First-day road log: From Cortez, Colorado to Montezuma Creek, Bluff, Aneth and Four Corners

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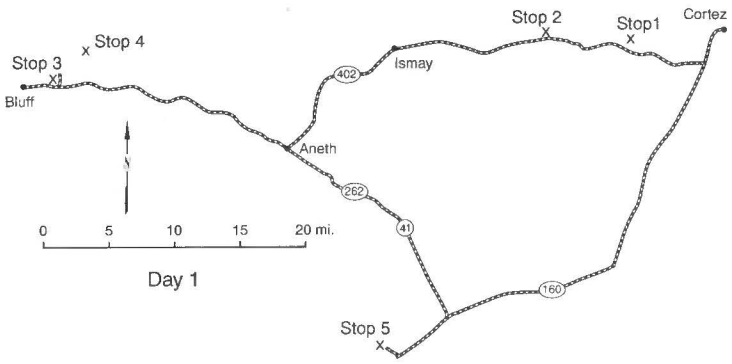
FIRST-DAY ROAD LOG, FROM CORTEZ, COLORADO TO MONTEZUMA CREEK, BLUFF, ANETH AND FOUR CORNERS

ORIN J. ANDERSON, SPENCER G. LUCAS, WILLIAM L. CHENOWETH and STEVEN C. SEMKEN

THURSDAY, OCTOBER 2, 1997

Assembly point: Holiday Inn, Cortez
Departure time: 7:30 a.m.
Distance: 162.1 mi
Stops: 5



Summary

Although outside of New Mexico, our assembly point is on the familiar turf of the Dakota Formation (Upper Cretaceous). As we begin the day's journey and head westward through McElmo Canyon, we will be descending stratigraphically from the position of the Dakota Formation. Excellent exposures of the Jurassic Morrison Formation and San Rafael Group are present along the route, with the oldest rocks, those of the upper Glen Canyon Group, being exposed at McElmo Dome, approximately 14 mi west of Cortez. From that point west, much of the terrain is developed on Morrison Formation, the Lower Cretaceous Cedar Mountain Formation and the Upper Cretaceous Dakota Formation.

At the Utah state line, we enter the petroleum-producing (Pennsylvanian production) areas of the Ismay and the Aneth fields. The route continues southwest to the San Juan River and thence westward to Bluff, Utah, our most distant point. At Bluff, we will have the opportunity to see the type area of some lithostratigraphic units that Gregory (1938) named and originally included in the Morrison Formation.

The return leg of the journey will take us through the Four Corners Monument, where one can be in four states at once and yet remain on Morrison strata. Other features, such as the intrusive mass of the Carrizo Mountains and the Carrizo Mountains uranium-vanadium mining district to the south will be addressed at the Monument. From the Four Corners into Cortez much of the landscape is developed on the Upper Cretaceous Mancos Shale, a prelude to Day 2.

Mileage

0.0 Assemble in parking lot of Holiday Inn on E Main Street (= U.S. Highway 160) in Cortez. Turn left and proceed west on US-160. **1.7**

1.7 Traffic light at intersection with Maple Street. Continue on 160 as it curves left to become S. Broadway. **1.4**

3.1 Outcrop of trough crossbedded sandstone bed in Upper Cretaceous Dakota Formation on right; intrusive mass (diorite) of Sleeping Ute Mountain visible at 2:00. **0.6**

3.7 Dakota Formation (sandstone) on right. From 9:00–12:00, on skyline North Rim exposes Upper Cretaceous Mancos Shale at base overlain gradationally by Point Lookout Sandstone (lower cliff), nonmarine Menefee Formation (wooded slope) and Cliff House Sandstone (upper cliff). **0.3**

4.0 Cross McElmo Creek. **0.6**

4.6 Turn right on McElmo Canyon road leading to Hovenweep National Monument and to Montezuma County Airport. After turn, note "toes" of Sleeping Ute at south end of mountain with same name. **0.4**

5.0 Airport at 9:00–10:00 is built on stripped surface of Dakota Formation. **0.4**

5.4 Note again toes and head of Sleeping Ute Mountain from 10:00–11:30. **0.2**

5.6 Road to left leads to airport. **0.9**

6.5 Dakota Formation forms surface on right. **0.5**

7.0 As we begin to descend into McElmo Canyon, sandstones of the Dakota Formation crop out on both sides of the road (Fig. 1.1). Coarse-grained sandstone facies plus numerous rip-up clasts and clay drapes suggest a fluvial origin for this part (lower half) of the Dakota Formation. Some (including Condon, 1991) would recognize both the Burro Canyon Formation and the Dakota in this area. As shown in Fig. 1.1, an upper sandstone with somewhat lighter weathering colors may be the reason both of these units are recognized. **0.2**

7.2 Carbonaceous beds at left are in Dakota Formation. **0.3**

7.5 Note claystones with greenish cast (probably due to celadonite) in Brushy Basin Member of Morrison Forma-

FIGURE 1.1. View to north of Dakota Formation outcrop at mile 7.0. Note the upper sandstone of the Dakota forming a ledge in the background.

tion on left, beneath sandstone of Dakota Formation. Darker-colored ledges in the Brushy Basin Member are micritic limestone and thought to be of lacustrine origin (floodplain lakes). **1.0**

8.5 Roadcuts on left expose claystones and thin, ledgy, well-indurated silcretes of Brushy Basin Member. McElmo Creek floodplain visible on right. **0.9**

9.4 Note trough-crossbedded multi-storied sandstones of the Brushy Basin Member, indicating fluvial deposition, in what has been claimed to have been a large alkaline, saline, Late Jurassic lake—Lake T'oo'dichi' of Turner and Fishman (1991). **1.1**

LAKE T'OO'DICHI' AND THE BRUSHY BASIN MEMBER OF THE MORRISON FORMATION

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As we shall see throughout the day's route, sandstone beds are present within the Brushy Basin Member (the upper member) of the Morrison Formation. The beds range in thickness from approximately 0.2 m to lenticular units in excess of 15 m. We regard these sandstones to have been deposited as overbank or crevasse splay beds (thinner sandstones) or as active channel-fill sandstones (thicker, crossbedded units). This is significant because the Brushy Basin Member commonly carries lithologic qualifiers like claystone–mudstone–shale.

Of greater significance is the fact that the entire Brushy Basin section has been attributed to deposition in a large lake, as much as 500 km in maximum dimension (NW–SE). This lake, termed Lake T'oo'dichi' (T'oo'dichi' is the Navajo word for "bitter water") by Turner and Fishman (1991), was thought to be shallow, perhaps periodically drying up, with widely varying water chemistry, including very high pH. The high pH values as well as high temperatures (minimum of 85°C) are necessary to produce the facies plus albite that are present in the Brushy Basin Member at Laguna, New Mexico, near the southern margins of "Lake T'oo'dichi'," and elsewhere across the Colorado Plateau.

It is as yet unclear how extensive the clinoptilolite facies is, but it is not co-extensive with or systematically present throughout the Brushy Basin Member. Thus, there are mudstone–claystone facies within the Brushy Basin Member that are not attributed to deposition in "Lake T'oo'dichi'." These areas or facies lie outside the hypothesized lake basin in the Front Range area of Colorado as well as in the high plains of eastern New Mexico, and the panhandle of Oklahoma. Aside from the rare clay-mineral assemblages, attributed by Turner and Fishman (1991) to extremes of water chemistry in the postulated lake, the lithology of the member is somewhat uniform throughout the area of occurrence—Utah to Oklahoma. Since a single, large, inland body of water is not plausible or indicated for the entire Brushy Basin Member (in an areal sense) it may well be questioned whether any of it was deposited in a large lake. It is difficult to envision such a large body of water (the size of proposed Lake T'oo' dichi') with wide variations or extremes of water chemistry and which periodically dried up. Furthermore, arguing that albite found in the Brushy Basin Member formed syndepositionally suggests water temperatures (85–100°C) in excess of those known from any lake. Lakes also thermally stratify, which means the bottom waters and pore fluids would be subject to far lower temperatures than those found in the epilimnion.

Based upon the above considerations plus the presence of fluvial facies vertically throughout the Brushy Basin Member, we prefer a depositional model consisting of smaller lakes in closed basins dotting a vast floodplain. This floodplain was associated with the large, generally eastward–southeastward flowing fluvial system that evolved from the Salt Wash depositional system that initiated Morrison Formation accumulation on the Colorado Plateau. The contrasting lithology of the two Morrison members is related to the presence of volcanic ash in the source area during deposition of the Brushy Basin, plus lower energy depositional systems and/or rise in base level resulting in the trapping of fine sediment in the depositional basin. Additional contrasts are provided by the presence of nodular (pedogenic) carbonates, limestone or micrite beds, silcretes, and the smectitic clays derived from volcanic ash falls in the upper part of the drainage basin. Most of these sedimentary features and sequences are more characteristic of an extensive floodplain environment dotted with shallow lakes (playas) in closed basins, some perhaps as large as 10–20 km in maximum dimension, rather than a large single lake, up to 480 km in diameter, such as the hypothesized "Lake T'oo' dichi'."

In summary, the recent interpretation of Brushy Basin Member deposition on the eastern Colorado Plateau in a large alkaline, saline lake (Lake T'oo'dichi') is contradicted by several lines of evidence: (1) the Brushy Basin Member throughout the Colorado Plateau contains sandstone bodies with features characteristic of meanderbelt channels; (2) there is little demonstrable concentric zonation of zeolite facies in the Brushy Basin Member; (3) Brushy Basin facies extend well beyond the Colorado Plateau, so they do not support the existence of a local lake; (4) it is highly improbable that lake temperatures reached levels high enough to produce albite, argued to represent the center of the lake basin; and (5) taphonomic and paleocological interpretation of Brushy Basin fossil plants and vertebrates does not indicate presence of a large lake.

10.5 Road curves right; prominent sandstone ledge on left is basal Salt Wash Member of Morrison Formation. **0.8**

11.3 At 3:00, near mouth of Trail Canyon, note crossbedded Bluff Sandstone near base at west end of ridge. Thin, grayish-red overlying slope-forming unit is Recapture Member of Bluff Sandstone overlain by relatively thick sandstone cliff of basal Morrison Formation (Salt Wash Member); a similar section can be seen in hill at 10:00. **0.4**

11.7 Mesa Point at 3:00 (Fig. 1.2) between Goodman and Trail

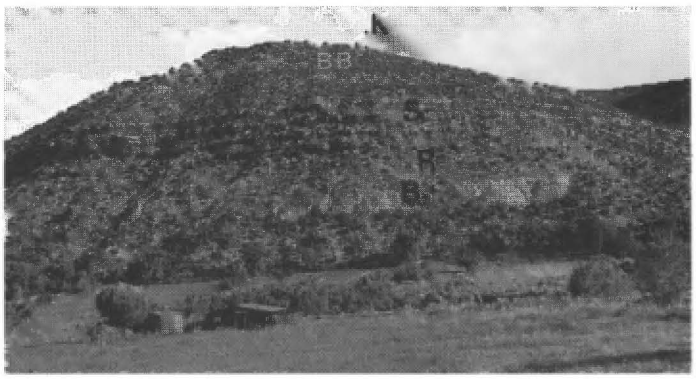

FIGURE 1.2. Mesa Point exposes Summerville (S), Bluff (B) Recapture (R), Salt Wash (S), Brushy Basin (BB) and Cedar Mountain or Dakota (K) formations.

FIGURE 1.3. Overview of section at Stop 1—Bluff Sandstone (B) overlain by thin, slope-forming interval of Recapture Member of Bluff (R) followed by multiple-ledge-forming Salt Wash Member of Morrison Formation (S).

Canyons exposes in ascending order, (1) red, cyclically-bedded Summerville Formation; (2) pink crossbedded sandstones (crossbeds dip E/NE) of the Bluff Sandstone; (3) thin slope of Recapture Member of Bluff; (4) thick sandstone cliff of Salt Wash Member of Morrison Formation; (5) slope of Brushy Basin Member of Morrison Formation; and (6) sandstone caprock of Cedar Mountain Formation. **0.4**

12.1 Turn right on unpaved County Road J. Bleached upper part of Entrada Sandstone visible ahead in central part of valley. **0.2**

12.3 Bridge over McElmo Creek; **road forks, bear right**. **0.2**

12.5 On left note Summerville Formation at base of slope overlain by cliff-forming Bluff Sandstone. **1.4**

13.9 **STOP 1**. Here we examine the Bluff Sandstone, including the Recapture Member (Figs. 1.3, 1.4), and the Salt Wash Member of the Morrison Formation. This section illustrates an important stratigraphic relationship that changes some long held ideas about regional geological history and paleogeography. The Bluff Sandstone is the youngest Jurassic erg deposit on the Colorado Plateau. Contrary to previous interpretation, we can now see that the lower Bluff is encased in arid coastal plain deposits—the Summerville Formation below and the Recapture Member of the Bluff above. The Bluff (= Junction Creek) crops out in the Four Corners region and San Juan Basin of New Mexico. Basinward, to the northwest in east-central Utah, the Bluff (including its Recapture Member) are laterally equivalent to arid coastal plain deposits of the Tidwell Member of the Summerville Formation. Thus, the Bluff represents the progradation of an erg across the arid coastal plain at about the Middle-Upper Jurassic boundary. However, a last episode of arid coastal plain deposition took place after Bluff deposition, represented here by the Recapture Member.

The base of the Morrison Formation tectonosequence can be clearly seen at this Stop as well. This is the sharp contact of fluvially-deposited conglomeratic sandstone (base of Salt Wash Member of Morrison Formation) on arid coastal plain deposits of the Recapture Member of the Bluff. This surface is the J-5 unconformity, although the temporal duration of that unconformity may be relatively short in geological terms, much less than an Age. The J-5 surface, nevertheless, represents a significant tectonic reorganization of the Jurassic depositional basin from an arid coastal plain with a paleoslope down to the N/NW to a fluvial basin with a paleoslope to the east and northeast.

After stop, retrace route to highway. **1.5**

15.4 At 2:00 note outcrop of bleached Entrada Sandstone near the base of the slope of Goodman Point. Entrada Sand-

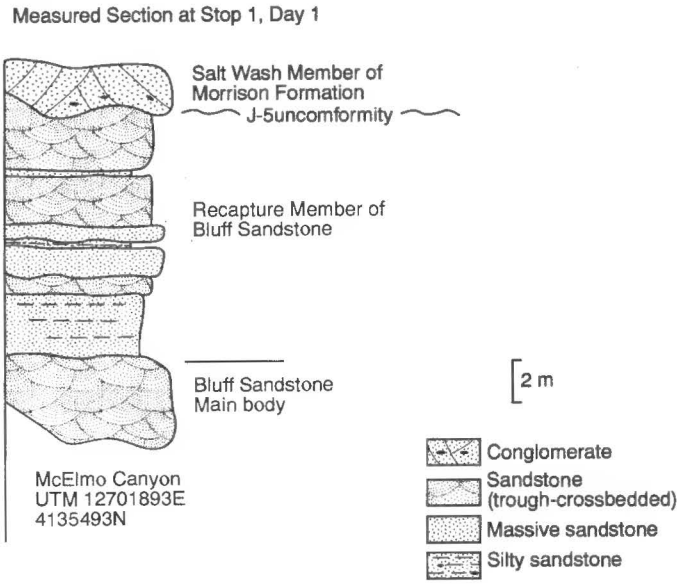

FIGURE 1.4. Measured stratigraphic section at Stop 1.

stone also exposed in the creek bank below the bridge. **0.2**

15.6 **Turn right** on paved road to proceed W. **0.4**

16.0 Outcrops on right side of road reveal that highway is on top of the Entrada Sandstone. Low roadcuts ahead are in basal part of Summerville Formation. **0.6**

16.6 **OPTIONAL STOP**; pull off to right on siding, on bleached, uppermost part of Entrada Sandstone. This bleaching is common in the Entrada, whether Todilto is present or not (obviously not, here) and may be due to the diagenetic reduction and removal of Fe. The overlying Summerville is associated with a transgression and thus it may be inferred that the groundwater table was rising, not falling during diagenesis. At the base of the Entrada, which is approximately 100 ft thick locally, is a slope-forming, bench-forming unit (Fig. 1.5) that has decided influence on the topography in McElmo Canyon. This fine-grained, slope-forming unit, as much as 60 ft thick, has been called Carmel Formation (Lupe, 1983) and Dewey Bridge Member of the Entrada (Ekren and Houser, 1965); these two units occupy the same stratigraphic position. We prefer the name Carmel Formation for this basal unit of the San Rafael Group. Westward and northwestward the Carmel contains thin limestone beds and is thought to represent a shallow marine transgression. Underlying, color-banded sandstones belong to the Navajo Sandstone(?) of the Glen Canyon Group. A good view ahead and to west of color-banded cliffs of Glen Canyon Group sandstones in McElmo Canyon. **0.1**

16.7 As road descends through the crossbedded to massive Entrada, note the moderate reddish-orange lower very fine-grained sandstones in roadcut on left. Bedforms in this unit suggest it is interdunal and water-laid; it is very similar to the type Carmel in Utah. **0.1**

16.8 Outrop to left of fine-grained, dark reddish-brown, slope-forming unit 50 to 60 ft below the top of the Entrada. This unit is the eastward extension of Carmel Formation. **0.8**

17.6 Cross bridge. Note north-trending basaltic dike to left of road just ahead. **0.7**

18.3 Road to right leads to Kelly Place bed and breakfast; "a living history and archeological preserve." Along this reach of McElmo Canyon are numerous archeological (Anasazi) sites. The possibility of high precision dating of late Holocene alluvium and chronostratigraphic control afforded by buried Anasazi remains was recognized by Force and Howell (1996) and in their continuing studies. **0.1**

18.4 To right, note thinning of Summerville Formation across crest of McElmo dome; also note crossbed sets dipping to SW in the underlying Entrada Sandstone. **0.3**

18.7 BOC Gases processing plant road to right. Since the 1980s, Shell Western has been producing CO_2 gas from McElmo Dome, a local uplift that appears to be, in some small part, of Jurassic age. The Summerville Formation (Middle Jurassic) thins across the top of the dome. The Summerville, however, is not a thick unit (<80 ft) in this part of Colorado, and the thinning noted does not account for much of the structural relief of McElmo Dome. Closure on the dome is approximately 1800 ft, (courtesy of J. B. Ward, Shell Western Co.). CO_2 is produced from Mississippian carbonates (Leadville Formation) from a depth of 8200 ft. Much of the reason for this seemingly great depth is a very thick (4300 ft) Pennsylvanian section. Annual production has been approximately 185 bcf. The gas is sent via a 42-inch pipeline to its ultimate destination in west Texas. There it is used for reservoir pressurization and stimulation in the mature and older oil fields. A small amount is delivered to Mobil Oil Company's nearby Aneth field. **1.3**

20.0 Cross bridge over McElmo Creek. **0.6**

20.6 Pull off to right. **STOP 2**, at Sand/East Rock Canyons trailhead. Here we will examine a thinned interval of Summerville Formation between the Bluff and Entrada Formations (Fig. 1.6). These beds have been termed Summerville west of here and Wanakah to the east by workers of the U.S. Geological Survey (Lupe, 1983; O'Sullivan, 1995; Fig. 1.7). Indeed, they are the same lithostratigraphic unit throughout the region, and the name Summerville Formation has precedence and should be applied (Anderson and Lucas, 1992). Thinning of the Summerville here reflects pre-Summerville topography (a positive) during the Middle Jurassic. A piping or dewatering feature that extends down into the Entrada Sandstone can be seen here and further complicates local Summerville stratigraphy.

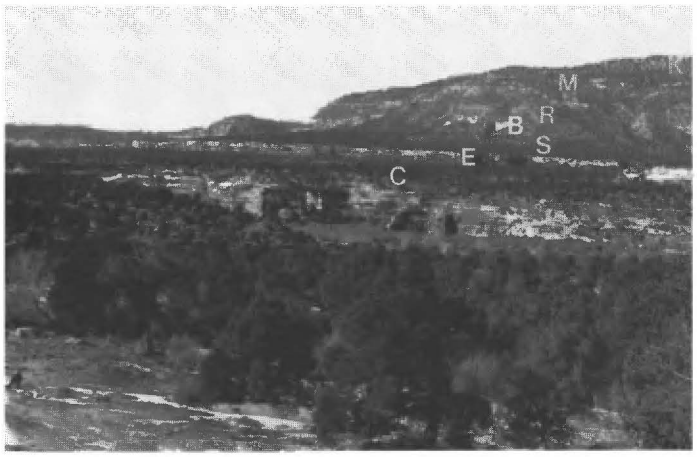

FIGURE 1.5. Bench-forming unit at base of Entrada Sandstone (E) is Carmel Formation (C). Navajo Sandstone (N) floors canyon and younger units are Summerville (S), Bluff (B), Recapture (R), Morrison (M) and Cretaceous (K) strata.

FIGURE 1.6. View of Bluff (B), Summerville (S) and Entrada (E) Formations at Stop 2.

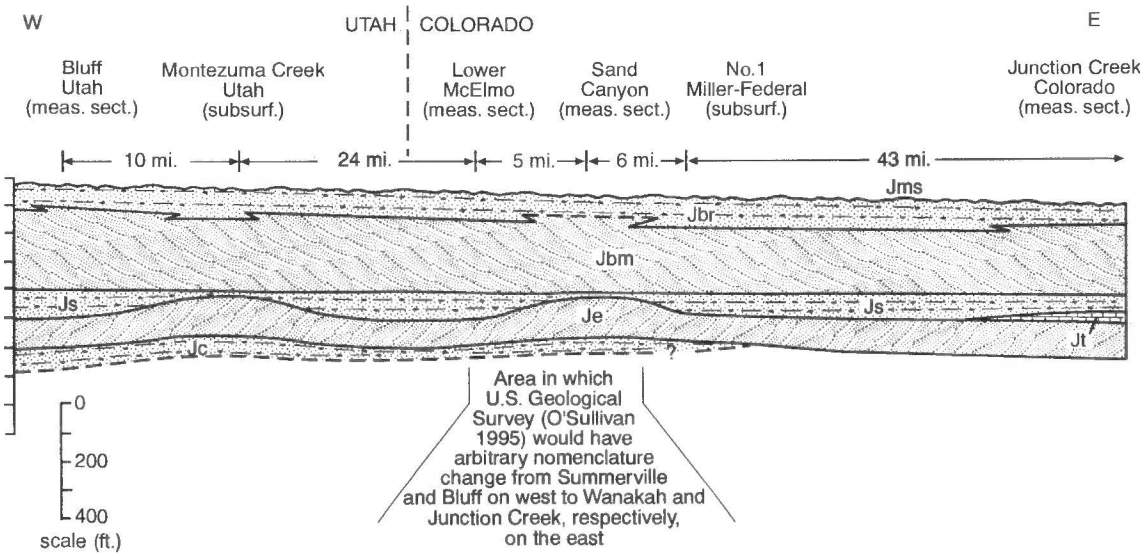

FIGURE 1.7. Regional stratigraphic cross section showing stratigraphy of Summerville Formation and related strata from eastern Utah into western Colorado. Units are Carmel (Jc), Entrada (Je), Todilto (Jt), Summerville (Js), main body of Bluff (Jbm), Recapture Member of Bluff (Jbr), and Salt Wash Member of Morrison (Jms).

A thin Carmel Formation intertongues with the basal Entrada locally and forms the base of the San Rafael Group. Lupe (1983) indicated that the Carmel Formation pinches out eastward in the subsurface near Cortez. Eastward from Cortez the basal Entrada may, according to Lupe's cross-sections, include equivalents of the Navajo Sandstone, which locally is lithologically nearly indistinguishable from the Entrada. This is an interesting problem, one not previously addressed, and it involves the important contact between the San Rafael and Glen Canyon Groups, by conventional wisdom an unconformity. We know the Navajo (Glen Canyon Group) is thinning eastward as the Carmel does, but does it persist as a lithostratigraphic unit eastward of the Carmel pinchout and essentially become "one" with younger Entrada? If so, we would have some converging time lines, a condensed section, which would encompass the time of deposition of much of the Navajo and all of the Carmel, all represented in a relatively thin lower Entrada section. Unconformities or diastems within the Entrada have not been reported, nor do geophysical logs suggest their presence. Green (1974) faced a similar problem in the southern San Juan Basin, in that he found no unconformity in this stratigraphic position and thus reassigned strata that had been included in the Glen Canyon Group, to the basal Entrada. But do we really understand the stratigraphy and age relationships of the basal Entrada eastward of the shallow marine-marginal marine influence represented by Carmel strata?

After stop continue W on paved highway. **0.6**

21.2 Note E-dipping foresets of Bluff Sandstone to left on topographic feature known locally as Battle Rock (Fig. 1.8). **0.5**

21.7 On right note dramatic change in bedforms between Bluff (main body) and overlying Salt Wash Member of Morrison; these two units are separated by the thin, poorly exposed Recapture Member of Bluff Sandstone. This relationship is visible for next 0.5 mi. **0.9**

22.6 On right note E-dipping foresets at top of Bluff Sandstone. **0.4**

23.0 At 3:00 near head of valley note well exposed section of Recapture Member of Bluff Sandstone between Bluff (main body) and Morrison Formation (Fig. 1.9). The highway now climbs up to the level of the Salt Wash. **2.1**

25.1 Mesa on right exposes sandstone ledges of Salt Wash Member overlain by claystone slope of Brushy Basin Member, capped in turn by Cedar Mountain (Lower Cretaceous) and Dakota Formations. **1.2**

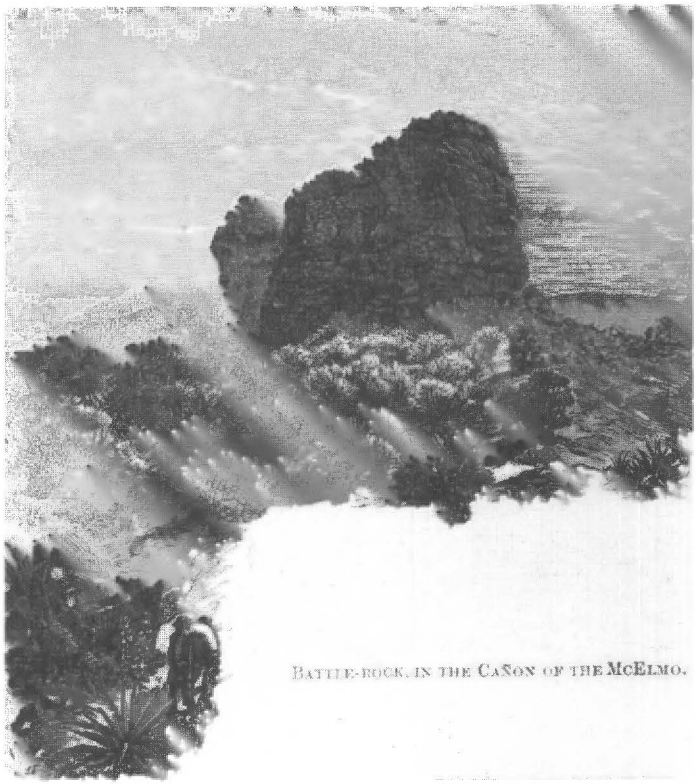

FIGURE 1.8. Battle Rock, as drawn in Jackson (1876).

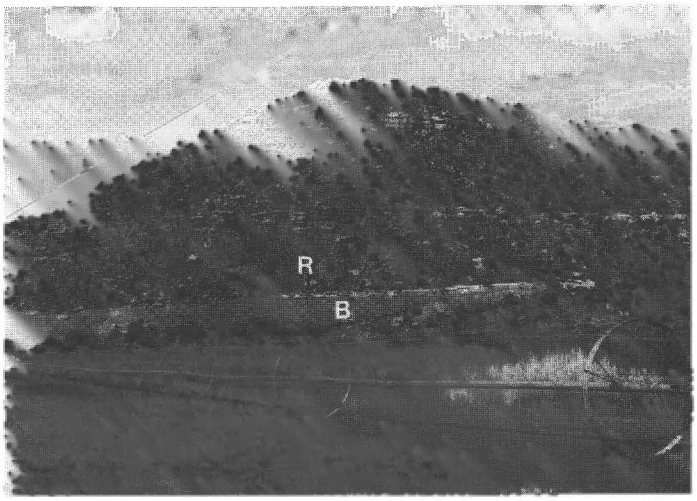

FIGURE 1.9. Note Bluff (B), Recapture (R) and Salt Wash (S) Member of Morrison Formation well exposed here.

LOWER CRETACEOUS STRATIGRAPHY ON THE COLORADO PLATEAU

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Cretaceous strata between the top of the Upper Jurassic Morrison Formation and the base of the Cretaceous (late Albian?-Cenomanian) Dakota Sandstone crop out in various parts of the Colorado Plateau, especially in eastern Utah. These strata are as much as 300 m thick and consist of fluvially deposited sandstone, conglomerate and non-carbonaceous mudstone.

Stokes (1944) named these strata the Cedar Mountain Formation (in the San Rafael Swell, Utah). Stokes and Phoenix (1948) renamed them Burro Canyon Formation for exposures in San Miguel County, Colorado. Burro Canyon has been widely used to refer to these strata, also present in northwestern New Mexico (e.g., Saucier, 1974). However, we agree with Young (1960) that it is an obvious and unnecessary synonym of Cedar Mountain Formation and should be abandoned.

The base of the Cedar Mountain Formation at most locations is a laterally persistent unit of sandstone and/or silica-pebble conglomerate. Stokes (1944, 1952) named this unit the Buckhorn Conglomerate and identified it as the basal member of the Cedar Mountain Formation. Ekren and Houser (1959) renamed this unit the Karla Kay Conglomerate, and obviously this name should be abandoned. Aubrey (1996) claimed that the Buckhorn intertongues with the underlying Morrison Formation so he recommended reassigning it to the Morrison Formation. Not only is Aubrey's (1996) evidence for Buckhorn-Morrison intertonguing unconvincing, but even if the units intertongue the Buckhorn can remain in the Cedar Mountain Formation; the Buckhorn-Morrison contact is the most readily and regionally mappable formation boundary.

Fossil vertebrates, palynomorphs and charophytes indicate the Cedar Mountain Formation ranges in age from Neocomian (Hauterivian or Barremian) to middle Albian (e.g., Mitchell, 1956; Tschudy et al., 1984; Kirkland, 1992; Lucas, 1993; Aubrey, 1996) (Fig. 1.10). The dinosaurs are particularly significant, as they can be divided into two temporally distinct assemblages. Dinosaurs from the lower part of the Cedar Mountain Formation in southeastern Utah include the ornithopod *Iguanodon* and the ankylosaur *Polacanthus*, which indicates correlation with the British Weald Clay of Hauterivian–Barremian age (Kirkland, 1992; Lucas, 1993). Dinosaurs from the upper part of the Cedar Mountain Formation (De Courten, 1991; Eaton and Nelson, 1991) can be correlated to dinosaurs from the Cloverly Formation of Wyoming-Montana, the Arundel Formation in Maryland and the Twin Mountains and Antlers Formations of the Trinity Group in central Texas, all units that approximately straddle the Aptian-Albian boundary (Lucas, 1993).

Aubrey (1996) argued that deposition of the Cedar Mountain Formation

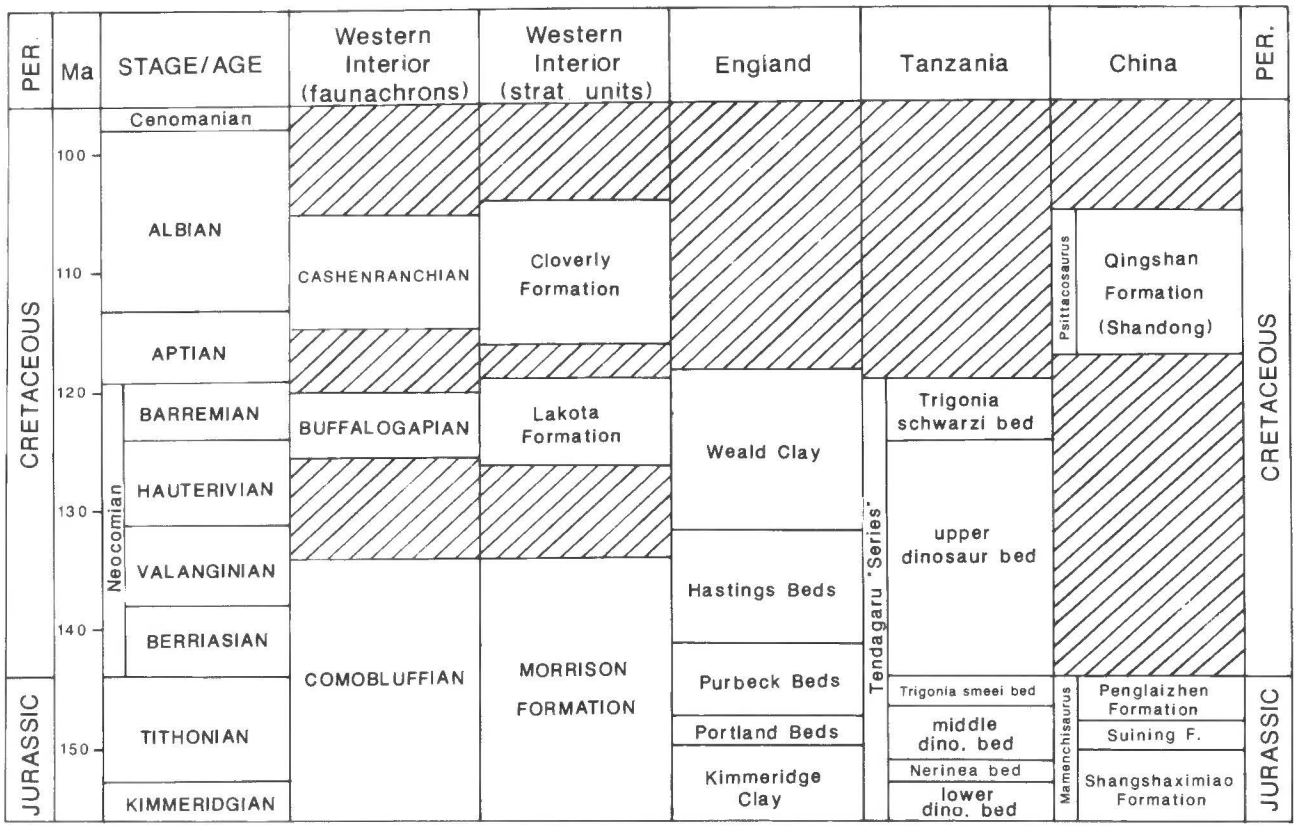

FIGURE 1.10. Global correlation of Colorado Plateau dinosaur horizons across the Jurassic-Cretaceous boundary (from Lucas, 1993).

took place in the Early Cretaceous Sevier foreland basin. Minor subsidence in the foreland basin is associated with crustal loading related to the Sevier overthrust. This generalized tectonic setting would seem to be correct. Perhaps of greater significance is an attempt to correlate or associate the erosion surface on which the Cedar Mountain rests with one of the pre-Aptian (Neocomian) sea-level lowstands. Several such lowstands have been identified within Neocomian age rocks; these were presented in the eustatic sea level curves of Haq et al. (1984) as having occurred at approximately 125.5 and at 128 Ma. Either one or both of these lowstands are perhaps responsible for the incised topography upon which the basal Cedar Mountain Formation (Buckhorn Conglomerate) was deposited. If these associations with the eustatic curve are valid we have set a maximum age for the Cedar Mountain Formation. Implications for the time represented by the basal Cretaceous unconformity are significant. Instead of this value being as much as 40–44 Ma in those areas were Dakota Group rests on Jurassic rocks, it is reduced to perhaps as little as 10–13 Ma in areas such as this where the Cedar Mountain Formation is present.

26.3 Highway crosses Salt Wash–Brushy Basin transitional contact. **1.5**

27.8 Cannonball Mesa at 12:00 is capped by Dakota Formation above Cedar Mountain Formation over Brushy Basin Member of Morrison Formation. **0.6**

28.4 Unpaved road to right. At 2:00–2:30 on slope of Cannonball Mesa note dark ledge of Buckhorn Conglomerate Member at base of Cedar Mountain Formation. **1.3**

29.7 Green, fine-grained sandstone on right is in Brushy Basin Member of Morrison Formation. **3.2**

32.9 Excellent exposures of red and green Brushy Basin mudstones. The overlying, darker colored ledge is Cedar Mountain Formation under mesa-capping sandstone of Dakota Formation. **0.9**

33.8 Ismay Trading Post. **0.2**

34.0 Cross bridge over Yellowjacket Canyon. **0.2**

34.2 Enter Utah and the Navajo Indian Reservation; begin paved highway 2414 in San Juan County, Utah. Mesa ahead exposes same Brushy Basin–Cedar Mountain–Dakota section we have seen for the last few miles. **Notice**: Persons wishing to conduct geological investigations on Navajo land, including stops described in this guidebook, must first apply for and receive a permit from the Navajo National Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515; (520) 871-6587. **0.8**

35.0 Terrace of McElmo Creek to right controlled by Salt Wash Member overlain by Brushy Basin–Cedar Mountain–Dakota section (Fig. 1.11). Road ahead is developed on bench at top of Salt Wash Member. **1.3**

36.3 Enter Ismay oil field. Production here is from Pennsylvanian sandstones (Paradox Formation of Hermosa Group). The Ismay field is part of the Greater Aneth field (Fig. 1.12). In addition to producing wells, carbon dioxide injection wells are seen on both sides of the road for next 25 mi. Greater Aneth field is the most productive oil field in Utah at 390 million barrels of oil with over 345 billion ft^3 of associated gas as of June 1996 (Utah Division of Oil, Gas and Mining, 1996). Oil and gas are produced from the Desert Creek and Ismay zones of the Paradox Formation. There are over 500 active production, water injection, and CO_2 injection wells in the field (courtesy of Utah Geological Survey).

Mobil Exploration and Producing Inc., the unit operator, began the CO_2 flood of the Desert Creek reservoir in 1985. The production response was one to two years. Oil production increased in the unit from 5500 barrels (875 m^3) per day in 1985 to 6500 barrels per day in 1995 (Lambert et al., 1996). The McElmo Creek Unit CO_2 flood is the only such project in Utah to date. Estimated secondary/tertiary recovery is 210 million barrels; estimated ultimate recovery is 408 million barrels (Moore and Hawks, 1993).

FIGURE 1.11. Colorful, variegated claystone-dominated slopes of the Brushy Basin Member of the Morrison Formation (Upper Jurassic) are overlain here by Lower Cretaceous sandstones and conglomerates of the Cedar Mountain Formation.

The discovery of the greater Aneth field began in 1951 when the Texas Company (Texaco) had obtained 32 sections of Navajo leases locally. As these leases were expiring in the fall of 1956, by 1954 the company felt it time to do some mapping and exploration work. In that year Robert Douglass, fresh out of school with an M.S. in Geology (University of Kansas), went to work for Texaco. He was assigned to work with Robert S. Breitenstein, geologist for the Texas Company's Farmington area. Breitenstein was an expert field geologist, having spent most of his career until that time in the wilds of South America, and was precisely the type of person that was needed for recon work in southeastern Utah.

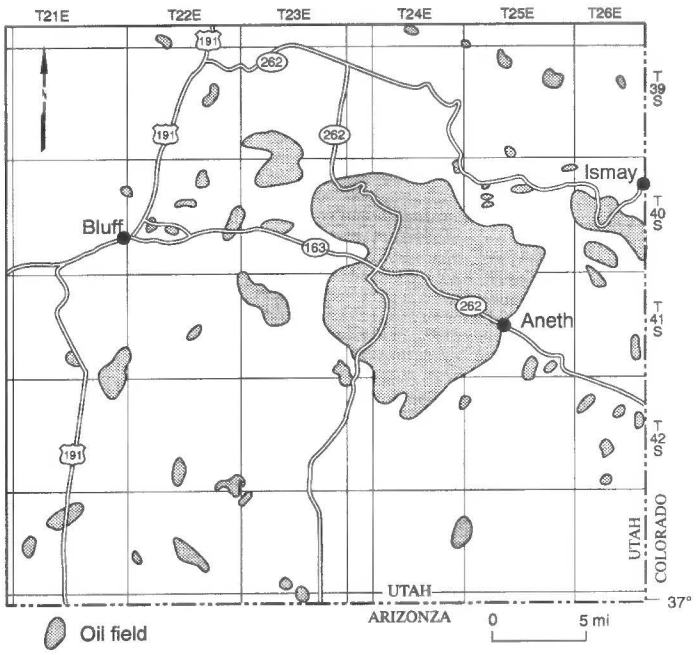

FIGURE 1.12. Map of greater Aneth oil field.

FIGURE 1.13. Robert S. Breitenstein mapping in 1954.

Breitenstein and Douglas arrived in the Ismay-Aneth area in the summer of 1954 (no paved roads anywhere) with jeep, plane table and alidade, some planimetric maps, and the right attitude. They set up locally, provisioned out of John Ismay's Trading Post "up on the state line," and began work.

The accompanying photograph (Fig. 1.13) was taken in October 1954 by Douglass, showing Breitenstein, then 51, with his plane table and alidade. They were set up on a triangulation point on the Cedar Mountain/Dakota(?) on the west side of McElmo Creek (not far from our present location). The photo is looking south with the San Juan River Valley and the Carrizo Mountains in the background.

They proceeded to map some structure—some sizable closure—which led to the drilling of the discovery well for the field in early 1956. The discovery well, The Texas Company—Superior Oil Company #1 Navajo C, was drilled as a "tight hole," forcing scouts to sit out amongst the rocks, shivering with binoculars, counting sections of drill pipe and monitoring the rig for signs of "non-routine activity." The well was ultimately completed in the Paradox Formation (Pennsylvanian), but seven more wells had to be drilled immediately to validate the entire 32-section lease.

When production commenced, there were of course no pipelines, and the crude had to be trucked, but the Navajo were reluctant to issue a trucking permit. When the company agreed to up the royalty from 1/8 to 1/6 the permit was issued. In November 1956, the Navajos held another lease sale. In what was very likely a record bid, a consortium of Pure Oil, Sun Oil, and Ohio Oil offered as much as $3,102 per acre for adjacent tracts. **1.2**

37.5 Carrizo Mountains on skyline to SW. **0.6**

38.1 Roadcut exposes pastel-pink claystone facies in Brushy Basin Member. **0.2**

38.3 Turnoff to right to Hovenweep National Monument; continue straight. **2.9**

41.2 At 8:00 to 9:00 good view of Sleeping Ute Mountain; ahead is valley of San Juan River. **1.8**

43.0 Highway bench is developed on top of Salt Wash Member. **1.2**

44.2 Highway is descending through Salt Wash Member. San Juan River ahead. **0.4**

44.6 Muddy interval of red mudstones and siltstones interbedded with thin white sandstones is in Salt Wash Member, though workers of the U.S. Geological Survey termed it Recapture Member of Morrison Formation. **0.6**

45.2 White sandstones (Fig. 1.14) have rip-up clasts and clearly are of fluvial origin. However, some earlier workers of the U.S. Geological Survey have regarded them as eolian, and this is one of the bases for the claim that eolianites are common in the lower part of the Morrison Formation. **1.5**

46.7 Highway curves; Aneth visible to left. Roadcuts on right are in Recapture Member of Bluff Formation (Fig. 1.15). Aneth was the site of a Navajo trading post in the early 1880s. In 1886, it was given the name Holyoak after an early settler. In the 1900s it was changed to Aneth after an operator of a nearby trading post. The village boomed for a few years following the discovery of oil here in the mid-1950s, but, it has since shrunk back to trading post size. **0.5**

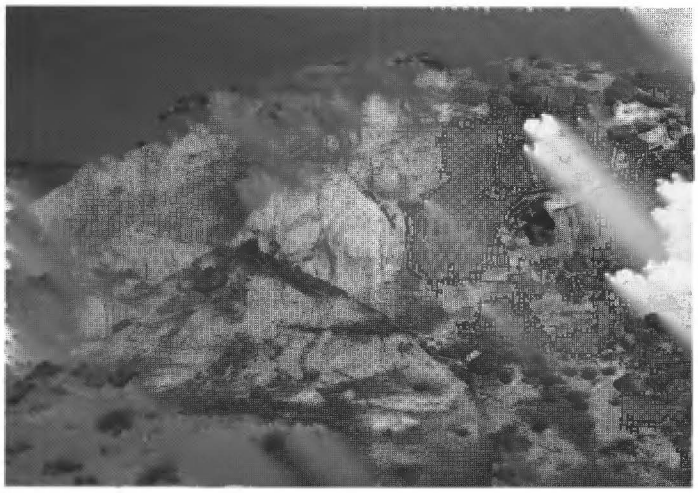

FIGURE 1.14. These crossbedded sandstones in the lower part of the Salt Wash Member of the Morrison Formation are of fluvial origin.

FIGURE 1.16. Note dramatic scour of basal, fluvial channel of Salt Wash Member of Morrison Formation (S) into underlying strata of Recapture Member of Bluff Formation (R).

47.2 Intersection with Utah Highway 262. Here McElmo Creek enters the San Juan River. Outcrops of Recapture Member of Bluff Formation on right. **Turn right** to proceed W on Utah 262. **0.4**

47.6 Slow down to note trough-crossbedded sandstone on the right (behind pumpjack) scoured into the Recapture Member; the sandstone forms the basal part of the Salt Wash Member of the Morrison Formation. **1.8**

49.4 On right is excellent exposure of the Recapture–Salt Wash contact (Fig. 1.16). Trough-crossbedded conglomeratic sandstone at base of Salt Wash is disconformable on fine-grained, laminated sandstone and siltstone. At 8:30–9:00 across river is cliff/bench of main body of Bluff Sandstone. **2.2**

51.6 Sandstone beds of Salt Wash Member ahead and to right. Again, white sandstones here have been regarded as eolian but are clearly of fluvial origin based on rip-up clasts, bedform geometry and the obvious overbank deposits associated with some of them. **1.6**

53.2 Red beds to right have been termed Recapture overlain by sandstone of the Westwater Canyon Member of the Morrison Formation. However, all these strata more properly belong with the Salt Wash Member. San Juan River on left side of road. **0.9**

54.1 Enter village of Montezuma Creek. **0.5**

54.6 Stop sign. **Turn right** then immediately **turn left** onto US-163 and proceed to Bluff. **1.4**

56.0 Cross bridge over Montezuma Creek, and leave Navajo Reservation. Note Salt Wash exposures to N of highway. **0.4**

56.4 Enter old Montezuma Creek. **1.7**

58.1 Level of highway is close to contact of sandstone-dominated Salt Wash Member with overlying mudstone-dominated Brushy Basin Member of Morrison; this contact is transitional and intertongued. **2.4**

60.5 Cross McCracken Canyon. In bottom of wash note Bluff–Recapture–Salt Wash section. Here, Recapture is 20–25 ft thick, and base of Salt Wash is both a prominent scoured surface and forms a sharp lithologic contrast to underlying beds. **1.0**

61.5 Canyon to left exposes excellent Bluff–Recapture–Salt Wash section (Fig. 1.17). **1.4**

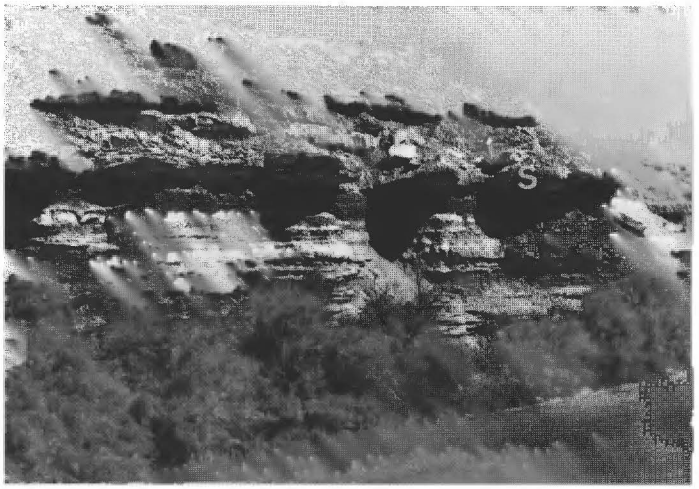

FIGURE 1.15. Typical thin-bedded sandstones and siltstones of Recapture Member of Bluff Formation overlain by Salt Wash (S) sandstones.

FIGURE 1.17. Characteristic exposures of Bluff (B), Recapture (R) and basal Salt Wash (S) units.

FIGURE 1.18. McCracken Point exposes Salt Wash (S)—Brushy Basin (B)—Cedar Mountain (C) section.

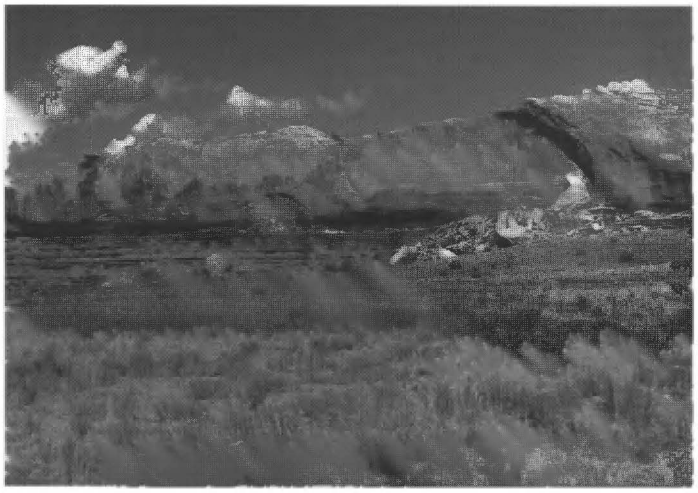

FIGURE 1.19. Thinly bedded Summerville Formation overlain by cliff of Bluff Sandstone (main body) of Stop 3. Note bedform change in cliff of Bluff-lower part laminar, upper part crossbedded.

62.9 Crest of hill. McCracken Point to N (Fig. 1.18) exposes Salt Wash–Brushy Basin–Cedar Mountain section. **0.7**

63.6 Highway at top of Bluff Sandstone. **0.2**

63.8 Cross bridge over Recapture Creek. **0.6**

64.4 Note terrace developed on Bluff Sandstone. **0.7**

65.1 At 3:00 the Horn and Recapture Pocket are composed of Salt Wash sandstones overlain by Brushy Basin mudstones. **0.7**

65.8 Highway descends into inner valley of San Juan River. Note Bluff Sandstone overlying Summerville Formation. Upper part of Bluff here is trough crossbedded (foresets are down to the E); this facies was included in Morrison Formation by Condon and Peterson (1986). **1.2**

67.0 **Turn right** onto local dirt road and park. Lunch and **STOP 3.** At this stop we will have the opportunity to examine upper San Rafael Group strata (Summerville and Bluff Formations) and compare them with these units in the southern San Juan Basin (Fig. 1.19). Although both the Summerville and Bluff are dominantly sandstone, bedding characteristics and grain size differ considerably. The Summerville is a thin, horizontally bedded unit that includes very fine to lower very fine-grained sandstone (62–125 μ). In addition, there are numerous siltstone or silty sandstone beds from 3 to 5 ft thick, with lesser mudstone. The entire unit is considered to have been deposited in a sabkha-arid coastal plain environment with periodic input and reworking of eolian sediment. The overlying Bluff Sandstone, however, is coarser grained (upper fine- lower medium-grained sandstone), thicker bedded, and contains thick sets of high-angle crossbeds, particularly near the top. It is considered to be dominantly eolian in origin. A very similar section may be seen at numerous localities in the San Juan Basin (New Mexico) where U.S. Geological Survey workers have assigned these rocks to the Wanakah Formation. Wanakah is a parochial name introduced by Burbank (1930) for these rocks in southeastern Colorado; it is an unnecessary junior synonym for Summerville-Bluff strata (Anderson and Lucas, 1992). We see little utility in multiple names for the same stratigraphic interval, which results in obfuscation. Recognizing the maximum areal extent of a stratigraphic unit or interval has the beneficial effects of (1) simplifying the nomenclature, (2) clarifying the paleogeography, and (3) initiating the right approach to basin analysis.

Note the bedform break at this locality here in the upper part of the Bluff Sandstone; lower part laminar, upper part crossbedded. Though subtle and transitional, the bedform break at the top of the Bluff Sandstone is another example of numerous and widespread occurrences of this readily observable feature. It has been noted in the San Juan Basin at Mesa Gigante, Mesita, Laguna, Acoma, Haystack Mountain, Thoreau, and at Zuni Pueblo. These occurrences plus those at Tsitah Wash in Arizona and Junction Creek near Durango establish the systematic, persistent, widespread nature of this eolian facies and bedform. It is present at the same stratigraphic position in all these locations and may represent an isochronous surface. What does it represent depositionally? Anderson and Lucas (1995) have related it to the northward drift of this part of the continent into the zone of prevailing westerlies at the close of San Rafael Group deposition (Fig. 1.20). This would correspond approximately to the end of Middle Jurassic time (end of the Callovian stage), which is the time frame in which Dickinson (1989) considered this portion of the continent to have entered the zone of prevailing westerlies. The resulting eastward-dipping foresets were subsequently preserved in the upper part of the Bluff Sandstone.

After stop, continue W to Bluff. **0.5**

67.5 Cottonwood bosque developed on terrace of San Juan River. **0.3**

67.8 Note syndepositional slumps on right in thinly-bedded Summerville strata. The overlying Bluff Sandstone is well-developed here in its type area, but thins at a rapid rate northward. The local section is strikingly similar to that near Mesita, NM, except that the Todilto Formation (evaporite and carbonate) is not present in this area. **1.2**

69.0 Note orange-colored top of Entrada Sandstone on right beneath Summerville strata. **0.3**

69.3 Junction US-91/163. at Cow Canyon Trading Post. Excellent Summerville and Bluff exposures here (Fig. 1.21); this is the type locality of the Bluff Sandstone (Gregory, 1938). The top of the Entrada crops out at the base of the cliffs. Turn around at this point and retrace route to E on US-163. **5.0**

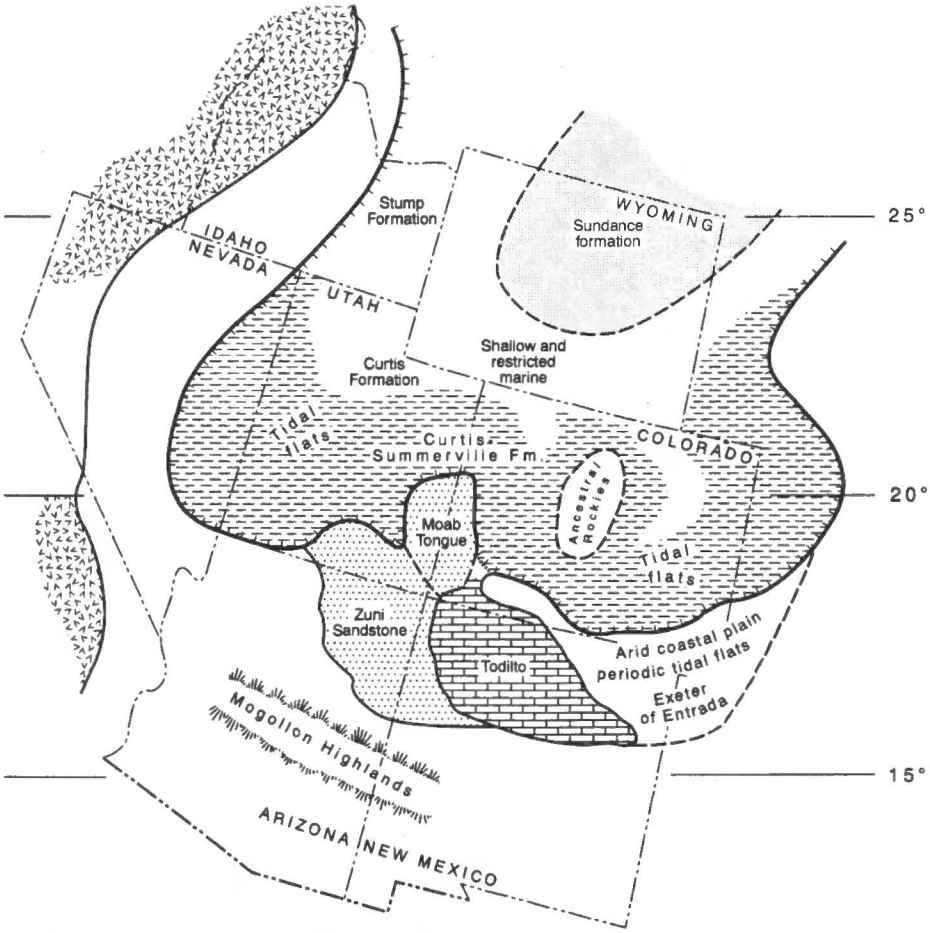

FIGURE 1.20. Paleogeography of the southwestern United States during deposition of the Summerville Formation.

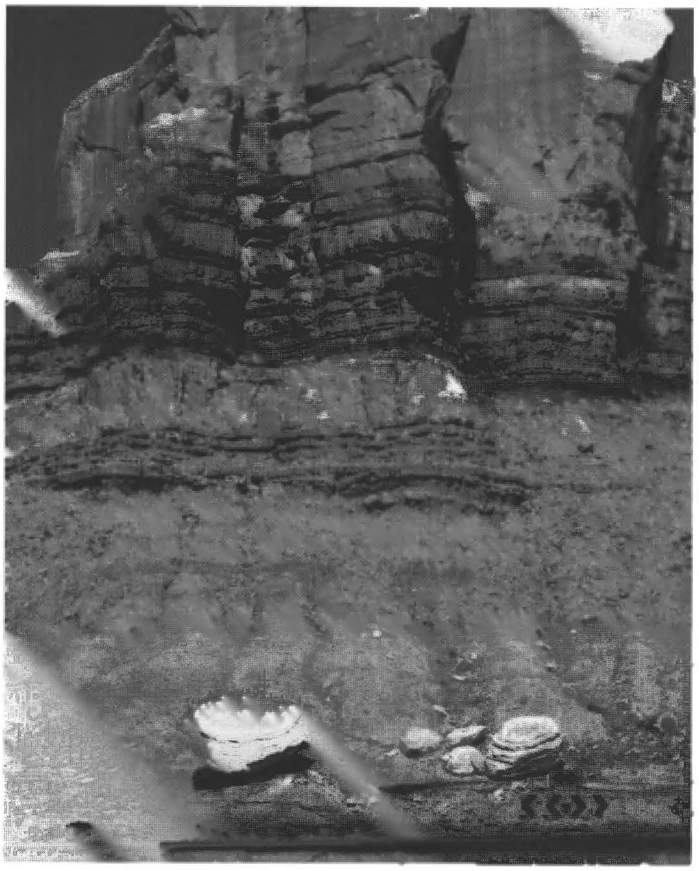

FIGURE 1.21. Sandstone at base of slope here is thin remnant of Entrada, overlain by slope and ribbed cliff of Summerville Formation capped by bold cliffs of type Bluff Sandstone.

74.3 Just before Recapture Creek turn left onto San Juan County 249, the Recapture Pocket Road, which follows the top of the Bluff Sandstone. **0.4**

74.7 Road forks; **go straight (to right)** onto lesser dirt road. **0.4**

75.1 Panorama to right reveals Bluff with Recapture Member at top, overlain by Salt Wash and Brushy Basin Members of Morrison, capped by Cedar Mountain Formation, the entire section exposed in Recapture Creek and up to McCracken Point. **0.2**

75.3 Road forks; **go right** on county 216. **0.3**

75.6 Cross Recapture Creek. **0.2**

75.8 Before road curves right, **turn left** onto smaller dirt road. **0.3**

76.1 Pass through gate; type section of Recapture Member ahead. **0.8**

76.9 **STOP 4**. Here, with the help of the geologic map and stratigraphic section (Figs. 1.22, 1.23), we examine the type section of the Recapture Member of the Bluff Sandstone (Fig. 1.24). Note the intertonguing of Bluff eolianites with the redbeds at the base of the type Recapture, and the similarity of these basal Recapture strata (50 ft thick) to those of the Summerville seen at Stop 3. Gregory (1938) relied heavily on color in his original definitions; red = Recapture, green/yellow = Westwater. Thus, his original Recapture Member included the redbeds immediately

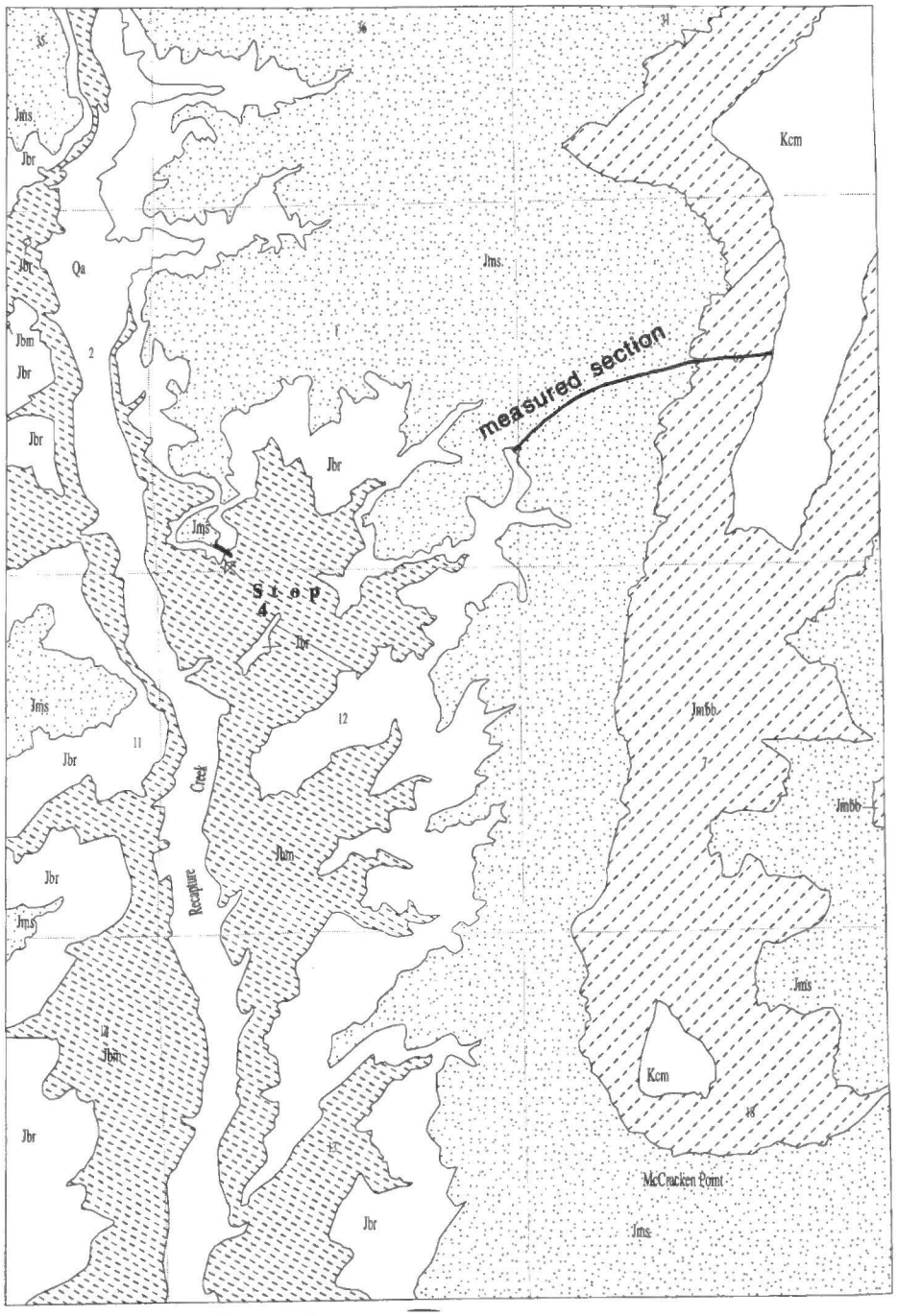

FIGURE 1.22. Reconnaissance geologic map of the Recapture Creek area in the vicinities of Stop 4 and McCracken Point. Geology by O. J. Anderson and S. G. Lucas.

overlying the Bluff, even though these beds differed in lithology, grain size, and sedimentary features from the Morrison Formation which overlies them. Understanding the original Recapture Member here in the type area is fundamental to the argument rejecting "Recapture" as a member of the Morrison in the San Juan Basin (Fig. 1.25).

The Morrison Formation, although considered nearly synonymous with uranium mineralization by many people, is not mineralized in this area. Even the experts on the geochemistry of uranium in the low temperature environment do not agree on the paragenesis and distribution of sandstone-hosted uranium mineralization. Considerably more is involved than the mere presence of volcanogenic (vitric) material in the overlying section, i.e., Brushy Basin Member claystones. The Brushy Basin Member is present throughout the outcrop area of the Morrison and indeed is virtually synonymous with Morrison Formation. The conventional wisdom is that dewatering of vitric-rich sediment of the Brushy Basin introduced fluids to the underlying porous sandstones. Apparently other factors also were important in localizing uranium deposition, including water chemistry, pH, Eh, temperature, dissolved organics, and post-depositional tilting. For additional information on this and associated subjects see Rautman (1980).

Sandstone-hosted uranium deposits in the Salt Wash

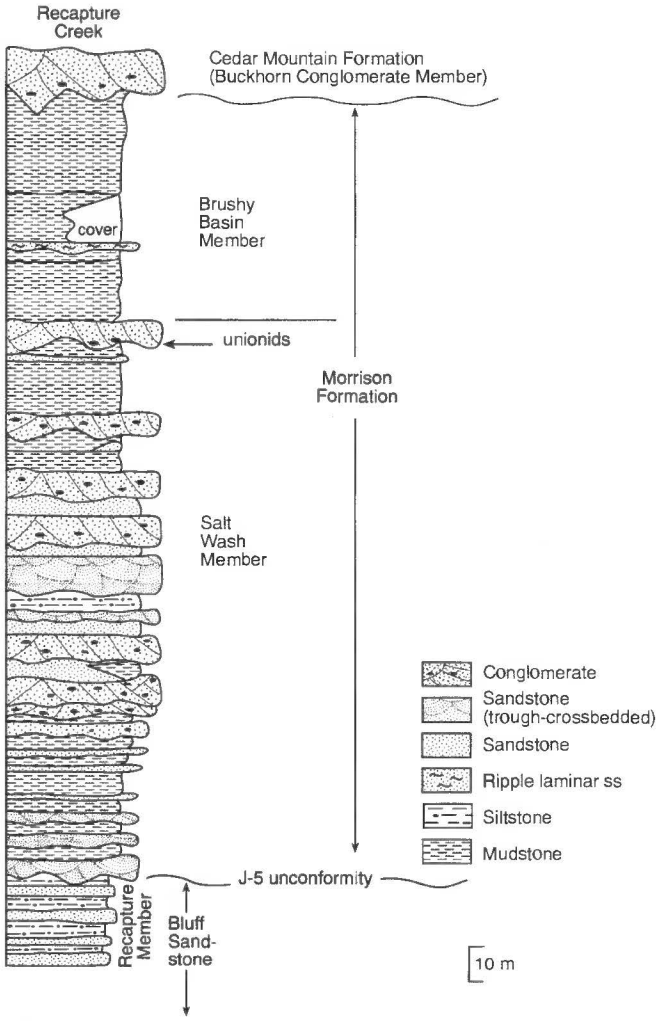

FIGURE 1.23. Measured stratigraphic section of Jurassic strata exposed in Recapture Creek. See Figure 1.22 for location of section.

FIGURE 1.24. Lectostratotype of Recapture Member of Bluff Formation (R), which overlies main body of Bluff (B) and is overlain by Salt Wash Member of Morrison Formation (S).

Member of the Morrison Formation have been known in southeastern Utah and northeastern Arizona since the 1910s, when they were first mined for radium. However, none are present in this area. A major discovery, north of here, by Charlie Steen in July 1952 fueled the uranium boom of the 1950s on the Colorado Plateau. The following account is revised and reprinted with permission from the National Mining Hall of Fame and Museum, Leadville, Colorado.

Charles August (Charlie) Steen's discovery of pitchblende in the Chinle Group in southeastern Utah's Big Indian district changed the course of the U.S. uranium industry. He proved that large, high-grade uraninite ore deposits could be found on the Colorado Plateau. His discovery helped ignite the 1950s uranium boom and made the impoverished prospector-geologist a wealthy and world-famous figure.

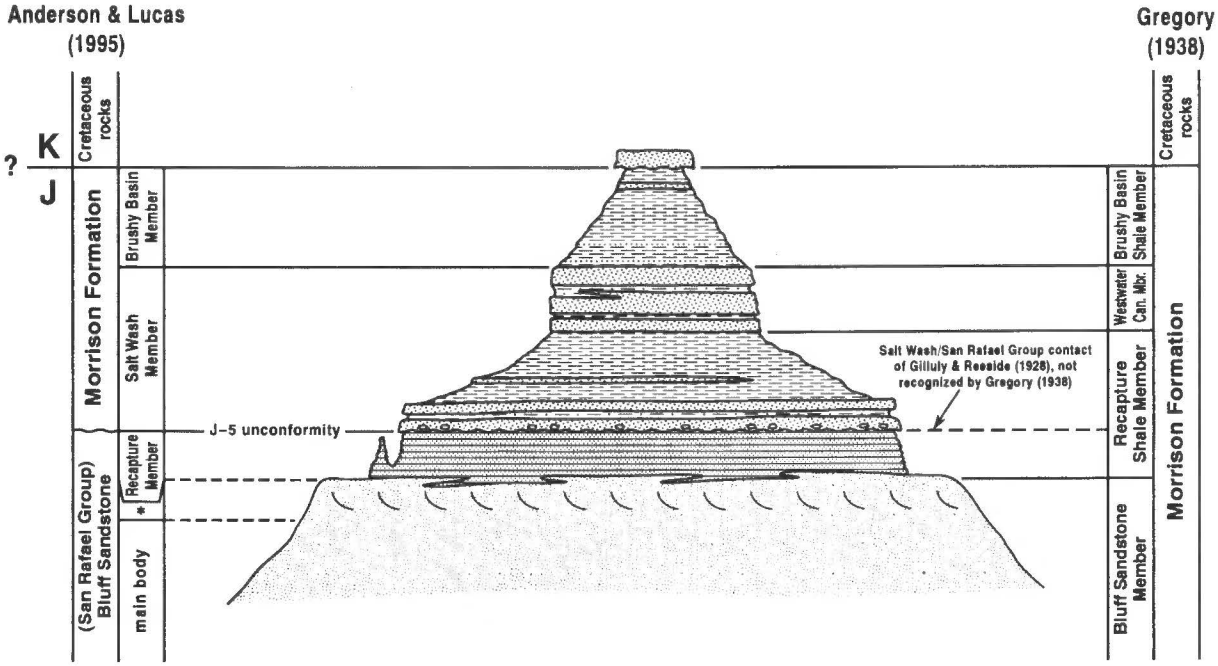

FIGURE 1.25. Diagram of stratigraphic section exposed at mouth of Recapture Creek contrasting the stratigraphic concepts of Gregory (1938) with those of Anderson and Lucas (1995).

In 1943, Steen graduated from the Texas College of Mines and Metallurgy at El Paso. He worked as a petroleum geologist in Bolivia and Peru before beginning his search for uranium in 1949. With his wife, M.L., and four young sons, Steen endured years of privation and hardship while he prospected the remote and desolate canyons and mesas of the Colorado Plateau. His four-year quest for uranium was not an erratic wandering. His search was based on his original geologic theory that uranium would be found concentrated along the flanks of anticlinal structures.

In 1951, Steen was drawn to the Lisbon Valley anticline some 75 mi north of here where low-grade uranium occurrences in the Cutler Formation attracted his attention. Although the area had been condemned as uneconomic by government experts, he figured the better grade uranium would be encountered down-dip and farther back from the meager rim outcrops. During spring 1951, he staked 12 claims covering this ground.

After raising a grubstake and obtaining a dilapidated, second-hand drilling rig from Bill McCormick, Steen had a 4 mi road built into his property. In July 1952, he started drilling on his Mi Vida claim. At a depth of 70 ft, the drill cored through 14 ft of a dark-colored sandstone unit low in the Chinle Formation. This proved to be the first commercial discovery of uraninite ore in the United States.

Steen then staked more claims and sank a shaft near his discovery drill hole. He mined the first of more than 9 Mt (10 million st) of uranium ore, worth more than $1 billion, that was produced from the Big Indian district during the next 30 years. Steen's rags-to-riches story caught the imagination of the press and public, and he became famous as the country's uranium king. In 1953, Steen and Bill McCormick bought the Big Buck claims for $2 million and formed the Standard Uranium Corp. to exploit the ore body adjacent to the Mi Vida Mine. In 1955, the pair formed the Uranium Reduction Co. and built the first privately financed uranium mill in the United States. In 1962, Steen sold the Mi Vida Mine and his interest in Uranium Reduction Co. to Atlas Corp. He applied the name Mi Vida to his restaurant which still operates on the north end of Moab.

Steen's venturesome nature and a series of bad investments cost him most of his fortune. Also, a serious head injury curtailed his prospecting career. In 1992, Moab, UT honored Charlie and M. L. Steen with a celebration to mark the 40th anniversary of Charlie's discovery and to recognize the couple's many contributions to the Moab area.

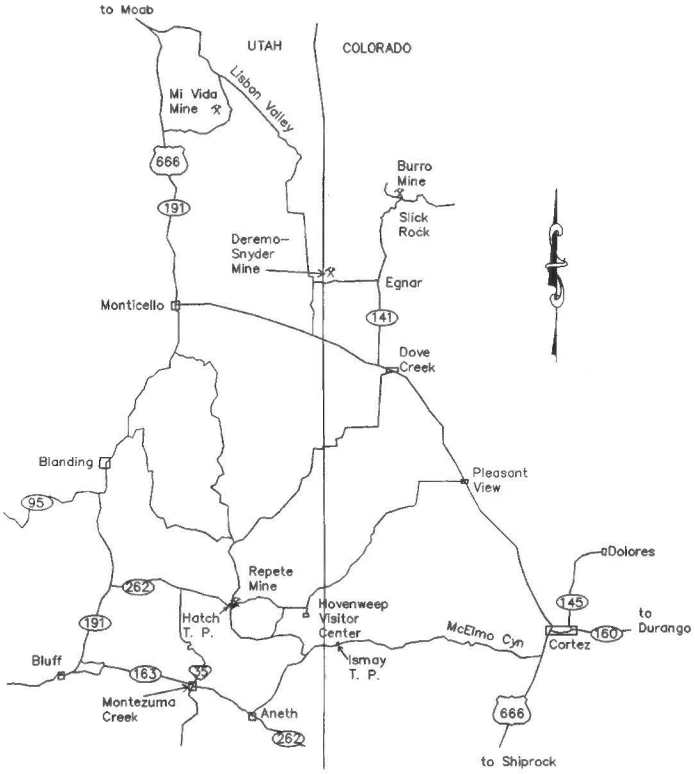

FIGURE 1.26. Map of selected uranium in Colorado-Utah border area.

METAMUNIRITE AND HAYNESITE FROM THE FOUR CORNERS AREA

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Occurrences of rare mineral species are scattered throughout the world, and the Four Corners area of the United States is no exception. The Four Corners sits on an edge of the Colorado Plateau, known for its deposits of uranium and vanadium. The type localities for seveeral minerals occur here. The following is a brief description of two of these minerals.

Metamunirite

In spring 1986 geologists Arnold Hampson and the author were at the Burro Mine, Slick Rock, San Miguel County, Colorado (Fig. 1.26). They were collecting samples of pascoite, $Ca_3V_{10}^{5+}O_{28}\cdot 17H_2O$, on the dumps when the author noticed a dense, black, vanadium-rich boulder, which had an area with a white efflorescent crust. The total area was only about 2.5 square inches, but it looked as if the white crust was composed of tiny, to 0.2 mm, acicular crystals. The associated minerals were efflorescent, orange pascoite and scales of gray metarossite, $CaV_2^{5+}O_6\cdot 2H_2O$. They occurred on a boulder composed of vanadium oxide minerals, probably corvusite, $(Na,Ca)\ V^{5+},V^{4+},Fe^{2+})_8O_{20}\cdot 4H_2O$; montroseite, $(V^{3+}, Fe^{3+})O(OH)$; and paramontroseite, VO_2. Efflorescent, white crusts of thenardite, Na_2SO_4, are common on the dumps, and I assumed that the acicular material was a common sulfate. A sample was ultimately sent to Dr. Howard Evans, Jr., a vanadium research chemist with the U.S.G.S. Dr. Evans x-rayed the material and immediately recognized it as the dehydrated form of munirite, $NaV^{5+}O_3(2-x)H_2O$. Munirite, found in Pakistan, was described in 1984. A dehydrated species was not described. This indicated that the material found at the Burro Mine was, potentially, a new mineral.

While Dr. Evans' research was underway I collected in the Deremo-Snyder Mine, west of Egnar, San Miguel County, Colorado. This was an active mine, and Mr. Phillip Allen, with UMETCO, had arranged for us to collect. Mr. Allen had already located some promising collecting areas. The collecting was about 700 ft underground, in a damp environment. We were in one area where efflorescent, orange pascoite crusts and crystals were common. The bright orange walls were quite spectacular. I noticed an oval-shaped, white efflorescent crust. It was about 30 by 13 cm and composed of colorless to white acicular crystals reaching 1 mm. Associated minerals were pascoite and rossite, $CaV_2^{5+}O_6\cdot 4H_2O$, on a dark vanadium-rich ore. It appeared to be the same as the unknown Burro Mine material, except of better quality. None of the material was encapsulated, and it readily dehydrated. Material was sent to Dr. Evans and confirmed to be the same as the Burro Mine material.

The research was submitted to the International Mineralogical Association (I.M.A.), approved, and later published. The new mineral was named metamunirite. It is orthorhombic and the formula is $B\text{-}NaV^{5+}O_3$.

More recently, I acquired an old sample of pascoite from a mineral dealer's stock, labeled as being from the Mi Vida Mine, San Juan County, Utah. On it are some 0.5 mm acicular crystals that resemble metamunirite. A quick test to distinguish metamunirite from thenardite is to place a fiber into dilute HCl, and observe it under magnification. Metamunirite dissolves and briefly colors the surrounding liquid orange, an indicator of vanadium. Thenardite dissolves without any discoloration. The Mi Vida specimen gave the orange discoloration in HCl, and it appears to be metamunirite. Thus, metamunirite may be found at other localities on the Colorado plateau, especially if thenardite (i.e., sodium) is common.

Haynesite

In summer 1986 I visited the Repete Mine to collect mineral specimens. Three secondary uranium minerals were found in the ore piles outside the mine. Permission was given to collect inside the mine, and the miners showed me where the secondary minerals were located. One of the minerals formed greenish-yellow spheres to about 1 mm. Another was yellowish, relatively massive, in thin mudstone cracks, and had a yellow-green fluorescence. The most common mineral occurred as yellow, acicular crystals to about 1 mm. Samples were sent to Dr. Peter Modreski, with the U.S.G.S., and to Paul Hlava, Sandia National Labs. They came up with comparable microprobe results, indicating a potential new mineral.

A few more visits were made to the mine, and a total of about ten boxes of the potential new mineral was collected. Eventually, samples were sent to Dr. Michel Deliens, in Belgium. Dr. Deliens and Dr. Paul Piret identified the microscopic spheres as boltwoodite, $HK(UO_2)SiO_4 \cdot 1.5H_2O$, and the highly fluorescent mineral as andersonite, $Na_2(UO_2)(CO_3)_3 \cdot 6H_2O$. They submitted their research on the acicular material to the I.M.A. The minerals was approved, and published as haynesite. It is orthorhombic and the formula is $(UO_2)_3(SeO_3)_2(OH)_2 \cdot 5H_2O$.

During active mining there were four accessible adits at the Repete Mine. The mine has been inactive since January 1987 and caving has now limited the access to just a single adit. Currently, the only readily collectible mineral is boltwoodite. If a person is careful, it can be found near some of the mine entrances. There is still some haynesite underground, but the lack of ventilation in the mine, and caving, makes collecting unsafe.

The Repete Mine is in the NE¼, SE¼ of section 8 and NW¼, SW¼ of section 9, T39S, R25E. It is 21.5 mi southeast of Blanding, Utah, and 2.5 mi east-northeast of the Hatch Trading Post. It can be found on the Cajon Mesa 15-minute quadrangle map.

After stop, turn around and return to highway. **1.1**

78.0 Road forks; **turn left** and ascend hill. **0.3**

78.3 Salt Wash sandstones well exposed on hill. **0.2**

78.5 View of McCracken Point ahead reveals Salt Wash–Brushy Basin–Cedar Mountain–Dakota section (Fig. 1.27). **1.0**

79.5 Road curves left. **0.1**

79.6 Junction with paved US-163. **Turn left** and proceed E toward Aneth. **15.9**

95.5 Intersection with San Juan County Road 402 on left which leads to Ismay; continue E and cross McElmo Creek. **0.3**

95.8 Aneth. Note that the floodplain of the San Juan River is broader here, where it is a stripped surface developed on the Bluff, but narrower to the W where it is cut into the Bluff. **0.4**

96.2 Leave Aneth. **0.6**

96.8 Aneth Point to left exposes Brushy Basin–Cedar Mountain–Dakota section. **1.3**

98.1 Aneth boarding school on right. **0.8**

98.9 Highway ascends through upper sandstones of Salt Wash Member. **0.2**

99.1 Highway crosses Salt Wash–Brushy Basin contact. **0.5**

99.6 Peter's Nipple at 12:00 has slopes of Brushy Basin Member with Cretaceous cap. Bench we drive on for next few miles is developed low in the Brushy Basin Member. **2.2**

101.8 Sleeping Ute Mountain at 9:30–10:30. **3.4**

105.2 Cross Marble Wash. **0.3**

105.5 Leave Utah and the Navajo Reservation; enter Colorado and the Ute Mountain Reservation on Colorado Highway 41. **1.0**

106.5 Highway has now climbed onto Dakota Formation plateau with low hills of Mancos shale, visible here to the NE and SE. Note Sleeping Ute Mountain on left to N of us. **0.9**

107.4 Note carbonaceous shale/coal of Dakota Formation on left. **2.1**

109.5 Road is on Mancos Shale; at 9:00–9:30 Bridge Creek Limestone Member caps low hills. Producing well on right is on the south edge of the small Sage Hen field, one of the Colorado oil fields of the Paradox Basin. Completed in January 1994, production is from the Ismay zone of the Paradox Formation; operator is Petro Corp, Inc. **1.7**

111.2 At crest of hill, note Shiprock at 1:00, and the Carrizo Mountains at 2:00. **3.8**

115.0 Junction of Colorado 41 and US-160; **turn right** to proceed toward Four Corners Monument. **0.8**

115.8 Note light-colored outcrops of fossiliferous Bridge Creek Member of Mancos Shale. This calcareous unit correlates with the upper part of the Greenhorn Formation. **2.0**

117.8 Carbonaceous shale in Dakota Formation to left; Graneros–Greenhorn–Carlisle interval of Mancos Shale visible to right. **0.7**

118.5 Highway begins descent to San Juan River. Gravel pit developed in terrace gravels to right. **1.2**

119.7 Cross San Juan River; note outcrops of Morrison Brushy Basin Member (green claystones) capped by Cedar Mountain Formation on N bank of river. **0.8**

120.5 Junction with Colorado 597; **turn right** to Four Corners Monument. **0.5**

121.0 Enter monument (Fig. 1.28), **STOP 5.** Here, we examine the Cedar Mountain Formation (described earlier in minipaper) and Brushy Basin Member of the Morrison Formation (Fig. 1.29) and discuss depositional environments of the upper Morrison. Note that the upper part of

FIGURE 1.27. Panoramic view looking east of Recapture Creek shows very mappable lithostratigraphic units—Bluff (B), Recapture (R), Salt Wash (S), Brushy Basin (BB) and Cedar Mountain (C).

FIGURE 1.28. The fabled monument at the Four Corners, thought by some to have been the goal of Coronado's expedition.

the Brushy Basin Member here contains sandstone bodies with conglomeratic lags and crossbedded sandstone units, some of which are laterally accreted foresets. These clearly represent deposition by meandering river channels, not in a large, shallow lake, such as the postulated Lake T'oo'dichi' of Turner and Fishman (1991). Admittedly much of the Brushy Basin was deposited in a lacustrine environment, but we contend these consisted of floodplain lakes, some of considerable size, associated with the vast Morrison fluvial system that developed in Late Jurassic time.

Paleoflow directions in the underlying Salt Wash Member of the Morrison (not exposed at this site) are generally southeastward and eastward (Craig, 1955). It has an intertonguing relationship with the overlying, claystone-dominated Brushy Basin and thus in typical fluvial fashion Morrison grain sizes become finer upward. In part the reason for this was the abundance of volcanic ash in the upper part of the drainage system, due to extensive back-arc silicic volcanism in the area to the west in eastern Nevada and adjoining areas (Kowallis et al., 1991). Reworking and devitrification of the volcanic material resulted in extensive smectite facies in the claystones of the Brushy Basin Member. These may be noted in a walk through the section exposed here. Commonly, however, the lowermost facies of the Brushy Basin Member are not as smectitic as the overlying strata. Where the Brushy Basin is smectitic at its base the Salt Wash Member is

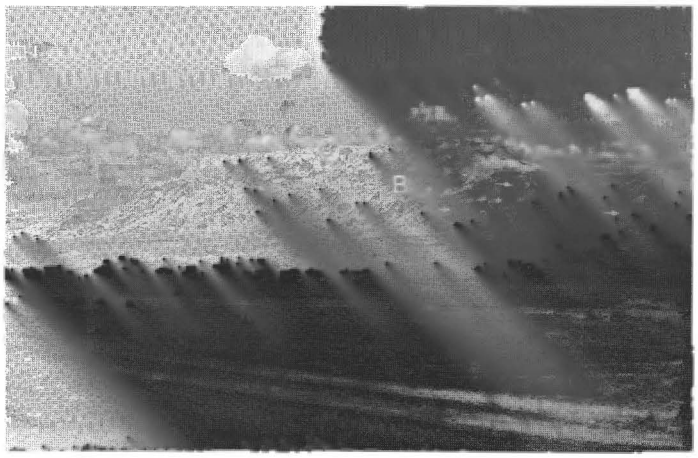

FIGURE 1.29. Strata of Brushy Basin Member of Morrison Formation (B) have large fluvial channels (arrows) and are overlain by Lower Cretaceous Cedar Mountain Formation (C) here at Stop 5.

commonly absent or thin, indicating that the basal Morrison unconformity is more profound in those areas (Anderson and Lucas, unpublished data).

The Carrizo Mountains Diorite forms the core of the Carrizo Mountains (due south on skyline). Recent radiometric age dates are presented by Semken et al. (this volume). After the stop, turn around and retrace route to US-160. **0.5**

121.5 Junction US-160; **turn left** and proceed N. **0.7**

122.2 Cross San Juan River. **2.0**

124.2 The Cretaceous section exposed here is in ascending order: Dakota, Graneros, Bridge Creek, Carlisle, Juana Lopez. **0.7**

124.9 Ledgy white limestone over gray slope to left (Fig. 1.30) is sandy limestone of Bridge Creek beds of the Mancos Shale containing fossils of *Pycnodonte newberryi* just below it (Fig. 1.31). **2.1**

127.0 Junction with Colorado 41. Continue N to Cortez on US-160. Mancos Canyon to E/SE. **2.6**

129.6 Cross bridge over Aztec Creek. Mesa to E is capped by Juana Lopez Member of Mancos. **0.9**

130.5 Note Mancos (Carlile equivalent) section on mesa to E (Fig. 1.32). **2.2**

132.7 Juana Lopez Member of Mancos is just above road level here. **2.6**

135.3 From 11:00 to 11:30, mesas and buttes are capped by Point Lookout Sandstone above slopes of Mancos Shale. Chimney Rock at 1:00. Tanner Mesa at 2:00 is capped by Cliff House Sandstone above Menefee slope over Point Lookout. **2.8**

GEOLOGIC FRAMEWORK OF CRETACEOUS AND TERTIARY ROCKS IN THE SOUTHERN UTE INDIAN RESERVATION AND ADJACENT AREAS

William M. Aubrey

(Reprinted from U.S. Geological Survey Bulletin 1505-B, 1991, R. S. Zech, ed.)

Cretaceous and Tertiary rocks on the Southern Ute Indian Reservation in southwestern Colorado represent a variety of depositional environments. The sediments of the lower Cretaceous Burro Canyon Formation were deposited on an alluvial plain. Upper Cretaceous rocks consist of marine,

FIGURE 1.30. Ledgy white mesa cap of Bridge Creek Member of Greenhorn Limestone above dark gray slope of Graneros Shale.

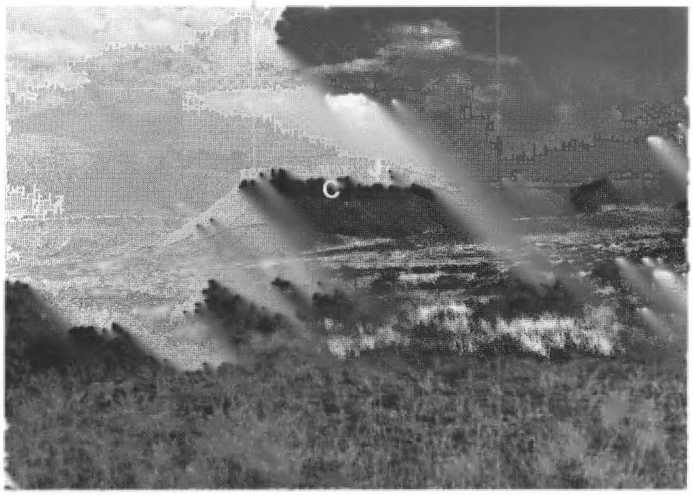

FIGURE 1.32. Juana Lopez Member (J) of Mancos Shale overlies Carlile Member (C).

coastal, and alluvial deposits that accumulated in or adjacent to the Western Interior seaway. A drop in sea level at the end of the Early Cretaceous caused streams to cut valleys into the top of the Burro Canyon [Burro Canyon = Cedar Mountain Formation; see Lucas and Anderson this road log]; forming a regional unconformity. Regression of the Early Cretaceous sea was followed by a transgression into southwestern Colorado that resulted in the deposition of the fluvial, deltaic, and marginal-marine sediments of the Upper Cretaceous Dakota Sandstone and overlying marine Mancos Shale. The Mesaverde Group forms a generally northeasterly prograding deltaic and strand-plain wedge that intertongues with the upper part of the underlying Mancos and the lower part of the overlying marine Lewis Shale. The marginal-marine sediments of the Pictured Cliffs Sandstone, which overlie and interfinger with the upper part of the Lewis Shale, were deposited during the final regression of the Western Interior sea from southwestern Colorado near the end of late Cretaceous time. The Pictured Cliffs is overlain by the alluvial, paludal, and lacustrine deposits of the uppermost Cretaceous Fruitland Formation and Kirtland Shale.

Tertiary rocks on the Reservation include parts of the Animas, Nacimiento, and San Jose Formations. These rocks, which are composed of sediments that are mostly fluvial in origin and have northerly sources, are the result of episodic uplift north of the San Juan basin during the early part of the Laramide orogeny. Tertiary dikes, sills, and stocks which are composed of basalt, diabase, and andesite, intrude the sedimentary rocks on the eastern side of the Reservation.

138.1 Yellow ledge on left is Juana Lopez Member of Mancos Shale. **1.1**

139.2 Cross Navajo Springs Wash. **0.7**

139.9 Chimney Rock to right (Fig. 1.33) is Point Lookout Sandstone transitional over Mancos Shale. At 11:00 is Squaw and Papoose. **0.5**

140.4 Junction with US-666; **turn left** and proceed N to Cortez. **1.0**

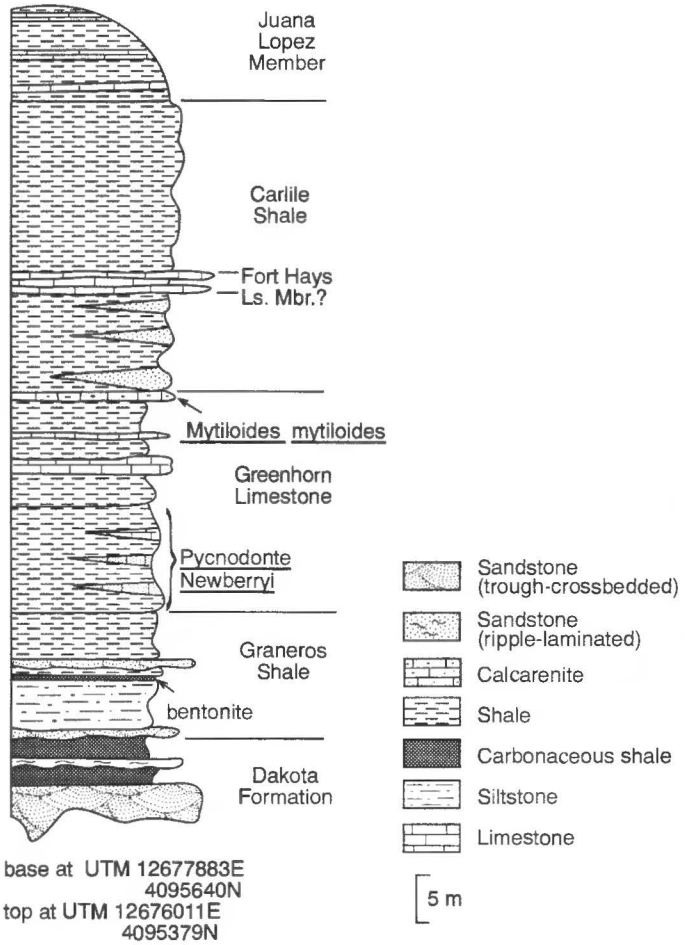

FIGURE 1.31. Measured section of Upper Cretaceous strata exposed near mile 124.9.

FIGURE 1.33. Chimney Rock and mesa beyond are capped by Point Lookout Sandstone, which overlies slopes of Mancos Shale.

141.4 Squaw and Papoose at 1:30; formed in lower part of Point Lookout Sandstone. **7.6**

149.0 Towac gambling casino on left with Sleeping Ute Mountain as backdrop. A legend is associated with Sleeping Ute Mountain. Apparently in the good old days the sleeping Ute was the Great Warrior God. He came to help fight against the evil ones who were causing a lot of trouble. A tremendous battle followed between the Great Warrior God and the evil ones. As they jumped about bracing for the fight, their feet pushed the land into mountains and valleys (evidence for catastrophism?). This is how the local area came to be as it is today. The Great Warrior God was hurt in the fray, so he lay down to rest and fell into a deep sleep. The blood from his wounds turned into living water for all creatures to drink.

If you look carefully and with a little imagination, you can recognize the Great Warrior God lying down to form Sleeping Ute Mountain. Etched against the sky is the perfect image of a giant man lying on his back. A feathered headdress streams outward from his reclining head. Arms are folded carefully across his chest. Thighs, knees, feet, and even his toes can readily be discerned.

Sleeping Ute Mountain is an Oligocene laccolithic diorite porphyry intruded into the Mancos Shale. Its highest peak is about 9900 ft above sea level. The highway extends down Montezuma Valley. Mesa Verde is east (left) and Sleeping Ute Mountain is west (right). **0.9**

149.9 Cross Ismay Draw, leave Ute Mountain Reservation. **0.2**

150.1 Rocky Ridge at 2:00 (Fig. 1.34) exposes Mancos–Point Lookout–Menefee–Cliff House section. **4.0**

154.1 Pulpit Rock at 3:00; escarpment exposes in ascending order Mancos Shale–Point Lookout Sandstone (cliff), Menefee Formation (vegetated slope), Cliff House Sandstone (top cliffs). **1.8**

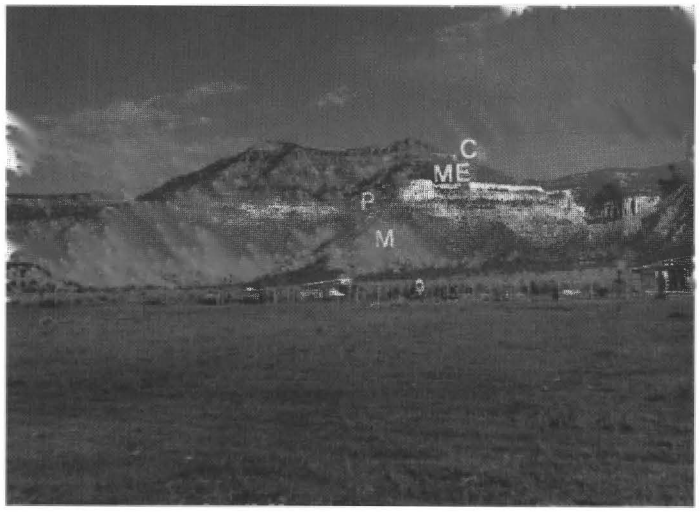

FIGURE 1.34. Rocky ridge exposes Mancos (M), Point Lookout (P), Menefee (ME) and Cliff House (C) Formations.

155.9 Juana Lopez Member of Mancos defends mesa to right with water tank on it. **1.6**

157.5 McElmo Canyon road to left; continue N. **0.6**

158.1 Headwaters of McElmo Creek. **0.2**

158.3 Cortez city limits; Dakota Formation crops out on both sides of road. **1.8**

160.1 US-160 divides; **proceed right** toward Durango. **2.0**

162.1 Holiday Inn, Cortez.

End of First-day Road Log.