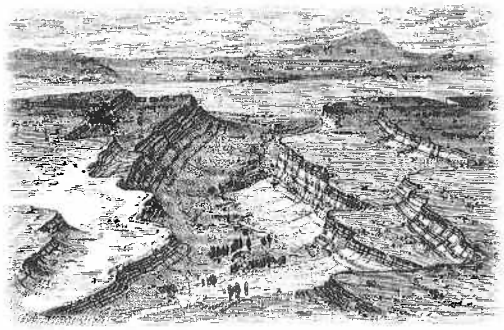

Chapter Twenty-Seven

The Bouse Formation and Post-Miocene Uplift of the Colorado Plateau

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Abstract: Sr-isotope analyses show that the Bouse Formation has ratios like those of modern Colorado River water. This similarity has been used to suggest that the Bouse Formation is nonmarine and thus cannot be used as a datum to determine uplift of the Colorado Plateau. However, a marine environment for the Bouse Formation is indicated by distribution and paleontologic data. The high Sr ratios can be explained by a Bouse-time drainage system that had a much smaller drainage basin than today's river and included rocks with high Sr ratios. When discharge from this system reached the restricted Bouse embayment, the high Sr ratios could have made marine water in the embayment appear to be fluvial to some research methods. We believe that available data support a marine origin for the Bouse and ~1 km of young uplift for the Colorado Plateau.

Uplift of plateaus—large and relatively undeformed parts of continents—has long interested earth scientists because the kinematic history of the uplifts illuminates and constrains the workings of the lithosphere (e.g., Lunar and Planetary Institute, 1978, and papers therein). In the case of the Colorado Plateau, the uplift history is also vital to understanding the carving of the immense canyons for which the region is justly famous. The principle is simple—no uplift, no canyons—but the timing of uplift and consequently the age of the canyons have been the subject of vigorous debate since the days of John Wesley Powell and, especially, Clarence Dutton (1882). The problem is that criteria by which to determine numerical values for the uplift (how much and when) are scarce at best.

As a consequence of studies of the Colorado River region in 1966 and 1967, Lucchitta (1972) proposed a history for the lower Colorado River west of Grand Canyon. An ancestral lower Colorado drainage system, not connected to a much older upper river in the inner regions of the Colorado Plateau, developed on top of the pre-river Hualapai Limestone Member of the Muddy Creek Formation by draining the postulated Hualapai lake(s) between 6 and 5 Ma (Faulds and others, this volume, propose the interval 6 to 4.4 Ma for this event). This system began incising the western edge of the Colorado Plateau; it included tributaries such as the Virgin River and Grand Wash. Two factors not found in other parts of the Basin and Range Province contributed to the development of this drainage system: (1) the slowing down—even the cessation—of vigorous normal faulting, which allowed the integration of closed basins; and (2) the encroachment of an arm, or embayment, of the proto–Gulf of California into what is now the lower Colorado River corridor, which provided base level and an outlet for the drainage system. The Bouse Formation was deposited in the shallow waters of this arm and in more open water farther south, and is generally considered marine to brackish on paleontologic criteria (Durham, 1950; Durham and Allison, 1960; Merriam and Bandy, 1965; Metzger, 1968; Smith, 1970; Winterer, 1975; Todd, 1976; Taylor, 1983; Buising, 1988, 1990, 1993; Buising and Beratan, 1993; Zullo and Buising, 1989). The ancestral drainage system flowing into the gulf would have reduced the salinity of the embayment.

According to Lucchitta (1972), fine-grained sediment in the upper part of the Bouse represents bottomset beds of a delta formed by the ancient drainage, prograding southward into the Bouse embayment. Metzger (1968) believed that the Bouse is older than Colorado River deposits, so it could not be part of a delta. However, later sedimentologic work (Olmsted and others, 1973; Buising, 1988, 1990, 1993) shows that clastic material in the Bouse is of Colorado River origin, and that the Bouse interfingers stratigraphically upward with sand and gravel deposits of the Colorado River. Evidently, fluvial material advanced southward with time on top of the deltaic sediment, filling the embayment and eventually reaching the Imperial Valley of California where it is represented by the Imperial Formation. The process has continued to the present delta in the Gulf of California. The appearance within the upper part of the Imperial Formation of Upper Cretaceous foraminifera derived from the Mancos Shale of the Colorado Plateau (Merriam and Bandy, 1965) marks the Pliocene time of capture of an ancestral upper Colorado River drainage by the young lower Colorado, and formation of the integrated river that we know today (Lucchitta, 1972).

A marine-to-estuarine Bouse Formation would have been deposited near sea level, but today remnants of the formation are preserved as high as 550 m a.s.l., presumably owing to uplift. The Hualapai Limestone, similar in age to the Bouse, is considered by Lucchitta (1979) to have been deposited near sea level but not actually in the sea, as proposed by Blair (1978). Faulds and others (this volume) also consider the Hualapai to be nonmarine. Today, the Hualapai is at elevation 880 m near the mouth of Grand Canyon. These data provide a rare opportunity to determine an absolute value for uplift of the Colorado Plateau—880 m in the past ~5.5 Ma (Lucchitta, 1979).

In 1996 Spencer proposed a model for uplift of the Colorado Plateau. Inasmuch as this model was more consonant with early rather than late uplift, Spencer and Patchett (1997) reexamined the origin of the Bouse Formation, on which interpretation for the young uplift is based. To this effect, they obtained samples from three areas: (1) the Bouse Formation from a little south of Bullhead City, Arizona, to the Exxon well in the Imperial depression south of Yuma, Arizona; (2) the Hualapai Limestone from the Lake Mead area; and (3) the Imperial Formation from Fish Creek, California. $^{87}Sr/^{86}Sr$ ratios obtained from the samples were plotted against distance upstream from the present mouth of the Colorado River. Bouse Formation values cluster around the values for modern Colorado River water (0.711), whereas the values from the Imperial Formation and Bouse Formation in the Exxon well are identical to that of late Miocene seawater (0.709). On the other hand, the Hualapai Limestone samples have very high and puzzling Sr-isotope values (0.715), far above the ratio for the modern Colorado River. Based on the results for the Bouse and Imperial, Spencer and Patchett (1997) concluded that the Bouse Formation signals "the first arrival of Colorado River water, presumably because of capture of the upper Colorado River basin and vastly increased influx of water," and cited Lucchitta (1989). They also concluded that the formation upstream from the Chocolate Mountains (Figure 1) was not deposited in an estuary or marine embayment, but in a string of saline lakes fed by the Colorado River, thus accounting for Sr values near those of the modern Colorado River. Marine organisms found in the Bouse of this area would have been imported into the saline lakes on birds' feet or by other such mechanisms. Furthermore, the subsurface deposits south of Yuma would be more like the Imperial than Bouse Formation, and both were seen as marine. A nonmarine origin for the Bouse upstream from Yuma is also proposed by Poulson and John (2000) on the grounds that its geochemical characteristics resemble those of the modern Colorado River.

We question the conclusion that the Bouse Formation is nonmarine on several grounds: (1) paleontologic work indicates that the Bouse Formation is marine, (2) the isotope-based conclusions rest on troubling assumptions, and (3) field characteristics such as distribution and thickness are consistent with deposition in a restricted arm of the sea north of Yuma, and in more open sea to the south. In this paper, we examine these various lines of evidence in the hope of contributing usefully to the important debate on the timing of uplift for the Colorado Plateau and the carving of Grand Canyon.

Bouse Formation: Distribution, Stratigraphy, Age, and Implications

Today, erosional remnants of the Bouse Formation (Metzger, 1968) are present in a belt 30 to ~50 km wide extending along the valley of the lower Colorado River for some 300 km from Lake Mohave to near Yuma. In the structural trough south of Yuma, similar strata rest on older marine rocks (Eberly and Stanley, 1978) and are widely present below the surface at depths that increase southwest and reach about 1000 m near the Mexican border, where their thickness in the Exxon deep well is reported as ~660 m (Olmsted and others, 1973; Eberly and Stanley, 1978). North of Yuma, the formation rests on subaerial deposits and generally interfingers with overlying Colorado River alluvium.

The Bouse Formation consists of a tufa unit and a basal limestone overlain by interbedded clay, silt, and sand. The tufa unit is interpreted as representing the Bouse shoreline and records fluctuations of sea level; algal laminae and tubules suggest a thriving biological community (Metzger, 1968; Buising, 1990, 1993). The tufa is overlain by the basin-fill association that includes a basal limestone, barnacle beds, and upward-coarsening terrigenous clastic sediments. Well-developed crossbedding of various types indicates strong currents, some north-directed, some south-directed (Buising, 1990). This strongly suggests tidal activity. The upper sediments record progradation from north to south of a deltaic complex that is overlain by Colorado River gravel.

The age of the prograding delta, which includes the Bouse Formation, is bracketed by overlying and underlying formations between ~4 and ~9 Ma (Buising, 1990). A tuff near the base of the Bouse Formation in

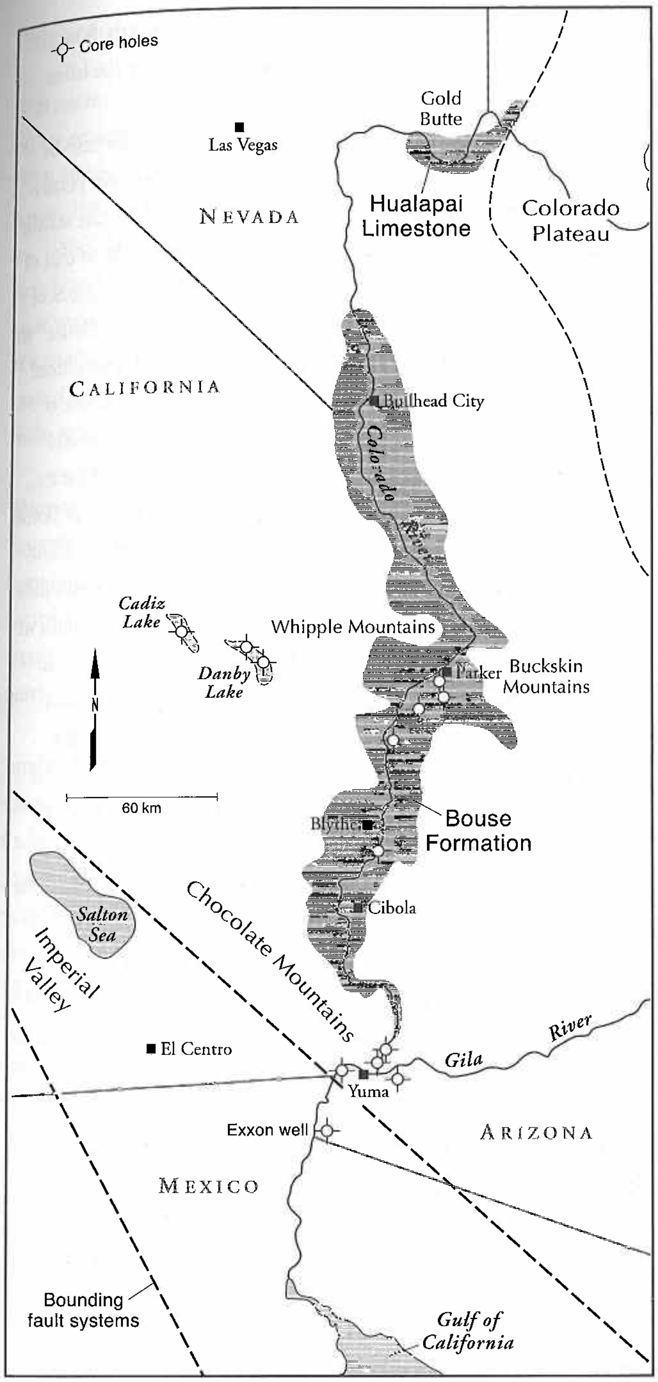

Figure 1. Location map, showing outcrop area of the Bouse Formation. The formation is present in the subsurface south of Yuma and at Cadiz and Danby dry lakes.

Milpitas Wash (Chocolate Mountains area) has yielded K-Ar ages of 3.02 ± 1.15 Ma and 8.1 ± 0.5 Ma (Metzger and others, 1973), and 5.47 ± 0.20 Ma (Shafiqullah and others, 1980). The 3.02 Ma age is considered a minimum because of devitrification. Another age constraint is provided by the first appearance of Colorado River sediments in the Imperial Formation at 4.3 Ma (Fish Creek section, Johnson and others, 1983; Winker, 1987; Winker and Kidwell, 1986; McDougall and others, 1999). The presence in the Imperial Formation, but not Bouse Formation, of reworked foraminifera that are characteristic of the Upper Cretaceous Mancos Shale of the Colorado Plateau (Merriam and Bandy, 1965) indicates a substantial portion of the Bouse Formation was deposited before the ancestral, and relatively local, lower Colorado River drainage captured the upper drainage 4.3 Ma to establish the modern Colorado (Lucchitta, 1972, 1989). Buising (1988) used grain analysis to conclude that quartz-rich deltaic sediments in the upper part of the Bouse were derived from the Colorado Plateau. However, rocks of this type were accessible to the ancestral lower Colorado drainage in the area of western Grand Canyon, and to the Grand Wash and Virgin River as well. These grains document the introduction of material brought in by the ancestral lower Colorado River, but not necessarily, or even likely, from the interior of the Colorado Plateau; that is, by a postcapture modern Colorado River. If that were the case, one would expect an abundance in the Bouse of reworked Cretaceous foraminifera, as is the case with the Imperial Formation.

Strontium-isotope Considerations

The similarity of Sr-isotope ratios from the Bouse Formation and the modern Colorado River led Spencer and Patchett (1997) to suggest that the Bouse Formation was deposited in a series of lakes along the course of a river essentially like the modern Colorado. However, there is much evidence that such a river did not exist in Bouse time. No evidence attests to a major throughflowing river system in the lower Colorado area up to Bouse time (papers in Sherrod and Nielson, 1993). Interior-basin deposits along the present course of the Colorado River and barely older than ~5 Ma show no evidence of a Colorado River issuing from the Colorado Plateau into the Grand Wash trough, immediately west of Grand Canyon (Lucchitta, 1966, 1967, 1972). And features as young as 6 to 7.5 Ma on the Shivwits Plateau, just inboard of the Colorado Plateau's edge, show no evidence of incision or drainage directions that could be ascribed to the modern Colorado River and its Grand Canyon (Lucchitta, 1975; Lucchitta and Jeanne, this volume). The conclusions are that deposition of the Bouse predates integration of the upper and lower river systems into the modern Colorado River, and that the modern river is not likely to be a good analog to the older, preintegration river, which would have had a different and much smaller drainage basin.

A significant proportion of the likely precapture drainage basin was underlain by alkali-rich, radiogenic granitoids such as the Gold Butte Granite, and by deposits with high Sr-isotope values such as the Hualapai Limestone (0.715), which received water from areas where the granitoids crop out. High-ratio source rocks within the small drainage basin are likely to have given the ancestral lower river a much higher Sr ratio than that of the modern river, whose very large drainage basin is not dominated by high Sr-ratio source rocks. As an illustration, the Ganges and Brahmaputra Rivers, which drain highly radiogenic rocks of the Himalaya basement (Sr ratio >0.790), have ratios of 0.725 and 0.721, respectively (Leeder, 1999). These rivers are thought to have affected the *earth's* oceans in a significant way. According to Richter and others (1992), "The combined Sr flux of rivers such as the Brahmaputra, Ganges and Indus, with headwaters in the Himalayan-Tibetan region, is of the right order of magnitude and isotopic composition to produce the observed seawater $^{87}Sr/^{86}Sr$ increase since 40 Ma." They use an average ratio of 0.713 for the rivers in their calculations, and the increase in seawater ratio is from 0.7078 to 0.7092. In the case of the restricted Bouse embayment, one would expect that even relatively little river water with these kinds of ratios would have a considerable effect on the water of the embayment, perhaps enough to make marine water appear to be nonmarine. Although high Sr-isotope source rocks do not dominate the modern Colorado River drainage basin, ground water from springs along the south rim of Grand Canyon has abnormally high Sr-isotope ratios (0.714 to 0.712, Monroe and Truini, personal communication, 2000). Today, water contributed to the Colorado River from such springs is enormously diluted by the great volume of the river; in the past, the dilution probably was much less. In any case, the springs show that high-ratio sources are present within the likely drainage area of the ancestral lower river.

Simple back-of-the-envelope calculations illustrate the effects of such mixing in a restricted environment. The Bouse-age proto–Gulf of California probably had limited access to the open ocean through a 1000 km long shallow seaway. Stock and Hodges (1989) documented Basin and Range extension of the protogulf after 5.5 Ma; only later did extension narrow to the modern, deeper, strike-slip-dominated basin south of Yuma. For illustration purposes, assume that the ancestral lower Colorado River system had a modest average discharge of ~140 m^3/sec (5000 cfs), into which are factored intervals of low discharge and intervals of flood. Such a discharge is not unreasonable for a time (5 Ma) when the Sierra Nevada, the Transverse Ranges, and the Peninsular Ranges did not exist, or were not in their present position, so little rain shadow existed in the region under discussion. The volume of river water contributed annually to the Bouse embayment would have been ~4.4 km^3. Given that much of the embayment was only ~30 km wide (on the basis of the distribution of Bouse remnants; Lucchitta, 1979; Spencer and Patchett, 1997), and 0 to 50 m (or at most 100 m) deep on the basis of faunal evidence (Smith, 1960, 1970; Winterer, 1975), each year's discharge would have filled the embayment for the considerable distance of 1.5 to 3 km along its axis, and the 300 km of embayment would be entirely filled with river water every 100 to 200 yrs. Such an influx from the north of water with high Sr ratio, together with limited mixing with distant open-marine water from the south, provides a mechanism for reconciling the well-known marine-to-brackish faunas with the nonmarine Sr ratios obtained by Spencer and Patchett (1997). In addition, tidal events within the embayment would help explain the crossbedding in the Bouse sediments, and the puzzling alternations between more saline and less saline conditions reflected by the fauna.

Although Spencer and Patchett (1997) tried to eliminate problems of contamination and poor preservation, such problems may have persisted. For example, the authors pointed out that mollusks from the subsurface part of the Bouse at the Exxon well have Sr ratios similar to that of Neogene seawater, different from the modern Colorado River values of the Bouse above Yuma. On this basis, they suggested that the "Bouse" in the well is more appropriately correlated with the Imperial Formation. The correlation of the Imperial and the southern part of the Bouse is also appropriate from the paleoecologic view since both areas would have been open marine and represent the deeper-water shelf biofacies. On the other hand, this biofacies is the deeper-water equivalent of Bouse faunas north of Yuma, which indicate a progressive northward shallowing of the water and an increase in the amount of fresh water input into the system. Furthermore, the sediments deep in the subsurface south of Yuma presumably have been saturated since the time of deposition in their original Neogene seawater, so may reflect the properties of that water. It is hard to see how younger and less dense nonsaline water could have displaced the seawater from these sediments, but technical reasons have made it impossible to test this possibility by recovering uncontaminated water from deep in these wells. In contrast, the same formation north of Yuma has been completely flushed by water from the modern Colorado River for much of the time since it was deposited, as shown by low salinity values (Metzger and others, 1973). This may explain Buising's (1988, 1990) observation that "barnacle shell material [from Milpitas Wash] yielded such strongly cratonic $^{87}Sr/^{86}Sr$ signatures that they were not usable for dating." Similarly, the problem of flushing affects Poulson's (2000) argument that the Bouse is likely to be nonmarine because its geochemical signature is that of the modern Colorado River.

Spencer and Patchett (1997) also analyzed two samples from the upper part of the Imperial Formation. This was done as a control to see whether the influx of Colorado River water might have affected the Sr ratio of known marine water. Since this ratio turned out to be that of seawater, they concluded that their technique was valid for the Bouse as well. But this is not necessarily so. In the first place, the samples come from material deposited when the Colorado was integrated into the present river, with a large drainage basin and modern Sr ratios. This water was much less likely to alter the marine signature of the Imperial delta than was the case for the Bouse in the embayment, when the ancestral drainage system, having a small drainage basin and probably high Sr ratios, could more easily have made marine water appear to be nonmarine. Second, the Imperial Formation was deposited in the open Imperial Valley, where marine currents and wind action would have been far more likely to mix and dilute the river water than as it was in the case for a very restricted embayment north of Yuma.

Paleontology

Both micro- (foraminifera, ostracods) and megafossils (mollusks, fishes) are reported from the Bouse Formation (Todd, unpublished report, 1953; Smith, 1960, 1970; Hamilton, 1960; Sohl, unpublished internal report, 1967; Winterer, 1975; Buising, 1990, 1993; McDougall and others, 1999). Although some freshwater snails and ostracod specimens have been found, the invertebrates indicate marine-to-brackish or estuarine waters. The microfauna also suggests that water depths increased in a southerly direction and that open-marine connections to the south existed at various times, although the embayment may have been generally restricted.

Winterer (1975) analyzed the salinity and temperature tolerance of the Bouse fauna and flora, concluding that the environment graded from an open shelf south of Yuma to a lagoonal environment to the north, connected to the open sea by a marine channel. With time, these environments gave way to an estuarine environment prograding from the north.

Benthic foraminiferal assemblages from the Bouse Formation contain abundant but not diverse faunas. Low-diversity assemblages in the Parker-Blythe area are dominated by *Ammonia beccarii, Bolivinia subexcavata, Eponidella palmerae,* and *Elphidium* spp. Although rare, agglutinated (*Trochammina*) and porcelaneous (*Quinqueloculina*) species are present. The foraminiferal composition is characteristic of a hyposaline lagoon or estuary rather than a saline lake (Todd, unpublished report, 1953, and 1976; Smith, 1960, 1970; Winterer, 1975). Foraminifera can occur in saline lakes, but such faunas have usually small numbers dominated by agglutinated species such as *Miliammina fusca* or the calcareous species *Ammonia beccarii* (Boltovskoy and Lena, 1971; Murray, 1973; Patterson and others, 1990; Lucas and Kietzke, 1994).

Importation of marine organisms aerially (by birds or wind) would have to occur periodically over several million years to account for the time range of occurrence. We assume that the marine organisms are not limited to one or a few short time periods in the Bouse Formation. Marine organisms limited to rare occurrences in a lake dominated by freshwater fauna would be excellent evidence for Spencer and Patchett's (1997) hypothesis. But occurrences of marine organisms over a large and nearly continuous time span with only occasional freshwater fossils require a marine connection (Hedgepeth, 1959). Aerially dispersed marine organisms could not long dominate the ecology of a saline lake against flood- or river-supported colonization events by lacustrine organisms.

In the Bouse Formation, faunal diversity and foraminiferal numbers increase from north to south. Faunal composition also changes from north to south, grading from northern faunas (listed above) that are characteristic of a hyposaline lagoon or estuary, to faunas around Yuma that have a composition characteristic of a shelf assemblage (≥50 m). Planktonic foraminifera present in the core holes around Yuma, in the Cadiz and Danby Lake core holes, and as far north as core hole LCRP20 (about 27.3 km south of Parker, Figure 1), support the interpretation of periodic open-marine conditions, as these organisms cannot exist in restricted-marine environments, nor in isolated inland lakes.

In 1965, Ron Cruzen collected two fish specimens from the lower limestone unit of the Bouse Formation near Cibola, Arizona. Todd (1976) identified these as *Colpichthys regis*, a marine species endemic to the Gulf of California, and stated, "Inasmuch as *Colpichthys regis* is found in warm and shallow brackish or marine waters in the Gulf of California, its presence in the Bouse Formation further substantiates the existence of a warm and shallow brackish or marine embayment of the Gulf of California during the Pliocene." Later, Crabtree (1989) discovered a brackish-water *Colpichthys, C. hubbsi*, in the Colorado delta part of the Gulf. *C. hubbsi* differs in several respects from *C. regis*; however, the Bouse fish are consistent with *C. regis* according to the characteristics given by Lavenberg and Chernoff (1995), so represent a species that now is marine, although the ancestral Pliocene form may have been tolerant of brackish conditions.

Fossils of the Bouse Formation include diverse marine organisms: mollusks, arthropods, foraminifera, and one species of fish. These are accompanied by scattered freshwater organisms. A hypothetical Bouse lake disconnected from the sea could not have maintained a marine fauna for extensive periods. Many of the marine representatives of the fauna are restricted to seas or lakes with relict marine waters (Hammer, 1986). Some have claimed that the organisms living in saline lakes are nearly the same as those living in brackish waters or the sea, but "there is no scientific evidence to support this proposition" (Hammer, 1986). Ponder (1986) suggested that some of the species in the mound springs of Australia's Great Artesian Basin could have been introduced by floods, birds, or winds, but the fauna of saline lakes, including the widespread desert goby of interior Australia, are derived from freshwater species. Just as the original fauna of the Salton Sea was derived from freshwater species (Evermann, 1916), saline lakes throughout the world are overwhelmingly dominated by species derived from fresh waters (Beadle, 1943, 1959; Bayly, 1969; Hedgepeth, 1959; Greenaway, 1986).

The fish specimens of the Bouse Formation almost surely lived in an environment at sea level and as part of an integrated and diverse marine and brackish-water community. Metapopulation theory predicts that populations of isolated species have a high probability of local extinction. It is a solid ecological conclusion that the marine elements in the Bouse Formation could not have been planted and maintained at a remote location above sea level by occasional aerial mechanisms such as transport by wind or birds.

Conclusions

In our opinion, the isotopic data do not successfully contradict the marine-estuarine origin of the Bouse Formation indicated by abundant paleontologic evidence and distribution characteristics. The isotopic analyses rest on the assumption that the Bouse-time ancestral Colorado River had a similar chemistry to that of today, which it most likely did not. To the contrary, the probably high Sr ratio of the ancestral river, produced by radiogenic source rocks within a relatively small drainage basin, combined with the small Bouse embayment, could well have made marine-brackish water of the embayment look nonmarine. This effect may have been enhanced because Bouse rocks in the embayment north of Yuma have been flushed for nearly 5 Ma by modern Colorado River water, whose Sr ratio is higher than that of marine water.

On balance, we feel that the evidence supports a marine-estuarine origin for the Bouse, so this formation continues to be a useful indicator of ~1 km uplift of the Colorado Plateau in the past ~5 Ma. This is in keeping with known young displacements on Colorado Plateau–bounding faults along the course of the Colorado River, the geomorphic youthfulness of canyons in the plateau, the high rate of incision by the Colorado River (Davis and others, this volume; Hanks and others, this volume; Lucchitta and others, this volume; Marchetti and Cerling, this volume; Kirkham and others, this volume), and the ongoing rapid intrusion of canyons into a mature and much older landscape on the Colorado Plateau (Lucchitta, 1984, 1989; Hanks and others, this volume).

When thinking about the lithospheric processes, uplift, and erosional history of the Colorado Plateau, it is important to keep in mind that the post-5 Ma uplift discussed here amounts to approximately 1 km, whereas another 2 km took place somewhere in the interval between 60 Ma and 5 Ma. However, it is the young uplift that, in our opinion, is responsible for carving of the canyons as we know them today, because it was during that time interval that critical events happened whose combination is unique to the area of the lower Colorado River: great decrease in the rate of normal faulting (which allowed the integration of closed basins), and encroachment of an arm of the sea to within <100 km of the Colorado Plateau (which provided a base level close to the edge of the Colorado Plateau and an outlet for developing drainage systems).

Acknowledgments

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