglomerate and showed its stratigraphic relationships to the latest enclosing Cretaceous and earliest Tertiary deposits. He concluded that the Red Narrows Conglomerate represents alluvial fans and piedmont deposits at the base of the newly folded Sevier orogenic belt and at the western edge of the dominantly lacustrine sequence of Late Cretaceous and Early Tertiary age in eastern Utah. The lower part of this formation in the Red Narrows is composed of massive conglomerate with minor interbedded sandstone, siltstone, and shale (fig. 6). Fragments up to 1 m or 1.5 m in diameter occur in the dominantly pebble and cobble conglomerate, where the unit is well exposed along Soldier Creek in Red Narrows. The middle part of the unit is less massive and consists of interbedded conglomerate channel-fillings, sandstone, and shale, and is generally finer textured than the lower part of the formation. In some exposures (Young 1976, pl. 1, fig. 1), channel-filling conglomerate is stacked in apparent point-bar or imbricate channel-filled sequence; in-

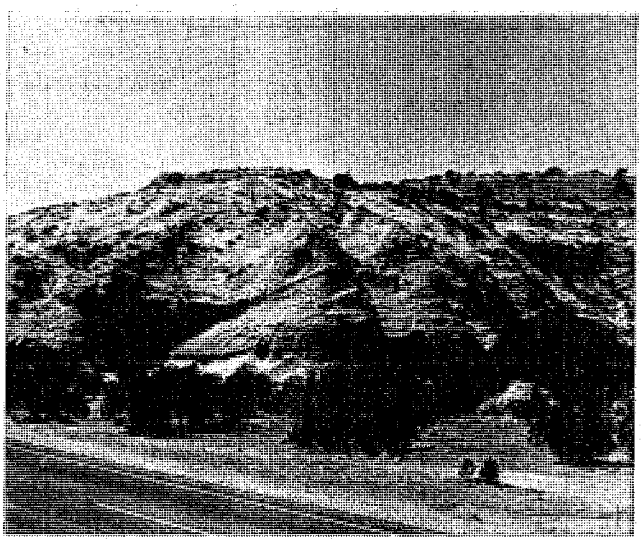

FIGURE 3.– Cross-bedded Navajo Sandstone forming the bluffs in the foreground, overlain by well-bedded limestone of the lower Carmel Formation at locality 23, figure 1; at mile 38.4 in Rigby, Hintze, and Welsh (1974).

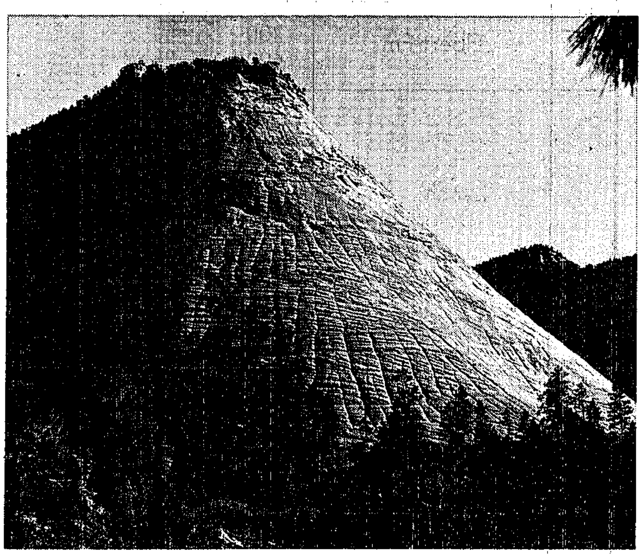

FIGURE 4.– Cross-bedded and jointed upper Navajo Sandstone below basal limestone of interfingering Carmel Formation at Checkerboard Mesa in the eastern part of Zion Canyon National Park in southwestern Utah.

dicating eastward migration of the depositing stream. The upper part of the formation is even finer textured, with interbedded conglomerate, common red-to-pink calcareous sandstone, shale, and some pinkish limestone, as the sequence grades from a dominantly piedmont alluvial fan or fluvial sequence into an interfingering deltaic and deltaic lacustrian section. The Red Narrows Formation grades, in part, into the dominantly lacustrian Flagstaff Limestone.

Considerably younger examples of piedmont deposits are those coarse gravel, sand, and siltstone deposits that spread out from the toe of the Book Cliffs and Wasatch Plateau across pediments cut on the Cretaceous Mancos Shale. These deposits are excellently exposed along U.S. Highway 50–6 at mile 84.3 and mile 88 of Rigby, Hintze, and Welsh (1974, p. 43). These thick coarse, conglomeratic units are obviously composed of several flow units, some with complexly channeled bases (fig. 7) and, in general, are upward fining sequences, as though deposits of flash floods. Many of the coarse blocks, which range up to about 3 m in diameter, must have been carried from the Book Cliffs by mudflows. These deposits, although thin, must have accumulated in essentially the same manner as alluvial fans, were the basin subsiding and accumulating sediments. Some of the fine-textured material must be similar to mudflow deposits like those shown by Bull (1972, p. 71), and other beds may have been a result of debris flows. In general, however, sieve deposits are not readily apparent here. Locally deposits of mudflows, debris flows, and flow levees occur on the upper surface of the accumulation. They are generally of coarser textured material than the central part of the flows, which may have moved on past and abandoned the coarse particles.

The roadcuts are essentially transverse to the direction of flow and produce cross sections of individual sedimentary units in sections across alluvial fans, like those shown by Bull (1972, p. 75, 77). Extent of individual flow units in the direction of flow is unknown, but, if modern analogs along the lower pediment surfaces are utilized, certainly individual flow accumulations will be relatively narrow but very long and will produce essentially the transverse sections that are shown in the roadcuts.

The coarse conglomerate of the Buck Horn Member of the Cedar Mountain Formation (fig. 2) and the Moss Back Sandstone Member of the Chinle Formation have both been interpreted to be pediment-veneering deposits and, hence, somewhat similar to those Pleistocene accumulations. Their exceedingly widespread distribution and the striking sorting and rounding of fragments, however, would suggest that perhaps they may be more closely related to braided stream deposits than to piedmont or pediment accumulations.

FLUVIAL ENVIRONMENTS

Fluvial and fluvial-deltaic sedimentary environments are present in many formations of the northern Colorado Plateau. The Triassic Chinle Formation, for example, exposes lacustrian and fluvial deposits, with fluvial deposits including both those of meandering upper delta-plain streams as well as braided streams in various members of the unit. Similarly, the Ankareh Formation in the southern Wasatch Mountains, near Thistle, exposes alluvial plain, natural levee, and fluvial sections east of the highway along Spanish Fork Creek.

Without question, one of the most spectacularly exposed sequences of fluvial rocks is that within the Jurassic Morrison Formation and the overlying Lower Cretaceous Cedar Mountain Formation, where those units are exposed around the flanks of the San Rafael Swell and in various areas in the northern Colorado Plateau. These units have been extensively investigated because of concentration of uranium minerals in some of the fluvial sandstones and associated sediments. Cretaceous Castle Gate Sandstone and Price River Formation and the overlying Tertiary-Cretaceous North Horn Formation (fig. 8) also exhibit extensive fluvial deposits and show varying types of sedimentary records for upper delta plain and braided-stream channel deposits associated with the marginal marine Mancos seaway and the piedmont zone at the base of the Sevier orogenic belt.

Visher (1972, p. 86) and Allen (1965) differentiate three types of streams which are recognizable by distinctive fluvial deposits. These include braided streams, low sinuosity

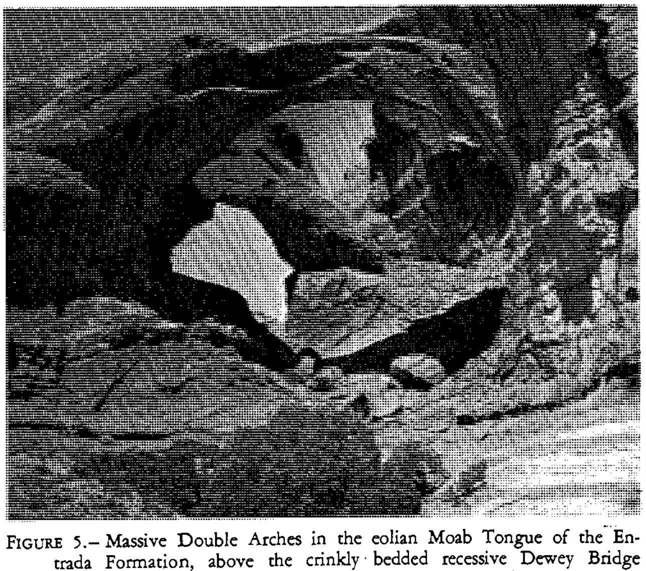

FIGURE 5.– Massive Double Arches in the eolian Moab Tongue of the Entrada Formation, above the crinkly bedded recessive Dewey Bridge Member of the Entrada Formation, Arches National Park.

FIGURE 6.– Massive lower part of the Red Narrows Conglomerate along U.S. Highway 50–6 in Spanish Fork Canyon at locality 5, figure 1; at mile 14.3 (Rigby 1968). Coarse fragments are, in large part, sandy quartzite or sandy limestone, derived from erosion in the Sevier orogenic belt, a short distance to the west. These are part of the piedmont apron at the east base of the orogenic belt.

streams, and strongly meandering streams. Examples of deposits of each of these kinds of streams are known in the Colorado Plateau.

Braided Streams

Braided-stream deposits are relatively common in some Cretaceous units of the northern Colorado Plateau. The Castle Gate Sandstone (fig. 9), for example, is a sand sheet that is thought to have been deposited by braided-stream complexes. It shows great lenticularity, textural variations, and sedimentary structures considered characteristic of that type of accumulation.

The widespread Shinarump Sandstone and the Moss Back Sandstone of the Chinle Formation are also considered to be distinctive braided-stream accumulations. Characteristics of the Moss Back Member of the Chinle formation are particularly well shown in the western part of the Sinbad, on the western flank of the San Rafael Swell, along Interstate 70, on the route covered by the field conference (fig. 10). An extensive literature has developed on the stratigraphy and sedimentary environments of these particular sandstone units because they have yielded considerable uranium ore from various parts of the Colorado Plateau.

Braided-stream channel deposits are also extensively developed in the Cutler Formation and the underlying Elephant Canyon and Honaker Trail formations of Late Paleozoic age near Moab (Terrell 1972, Melton 1972). The Cutler Formation appears to be an interbedded sequence of braided stream channels, meandering stream channels, dunes, and alluvial plain deposits. This sequence is particularly well exposed in the Red or Moab Canyon area, near the Big Cut along the Denver and Rio Grande Western Railroad spur line that connects Potash to the main line at Crescent Junction.

Low-Sinuosity Streams

Deposits associated with low-sinuosity streams are apparently recorded in the upper part of the piedmont conglomeratic section of the Red Narrows Conglomerate and the underlying Indianola-Price River beds. These formations grade laterally into low-sinuosity stream deposits in the lower part of the sequence, particularly as visualized by Young for the upper part of the Red Narrows Formation.

The Ankareh Formation, as it is well exposed near Diamond Fork along Spanish Fork Creek north of Thistle, is also apparently an accumulation of low-sinuosity streams. Broad alluvial plains and low levees, with minimal development of broad point-bar accumulations, seem characteristic of the formation, although these rocks have not been worked in detail in any of the exposure belts of the Wasatch Mountains.

Strongly Meandering Streams

The Morrison Formation probably is one of the most spectacularly exposed fluvial sequences in the Colorado Plateau, particularly in that part of the plateau to be traversed by the field conference. Here thick, resistant, channel-filling sandstones and point-bar deposits record the position of ancient meandering streams (fig. 11). Several of these have

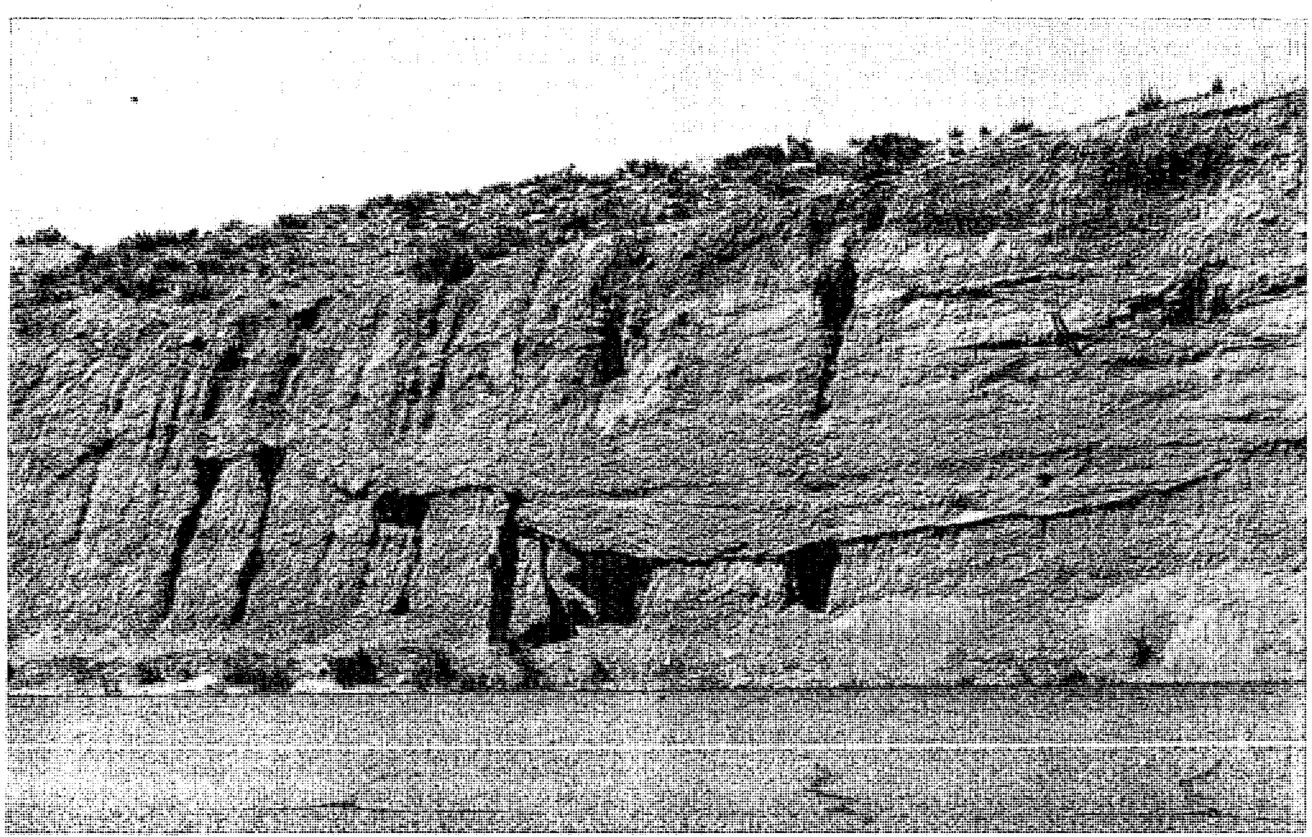

FIGURE 7.– Channeled base of pediment-veneering Pleistocene(?) gravels which extend westward from the Book Cliffs in the West Tavaputs Plateau, north of Woodside at locality 15 of figure 1; at approximately mile 88 of Rigby, Hintze, and Welsh (1974). Several flow units are represented in the accumulation, and they also show lateral migration of deposition.

been extensively described by Derr (1974) where the units are exposed east of the Hanksville interchange on Interstate 70, along the east side of the San Rafael Swell.

Broadly sinuous, laterally migrating accumulations of conglomerate and sandstone have cut into the laterally nearly time-equivalent siltstone and shale. In areas where the units have been uncovered, the resistant channel fillings now stand as inverted valleys, or as ridges, above the surrounding allu-

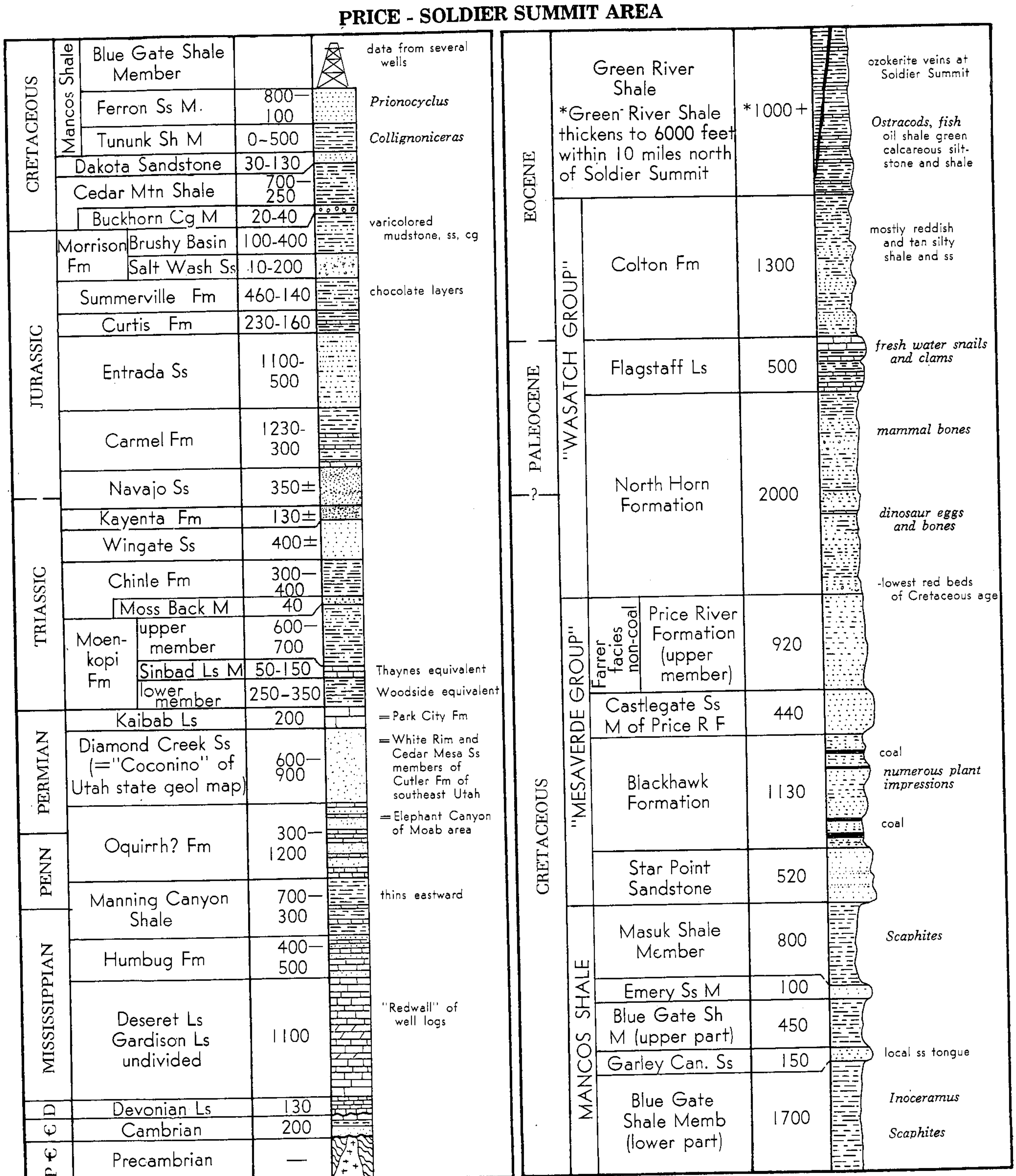

FIGURE 8.– Stratigraphic column of rocks exposed in the Price area and encountered in the subsurface in wells drilled in the region (from Hintze 1973).

vial plain where the soft sediments generally have been stripped and removed.

Like rocks included in the Chinle Formation, Morrison sedimentary rocks have been intensely investigated throughout the Colorado Plateau because they have been significant uranium producers. In general, however, the greatest concentration of uranium production appears to have been from the braided-stream deposits rather than from the strongly meandering stream accumulations. Locally, however, high concentrations have been developed where uranium salts have replaced organic materials in the downstream part of broad meander sweeps.

The greatest concentration of fluvial deposits in an intergrading series of braided-stream and meandering-stream accumulations are in the Salt Wash Member in the lower part of the Morrison Formation. Broad, sweeping meandering channels are also present, however, and are well exposed, in the upper part of the Brushy Basin Member of the formation, where Interstate 70 crosses that unit along the eastern flank of the San Rafael Swell.

The Cedar Mountain Formation also includes extensive fluvial deposits of strongly meandering to weakly meandering streams, in the area west and south of Green River, Utah, along the flank of the San Rafael Swell and around the south margin of the Tavaputs Plateaus. South of Green River a single channel, now preserved as an inverted valley ridge, is traceable for approximately 26 km along the flank of the uplift. It is a rather characteristic avulsion channel and is associated with a variety of deposits, from similarly weakly meandering to strongly meandering streams. These deposits are currently under study at Brigham Young University.

The Price River and North Horn formations, as exposed in Price Canyon (fig. 12), show gross series of interbedded braided-stream deposits and strongly meandering stream accumulations. These rocks are a series of complexly, lenticularly arranged, rather massive sandstone and conglomeratic sandstone beds, probably representing a characteristic upper delta plain sequence. Spieker (1931, 1946, 1949) set the general stage for these formations as they are associated with the upper Cretaceous coals and uplifts of the central and eastern Utah part of the plateau. Young (1955, 1957, 1966) followed up the work of Spieker and added more detail, particularly to the lower delta plain, lagoonal coal-forming, and barrier is-

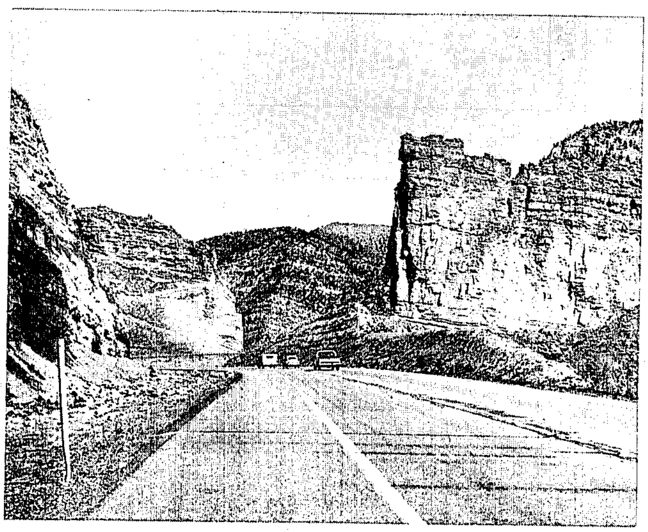

FIGURE 9.– The Castle Gate, as viewed from the south. The vertical cliff is composed of complexly lenticular-bedded Castle Gate Sandstone, which is considered to represent braided-stream channel deposits. The well-bedded sequence below the cliff is upper lagoonal beds of the Blackhawk Formation. The ledges and slopes in the background are in the Price River and North Horn formations, which also include braided-stream as well as meandering-stream deposits.

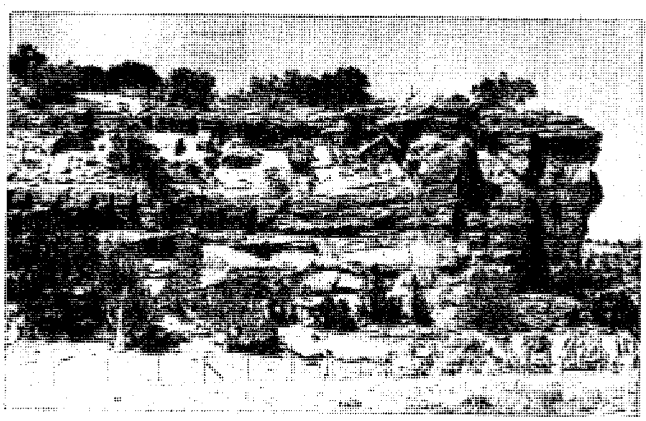

FIGURE 10.– Roadside exposures along Interstate 70 of the Moss Back Sandstone Member of the Chinle Formation at locality 21 of figure 1; at mile 30.8 of Rigby, Hintze, and Welsh (1974). Irregular lenticularity and varying composition of the individual small lenses are characteristic of the unit and suggest a braided-stream accumulation.

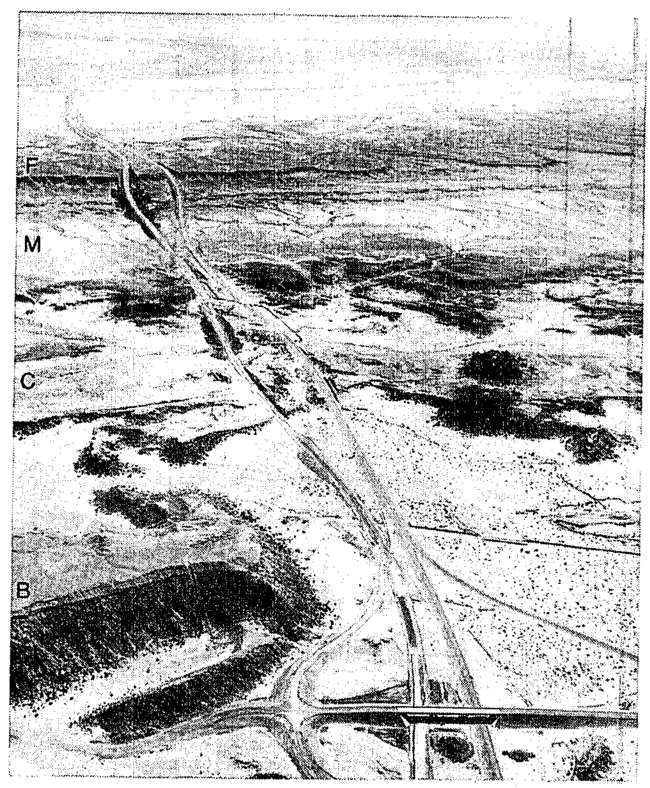

FIGURE 11.– View eastward along Interstate 70 from the Hanksville interchange at approximately locality 17, where the elongate ridges are exhumed channel fillings in the Morrison Formation (B) and overlying Cedar Mountain Formation (C). The cuesta in the background is held up by the Ferron Sandstone (F) in the Mancos Shale (M). Roadcuts through the Ferron Sandstone are at locality 16 of figure 1; at mile 7.9, part 2, Rigby, Hintze, and Welsh (1974). Channels described by Derr (1974) are in the lower right and in the double roadcuts in the center, midway between the interchange and the Ferron Sandstone bluff (photograph by W. K. Hamblin).

land sequences of the formation. He also aided in investigation of the fluvial part of the sequence.

The Colton Formation was named by Spieker (1946, p. 149) for exposures in the subsequent valley carved along these redbeds in the upper reaches of Price River. In this area the formation exposes a fluvial-deltaic sequence, with massive sandstone lenses (fig. 13) representing the channel fills of the numerous distributary and meandering streams. Peterson (1976) described the paleoenvironments of the lower Colton Formation and documented the occurrence of delta plains rocks throughout the western part of the formation. Sinuous channel-fill sandstone of the formation show rather characteristic point-bar migration where they have cut into rooted sandstones, clays, and siltstones of the natural levees and the flood plains. Associated splay sandstone and overflow sandstone are also common features of the Colton Formation where Peterson worked with the unit in the western part of the exposure belt. Details of the eastern part of the formation have yet to be described, but similar rocks and sedimentary environments are also represented in the middle and upper part of the formation for several miles to the east.

LACUSTRIAN ENVIRONMENTS

Lacustrian rocks are well represented through the northern Colorado Plateau, particularly in the High Plateaus section where the Green River, Flagstaff, North Horn, and Morrison formations are all well exposed. The Morrison Formation and some of the lacustrian part of the Cretaceous Cedar Mountain Formation are also well exposed along the eastern flank of the San Rafael Swell.

Much of the varicolored and candy-striped Brushy Basin beds of the Morrison Formation (fig. 14) probably represent lacustrian units. Craig et al. (1955) concluded that discontinuous limestone within the formation represents local lakes on the alluvial plain. The lacustrian part of the formation has received far less attention than the associated fluvial deposits, even though they are brightly colored and exceedingly well exposed locally. They probably have not received much attention because they are of less economic importance than the interbedded sandstone.

The North Horn Formation includes a variety of lacustrian beds in the High Plateaus part of the northwestern Colorado Plateau, including some interbedded pisolitic limestone units, like those described by Young (1976, p. 244). These rocks are somewhat like the pisolitic Flagstaff Limestone, where that unit is exposed far to the south. The locally famous algal-ball "Birdseye Marble," from near the little community of Birdseye in the northern Wasatch Plateau is

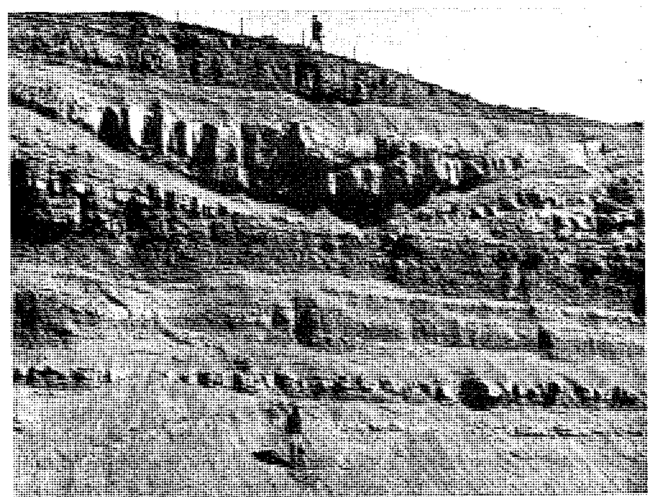

FIGURE 13.– North side of deep double roadcuts through the Colton Formation at locality 8 of figure 1; at mile 32.5, pt. 1, of Rigby, Hintze, and Welsh (1974). Thin, prominent light-colored units in the lower part are interpreted as shallow lacustrian deposits by Peterson (1976). They are overlain by churned alluvial plain and moderately well-bedded levee deposits into which is cut the asymmetric channel. The gentle slope zone above the prominent ledge is, in general, an ox-bow filling of fine-textured sediments above the coarse bed-load and point-bar section.

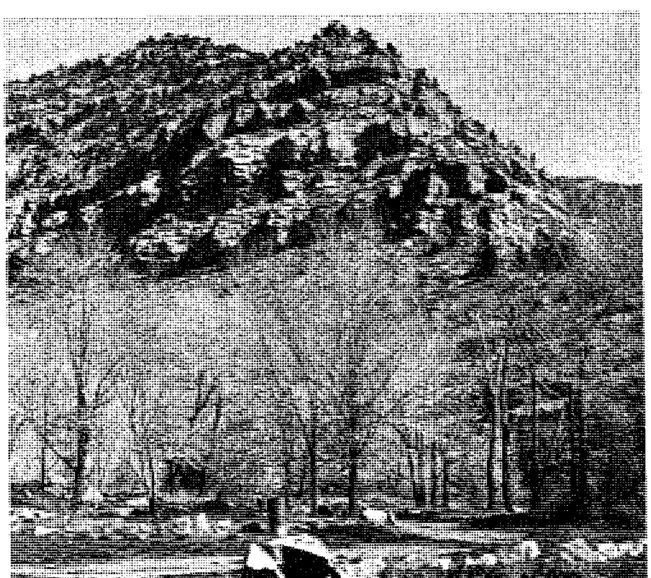

FIGURE 12.– Lenticular Price River beds in the lower part of the cliff, overlain by somewhat more regularly bedded North Horn sandstone and shale in the upper part of the exposure. These are interbedded, braided-stream-channel, and meandering channel-fill deposits, at locality 9 of figure 1; at mile 42, pt. 1, of Rigby, Hintze, and Welsh (1974).

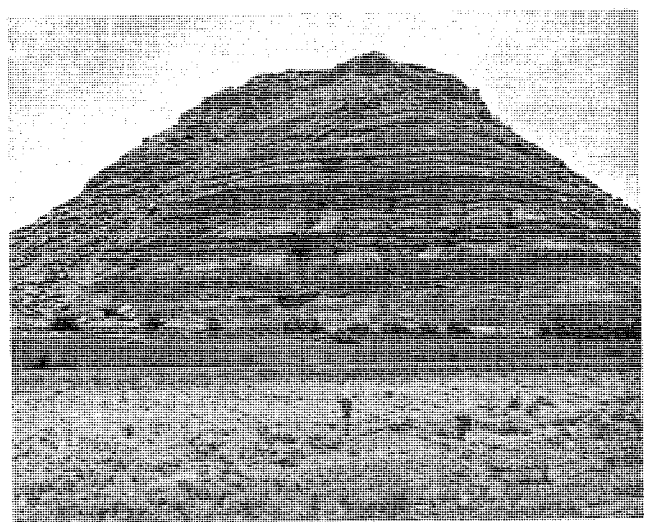

FIGURE 14.– Varicolored, striped, possibly lacustrian, rocks of the Brushy Basin Member of the Morrison Formation in exposures south of the Hanksville interchange on Interstate 70 at approximately locality 17 of figure 1; at mile 10.0, pt. 2., of Rigby, Hintze, and Welsh (1974). Resistant, light-colored sandstone units are apparently splay or minor deltaic sandstones. The entire unit is capped with the massive pediment-veneering Buck Horn Conglomerate at the base of the Cedar Mountain Formation.

considered by Pinnell (1972) to be from the North Horn Formation.

The Flagstaff Limestone is a Tertiary lacustrian unit initially named by Spieker and Reeside (1925). Flagstaff beds interfinger with the North Horn Formation, below, and with the Colton Formation, above, and represent a Paleocene to Eocene lacustrian set of environments in the area now largely occupied by the Wasatch Plateau. The formation is a bright, white-weathering, light gray limestone that caps much of the Wasatch Plateau and several of the high peaks above the Wasatch monocline along the western part of the exposure belt. Flagstaff Limestone wedges out to the south into the brightly colored Wasatch or Bryce Canyon Formation (Schneider 1967), but throughout most of the northwestern part of the High Plateaus the unit is an easily defined, well-bedded, fresh-water lacustrian formation. It is principally an interbedded crystal and oolitic and algal limestone, with some tuffaceous beds and some moderately thick interbedded yellowish gray and greenish gray sandstone over much of the plateau. However, where the route of the field trip crosses the formation in lower Salina Canyon, the shore facies of reddish deltaic and marginal lacustrian fluvial beds (fig. 15) are exposed above the angular unconformity (Rigby, Hintze, and Welsh 1974, p. 88, at mile 88.2).

Without question the most extensively investigated lacustrian sequence in the Colorado Plateau is that of the Green River Formation, which is exposed on the uplands of the Wasatch Plateau and around the south flank of Uintah Basin, in the East and West Tavaputs Plateaus. One of the most detailed studies of the lower part of the formation is that of Baer (1969). He investigated the cyclic lacustrian and marginal deltaic deposits of the basal part of the Green River Formation (fig. 16) in the area east of the Red Narrows, along U.S. Highway 50-6 (Rigby, Hintze, and Welsh 1974, p. 12, mile 8.6). Here yellowish and grayish green sandstone beds of the lower western part of the outcrop represent marshy deposits that grade upward and eastward into open lacustrian rocks, including greenish oil shale and light-gray to tan ostracod and fossil-fish-bearing limestone and dolomite. The unusual horizontal laminations and bedding of some of the dolomitic units have produced "paper shale," which is rather characteristic of the lacustrian Green River rocks. It is perhaps the Green River Formation which shows most of the diagnostic lacustrian features discussed by Picard and High (1972) better than other units in the Colorado Plateau.

MARSH OR SWAMP DEPOSITS

Marsh and swamp deposits are associated with lacustrian or with marginal marine deposit at various horizons in the northwestern Colorado Plateau. Unquestionably the most extensive series of marsh or swamp accumulations in the northern plateau are those in the Cretaceous coal-bearing sequence (fig. 17). Such rocks are particularly common in the Blackhawk Formation (fig. 8) where that unit is exposed around the eastern flank of the Wasatch Plateau and on eastward in the Book Cliffs. These rocks have been moderately well investigated in a regional stratigraphic sense by Young (1955, 1966) and many others. Renewed interest in coal will spur renewed interest in the sedimentary petrology and stratigraphic relationships of these rocks through much of the border of the High Plateaus section.

Spieker (1949), Young (1955, 1957, 1966, 1976), and many others who have published on the geology of the plateau have described the coal-bearing sequence related to the marshy environments. Parker (1976) and Tidwell, Thayne, and Roth (1976) have discussed the paleoecology of these Cretaceous and early Tertiary swamp and marsh environments, particularly as they are related to plant distribution.

An instructive series of swamp deposits are thoe exposed between the Flagstaff and Green River formations, in a marginal deltaic sequence immediately east of Red Narrows at mile 8.1 of Rigby, Hintze, and Welsh (1974, p. 11). Here fragments of crocodiles, turtles, abundant snails, and bivalves are associated with extensive plant debris, and all occur in sediments which are interpreted to represent the well-defined marsh deposits. Large plants are wanting here, but at other localities at about the same horizon, or lower in the sequence, large plants occur and represent swamp environments.

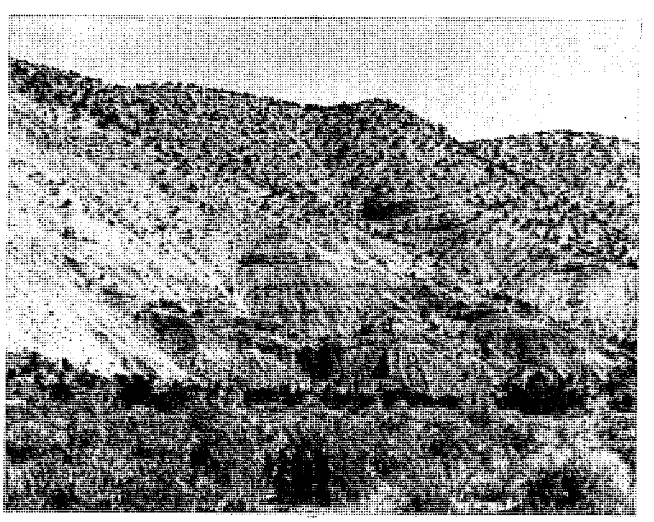

FIGURE 15.– Angular unconformity in the lower part of the Salina Canyon at locality 32 of figure 1; at mile 89.2, of pt. 2, of Rigby, Hintze, and Welsh (1974). Lacustrian Flagstaff and Green River beds overlie the vertical Jurassic Arapien Shale and Morrison Formation.

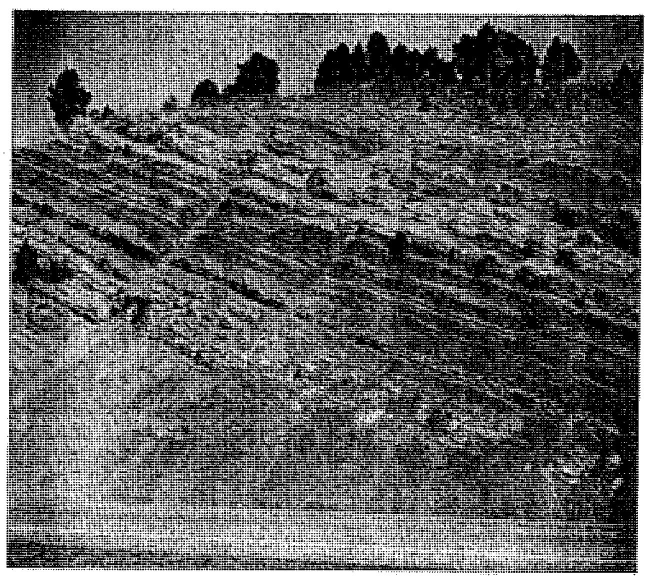

FIGURE 16.– Baer's Bluff along the north side of U.S. Highway 50-6, at locality 7 of figure 1; at mile 8.6 of Rigby, Hintze, and Welsh, pt. 1, (1974). Light-colored units are fossiliferous limestone and laminated dolomite. Intervening darker beds are greenish low-grade oil shale (photograph by J. L. Baer).

MARINE MARGIN ENVIRONMENTS

Sedimentary rocks of the northern Colorado Plateau which are thought to have been deposited in marine margin environments include those which accumulated under tidal flat conditions, deltaic conditions, barrier-island conditions, or under different circumstances where sabkha-related evaporites are recorded. The northern Colorado Plateau was not covered by the sea during much of Mesozoic and Cenozoic time, but the sea did lap around the block margins or into isolated basins. Marginal marine deposits, consequently, are moderately common over this somewhat stable block along the western part of the American craton.

Summerville, Entrada, Curtis, and Carmel rocks in the Jurassic, parts of the Moenkopi and Thaynes formations in the Triassic, and the Elephant Canyon and Honaker Trail formations of the Late Paleozoic all record at least limited tidal flat deposits. Extensive deposits occur in units which also contain interbedded cyclic open marine, dune, and intervening tidal flat sedimentary sequences.

Deltaic beds are represented in the Tertiary Colton Formation and the Cretaceous Blackhawk Formation and Ferron Sandstone. Barrier-island deposits are extensively developed along what was the western shore of the Mancos seaway, including rocks of the Emery and Ferron Sandstone tongues and several sandstone units within the Blackhawk and Star Point formations. To some degree part of the Curtis Formation and, perhaps, some of the Carmel Formation, may be of barrier-island-complex origin, as well.

Several formations contain evaporites in the northern and northwestern part of the Colorado Plateau and represent environmental shifts from normal, open marine conditions to low-energy, arid, restricted lagoons. The Carmel, Summerville, and Arapien formations and the roughly equivalent Twin Creek Limestone of the Wasatch Plateau all represent sabkha or low-energy, evaporite, lagoonal sequences. As a consequence, within the plateau we can see a variety of marginal aqueous environments, from those dominated by inflowing streams, to those of secondary coastlines with marine deposits, to those low-energy, lagoonal environments characterized by evaporitic sequences.

Tidal Flat Environments

In the general vicinity of the Wasatch Plateau and the southern end of the Wasatch Mountains, marine rocks of the Triassic Thaynes Limestone, on the west, interfinger with the Lower Triassic nonmarine rocks, on the east. As a consequence, in the vicinity of Thistle and elsewhere along the eastern margin of the Wasatch Mountains, tidal flat deposits interfinger with normal, open marine carbonates and with redbeds of the more consistently nonmarine parts sequence.

Instructive exposures of these facies relationships can be seen in the vicinity of Diamond Fork, north of Thistle, along U.S. Highway 50–6 (mile 6.1, Rigby 1968). Preliminary investigations show cyclic deposits of normal, open marine, skeletal carbonates; intervening gray-green sandstone; siltstone; and minor, ripple-marked limestone. These latter greenish rocks show raindrop impressions, dessication cracks, and, more conclusively, bidirectional current ripple marks. The latter suggest that flooding and ebbing currents swept back and forth across the Thaynes shelf, from the sea in the northwest to the redbed areas in the east or southeast. Rocks deposited on the more subaerially exposed parts of the tidal flat tend to be reddish and finally grade into the overlying dominantly redbed Ankareh Formation, which must have been upper tidal flat to fluvial plain, certainly in a relatively low-energy environment.

Similar rocks have been described by Newman (1974) from areas to the north in the Cascade Springs area, along the east side of the Mount Timpanogos massif, and by Smith (1969), in the type area farther to the north, where the unit was initially defined by Boutwell (1907) in the Park City mining district.

The Moenkopi Formation is, in large part, equivalent to the Thaynes Limestone and also includes some tidal flat deposits. The Moenkopi Formation is broadly exposed in south-

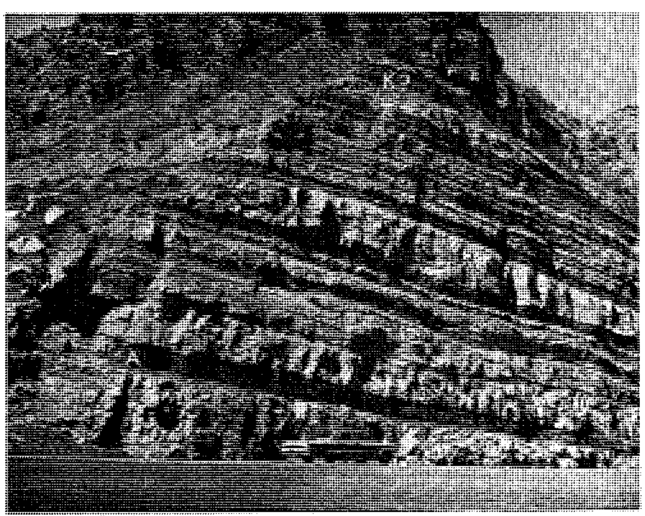

FIGURE 17.– Upper Aberdeen Sandstone, the lower, massive, light-colored cliff, overlain by thick Aberdeen coal (A) in the Blackhawk Formation at the rest area, near the former community of Castle Gate at mile 44.4 of Rigby, Hintze, and Welsh (1974). The Aberdeen Member includes the basal barrier-island sandstone, the prominent overlying coal, as well as the irregular, lenticular, bedded lagoonal rocks of most of the cut. The projected position of the Kenilworth coal and the beginning of the Kenilworth Member (K?) is at about the level of the upper vertical part of the cut. Locality 11 of figure 1.

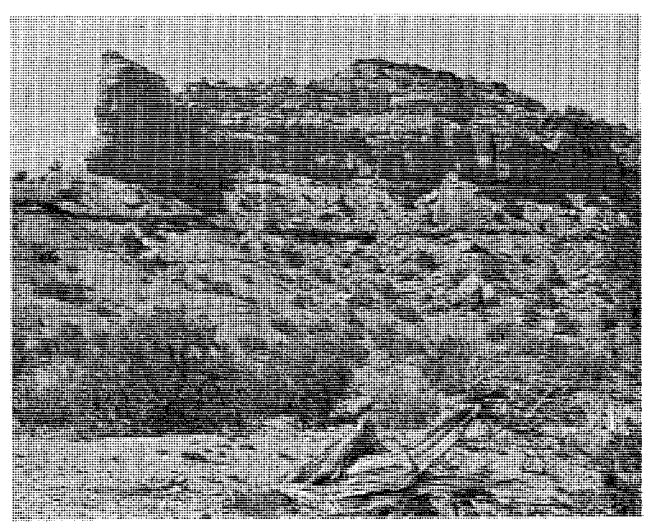

FIGURE 18.– Upper Moenkopi beds overlain by the Moss Back Sandstone member of the Chinle Formation, at approximately mile 30 of Rigby, Hintze, and Welsh (1974); at locality 20 of figure 1. Slope-forming upper Moenkopi beds are ripple marked and show several directions of current motion. These are possibly tidal flat deposits which were buried by the braided-stream accumulation of the overlying Moss Back Sandstone. Some uranium ore has been produced from the basal part of the Moss Back Sandstone in areas to the north.

eastern Utah, but only in limited fashion in the San Rafael Swell along the field-trip traverse (fig. 18). Stratigraphic and deposition analyses of the formation have been recently published by Blakey (1974). He recognized a variety of genetic units within the formation, including beaches, delta fronts, offshore bars, carbonate shorelines, and offshore, open marine sediments as well. Some of the flaser-bedded units within the Moenkopi Formation, particularly rocks associated with the Sinbad Limestone and some of the immediately overlying and underlying beds, may well have been tidal units. Preliminary current studies suggest two opposed directions of current transport in thin local rock units. Such patterns would suggest tidal deposition around the eastern shoreline of this very shallow carbonate, shale, and clastic shelf sequence.

The Jurassic Summerville Formation has been interpreted by Stanton (1976) as a tidal flat deposit. The lower part of the formation consists of interbedded dark red siltstone and pinkish brown and red sandstone in rather rhythmic alternation (fig. 19). The middle and upper parts of the formation are composed of thin alternating units of dark red siltstone and gray-green channel-filling sandstones. Rocks show complex lenticularity in the upper part of the formation. Uppermost beds of the formation are red clastic units alternating with gypsum. Finally the formation is capped by a thick, massive gypsum unit below the Morrison Formation. Northeastward-draining tidal channels were depositional sites of the resistant, somewhat dolomitic, gray-green sandstones. These lenses contain clay pebbles and some limited trace fossils in the lower part of the channel-filling sequence.

Sediment transport directions are strongly bimodal in the channel fills, with dominant current motion towards 70° and less consistent current toward 250°, although there is some scatter even in individual channels. Two directions of sediment transport are well illustrated by Stanton (1976, pl. 2, fig. 4) from a sandy unit which shows a regular shift in direction of foreset bedding on small ripples.

Somewhat more equivocal tidal flat deposits are those of the Entrada Formation along the western side of the San Rafael Swell. These rocks are exposed in the vicinity of Interstate 70 and have been well described by Smith (1976). He concluded (1976, p. 153) that the lower Entrada sediments reflect deposition in a cyclic tidal-deltaic environment, with brief transgressive and regressive cycles. The lower and middle redbed parts of the formation are separated by a relatively thin transgressive, somewhat discontinuous, green sandstone. Cyclic tidal-deltaic environments resumed in the middle part of the unit but gave way vertically to a second transgressive sandstone that interrupts the dominantly red beds. Red dolomitic sandstone makes most of the upper part of the formation (fig. 20). Entrada sedimentation ceased with the major transgression in which the marine Curtis Formation was deposited.

The contact between the dominantly nonmarine Entrada Formation and the overlying Curtis Sandstone is relatively abrupt. It lacks the interfingering green sandstone and dolomitic sandstone alternations with redbeds that characterize the regressive deposits which separate the dominantly barrier-island sandstone deposits of the Curtis Formation from the tidal flat sequence of the overlying Summerville Formation.

Cyclic marine-to-nonmarine and evaporite rocks of the lower part of the Carmel Formation (fig. 21) have been described by Bagshaw (1977). He studied the excellent exposures in a deep roadcut along Interstate 70 on the west side of the San Rafael Swell. At this locality normal, open marine, fossiliferous carbonates bury the upper edge of the cross-bedded Navajo Sandstone. The Carmel section becomes increasingly sandy and more dolomitic vertically. It also shows a general increase, in a cyclic way, in the amount and thickness of evaporites in the sequence. Some of the reddish and greenish gray siltstone and sandstone between the underlying dominantly carbonate open marine units and the overlying redbed or dolomitic evaporitic units must represent tidal flat accumulations. Ripple marks on some of these possible tidal flat beds show two directions of sediment transport, as well as many cracks, rain-drop impressions, and other evi-

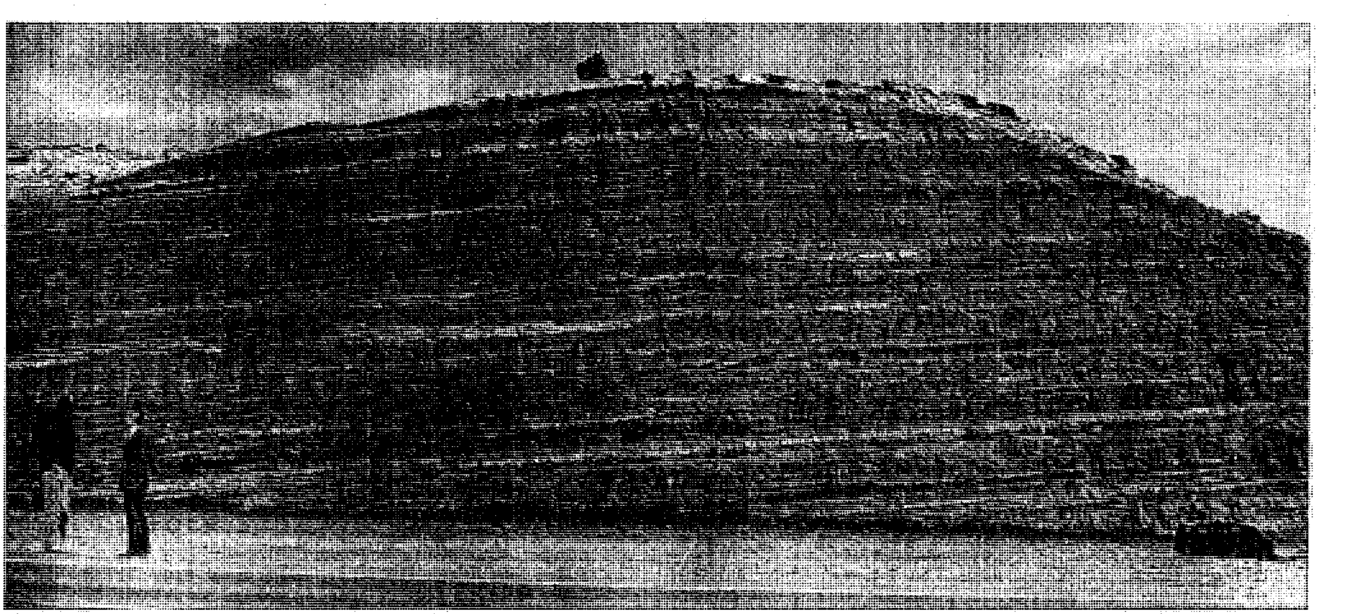

FIGURE 19.– Deep roadcut along the westbound lane of Interstate 70 through the middle part of the Summerville Formation, showing the characteristic alternating sequence of reddish and orange units with prominent, resistant, dolomitic sandstone channel-fillings, which are interpreted to be tidal-channel deposits, as described by Stanton (1976). These exposures are at approximately mile 50, pt. 2, of Rigby, Hintze, and Welsh (1974).

dences of having been deposited in shallow water or possibly supratidal environments.

Similar deposits occur in the Carmel Formation along the east side of the San Rafael Swell, and somewhat related facies have been well described from the Uintah Mountains by Lowry (1976), where gray-green and pinkish siltstone and sandstone beds are thought to have been deposited under tidal flat conditions.

Barrier-Island Coastline Environments

The complexly interbedded massive sandstone, bedded sandstone, shale, siltstone, and coal beyond the western border of the Mancos Shale have been interpreted for some time as barrier-island and lagoonal complexes (fig. 22). Thick coals, for which the area is famous, apparently accumulated in sheltered lagoons and swamps behind the protective barrier-island sequences. The gray siltstone and clay sediments of the Mancos Shale were deposited offshore.

Regional stratigraphic relationships were early documented by Spieker (1931, 1946, 1949a, 1949b) and more recently by Young (1955, 1966, 1976). One of the most detailed studies of a single barrier-island sandstone complex in the region is that by Howard (1966a, 1966b) of the Panther Sandstone Tongue of the Star Point Formation. This unit shows, more or less, the various facies developed in each of the lenticular regressive sandstone tongues of the sequence and is moderately accessible for study. The Panther Sandstone was named for exposures in Panther Canyon (fig. 23), a tributary to the lower part of Price Canyon, below the now defunct community of Castle Gate. Here imbricate shingles of sandstone and siltstone show the upward coarsening sequence characteristic of regressive barrier-island development. In exposures farther to the west, however, the main massive core of the island complex, or of tidal deltas interrupting the island complex, are seen in the vicinity of Spring Canyon. Unfortunately, these are the westernmost exposures of this particular sandstone so that relationships of the massive sandstone to possible washover fans and lagoonal coal-bearing beds are all underground and are not accessible for detailed observations.

To the east of Price Canyon, in the Book Cliffs, along the south edge of the West Tavaputs Plateau, the gradual decrease in sandstone content and increase in clay content, together with a variation in degree of bioturbation and kinds of trace fossils, show the gradation from shorefront to shoreface and offshore sandstones. Finally the sandstone disappears altogether and is represented by only a few silty breaks in the vicinity of Coal Canyon northeast of Price. Equivalent beds northeast of the community of Wellington show little differentiation from overlying and underlying thick, gray Mancos Shale, other than minor silty partings that do form somewhat steeper slopes in the badland topography of the Mancos Shale. The same general facies patterns repeat several times in the regressive Blackhawk and Price River sections, as shown by Young (1955, 1966).

The Panther Sandstone appears to have been the downcurrent accumulation of clastic debris from a deltaic mass to the north. The imbricate shingling deposits in the Panther Sandstone in the eastern Wasatch Plateau indicate longshore

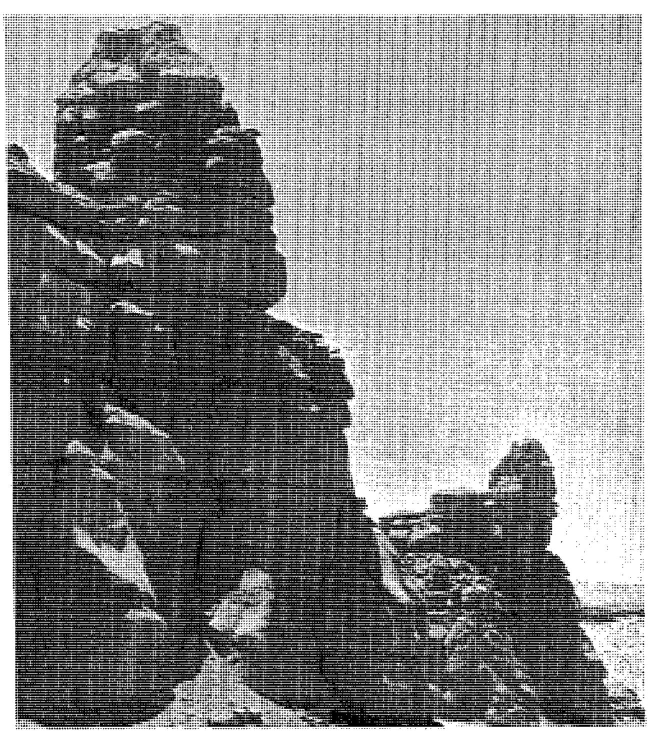

FIGURE 20.– Massive dolomitic sandstone beds of the "stone-baby" facies of the Entrada Formation as exposed north of Hanksville. Rocks of this general composition form the massive, irregular-weathering unit in the upper part of the formation along Interstate 70, at mile 38, pt. 2, of Rigby, Hintze, and Welsh (1974).

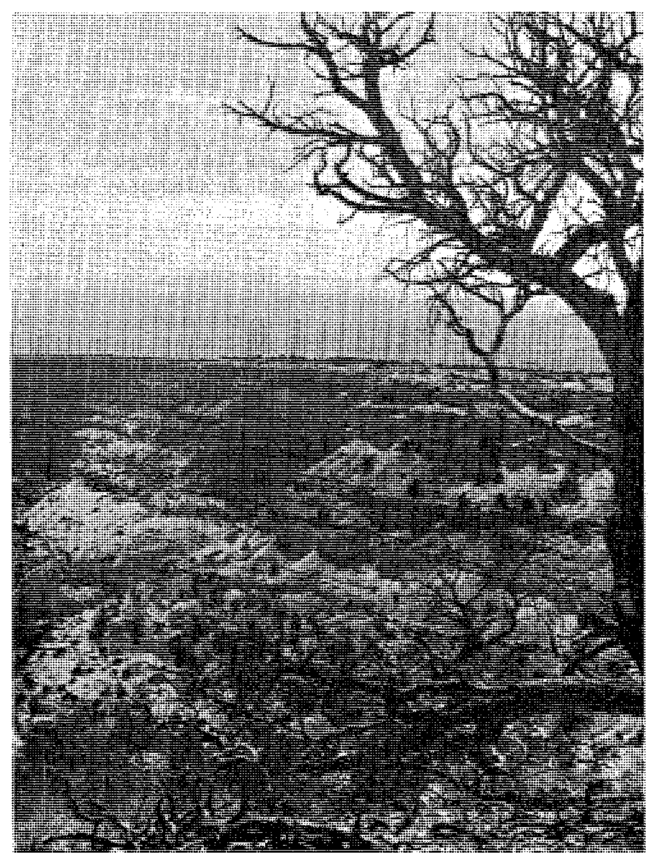

FIGURE 21.– View westward from the rest area at locality 24; at mile 41.1, pt. 2, Rigby, Hintze, and Welsh (1974), showing massive cross-bedded Navajo Sandstone, in lower light-colored bluffs, overlain by well-bedded dolomitic, sandy, and evaporitic lower Carmel Formation.

transport toward the south-southwest, along the shoreline out from the piedmont zone in front of the Sevier orogenic belt. This pattern establishes a paleogeography for the Panther Sandstone and equivalent beds essentially like that of Galveston Island or other islands of the Texas coast in their relationships to the Mississippi Delta. The deltaic source for the Panther Sandstone probably would have been in the Uintah Basin or in southern Wyoming.

Some parts of the Star Point Sandstone (fig. 24) or the Ferron Sandstone also show as deposits on a barrier-island-type coastline (Cleavinger 1974). Ferron Sandstone sedimentary environments are considerably more complicated, however, because the sandstone tongue also includes a deltaic complex (fig. 25) which is well exposed (Cotter 1971, 1975, 1976) along the western flank of the San Rafael Swell. The Ferron beds are particularly instructive in the vicinity of Interstate 70, southeast of Emery. Other possibly contemporaneous deltaic masses also occur to the north of the San Rafael Swell, in the western part of the Uintah Basin.

The Curtis Sandstone is excellently exposed along the western side of the San Rafael Swell (fig. 26), in the vicinity of Interstate 70, and apparently represents a barrier-island complex, in part. It was probably deposited along the low-energy, arid coastline, considerably different from the coal-producing environments of the overlying Cretaceous rocks. The Curtis Sandstone represents a minor sharp invasion of the Sundance Sea from the north or northwest, which resulted in development of broad sheeted sandstones and locally low barrier-island sandstone in the very shallow seaway.

Several workers have described the Curtis Sandstone in a cursory way, but the detailed work of Smith (1976) in road-cuts along Intertate 70 documents the internal characteristics of the sandstone. The formation grades up from an argillaceous, locally somewhat conglomeratic, base into a clean, well-sorted sandstone. The sandy beds show, to some degree, tidally distributed sediments and development of low, shingled sandstone units, possibly with some tidal flat sediments in uppermost beds as the unit grades into the overlying Summerville Formation.

Terrell (1972) and Melton (1972) have described low energy, barrier-type deposits as part of the Pennsylvanian–Permian Honaker Trail and Elephant Canyon formations in the Potash and Moab areas of the Canyonland section of the Colorado Plateau. Moderately well-sorted, relatively coarse sandstones appear to be stratigraphically inter-

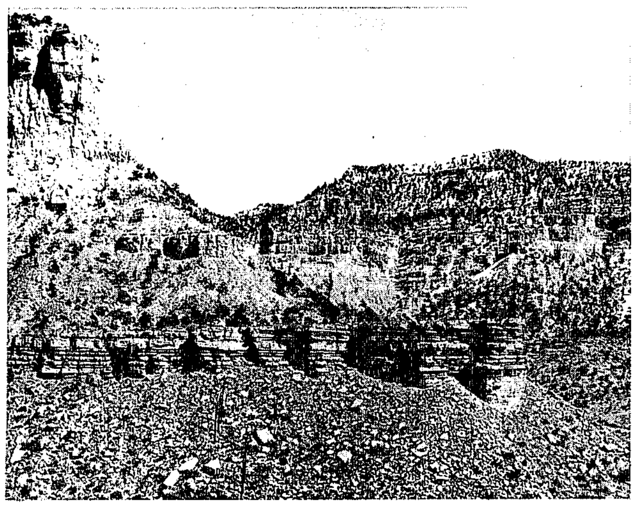

FIGURE 23.– View eastward to the type locality of the Panther Sandstone along the north margin of Panther Canyon, between localities 11 and 12 of figure 1; at mile 46, pt. 1, in Rigby, Hintze, and Welsh (1974). Prominent shingles of interbedded massive sandstone and nonresistant siltstone characterize this facies of the member. These beds are inclined toward the right and indicate longshore drift in that general direction. The Storrs Sandstone Tongue is the low bluff above the Panther Sandstone, in the marine shale section in the upper part of the Star Point Formation. The slope above the Storrs Sandstone is on the Spring Canyon Member of the Blackhawk formation and is overlain by the massive Aberdeen Sandstone at this locality.

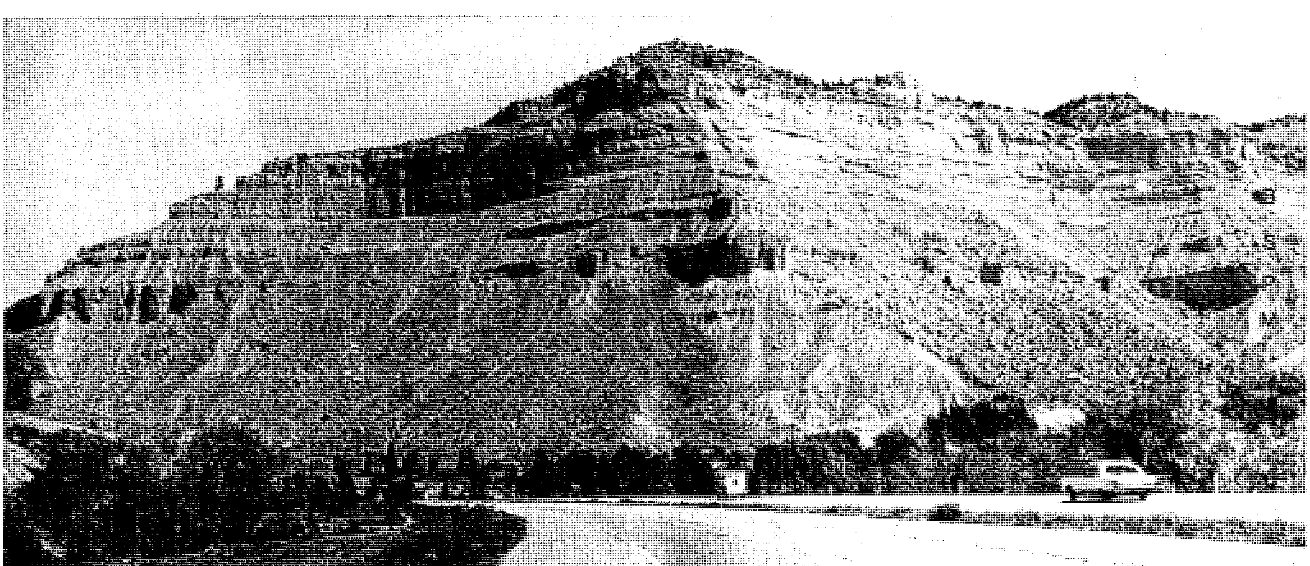

FIGURE 22.– View northward to the Helper Face, near locality 12; at approximately mile 48, pt. 1, Rigby, Hintze, and Welsh (1974). Thick, gray, slope-forming Mancos Shale is veneered by slope wash below the prominent bluffs. The first prominent ledge is held up by the Panther Sandstone, a member in the Star Point Formation. Rocks above are in the Blackhawk Formation, which is the prominent coal-bearing unit in this part of the Book Cliffs. Lagoonal beds are exposed along the skyline at the left, and grade into a massive sandstone barrier sequence in the reentrant to the right of center.

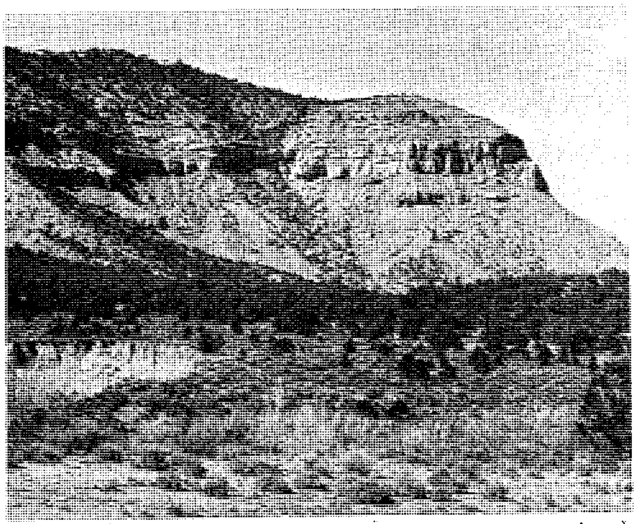

FIGURE 24.– View northward from locality 29 of figure 1; at approximately mile 63 of pt. 2, Rigby, Hintze, and Welsh (1974), along the east edge of the Wasatch Plateau. The recessive juniper-covered slope zone in the foreground and middle distance is on the upper Mancos Shale, which is capped by massive Star Point Sandstone. Blackhawk beds form the upper tree-covered slope zone and are capped by the thin Castle Gate Sandstone. The Star Point Sandstone is characteristic of the massive barrier-island sandstones deposited at the western margin of the Cretaceous Mancos seaway.

vening between tidal flat or open marine deposits on one side and marginal deltaic or lagoonal deposits on the other side, or are similarly layered in vertical sequences.

Evaporite Environments

Evaporite deposits occur in several formations in the northern part of the Colorado Plateau. Halite and gypsum occur in the Arapien Shale along the western part of the exposure belt, in Sanpete Valley, and beneath the Wasatch Plateau. This unit grades eastward beneath the Cretaceous and Tertiary rocks of the plateau into Carmel–Entrada–Summerville beds, which in the San Rafael Swell also contain evaporite units.

The upper part of the Carmel Formation contains several thick, massive gypsum units (Bagshaw 1977). They are interbedded with reddish brown or gray-green siltstone and sandstone (fig. 21) in what appears to be tidal flat or, at the most, restricted marginal marine deposits. Some of the evaporite beds are gradational with underlying dolomite beds. Gypsum rosettes appear as small dots in the lower part of the carbonate beds but increase vertically until they become the dominant lithology in the upper part of individual beds. The rocks finally grade into the overlying massive gypsum.

Massive gypsum of the upper part of the younger Summerville Formation records the last regressive facies of the Sundance Sea, before burial of these rocks by the overlying Upper Jurassic Morrison Formation. Gypsum deposits of the

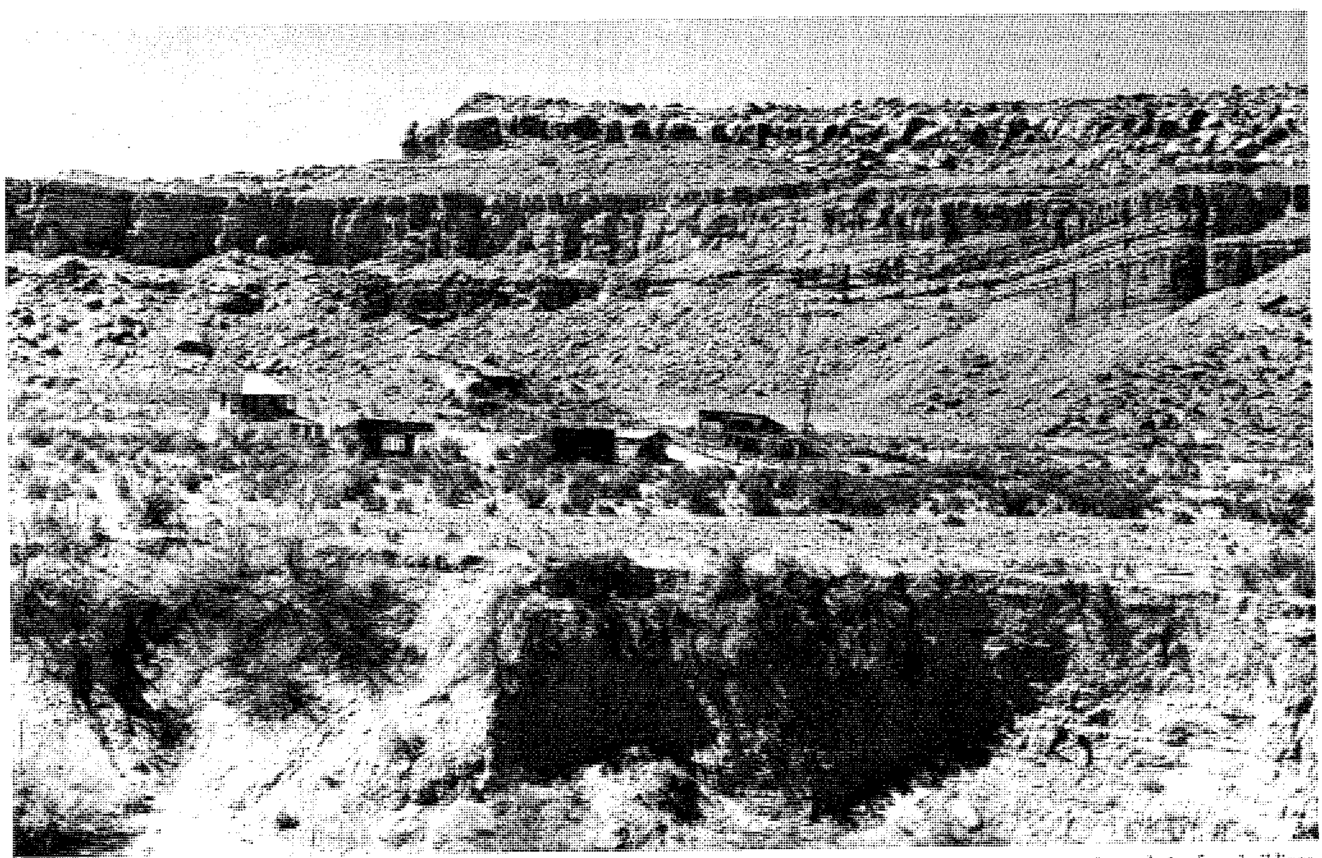

FIGURE 25.– View northward across Ivy Creek to massive sandstone ledges of the Ferron Sandstone Tongue. Lowermost exposures beyond the farm buildings are in Mancos Shale. Uppermost, light-colored, rounded sandstones are fluvial deposits, as described by Cotter (1955, 1976) and are part of the Last Chance Delta of the Ferron Sandstone Tongue. Lower units are variously considered to be barrier-island complexes or prodeltaic sequences in front of the advancing Last Chance Delta. Locality 28, figure 1; at mile 55.6, pt. 2, of Rigby, Hintze, and Welsh (1974). These exposures are near localities described by Cleavinger (1974).

Summerville Formation (fig. 27) grade upward from the dominantly redbed tidal flat rocks of the lower and middle parts of the formation by increasing gypsiferous content in the sandstones and siltstones (Stanton 1976). Knobby, irregularly bedded gypsum grades upward into massive gypsum in the upper part of the formation.

The Twin Creek Formation is approximately equivalent to the Carmel Formation of the Colorado Plateau and has an upper evaporitic facies in the northernmost Wasatch Plateau and the southeastern part of the Wasatch Mountains, in the vicinity of Thistle (Bullock 1965; Bordine 1965). Where U.S. Highway 50-6 crosses the formation, however, these rocks have been faulted out so that the upper evaporitic facies is not exposed, but these rocks are exposed in canyons to the north. The Twin Creek-Carmel beds near Thistle show, more or less, the characteristic classic gradation from normal salinity, open marine, fossiliferous limestone upward through micritic carbonates into fine-textured dolomite beds, with limited gypsum, and finally into massive gypsum.

Over most of the exposure belt, however, desiccation apparently did not continue to precipitation of sodium chloride but terminated with the gypsiferous phase, apparently as the evaporating pan was reinundated. Locally, however, considerable thickness of halite did accumulate in restricted basins during deposition of the Arapien Shale. One such deposit is exposed in open-pit and underground salt mines near Redmond. Gypsum of the Arapien Shale (fig. 28) is also the basis of the plasterboard industry near Sigurd, south of Salina.

Triassic Moenkopi Formation also contains veinlets of gypsum, but in the northern part of the Colorado Plateau these beds are not as evaporitic as they are in the southern and southwestern part of the state. Thick, massive gypsum beds occur there in these red Triassic rocks.

DEEP OR OPEN MARINE SEDIMENTS

Deposits of open marine or deep marine sedimentary environments are markedly restricted stratigraphically in the Colorado Plateau. In the southern Wasatch Mountains, the Oquirrh Formation has been interpreted by Chamberlain and Clark (1973) as a deep-water sequence. This interpretation is, in large part, based on suites of trace fossils, as well as on the stratigraphic succession and distribution of various units within the Oquirrh Basin. The Oquirrh Formation probably

FIGURE 26.— View southward along the escarpment held up by the massive, light-colored Curtis Formation, which here may represent a barrier sequence, at locality 26 of figure 1; at mile 48.8, pt. 2, of Rigby, Hintze, and Welsh (1974). Upper, reddish, "stone-baby" beds of the Entrada Formation underlie the Curtis Sandstone and are underlain by a light-colored barrier sequence in the middle of the Entrada beds, exposed along the drainage in the middle background.

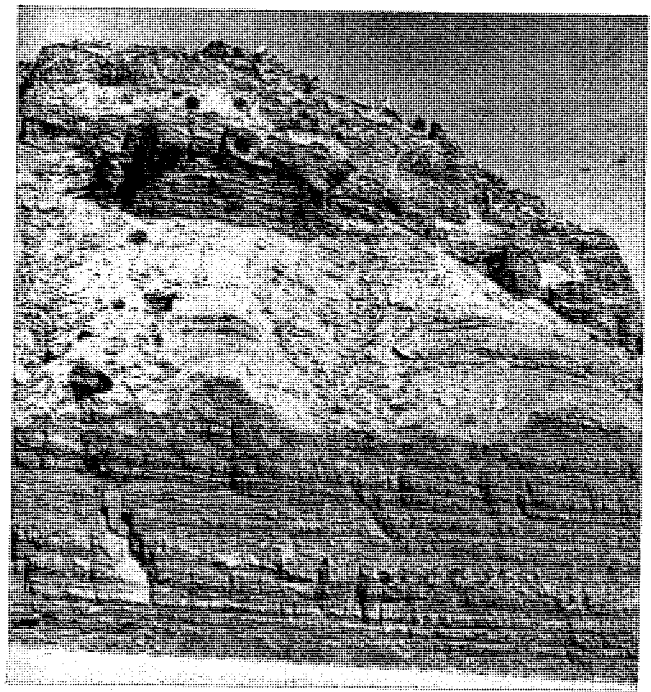

FIGURE 27.— Upper Summerville Formation capped by massive gypsum at approximately locality 27 of figure 1; at mile 50 of pt. 2, Rigby, Hintze, and Welsh (1974). Lower reddish units are considered to be low-energy hypersaline tidal flats, capped by the massive gypsum which marks the top of the formation.

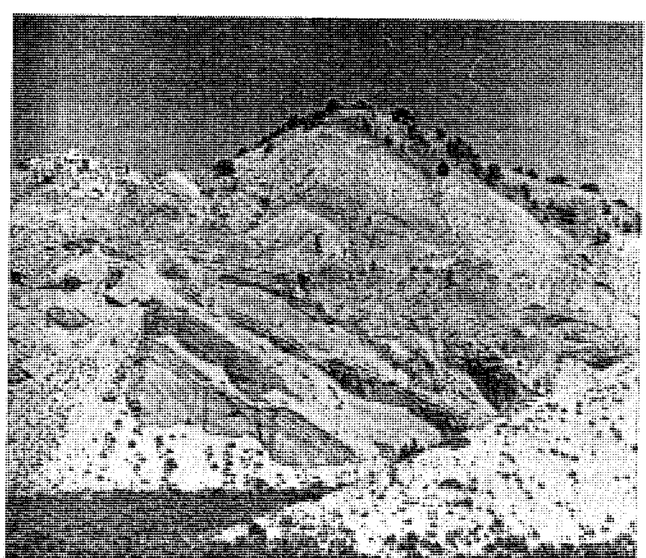

FIGURE 28.— Evaporite-contorted, possible piercement, exposures of the Arapien Shale southeast of Sigurd, Utah. Light-colored, ledge-forming units are massive gypsum and are separated by gray-green and pinkish siltstone and sandy units of the formation.

represents the deepest marine accumulation in the southern Wasatch Mountains and certainly was deeper than any unit exposed in the adjacent northern Colorado Plateau.

In roughly equivalent beds of the Honaker Trail and Elephant Canyon formations in the Moab area (Melton 1972, Terrell 1972), we also see evidence of rocks deposited in open, normal marine salinities, as indicated by abundant echinoderms and corals. These relatively clean, blue-gray to blue-green, slightly argillaceous limestones are interbedded, however, with marginal marine and nonmarine rocks, and certainly represent shallow water, although of normal open marine salinity. These rocks (fig. 29) have been well described in recent years by Melton (1972) and Terrell (1972), among others. These formations show almost classic cyclic patterns that repeat with gradual shifts, either shoreward or seaward, through vertical sections several hundred feet thick.

Somewhat restricted, but now dolomitized, deposits of the "Kaibab" Limestone are exposed in the San Rafael Swell (fig. 30). These sandy and cherty carbonate rocks contain ghosts of marine fossils, including productid brachiopods, crinoid stems, and corals, which indicate that the rocks were probably deposited under nearly normal marine circumstances. Much of the dolomitization of the "Kaibab" beds is thought to be a result of reflux modification by fluids from the overlying, somewhat gypsiferous Moenkopi Formation. "Kaibab" rocks are moderately well exposed along the eastern flank and the structural crest of the San Rafael Swell, particularly along Interstate 70, west of Green River from miles 14.4 to 19.5 of Rigby, Hintze, and Welsh (1976, p. 62–65).

Somewhat similar Triassic Sinbad Limestone, a medial marine unit within the dominantly nonmarine Moenkopi Shale, is exposed over The Sinbad, the central open section of the San Rafael Swell (Blakey 1974). The relatively thin dolomitic and limestone unit contains a *Meekoceras* and limited bivalve fauna, particularly in lower beds. It is more dolomitic, sandy, and silty in upper beds. The lower more fossiliferous units represent a flood of nearly normal marine salinity across the shelf area. The upper, more dolomitic and sandy parts of the member, however, record regression and replacement of the open marine limestone with dolomite and clastic sandy, probably tidal flat, sediments.

Lower limestone and dolomite beds of the Carmel Formation represent deposits of open marine conditions. In part of the sequence crinoid columnals indicate approximately normal marine salinities, but the overlying rocks that have a low-diversity molluscan fauna are less certainly normal marine deposits. Dolomitization of some of the carbonate units is

FIGURE 30.–View eastward along Interstate 70 through the Narrows cut in the San Rafael Reef. "Kaibab" limestone (K) is exposed as the juniper-veneered, light-colored unit near the bend in the highway. Light-colored lower Moenkopi Formation overlies the "Kaibab" rocks here. Ledge-and-slope zone in the distance is upper Moenkopi and Chinle formations and is capped by the bluff of Wingate Sandstone. Younger Jurassic and Cretaceous rocks are exposed through the notch in the far distance. Rest area in the foreground, at locality 19 of figure 1, is on the Sinbad Limestone Member (S) of the Moenkopi Formation.

FIGURE 29.–View southward across the west end of Spanish Valley to exposures in the bluffs along the lower part of Red Canyon. Oldest rocks along the railroad tracks are of the Honaker Trail Formation (H). These are overlain by somewhat slope-forming Chinle (C) and Moenkopi (M) beds to the west. The bluffs are capped by massive angular-weathering Wingate Sandstone (W). The lower ledge-and-slope units show excellent cyclic patterns in detail.

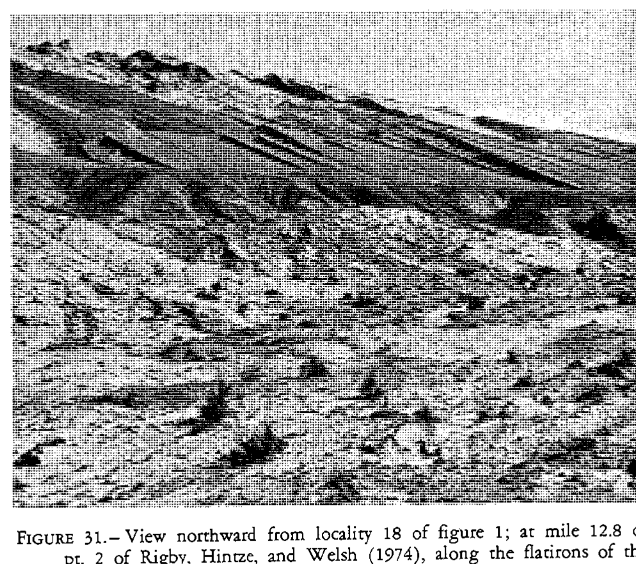

FIGURE 31.–View northward from locality 18 of figure 1; at mile 12.8 of pt. 2 of Rigby, Hintze, and Welsh (1974), along the flatirons of the lower fossiliferous, open marine part of the Carmel Formation, on the eastern reef of the San Rafael Swell. Massive cross-bedded Navajo Sandstone forms the bluff and cliff crests below the fossiliferous Carmel Limestone beds. Massive light sandstone in the foreground is the Slick Rock Member of the Entrada Formation, which here overlies the gypsiferous upper Carmel Formation that is exposed in the gully, in the distance below the flatirons.

probably associated with reflux solutions from the younger evaporites of the formation. The lower carbonate units form flatirons along the eastern margin of the San Rafael Swell (fig. 31) and also cap gentle cuestas along the western flank of the fold where the overlying argillaceous sediments have been stripped back (fig. 21).

The Mancos Shale (fig. 32) is one of the thickest marine formations in the plateau and is extensively exposed around the San Rafael Swell, at the foot of the Book Cliffs and out across the subsequent valley that it forms. The silty shale is the fine-grained eastern facies of the clastic wedge derived from erosion of the Sevier orogenic mountains and is laterally equivalent to the coal-bearing formations exposed in the Book Cliffs. It was apparently deposited in a shallow, probably muddy, seaway. No conclusive indicator fossils that were sensitive to salinities are present in the unit, although bivalves and ammonoids are locally abundant, sometimes forming widespread coquinas like the *Gryphaea newberryi* beds. These low-diversity faunas suggest rigorous conditions for organisms. Foraminifera are also abundant, particularly in the lower part of the formation where up to 18,000 tests per gram dry weight of sediments occur in the shales.

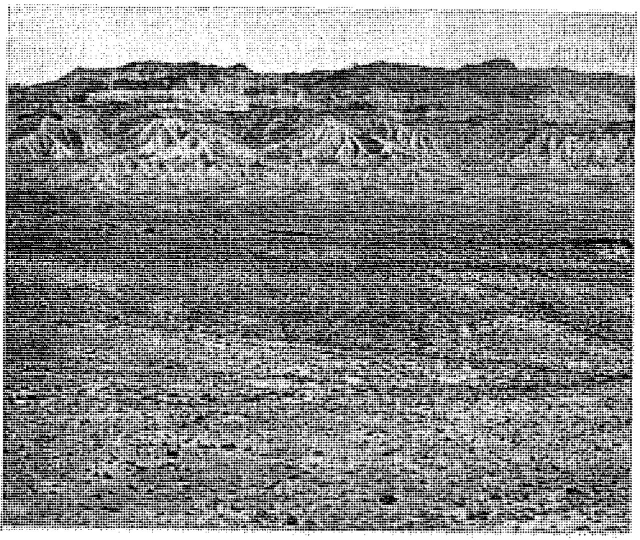

FIGURE 32.– View eastward across the marine Mancos Shale to the overlying Blackhawk, Castle Gate, and Price River beds of the West Tavaputs Plateau, near locality 14 figure 1; at approximately mile 96, pt. 1, Rigby, Hintze, and Welsh (1974).

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