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ABSTRACT

A reasonable interpretation of the geologic history of the Colorado River in the Basin and Range province can be put together by considering the work done by several geologists in the Imperial Valley, California, the Parker–Blythe–Cibola area, California and Arizona, and, the Lake Mead and Hualapai Plateau areas, Arizona.

In the Imperial Valley, the Imperial Formation, whose age has been interpreted variously as late Miocene or early Pleistocene but most commonly Pliocene, records a transgression of the marine waters of the Gulf of California and deposition of sediments very probably of Colorado River origin. These sediments contain reworked Late Cretaceous foraminifers derived from the Mancos Shale of the Colorado Plateau. Later sediments record a gradual change from marine to continental conditions.

In the Parker–Blythe–Cibola area, extending along the Colorado River, the Bouse Formation (Metzger, 1968), of Pliocene age, records a marine transgression in the form of an embayment of the Gulf of California. A possible northward decrease in salinity, evidenced by faunas in the Bouse Formation, and a volume of sediments too large to be accounted for by local sources, suggest that a large river emptied into the Bouse embayment from the north. Although other streams and washes may have contributed sediments to the embayment, it is probable that the main source was the ancestral Colorado River. The Bouse Formation does not contain Mancos-type foraminifers but, in some surface exposures, does include Late Cretaceous coccoliths, probably of relatively local derivation. Deposits younger than those of the Bouse Formation consist of Colorado River alluvium generally unconformable on the Bouse, but locally conformable.

In the Lake Mead area, deposits as young as 18 to 20 m.y. indicate drainage northward, across the present site of Lake Mead, and northeastward onto the Colorado Plateau. None of these drainages can be interpreted as being an ancestral Colorado River. The next youngest deposit is the Muddy Creek Formation, which was laid down in interior basins formed when basin-range faulting disrupted the older topography and drainage some time after 18 to 20 m.y. ago. There was no Colorado River at this time. Deposition of the Muddy Creek Formation ended some time after 10.6 m.y. ago. Younger deposits reflect the Colorado River which, by 3.3 m.y. ago, was a well-incised stream flowing within 350 ft of its present grade.

Deposits and erosion surfaces on the Hualapai Plateau reflect drainage northeastward onto the region of the present plateau from the Basin and Range province until about 18 m.y. ago, when the two provinces became separated topographically by movements along the Grand Wash fault. No Colorado River existed before the faulting. After faulting, drainage became interior. In none of the areas is there evidence to suggest that the Colorado River has departed appreciably from its present course.

This information leads to the following hypothesis: until about 10.6 m.y. ago, or shortly thereafter, there was no Colorado River. After that date, waters of the Gulf of California invaded the Bouse embayment, and the ancestral Colorado River became established in the Lake Mead area. The river emptied into the embayment, which it progressively filled with its sediments from north to south. At this time, the head of the river had not yet reached areas where the Mancos Shale cropped out (probably east of the Kaibab upwarp). As the sediment fill continued to build toward and into the Imperial Valley area, the headwaters of the river breached the uplift and reached the Mancos Shale. The sediments then continued

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to build southward, filling the head of the Gulf of California, a process still going on. By 3.3 m.y. ago, the river was a well-established stream in the Lake Mead area, where it had cut to within a few hundred feet of its present grade.

By this interpretation neither the Bouse Formation nor the part of the Imperial Formation containing Colorado River material is older than 10.6 m.y. If true, the Bouse Formation is in part older than and in part equivalent in time to the Imperial Formation.

INTRODUCTION

The origin, age, and history of the Colorado River have long been of interest to geologists, partly because unusual conditions must have existed to produce the Grand Canyon, and partly because great difficulties are encountered in explaining how the river could establish a course so independent of the major topographic and structural features that lie across its path. Probably the most impressive of these features, and the one that raises most problems in understanding the history of the river, is the Kaibab upwarp, a structural and topographic high trending approximately north, directly athwart the general course of the river at the eastern, or upstream, end of the Grand Canyon. Largely because of this, recent work on the history of the Colorado River often considers this upwarp as the dividing line between an upper and lower section of the Colorado River, and therefore tends to treat the two sections individually, subsequently attempting to tie them together across the upwarp.

The scope of the present paper is restricted to the section of the Colorado downstream of the Kaibab upwarp, specifically from near the mouth of the Grand Canyon to about 100 mi upstream from the mouth of the river. Its purpose is to summarize and tie together results obtained by various geologists from key areas in this section. Although this part of the river is largely in the Basin and Range province, it has a profound influence on interpretations of the history of the Grand Canyon and indeed of the river as a whole.

Information currently available is fragmentary, obtained from widely scattered sources, and in some instances rather controversial. Nevertheless, it should be brought together to provide a frame of reference that underscores key information, clarifies the relations between the various areas, and points out problems still unsolved. In addition, this information supports a hypothesis that, though highly tentative, can nevertheless provide a context for further research. This hypothesis is controversial. I present it in the deliberate hope that it will stimulate productive discussion of the problem and perhaps bring out important information not now generally available. This paper does not attempt to be an exhaustive treatment of the subject, and many questions are touched on lightly or not at all. Some of these questions will be discussed in a paper being prepared by Lucchitta and Young. Others are treated in syntheses such as those of McKee and others (1967), and C. B. Hunt (1969), which provide a broad perspective and points of view in part alternative to that presented here.

The four areas considered in this report are (Fig. 1): Imperial Valley; Parker–Blythe–Cibola area; Lake Mead area; and the Hualapai Plateau. Of these, I am personally acquainted with the last two, especially the Lake Mead area. Information for the other areas has been obtained from the literature and from communication with geologists who have experience with these areas.

IMPERIAL VALLEY AREA

This synthesis is made chiefly from the papers of Allison (1964), Dibblee (1954), Durham (1950), Durham and Allison (1960), Merriam and Bandy (1965), and Muffler and Doe (1968). Additional information is obtained from Smith (1970) and Bukry (1969, 1970, written commun.).

The Imperial Valley is in the Salton Trough, a tectonic feature consisting of the northwest or landward extension of the Gulf of California structural depression. The valley is traversed at its southeastern end by the Colorado River, which in that area is about 100 mi upstream from its mouth. The highlands bordering the valley reach altitudes of 6,000 ft in the Peninsular Range to the west. The San Andreas fault zone runs along the eastern margin of the valley (Fig. 1).

The Cenozoic fill of the valley, as much as 20,000 ft thick, can be subdivided into two groups: (1) coarse sediments of local derivation at the margins of the valley, grading basinward into (2) fine-grained sediments, at least in part of distant derivation. The deposits and their mutual relations are shown in Figure 2.

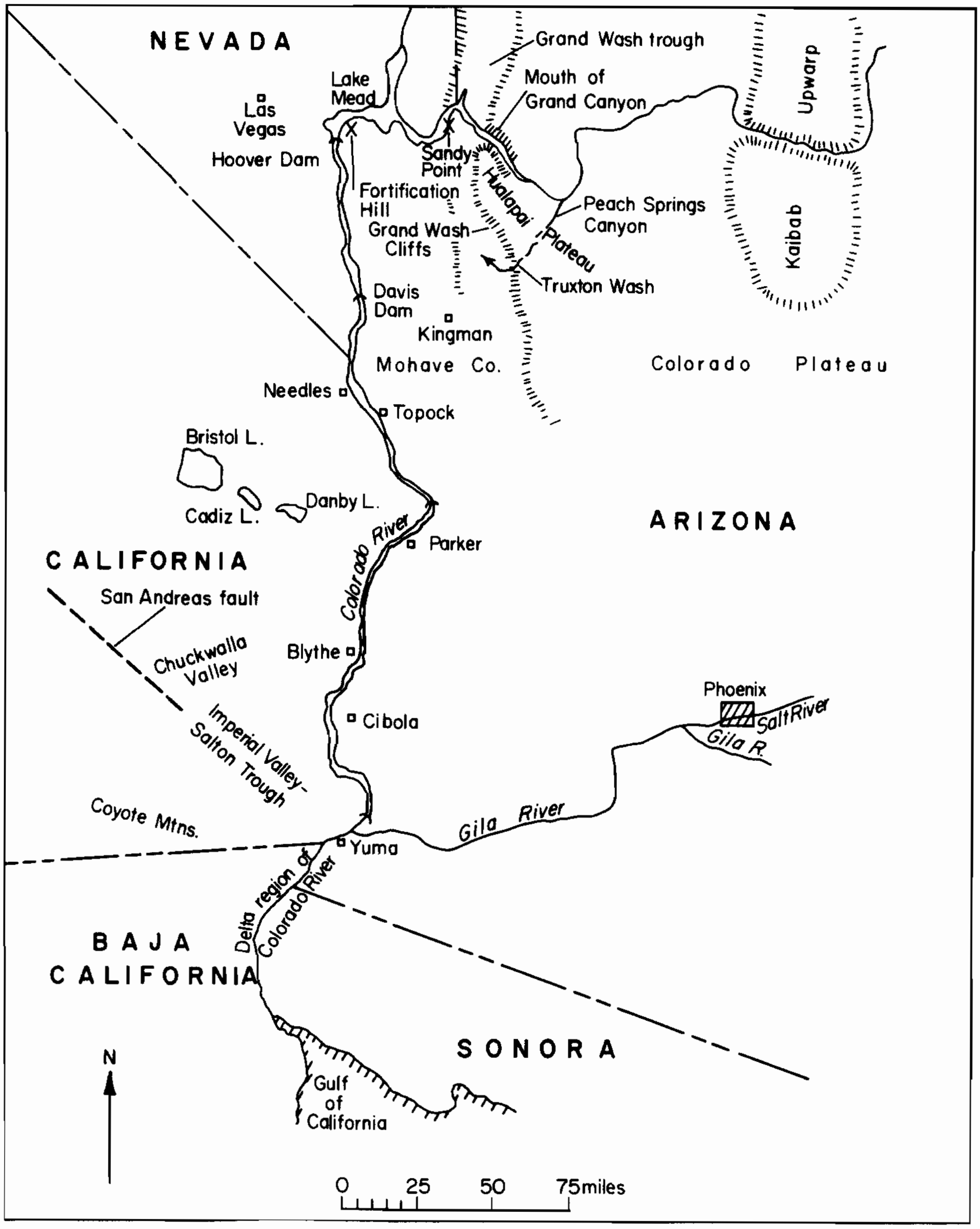

Figure 1. Location map.

The Imperial Formation consists of marine fine grained sandstone, siltstone, and claystone; younger deposits are nonmarine. The Imperial Formation also marks the lowest horizon at which far-traveled material of postulated Colorado River origin is present. This origin is inferred by comparing grain size, mineral composition, chemical composition, and trace element content of the Imperial Formation with similar parameters for undoubted Colorado River sediments (recent delta, delta in Lake Mead from Merriam and Bandy, 1965; recent deltaic sediments in the Salton Basin from Muffler and Doe, 1968). As a similar origin applies to the fine-grained material overlying the Imperial Formation, according to Muffler

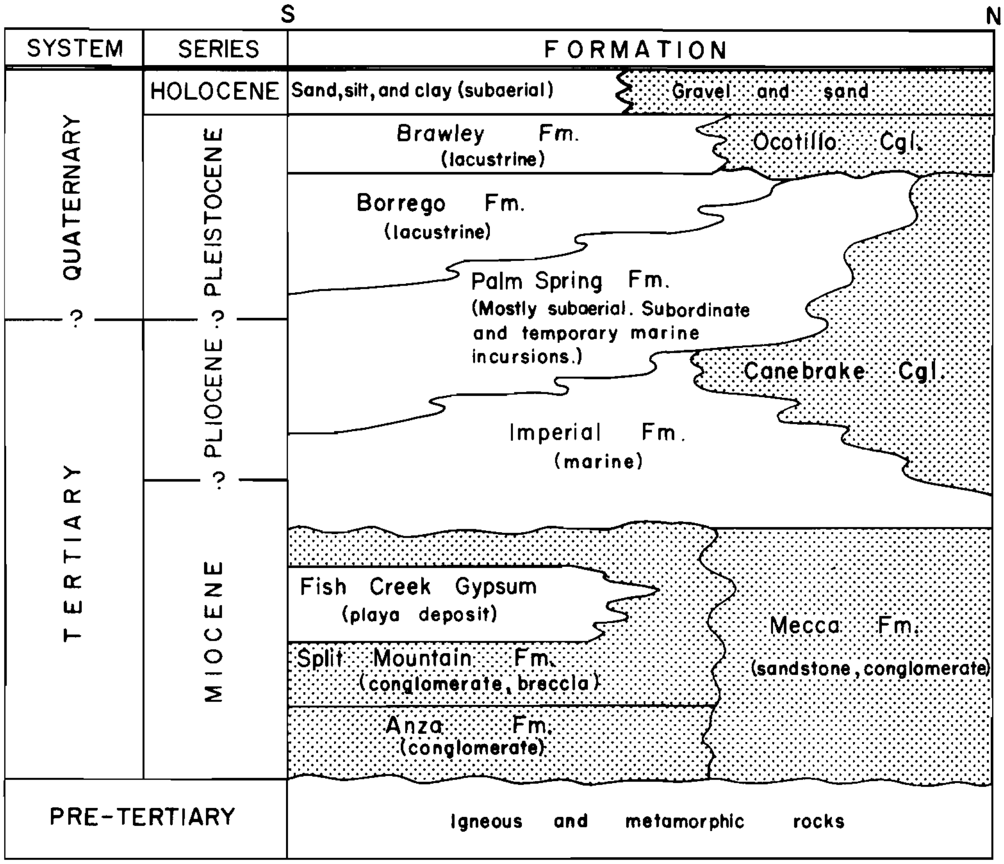

Figure 2. Generalized stratigraphy of the Salton trough. From Muffler and Doe (1968, Fig. 2). This figure is presented here to show stratigraphic relations. See text for disagreement on the age of Imperial Formation. Coarser grained deposits are shown as screen pattern.

and Doe (1968), the entire fine-grained section above and including the Imperial consists essentially of deltaic deposits of the Colorado River.

Late Cretaceous foraminifers similar in type and mode of preservation to those of the Mancos Shale of the Colorado Plateau have been reported from the Imperial and younger formations by Merriam and Bandy (1965) and by Allison (1969, written commun.), who found them associated with Late Cretaceous coccoliths. According to Bukry (1970, written commun.), these coccoliths are also found in the Imperial Formation of the Coyote Mountains (Fig. 1); this flora is similar to the less abundant one taken from the Bouse Formation (see below) along the Colorado River. According to Smith (letter to Bukry, 1968) the Coyote Mountains material also contains a shallow marine foraminiferal fauna that is mostly Pliocene to Holocene, but that is associated with a puzzling abundance of *Bolivina guadalupae* Parker, characteristic of the middle and late Miocene of California.

Whereas the Late Cretaceous coccoliths are present in rocks cropping out near the Imperial Valley (for example, the Penisular Range) and could thus be of relatively local derivation, the Late Cretaceous foraminifers must be reworked because they are found only in the Mancos Shale of the Colorado Plateau and not locally. The Miocene and Pliocene foraminifers lived in the Imperial Sea, which may have extended as far north as the present Danby and Cadiz dry lakes (Durham and Allison, 1960).

The age and correlation of the Imperial Formation are controversial. Earlier reports placed the formation in the late Miocene or early Pliocene, but in the more recent view it generally is considerably younger. Thus, Dibblee (1954) considers the formation of "upper Miocene or possibly lower Pliocene age"; Durham (1950), early Pliocene; Merriam and Bandy (1965, p. 913), late Miocene for some sections, but younger, perhaps Pliocene, for others; Muffler and Doe (1968), late Miocene to Pliocene (after Dibblee, 1954 and Merriam and Bandy, 1965). Bandy now considers the Imperial Formation younger than 6 or 7 m.y. (1968, written commun.), whereas Allison (1969, written commun.) stated that "most Imperial faunas seem to be close to the Pleistocene–Pliocene boundary or above." Allison however, did not discount the possibility of finding rocks of Imperial Formation type with Miocene fossils (1968, written commun.). On the other hand, Wendell Woodring considers it late Miocene or early Pliocene (1971, oral commun.), and Louis J. Simon feels that it is Miocene (Patsy Smith, 1970, oral commun.). The foraminifers described by Smith (see above) indicate a Pliocene to Holocene age, except for the common *Bolivina guadalupae* Parker, which points to a late Miocene age for at least part of the formation.

The problem of the age and correlation of the Imperial Formation was summarized by Allison (1964), who stated that a correlation between much of the Imperial and the San Diego Formation of Southern California is suggested by the presence of the warm-water echinoid, *Encope tenuis* Kew in both formations, which indicates a Pliocene age. Furthermore, strata with the oldest recognized Imperial Formation faunas near San Felipe, Baja California, are underlain unconformably by marine diatomite and mudstone of late Miocene age, which have as yet failed to produce the reworked Upper Cretaceous microfossils common in the Imperial Formation (Allison, 1969, written commun.). The Imperial Formation would thus seem to be mostly younger than late Miocene and probably of Pliocene age. But if the boundary between the Pliocene and the Pleistocene is to be drawn at the base of the marine Calabrian and nonmarine Villafranchian stages as decided by the 1948 International Geological Congress, the San Diego and, by correlation, the Imperial would be more likely Pleistocene than Pliocene in age (Allison, 1964). These uncertainties, which probably stem from the Imperial being a unit that includes rocks of different ages in different places, compound the difficulties encountered in placing the Imperial Formation in context with radiometric dates obtained elsewhere along the Colorado River (see below).

Whatever the exact age of the Imperial Formation, in Imperial time a large river carried material similar to that of the Colorado River into the sea occupying the general area of the present Salton Trough.

Parker–Blythe–Cibola Area

Deposits present in and near the valley of the Colorado River from near Yuma to as far north as Davis Dam (Metzger, 1969, oral commun.) have been studied by Metzger (1968), who has named them the Bouse Formation. Smith (1970) has studied the fauna of the Bouse and made paleoecologic interpretations.

The information presented below is from Metzger's 1968 paper except where otherwise indicated.

The Bouse Formation is exposed as scattered erosional remnants attaining a maximum thickness of 215 ft. In the subsurface it is present throughout the area and attains a maximum known thickness of 767 ft; the maximum actual thickness may be considerably greater. Metzger recognizes three units: (1) basal limestone, overlain by (2) interbedded clay, silt, and sand, mostly evenly bedded but with local crossbedding in the sand layers; both contemporaneous with (3) tufa that was being deposited against topographic highs formed by older rocks. The Bouse rests unconformably on a Miocene (?) fanglomerate of local derivation and is generally overlain by Colorado River alluvium resting on an erosional surface. Near Yuma, however, the Bouse grades upward into, and interfingers with, the Colorado alluvium (Metzger, 1969, oral commun.).

Fossils are common in the Bouse Formation, but the number of species is small. Represented are foraminifers, mollusks, ostracodes, charophytes, and barnacles. The fossils, though not adequate to assign an age, show that the environment of deposition was brackish water and suggest that this environment was progressively fresher to the north. Smith (1970) admits the presence of brackish water, but denies the existence of definite trends in salinity. Her data, however, are not incompatible with the near-estuarine environment and with the northward decrease in salinity postulated by Metzger. No Mancos-type foraminifers similar to those in the Imperial Formation have been found, but identical coccoliths have been obtained from the surficial exposures of the Bouse though not from subsurface rocks (Patsy B. Smith, 1969, written commun.). Metzger feels that the stratigraphic level of these coccolith-bearing rocks is not known at this time (Metzger, 1968, oral commun.).

The nondevitrified fraction of a tuff layer near the base of the Bouse Formation has yielded K/Ar ages of 5.4 ± 0.2 m.y. (Damon, 1972, oral commun.) and 8.1 ± 0.5 m.y. (Damon, 1970). Damon (1972, oral commun.) considers the 5.4 m.y. date to be the most reliable. An earlier determination on the same tuff but without separation of the nondevitrified material yielded an age of 3.02 ± 1.15 m.y. (Damon, 1968). This represents a minimum age for the tuff. Vertebrate fossils of middle Miocene age are found in steeply dipping beds in the Sacramento Mountains west of Needles, California. Similar beds occur south of Needles, where they are overlain unconformably by Miocene (?) fanglomerate which, in turn, is overlain by the Bouse. The Bouse therefore, cannot be older than middle Miocene (Metzger, 1970, written commun.). Metzger feels that the formation can be assigned safely to the Pliocene. Smith (1970) states that the Yuma section and, by inference, the Parker–Blythe–Cibola section are post-Miocene, and probably Pliocene.

According to Metzger, Bouse-like deposits extend into the Chuckwalla Valley, possibly into the Cadiz and Danby dry lakes (which deposits may also correlate with the Imperial Formation, see above) northward to Cottonwood Valley north of Davis Dam, along the lower Gila River, and into the Salt River Valley west of Phoenix, Arizona.

It would appear, then, that in Bouse time, about 5 m.y. ago, an embayment of the Gulf of California extended into the Parker–Blythe–Cibola area as well as some of the surrounding country, and probably reached as far north as Davis Dam. A large river emptied into this embayment, as shown by the decreased salinity in the embayment and by the volume of Bouse sediments, which Metzger considers too great to be accounted for solely by erosion of local highlands. That this river emptied into the embayment from the north is suggested by the apparent decrease in salinity from south to north, by the distribution of the Bouse Formation along the present valley of the Colorado River in the Parker–Blythe–Cibola area, and by the fact that the north was generally the landward side of the embayment. Such a river, with a course probably similar to that of the present Colorado River, very likely was the ancestral Colorado. At least, no evidence of other major rivers with a different course has yet been found in the Parker–Blythe–Cibola area, although sediments may have been contributed by washes heading in the Great Basin. Other rivers may have existed to the south and east, near the present Gila and Salt Rivers. Additional information on the source of the Bouse Formation can be obtained from a comparison of Bouse sediments with those of the modern Colorado, as was done for the Imperial Formation.

LAKE MEAD AREA

The Lake Mead area, described by Longwell (1936, 1946, 1963) and more recently by Lucchitta (1966), provides key information on conditions existing both before and after establishment of the Colorado Plateau and the Basin and Range province.[1]

The Colorado River leaves the plateau and the Grand Canyon at the Grand Wash Cliffs, a north-trending fault scarp. Thence, the westerly course of the river cuts across north-trending fault-block ranges and intervening basins that are typical of the Basin and Range province. The basins are filled by the Muddy Creek Formation, a typical interior basin deposit. The Muddy Creek rests unconformably on all older rocks, and is overlain unconformably by Colorado River deposits. The Muddy Creek Formation is much less deformed than older rocks. Fossils in the Muddy Creek are scarce, poorly preserved, and of little diagnostic value for age assignment. At Fortification Hill (Fig. 1), a sequence of lava flows, the type Fortification Basalt Member, occurs high within the Muddy Creek section. Their smooth and conformable basal contact is interpreted by Longwell as a surface aggradation (Longwell, 1936).

[1] As this paper went to press, Anderson and others (1972) published an article giving new radiometric ages and geologic interpretations for Tertiary rocks in the western Lake Mead region. These results are not incorporated in this paper. Although their ages for the Muddy Creek and the Horse Spring Formations include values younger than those given here, no serious difficulty arises with the interpretations presented herein. It should be noted that Anderson and others (1972) have expanded the definition of the Fortification Basalt Member of the Muddy Creek Formation to include rocks from various localities and stratigraphic positions, whereas the term, as used here, refers specifically to the lavas capping Fortification Hill.

The flows have been dated by Damon (1965) at 10.6 ± 1.1 m.y. Before filling of Lake Mead, similar lava flows, correlated by Longwell with those of Fortification Hill, were exposed within the Muddy Creek section near the mouth of Las Vegas Wash, 3 to 4 mi northwest of Fortification Hill. No thickness is given by Longwell for the section above the lava, but judging by his cross-section for the area (Longwell, 1936, Pl. 2), the thickness is not great. The top of the section appears to be erosional. The correlation, if correct, indicates that the Fortification Basalt Member is not the youngest part of the Muddy Creek Formation and that Muddy Creek deposition continued until some unknown time after 10.6 m.y. ago. Edwin H. McKee (1971, oral commun.) has obtained a whole-rock K/Ar age of 10.6 m.y. on basalt (not the Fortification Member) in the Muddy Creek Formation. The youngest pre-Muddy Creek deposit in the Lake Mead area is the Horse Spring Formation, which crops out north of the lake. Various K/Ar dates on the Horse Spring cluster around 20 m.y. (Tschanz, 1960; Armstrong, 1963; Damon, 1965). The Muddy Creek Formation is thus younger than about 20 m.y. and mostly older than 10.6 m.y. The dates obtained from the upper part of the Muddy Creek Formation are near the Miocene-Pliocene boundary. Considering that the Muddy Creek is the fill of structural troughs formed by basin and range faulting, and that some deformation of this kind had already occurred by about 18 m.y. ago, as documented for the Grand Wash fault (see below), it seems likely that deposition of the Muddy Creek Formation began in the Miocene and continued into the Pliocene.

The Horse Spring Formation consists of lacustrine deposits, with minor admixtures of fluvial material. As it is cut and tilted by the basin-range faulting, it predates the faulting. At the outcrop scale, the formation is, in many places, structurally conformable with older rocks, from which it is separated by an erosion surface of low relief. Regionally, however, the base of the formation truncates older rocks and rests on successively older units toward the south. These characteristics indicate a source area toward the south.

Cretaceous and sedimentary rocks older than the Horse Spring Formation are restricted to the area north and northwest of Lake Mead. According to Longwell and others (1965), a southerly provenance for some of these rocks is indicated by a thickening and coarsening in that direction by the bevelling of progressively older rocks to the south, and by the inclusion of igneous and metamorphic material which can only have been derived from the Precambrian terrane south of the lake, where the Precambrian is directly overlain by Tertiary volcanic rocks and Tertiary and Quaternary basin fill and alluvium. This terrane, which occupies much of western Mohave County, Arizona, must have been a topographic high and a source of sediments for most of the Cenozoic and part of the Cretaceous.

All available evidence thus suggests that in pre-Muddy Creek time, drainage was generally to the north and northeast, a direction quite different from that of the present Colorado River. It is unlikely that a Colorado River with a course at all similar to its present one existed in pre-Muddy Creek time in the area west of the Hualapai Plateau, especially since this hypothesis implies that the drainage would have survived an intense episode of basin and range tectonism that completely changed the geography of the region.

No evidence for an ancestral Colorado River debouching from the Colorado Plateau in Muddy Creek time, as suggested by Lovejoy (1969), is present in Muddy Creek deposits of the Grand Wash trough. Instead, these deposits reflect a typical interior basin environment with the bulk of the material coming from west and north. Short and steep canyons of Muddy Creek age are present in the Grand Wash Cliffs. These canyons are choked by coarse and angular Muddy Creek debris of local derivation; the associated fans are also locally derived. These rocks grade basinward into fine-grained material. At the mouth of the Grand Canyon, one can find neither the remnants of a large ancient canyon nor the far-traveled Muddy Creek material that one should find at that location had a Colorado River of that age existed. There are indeed remnants of a Muddy Creek fan near the mouth of the Grand Canyon, but the material making up the fan is all locally derived, and the structure reflects a steep and short canyon, rather than the large canyon of a through-flowing master stream.

In places, the highest and youngest member of the Muddy Creek Formation is the Hualapai Limestone, a fresh-water deposit locally as much as 1,000 ft thick. Hunt (1969) considers the limestone to have been deposited in a large deep lake, centered near the mouth of the Grand Canyon. The lack of clastic material in the limestone suggests to him that no large stream emptied into the lake. Yet a large lake needs to be maintained against evaporation. Hunt solves the problem by invoking large-scale piping of water from the ancestral Colorado River, at that time supposedly dammed in Peach Springs Canyon (Fig. 1), to the Hualapai Lake which was located where the mouth of the Grand Canyon is now. According to Hunt (1969, p. 113) this hypothesis is reinforced by the presence of an unconformity between the limestone and the underlying Muddy Creek rocks, which would make the limestone younger than the Muddy Creek and perhaps nearly as young as the oldest Colorado River gravels. The problems involved in routing an ancestral Colorado River through Peach Springs Canyon are discussed later in this paper. Other aspects of Hunt's hypothesis do not appear consonant with the following data, obtained by Lucchitta (1966) in a detailed study of the upper Lake Mead area:

1. The Hualapai Limestone is not centered about the mouth of the Grand Canyon, but rather extends more than 20 mi southwestward from that point. As exposures preserved are erosional remnants, the original extent of the limestone probably was even greater. Erosional remnants in widely scattered localities are as impressive as those near the mouth of the canyon.

2. The limestone was not laid down in one lake. At least two lakes can be documented in the upper Lake Mead area; these lakes probably were not connected, and occupied basins with independent tectonic and geomorphic histories. The same may well hold for areas farther west, which were also tectonically active.

3. The limestone was not laid down in a deep lake. The distribution of facies in the old basins, and internal characteristics of the Hualapai Limestone, such as plant stem impressions and interbedded evaporites, all point to a classic interior basin in which the topographically lowest part is occupied by playas and shallow lakes rich in salts, both of which become more extensive as the basin is filled, relief reduced, and the contributions of coarse-grained detrital material from surrounding highlands decrease. No evidence is present for a large stream emptying into the lakes, either directly or by means of large-scale piping.

Muddy Creek deposits are widely distributed in the entire Lake Mead region as well as in other adjoining basins, indicating that conditions of interior drainage were general rather than local.

The oldest datable deposits of the Colorado River in the Lake Mead area are cemented river gravel cropping out in various localities along the course of the river. Before filling of the lake, many of these remnants could be seen at or near river level (Longwell, 1936); one of the more conspicuous remnants preserved above the waters of the lake is at Sandy Point (Fig. 1), where the base of the gravels is about 350 ft above river grade. According to Longwell (1936), the base of another remnant less than one mile away from Sandy Point was only 150 ft above river grade. The basalt flow included in the remnant at Sandy Point has been dated at 3.3 $\pm$ 0.4 m.y. (Damon, 1972, oral commun.), showing that the Colorado River is at least that old. In fact, the river is probably considerably older, as the time required for the river to cut its valley to almost the present depth must be added to the age indicated by the lava.

In summary, the Colorado River in its present course through the Lake Mead area is at most 10.6 m.y. old (earliest Pliocene), probably somewhat less. And as the river had cut down to near its present depth by 3.3 m.y. ago, it was by that time (late Pliocene) a well-established river flowing in a deeply incised channel. And as the Grand Canyon debouches directly into the Lake Mead country, these age limits hold for the Grand Canyon as well, or at least for its western part.

HUALAPAI PLATEAU

The Hualapai Plateau has been studied recently by Young (1966a, 1970), from whom most of the following information was obtained. The plateau is the westernmost part of the Colorado Plateaus province directly south of the Grand Canyon. Its western margin is the scarp of the Grand Wash Cliffs, which separates it from the Basin and Range province and the Lake Mead region to the west.

The Hualapai Plateau consists of an erosion surface that slopes gently northeast and is cut into Paleozoic rocks dipping a few degrees in the same direction and, locally, into Precambrian rocks. The rocks dip more steeply than the surface, so that progressively younger rocks are exposed to the northeast. The surface is

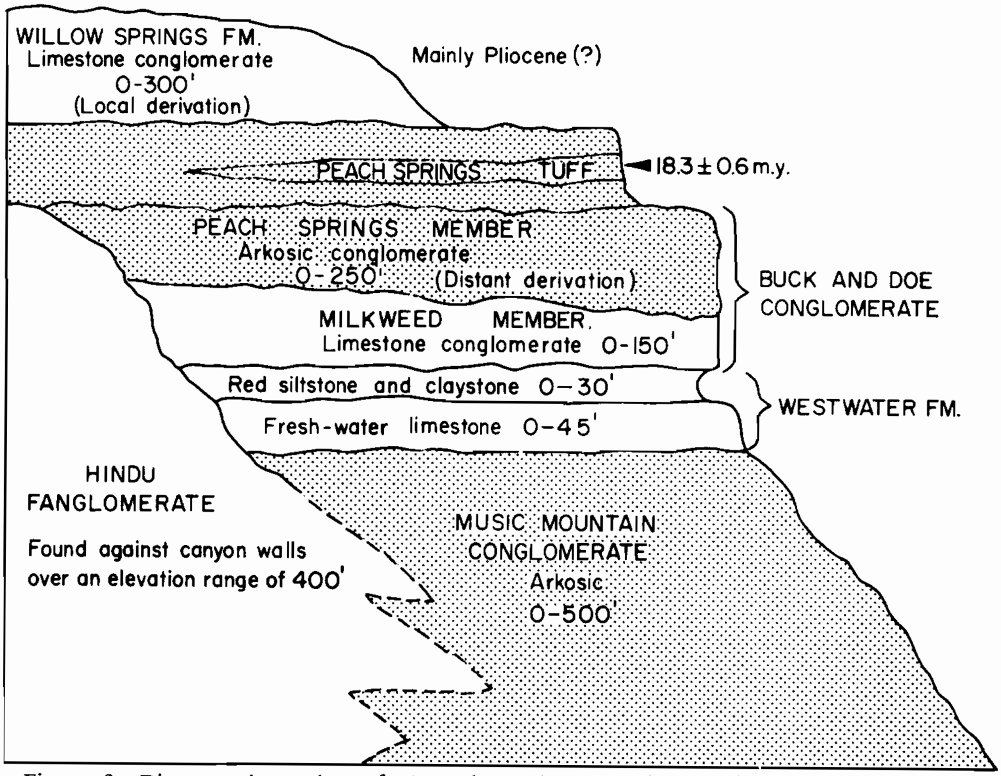

Figure 3. Diagrammatic section of Cenozoic deposits on the western part of the Hualapai Plateau, showing composite thicknesses and relationship of units. Nomenclature is that of Young (1966a, 1966b, 1970). Units of distant derivation are shown as screen pattern.

older than the Colorado River, which dissects it, and also older than the Grand Wash Cliffs, which truncate it. The surface thus predates faulting along the Grand Wash Cliffs, and dates back to the time when the Colorado Plateau and the Basin and Range province were not differentiated in the area and the plateau was topographically and structurally low. Channels that also trend northeast are incised into the erosion surface and are beheaded by the Grand Wash fault. The channels contain old gravel beds that are in part arkosic and thus could have come only from Precambrian rocks in the present Basin and Range province to the west and southwest. This provenance is supported by directions of imbrication. The intercalation of far-travelled arkosic gravels with gravels of local derivation indicates repeated and temporary interruptions of drainage, probably by early movements on the Grand Wash fault to the southwest. The gravels in the channels are overlain by other gravel beds, lava flows, and a welded tuff (Fig. 3), all of which are widely distributed over the erosion surface mentioned earlier. The flows and the tuff have a southwesterly derivation, from the present Basin and Range province, and are cut by the Grand Wash fault. The tuff (Fig. 3), the Peach Springs Tuff of Young (1966b), has yielded a radiometric age of 18.3 ± 0.6 m.y. Deposits younger than the flows and the tuff, and probably of Pliocene age, reflect conditions of local and interior drainage.

The arkosic gravel beds in the old channels can be traced to a point in Peach Springs Canyon now at an altitude of about 3,300 ft. No satisfactory continuation has yet been found. Hunt (1969) suggests that the old channels were tributary to the ancestral Colorado River, at that time flowing southwestward through Peach Springs Canyon-Truxton Wash (Fig. 1), and thence to a gap near Kingman. However: (1) no distinctive Colorado River gravels have been found in the old gravel beds in Peach Springs Canyon or in the gap near Kingman, (2) the bedrock floor of Truxton

Valley probably slopes northeast, and (3) gravels, lavas, and the Peach Springs Tuff reflect a regional slope to the northeast, opposite to that the postulated drainage. More likely, the old drainage continued northward from Peach Springs Canyon into a relatively low area located north of the Colorado River and about 40 mi away. Although this area is now 2,000 to 3,000 ft higher than the lowest gravel beds in Peach Springs Canyon, the slope represented is only .5 to 1 degree, and could well have resulted from tilting caused by the extensive faulting and epeirogenic warping experienced by the area since the time when the gravel beds were laid down.

The Peach Springs Tuff gives the youngest date currently available at which the northeasterly drainage from the area of the present Basin and Range province onto what is now the Colorado Plateau was still active, and therefore an upper age limit for major movement along the Grand Wash fault. As the Muddy Creek Formation was deposited in the interior basins formed when faulting destroyed this old drainage, the Peach Springs Tuff also gives a limiting value for the age of the Muddy Creek Formation in the area adjacent to the Hualapai Plateau.

The geology of the Hualapai Plateau shows that, until 18 m.y. ago or less, drainage was to the northeast, down the structural and topographic slope, onto the plateau, and nearly at right angles to the present trend of the Colorado River; at an unknown, but probably not great time after 18 m.y. ago, drainage became local and interior.

INTERPRETATION

The information presented in this report for the four areas discussed is summarized in Table 1. The information suggests that the various deposits considered to contain material of fluvial origin do reflect an ancestral Colorado River rather than other rivers, possibly unrelated to each other.

In the Imperial Valley and Parker–Blythe–Cibola area, there is no evidence for ancient major drainages other than that of the Colorado, and considerable evidence pointing to an ancestral Colorado River. In the Lake Mead area, a long period of widespread interior basin conditions predated establishment of the Colorado River, which is the only through-flowing drainage of such proportions for which there is record. And for both the Lake Mead area and the Hualapai Plateau, the drainage predating the episode of interior basin deposition was so different from that of the present Colorado that it can scarcely be related to it. One can tentatively conclude that the Colorado River contributed the bulk of the material in question that is of fluvial origin and of post-Muddy Creek age; that the river during its known history has followed approximately its present course in the Basin and Range province; and that it became established after 10.6 m.y. ago.

Still to be clarified are: (1) The environment of deposition of the Imperial and Bouse Formations. (2) The temporal and stratigraphic relations between the Imperial, Bouse, and Muddy Creek Formations. (3) The presence of Late Cretaceous coccoliths in both the Imperial and Bouse Formations. (4) The presence of Late Cretaceous foraminifers in the Imperial but not in the Bouse so far as is now known.

The Imperial Formation has been described as a deltaic deposit of the Colorado River (Muffler and Doe, 1968). I would interpret the Bouse Formation in the same way, although both Metzger and Smith (1970, written commun.) disagree. It is not crucial to the analysis presented here that either of these deposits be strictly deltaic, only that they be of Colorado River origin. But in my opinion, a deltaic environment of deposition is the one that best fits the known facts and most easily leads to a reasonable interpretation of the early history of the river.

The early river and its tributaries flowed in large part over young and poorly consolidated basin deposits. Thus a large volume of detritus probably was carried by the Colorado River from its earliest times, even when the length of the river was considerably less than it is now. This detritus was brought into the Bouse embayment; part must have settled out near the mouth of the river, part was probably carried much farther into the Bouse embayment and presumably into the Imperial Sea as well. This far-traveled fraction represents what might be called large-scale "bottomset" beds, although the boundary between bottomset beds and pelagic sediments that are mostly, but not entirely of Colorado River derivation probably is a matter of individual definition. These "bottomset" beds may well have constituted a substantial fraction of the fill of the Bouse embayment and of the Salton Trough as well, particularly if sedimentation was accompanied by sinking of the area, as suggested for the

TABLE 1. STRATIGRAPHIC UNITS OF IMPORTANCE TO COLORADO RIVER HISTORY IN BASIN AND RANGE PROVINCE

Area	Deposit	Age	Characteristics	Environment of deposition	Comments
Imperial Valley	Imperial Formation and younger rocks	Imperial Formation, late Miocene, or early Pliocene; may be as young as early Pleistocene.	Coarse grained sediments at margins grading basinward into fine grained sand, silt, and clay. Sediments in central part of basin similar in grain size and mineralogy to Colorado River material. Contain Mancos-type Late Cretaceous foraminifers, and Cretaceous coccoliths.	Subaerial for coarse grained marginal deposits. Marine for fine grained deposits of Imperial Formation, becoming lacustrine and then subaerial in younger formations. Imperial Formation deposited in northward extension of Gulf of California.	Imperial Formation marks first influx of far-traveled sediments of Colorado River type. Younger fine grained deposits are mostly laid down by the river.
	Late Cenozoic rocks of pre-Imperial age	Mostly Miocene	Conglomerate and breccia of granitic, dioritic, and metamorphic composition, grading laterally (basinward) into finer-grained rocks of the same composition.	Subaerial	Materials derived from erosion of local highlands.
Parker-Blythe-Cibola	Bouse Formation	Pliocene. At least as old as 3.02 ± 1.15 m.y., probably older.	Basal limestone, overlain by interbedded sand, silt, clay; marginal tufa. Interbedded unit has regular, well-developed bedding; sand layers locally cross bedded.	Embayment of Gulf of California. Water shallow, brackish. Apparently was fresher northward toward Topock and Needles	Freshening of water and the volume of sediments can only be explained by proximity of large river. Geographic location of Bouse suggests that river was the Colorado.
	Fanglomerate	Miocene(?)	Cemented gravel and sand of local derivation.	Debris aprons and wash deposits from surrounding highlands, at least in part subaerial.	Predates Bouse marine transgression.
Lake Mead	Cemented Colorado River gravels	Include basalt flow dated at 3.3 ± 0.4 m.y. Late Pliocene to early Pleistocene.	Very well rounded gravel interbedded with coarse crossbedded sand. Moderate calcite cementation. Clasts include wide variety of rocks present along Colorado drainage, but more resistant lithologies predominate.	Scattered remnants restricted to valley of Colorado River, locally only a few hundred feet above present grade. Deposited when valley had been incised and essentially had present configuration.	Indicate Colorado had present course, and had cut down to within a few hundred feet of present grade, by 3.3 ± 0.4 m.y. ago.
	Muddy Creek Formation	Miocene(?) and Pliocene. Younger than Horse Spring Formation (20 ± m.y.), mostly older than 10.6 m.y. In Hualapai Valley, younger than Peach Spring Tuff (18.3 ± 0.6 m.y.) of Young (1966b).	Conglomerate, breccia, sandstone, siltstone, chemical precipitates, vitric and vitric-crystal tuffs. Rapid lateral and vertical variation. Extensive intertonguing of facies. Lava flows present locally.	Interior-basin deposits filling basins formed by basin-and-range faulting. Deposits reflect fans, pediments, bahadas, playas, saline lakes. Some basins interconnected, others not. Tectonism continuing during Muddy Creek time, but Muddy Creek Formation is much less deformed than older rocks. Effusive and pyroclastic volcanism active.	No through-flowing drainage. No major canyon at present mouth of Grand Canyon. Other canyons, as deep as the modern ones, but shorter, present elsewhere along Grand Wash Cliffs; mostly choked by Muddy Creek conglomerates and breccias of local derivation.
	Horse Spring Formation	Early and middle Miocene. Radiometric ages on tuff cluster around 20 m.y.	Fresh water limestone, dolomite, magnesite, tuff, bentonitic clay, intermixed with detrital material ranging from shale to conglomerate.	One or more basins intermittently occupied by lakes rich in salts, fed by streams flowing predominantly north. Region had considerable relief, was possibly tectonically unstable. Pyroclastic volcanism outside of area of deposition, probably to west.	Predates most basin-and-range faulting in area. Deposited chiefly north of present Lake Mead. Materials mostly derived from south.
Hualapai Plateau	Willow Springs Formation Hualapai Volcanics, Buck and Doe Conglomerate, Westwater Formation, Hindu Fanglomerate, Music Mountain Conglomerate, all of Young (1966a, 1970).	Peach Springs Tuff, part of Hualapai Volcanics and high in section, dated at 18.3 ± 0.6 m.y. Youngest deposits (Willow Springs Formation) are Pliocene(?)	Fanglomerate, conglomerate, with interbedded siltstone, claystone, limestone, and volcanics. Conglomerates are alternately of local (limestone) and of distant (arkose) derivation.	Deposited in channels and on erosion surface cut into Paleozoic rocks dipping gently northeast. Channels and surface also dip gently northeast. Far-traveled conglomerates derived from Basin and Range province, which was higher than plateau. Locally derived conglomerates, as well as limestone and claystone, indicate interruption of drainage and local ponding, presumably resulting from movements on Grand Wash fault. Youngest deposit (Pliocene(?)) is locally derived and may be correlative with the Muddy Creek Formation.	Deposits on the Hualapai Plateau indicate drainage to the northeast and local ponding. None are related to the Colorado River. By Peach Springs Tuff (middle Miocene) time, the Grand Wash fault had already been active, but movement was not sufficient to interrupt drainage from the Basin and Range area to the southwest. After Peach Springs Tuff time, major movements interrupted drainage and formed the Grand Wash Cliffs.

Salton Trough by Muffler and Doe (1968). Eventually, shallowing of the water in the Bouse embayment would have allowed the mouth of the Colorado River to migrate southward, depositing foreset beds over the older "bottomset" beds and completing the filling of the embayment with sediments. The process would have continued into the Salton Trough, and, indeed, to the modern delta of the river. After deposition, the foreset beds would have been subject to subaerial erosion by the river. This, together with the large scale and the gentle dip, can explain why deltaic (that is, foreset) structures are not visible in the outcrop. But the interbedding of sand, silt, and clay, the abundance of sand in the section, the channels filled with crossbedded sand described by Metzger (1968) all suggest that a delta, in the sense used above, is indeed a reasonable environment for deposition of the Bouse Formation. For the Imperial Formation, the enormous volume of sediment of Colorado River origin and analogy with the modern delta suggest a similar origin.

A specific objection to the delta hypothesis for the Bouse Formation has been raised by Metzger (1970, written commun.), who points out that in a well near Parker, Arizona, foraminifers are present throughout the 767 ft of section. This would indicate uniform salinity for the time interval represented by these rocks, serving evidence against the gradual encroachment of the river in the area. However, little is known about how much section has been eroded from above the 767 ft now present, which could well represent mostly "bottomset" beds laid down at some considerable distance from the mouth of the river. Moreover, the presence of foraminifers does not necessarily indicate that they lived where they were buried; in an environment like that postulated for the Bouse, most, or even all, of the foraminifers could be brought by tides and currents into localities where they would not normally live.

The disagreement on whether the Imperial and Bouse Formations are deltaic probably stems chiefly from how one defines a delta. In any case, it is likely that the deposits in question are mostly of Colorado River origin, with subordinate contributions from drainages heading in the Basin and Range province. A possible exception, in terms of volume of sediment contributed and of source area, could be an early Gila River drainage, heading in central Arizona and contributing material to the Bouse and perhaps to the Imperial from near Yuma to the south.

As there was no through-flowing drainage in the Lake Mead area until less than 10.6 m.y. ago, the bulk of sediments in the Bouse and the Imperial Formations is likely to be not much older than that date. Conversely, it is likely that the beginning of deposition of the Bouse and the Imperial sediments goes back to considerably more than about 3.3 m.y. ago, for by that time the Colorado was a well established and incised stream in the Lake Mead region. Damon's (1972, oral commun.) date on the Bouse Formation shows that this formation was already being deposited by 5.4 m.y. ago. These dates are believed to bracket as Pliocene the age of the Bouse and that part of the Imperial Formation that contains Colorado River material.

The distribution of the Mancos-type Late Cretaceous foraminifers and of the Late Cretaceous coccoliths is puzzling. If both types of microfossils were transported by the Colorado River, how could the Imperial Formation contain both, and the Bouse, farther upstream along the course of the same river, the coccoliths but not the foraminifers? Two explanations can be advanced: (a) When the coccolith-bearing part of the Bouse Formation was being laid down, the Colorado River (or the Gila drainage) had begun eroding rocks containing the coccoliths, but not the Mancos and its foraminifers. By the time the delta of the river had reached the Imperial Valley area, both coccolith-bearing and Mancos rocks were being eroded. (b) The coccoliths were derived from local sources.

Although the first possibility cannot be excluded, the second seems simpler and more plausible, especially as the coccoliths are a widespread species, by no means restricted to the Cretaceous of the Colorado Plateau. David Bukry (letter to Metzger, 1968) points out that for three areas inspected, though admittedly a small sample, the abundance of coccoliths increases from the Bouse of the Big Maria Mountains (about 15 mi north of Blythe) to the Imperial of the Coyote Mountains (western side of Imperial Valley). This would suggest dispersal of coccoliths by marine currents of the Gulf in Imperial and Bouse time from a source area in the Peninsular Range as far as the Bouse embayment, which is not unreasonable in terms of the distances involved.

The Late Cretaceous foraminifers are a greater problem because their provenance is not local. Their presence in the Imperial Formation and absence in the Bouse can be explained most readily in two ways:

1. The foraminifers were carried by the early Gila-Salt River drainage and deposited from near Yuma, where the drainage presumably emptied into waters of the Gulf of California, generally westward toward and into the Salton Trough area. The headwaters of this river system could have reached Upper Cretaceous foraminifer-bearing rocks in Central Arizona. While this was taking place, the Colorado River would not yet have reached areas of outcrop of the Mancos Shale, and the sediments contributed by the Colorado to the Bouse Formation in the Parker–Blythe–Cibola area therefore would not contain the foraminifers. This hypothesis implies (a) an abundance of the Late Cretaceous foraminifers in the Bouse of the Yuma area; (b) a gradual decrease in the abundance of these foraminifers in the Bouse as one goes northward from Yuma toward the Parker–Blythe–Cibola area, as undoubtedly some of the foraminifers would have been dispersed in that direction; (c) a low-salinity anomaly in the vicinity of Yuma; and (d) a mineralogic and perhaps textural difference between the Bouse at Yuma and the same formation farther north. None of these characteristics has been detected so far, although admittedly work in the Yuma area has not been sufficient to determine this beyond doubt.

2. When the sediments now present in the Parker–Blythe–Cibola area as the Bouse Formation were being laid down, the Colorado River had not yet extended headward to areas on the Colorado Plateau where the Mancos Shale cropped out. By the time the headwaters of the river had reached areas underlain by the Mancos Shale, the Bouse embayment was mostly or entirely filled up, and the locus of heaviest deposition had shifted to somewhere between the Parker–Blythe–Cibola area and the Salton Trough. Probably, the area of outcrop of the Mancos at the time was generally east of the Kaibab upwarp, as suggested by original non-deposition westward, rapid westward facies change from shale into sandstone and conglomerate, and extensive early and middle Cenozoic erosion. Therefore, the first appearance of Mancos foraminifers in the Imperial Formation, or in sediments transitional between the Imperial and the Bouse, would mark the time when the Colorado cut through the upwarp.

The *second* model seems to run into the fewest difficulties, and is therefore used in the following synthesis.

SYNTHESIS

The information and the speculations presented in this report can be synthesized as follows, attempting to tie together the data now available into a consistent, though painfully tentative, account of the early history of the Colorado River in the Basin and Range province.

1. Until some unspecified time after 18 m.y. ago (Peach Springs Tuff time) major basin-range faulting had not yet occurred in the Lake Mead area. The Colorado Plateau was topographically low, the Basin and Range province to the west relatively high. Drainage was northeast onto the plateau and north. The Colorado River did not exist. Vulcanism produced lava and welded tuff that flowed onto the Hualapai Plateau.

2. Between about 18 and 10 m.y. ago, basin-range faulting occurred in the Lake Mead area and possibly farther west, resulting in the structural and topographic differentiation between the plateau and the Basin and Range province. Tectonic basins were formed and filled by interior-basin deposits (Muddy Creek Formation) in the Lake Mead area. Pre-existing drainage was disrupted, and interior drainage became widespread. The Colorado River still did not exist. Subaerial fanglomerate material was deposited in the Parker–Blythe–Cibola area. On the Hualapai Plateau, drainage became interior and was accompanied by the deposition of locally derived material.

3. Between about 10 and 3.3 m.y. ago, but probably no less than 5.4 m.y. ago, waters of the Gulf of California encroached into the Parker–Blythe–Cibola area, forming the Bouse embayment. Drainage in the Parker–Blythe–Cibola, Lake Mead, and Hualapai Plateau areas became integrated and through-flowing, probably by headward erosion, and formed the ancestral Colorado River. The river emptied into the Bouse embayment, progressively filling it and advancing toward the Salton Trough area. The fine-grained fraction from the river sediments may have been widely distributed in the upper Gulf of California, some of the material possibly being deposited

in the Salton Trough area as offshore deposits. Conversely, fine-grained material and detrital Cretaceous coccoliths of local derivation probably were carried into the Bouse embayment by marine currents. At this time, the headwaters of the river had not yet reached areas where the Mancos Shale cropped out.

When the delta had advanced to some point between Parker–Blythe–Cibola and the Salton Trough, the headwaters of the river reached areas where the Mancos Shale was exposed, probably east of the Kaibab upwarp. In cutting across the upwarp, the river may have captured an ancestral upper Colorado River postulated by McKee and others (1967).

As the delta of the Colorado River advanced toward the Salton Trough, which it eventually filled with a great thickness of deltaic deposits, the older deltaic sediments in the Parker–Blythe–Cibola area were eroded and capped unconformably by a veneer of Colorado River alluvium, although locally the alluvium may have been deposited directly on the delta sediments without an intervening period of erosion.

As the delta filled the Salton Trough, conditions gradually changed from marine to deltaic to subaerial. The delta then continued to build up into the Gulf of California, as it does today.

4. By about 3.3 m.y. ago, the Colorado River had cut down to almost its present depth in the upper Lake Mead area, only a few miles west of the plateau. Clasts in the river gravel of this age are well rounded, far traveled, and represent a variety of the lithologic types exposed in the Grand Canyon. A well-developed Grand Canyon existed at that time.

As a consequence of the hypothesis presented here, the Imperial would in part be younger than the Bouse, in part a time-equivalent offshore facies of the Bouse delta. But even for the parts differing in age, the difference could be small in terms of geologic time. The horizon at which the Mancos foraminifers first appear should be at the present topographic surface somewhere between the Bouse and the Imperial areas and should dive progressively deeper as one approaches the Imperial Valley. This horizon should provide a reasonably good time marker and would indicate the time when the Colorado River cut across the Kaibab upwarp and possibly captured a pre-existing upper Colorado River. An accurate reconstruction of the course followed by the river in Bouse and Imperial time is a difficult undertaking, as the Parker–Blythe–Cibola area and the Imperial Valley are separated by the San Andreas fault zone. On the other hand, an improved understanding of the lithosomes in the Bouse and Imperial Formations may shed some light on the amount, rate, and timing of deformation along the San Andreas fault in the region.

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