Origin and Paleogeography of an Immense, Nonmarine Miocene Salt Deposit in the Basin and Range (Western USA)[1]

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ABSTRACT

The Hualapai basin, northwestern Arizona, contains one of the thickest known, nonmarine halite deposits in a continental rift. The basin is a large half-graben in the hanging wall of a listric normal fault along the eastern margin of the Basin and Range province. Seismic reflection and drill-hole data indicate that the little-deformed halite is 2.5 km thick in the central part of the basin, approaches ~200 km^3 in volume, and has a three-dimensional lenticular-wedge geometry. An age of 9–13 Ma is suggested for the salt because it lies in the upper, more gently tilted part of a growth-fault sequence, and extension in the region is bracketed between 16 and 9 Ma. The texture and bromine content of the halite, dominance of halite, and S and O isotopic values of intercalated and capping anhydrite indicate that halite deposition took place in an intracontinental playa that accommodated regional groundwater discharge. Several events conspired to produce this unusually thick salt deposit, including regional aridity, a broad catchment basin with a closed drainage network, ample supplies of Na^+ and Cl^-, and rapidly developing accommodation space. In addition, oxygen isotopic values indicate a lacustrine origin for a thick (~300 m) upper Miocene–lower Pliocene limestone in the Grand Wash trough directly north of the Hualapai basin. Thus, Miocene-Pliocene evaporite deposits in northwestern Arizona and southern Nevada do not represent the northern extent of the ancestral Gulf of California. A lack of upper Miocene-Pliocene marine deposits and little recent faulting in the region imply that most of the differential relief between the southwestern Colorado Plateau and adjacent Basin and Range developed 16–9 Ma during major extension. The abundance of Cenozoic nonmarine evaporites in the Basin and Range implies that a nonmarine origin should not be overlooked for large belts of synrift evaporites on passive continental margins. Primary, lenticular-wedge geometries characterize synrift salt deposits and may facilitate the development of large salt diapirs.

Introduction

Extended terranes commonly experience widespread and protracted deposition of evaporites. During the early and main phases of rifting, the developing arrays of fault blocks promote development of closed drainage networks while subsiding half grabens accommodate evaporite accumulation. More widespread evaporite deposition characterizes the late stages of rifting, as regional subsidence of the extended terrane (e.g., McKenzie 1978; Royden et al. 1980; Sclater and Christie 1980; Bally and Oldow 1984) allows marine waters to invade restricted embayments. Consequently, rift-related salt deposits generally fall into two broad categories: (1) wedge-shaped, synrift bodies within individual half grabens (Holwerda and Hutchinson 1968; Lowell and Genik 1972; Tankard and Balkwill 1989) and (2) blanket-like, late-rifting to drifting-stage marine deposits that mantle arrays of fault blocks (e.g., Jackson and Seni 1983).

Although nonmarine evaporites are common in modern arid closed basins (Smoot and Lowenstein 1991) and nonmarine synrift halite deposits have been recognized in ancient continental rifts (Balkwill and Legal 1989; Warren 1989), thick halite deposits are generally attributed to a marine origin (Holwerda and Hutchinson 1968; Lowell and Genik 1972; Austin et al. 1989; Heyman 1989). As-

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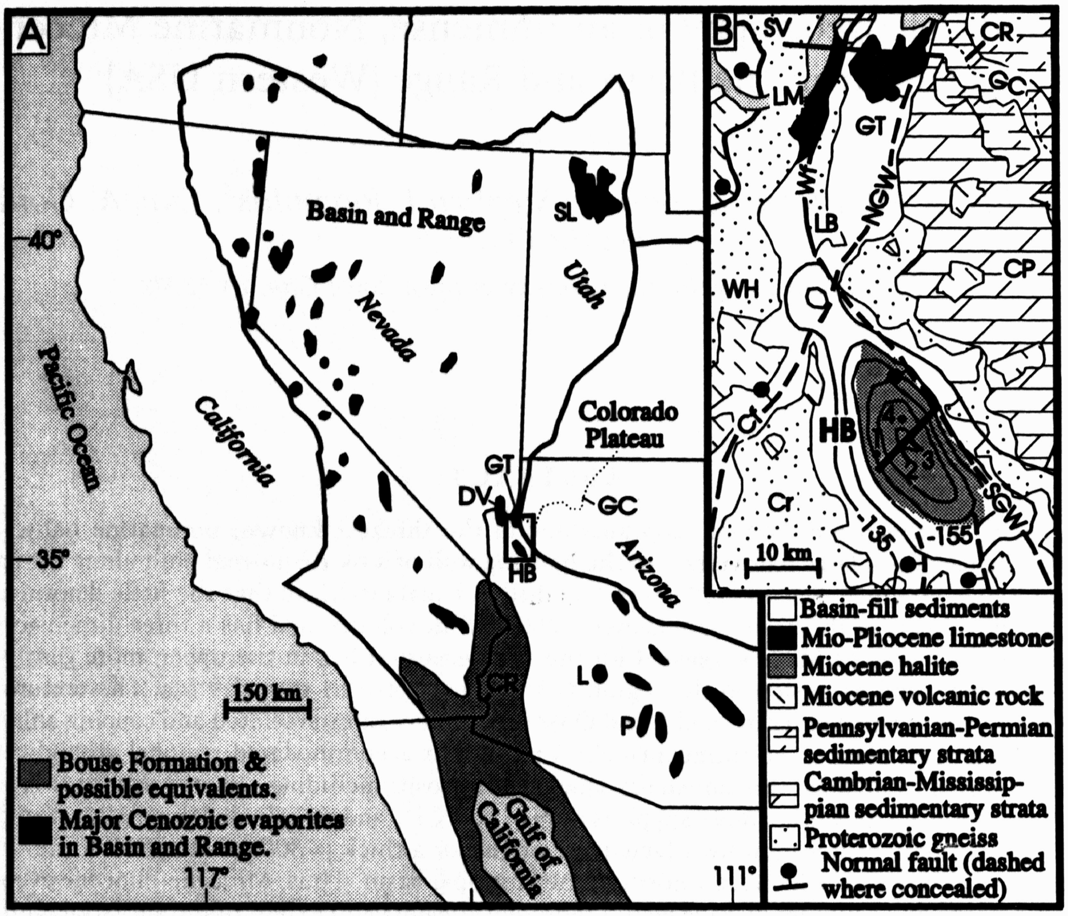

Figure 1. (*a*) Major Cenozoic evaporite deposits in the Basin and Range (from Peirce 1976; Busing 1990; Smoot and Lowenstein 1991). (*b*) Generalized geologic map of the Hualapai basin area showing Bouguer gravity contours (10 mgal intervals; from Davis and Conradi 1981) and location of the seismic reflection profile, drill holes (1–4, table 1), and cross sections (figures 2 and 3*b*). Cf, Cerbat Range fault; CP; Colorado Plateau; Cr, Cerbat Range; CR, Colorado River; DV, Detrital and Virgin River basins; GC, Grand Canyon; GT, Grand Wash trough; GV, Grapevine Mesa; HB, Hualapai basin; L, Luke basin; LB, Lost Basin Range; LM, Lake Mead; NGW, northern Grand Wash fault; P, Picacho basin; SGW, southern Grand Wash fault; SL, Great Salt Lake; SV, South Virgin Mountains; Wf, Wheeler Ridge fault; WH, White Hills.

certaining the depositional environment and original geometry of thick, synrift halite deposits is difficult, however, because most have been deformed into diapirs and/or recrystallized. Furthermore, contemporary deposits are commonly concealed within deep basins in continental interiors and cannot be readily interpreted without appreciable subsurface data.

Although commonly difficult to study, evaporite deposits represent one of the more important economic resources within continental rifts. They furnish strategic minerals (halite, gypsum, borates), storage capacity for natural gas and nuclear wastes (e.g., Johnson and Gonzales 1978; Dean and Johnson 1989), and effective seals for hydrocarbons (e.g., Etheridge et al. 1988; Warren 1989; Morley et al. 1990). Conversely, extensive salt deposits can also have a negative effect by limiting supplies of fresh ground water. Thus, the overall distribution, depositional environment, and three-dimensional geometry of evaporite deposits can have significant economic implications, especially in relatively arid regions such as the Basin and Range of the western USA, where fast-growing cities and agricultural demands are rapidly depleting supplies of fresh ground water.

Synextensional Cenozoic evaporites are common in the Basin and Range province (figure 1*a*), but limited exposures have generally precluded detailed study (e.g., Peirce 1976). In addition to important economic considerations, the distribution and origin (marine vs. nonmarine) of these evaporites have significant implications for the Cenozoic paleogeography of the western Cordillera. For example, unusually thick (commonly >1 km) Miocene-Pliocene deposits in western Arizona and southern Nevada bear directly on the timing of Colorado Plateau uplift, evolution of the Grand Canyon and Colorado River, and extent of the proto-Gulf of California, a proposed late Miocene–early Pliocene marine embayment (Lucchitta 1979; Buising 1990). If marine in origin, these deposits would indicate significant regional uplift since late Miocene–early Pliocene time, as many of the deposits currently reside at elevations substantially above sea level. On the other hand, a nonmarine origin raises questions about the depositional environment responsible for producing such thick deposits and whether such conditions are common within continental rifts.

This paper focuses on the origin, geometry, and implications of an unusually thick, Miocene halite deposit within the Hualapai basin of northwestern Arizona along the eastern margin of the Basin and Range (Faulds et al. 1995*a*). This deposit was chosen for study due to a wealth of subsurface data and proximity to both the Colorado Plateau and proposed, proto-Gulf of California (figure 1*a*). A seismic reflection profile, Bouguer gravity data, and the texture and chemical composition of the salt and associated sulfates are utilized to determine the geometry and origin of the deposit. The origin of a Miocene-Pliocene carbonate deposit in the Grand Wash trough directly north of the Hualapai basin is also assessed. We conclude that the salt body is essentially an undeformed lenticular wedge, ~2,500 m thick, and that both the salt and carbonate are nonmarine in origin. The composition, geometry, and regional setting of the halite deposit are then utilized to model the depositional environment of extremely thick, synextensional nonmarine salt deposits and discuss their significance.

Geological Setting

Basin and Range Evaporites. Little-deformed evaporites constitute an integral part of the Cenozoic stratigraphy within many basins of the Basin and Range province (e.g., Holser 1970; Peirce 1976; Handford 1982; Bohannon 1984) (figure 1*a*). Although the geometry of individual deposits has generally not been well defined, the regional extent and volume of the nonmarine, Basin and Range evaporites appear to rival that of some synrift evaporite belts on passive continental margins (see Tankard and Balkwill 1989). Most of the thicker known evaporites occur near the margins of the Basin and Range, proximal to topographically elevated areas such as the Colorado Plateau and Sierra Nevada. The terrestrial Cenozoic setting for the bulk of the province indicates that most of the evaporites accumulated in isolated interior-drainage basins.

The origin (marine vs. nonmarine) of some Miocene-Pliocene evaporites in Arizona, southern Nevada, and southeastern California has stirred debate, however, because of their proximity to the contemporary Gulf of California. For example, in the lower Colorado River region a widespread unit of upper Miocene–lower Pliocene siltstone and limestone, the Bouse Formation (figure 1*a*), has long been interpreted as marine in origin on the basis of vertebrate fossils, found up to 150 km north of the present Gulf of California (Todd 1976), and invertebrate fossil assemblages located as far north as the southernmost tip of Nevada (Metzger 1968; Smith 1970; Buising 1990). The age of the Bouse Formation has been bracketed between 9 and 4 Ma (Buising 1990) based on a K-Ar date of 9.2 ± 0.3 Ma on sanidine from a tuff intercalated in clastic rocks beneath the formation (Buising and Beratan 1993) and magnetostratigraphy from overlying Colorado River clastic sediments in the Imperial Formation (Johnson et al. 1983; Kerr and Kidwell 1991). Lucchitta (1979) and Buising (1990) concluded that the Bouse Formation records the northern extent of the proto-Gulf of California (figure 1*a*). The elevations of the highest erosional remnants of the Bouse Formation have been used to infer 550–800 m of uplift of the lower Colorado River region and western Colorado Plateau since late Miocene time (Lucchitta 1979). Patchett and Spencer (1995) recently determined, however, that Sr isotopic values from barnacles and calcareous sediments within the Bouse Formation show no evidence of marine water but are instead consistent with a lacustrine origin. This raises serious questions about the proposed late Miocene–early Pliocene marine embayment and late Cenozoic regional uplift of the region.

Miocene-Pliocene carbonates of possible marine origin have also been reported from the Lake Mead region in northwestern Arizona and southern Nevada (Blair 1978; Blair and Armstrong 1979). On the basis of fossil diatoms and radiaxial fibrous calcite cementing algal oncolites, Blair and Armstrong (1979) concluded that the Hualapai Limestone Member of the Muddy Creek Formation was deposited in marine or brackish waters in an estuary of the ancestral Gulf of California. The estuary was presumed to extend as far northeast as the base of the Colorado Plateau, because the Grand Wash trough contains a 300 m-thick section of Hualapai Limestone (figure 1*b*). The age of the Hualapai Limestone is roughly bracketed between 10.8 and

3.8 Ma, which overlaps with that of the Bouse Formation. K-Ar and fission-track dates of mafic lavas and tuffs intercalated within clastic sediments below the limestone range from 10.8 to 11.6 Ma (Blair and Armstrong 1979; Bohannon 1984). An air-fall tuff interbedded with the limestone has yielded a K-Ar date of 8.66 ± 2.2 Ma (Blair 1978), whereas basalt flows that cap the Tertiary section in the Grand Wash trough have rendered K-Ar ages of 3.8 Ma (Shafiqullah et al. 1980). If marine in origin, the present elevation of the Hualapai Limestone implies 400–800 m of uplift since early Pliocene time. Based on facies relationships within the Muddy Creek Formation, however, Lucchitta (1979) concluded that the Hualapai Limestone is lacustrine in origin. Extensive Miocene carbonate deposits in several other basins in the region have also been interpreted as lacustrine in origin (Bohannon 1984).

A group of little-studied, but unusually thick late Tertiary evaporite deposits, consisting primarily of halite, stretches from eastern Arizona to the Lake Mead region of southern Nevada (figure 1*a*). Some of the thickest documented Cenozoic evaporites in the Basin and Range occur within this group, including 1800 m of anhydrite in the Picacho basin (Peirce 1976), >1200 m of halite in the Luke basin (Eaton et al. 1972), >500 m of halite in the Virgin and Detrital basins (Mannion 1974), and >1280 m of halite in the Hualapai basin (Peirce 1976) (figure 1*a*). Most of these deposits have been interpreted as nonmarine in origin on the basis of regional relations (Mannion 1974; Peirce 1976; Lucchitta 1979; Bohannon 1984) and, in the case of the Luke (Eaton et al. 1972) and Virgin basins (Holser 1970), low bromine contents (2–6 ppm) in halite. Despite their potential paleogeographic and economic significance, however, very few of these deposits have been comprehensively examined in terms of composition, texture, depositional environment, and three-dimensional geometry.

Hualapai Basin and Grand Wash Trough. The Hualapai basin and Grand Wash structural trough are large northeast-tilted Tertiary half grabens situated along the eastern margin of the Basin and Range province near the mouth of the Grand Canyon of the Colorado River (figure 1*b*) (Lucchitta 1966). The west-dipping, southern Grand Wash fault and gently (10°–20°) northeast-tilted Cerbat Range bound the Hualapai basin on the east and west, respectively. Despite its proximity to the Colorado River and Grand Canyon, the Hualapai basin is currently an internally drained, closed depression. The west-dipping, northern Grand Wash fault and moderately to steeply east-tilted fault blocks, including the Lost Basin Range and South Virgin Mountains, bound the Grand Wash trough on the east and west, respectively. The Colorado River empties into the central part of the Grand Wash trough at the mouth of the Grand Canyon. Based primarily on the distribution of upper Miocene basalt lavas, Lucchitta (1989) concluded that the Grand Canyon was largely cut since ~6 Ma.

The Hualapai basin and Grand Wash trough lie within the eastern part of the northern Colorado River extensional corridor, a 70- to 100-km-wide highly extended part of the Basin and Range province situated between the unextended Colorado Plateau on the east and Spring Range and central Mojave Desert region on the west (Howard and John 1987; Faulds et al. 1990). The transition between the Colorado Plateau and Basin and Range province is abrupt in this region, as evidenced by an appreciable westward decrease in crustal thickness (Thompson and Zoback 1979) commensurate with sharp increases in fault block tilting and normal faulting. Most of the extension in nearby areas of the corridor occurred between ~16 and 11 Ma (Anderson et al. 1972; Gans et al. 1992; Faulds 1993; Faulds et al. 1990, 1995*b*).

The west-dipping Grand Wash fault zone and associated Grand Wash cliffs form a sharp structural, stratigraphic, and topographic break between the Colorado Plateau and Basin and Range province (Lucchitta 1966). The Grand Wash fault zone may represent the southern part of a breakaway zone for a major west-dipping detachment system that floors much of northwestern Arizona and southern Nevada (Wernicke 1985; Spencer and Reynolds 1989). West of the Grand Wash Cliffs, Tertiary volcanic and sedimentary strata rest directly on Proterozoic and Mesozoic plutonic and metamorphic rock. Mesozoic and Paleozoic strata were eroded from most of this region prior to early Miocene time (Bohannon 1984). In the northern Cerbat Mountains and White Hills (figure 1*b*), Tertiary strata include (1) a basal sequence of 19.2 to 18.0 Ma (J. Faulds and P. Gans unpub. $^{40}Ar/^{39}Ar$ whole-rock dates) arkosic conglomerate, basaltic andesite and basalt lavas, volcaniclastic conglomerate, and minor nonwelded tuff; (2) 18 to ~16 Ma andesite and dacite lavas; (3) ~16 to 15 Ma felsic volcanic sequence consisting of rhyolite lavas and tuffs; and (4) an upper sequence of ~14 to 9 Ma basalt and basaltic andesite lavas and conglomerate (Calderone et al. 1990; McDaniel 1995; J. Faulds unpub. data). The Paleozoic section is preserved east of the Grand Wash Cliffs but is truncated southward by an early Tertiary erosion surface (e.g., Lucchitta and Young 1986) such that only Cambrian strata

Table 1. Drill Hole Data, Hualapai Basin

Drill Hole	Source[a]	Collar Elevation (m)	Total Depth (m)	Anhydrite-Gypsum Depth[b] (m)	Halite Depth[b] (m)	Halite Thickness[c] (m)
D1	Kerr-McGee #1	836	795	396	433	362
D2	Kerr-McGee #2	859	651	444	459	192
D3	El Paso Natural Gas	855	1827	490	547	1280
D4	Tran Am Energy Co.	850	753	564	671	82

[a] Drill hole logs are on file with the Arizona Geological Survey.
[b] Depths are shown for the top of the halite and anhydrite-gypsum deposits.
[c] Penetrated thickness; all drill holes terminated in halite.

remain directly east of the southern part of the Hualapai basin. Tertiary volcanic and sedimentary strata were only locally deposited east of the Grand Wash Cliffs on the Colorado Plateau.

Deep drilling has shown that the Hualapai basin contains a large, unexposed body of salt exceeding 1280 m in thickness (Table 1). Reports of abundant saline ground-water prompted the first deep drilling in the basin in 1958 (H.W. Peirce written comm. 1993). The salt has since been studied as a potential repository for nuclear wastes (Johnson and Gonzales 1978) and natural gas (FERC 1982). Bouguer gravity data (figure 1*b*) imply that the salt body is about 1830 m thick, 8 km wide, and 19 km long (Davis and Conradi 1981). The salt body has been variously interpreted as a dome of Triassic-Jurassic salt (Koestler 1971) and as a little-deformed, late Cenozoic nonmarine evaporite (Peirce 1976; Faulds et al. 1995*a*).

The Grand Wash trough contains up to 300 m of the upper Miocene–lower Pliocene Hualapai Limestone Member of the Muddy Creek Formation, which grades laterally into fine-grained clastic rocks and coarse fanglomerates (Lucchitta 1979). The limestone is generally tilted gently to the east (<5°). The limestone body has a V-shaped prism-like geometry, the long axis of which coincides with the axis of the half graben (Lucchitta 1979). The limestone onlaps both steeply tilted Paleozoic strata on the west side of the Grand Wash trough and flat-lying Paleozoic strata along the margin of the Colorado Plateau on the upthrown side of the northern Grand Wash fault. The upper part of the limestone is not cut by the northern Grand Wash fault, but is truncated by the Wheeler fault (figures 1*b* and 2). The Hualapai Limestone has been interpreted as both a marine-estuarine deposit formed at the northern end of the ancestral Gulf of California (Blair 1978) and as a lacustrine deposit (Lucchitta 1966, 1979).

Subsurface Data and Interpretations, Hualapai Basin

A previously unpublished, seismic reflection profile documents the half-graben morphology of the Hualapai basin and associated growth-fault relations (figures 1*b* and 3*a*). The profile parallels the dip-line of the southern Grand Wash fault and tilted strata. Bouguer gravity data indicate that the profile extends across the deepest part of the basin. Two drill holes along the profile penetrate the upper basin fill. Gamma ray logs from the drill holes were used to calculate densities and seismic veloci-

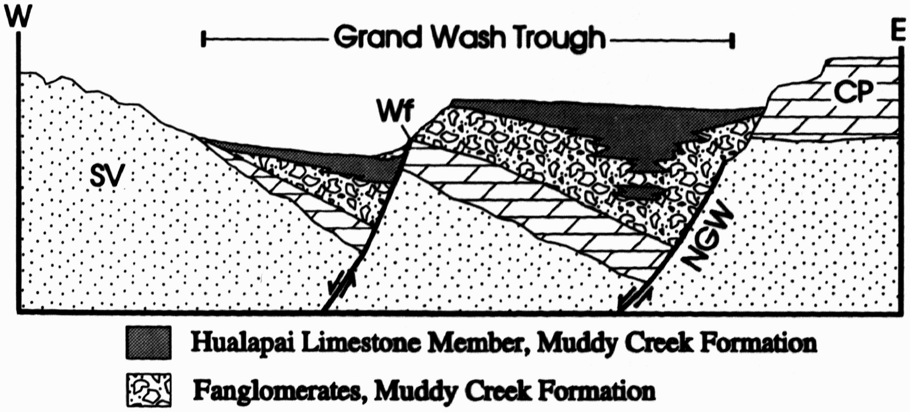

Figure 2. Diagrammatic cross section of the Grand Wash trough adapted and slightly modified from Lucchitta (1979). The location of the cross section, as well as the undefined abbreviations and patterns, are shown and described in figure 1*b*.

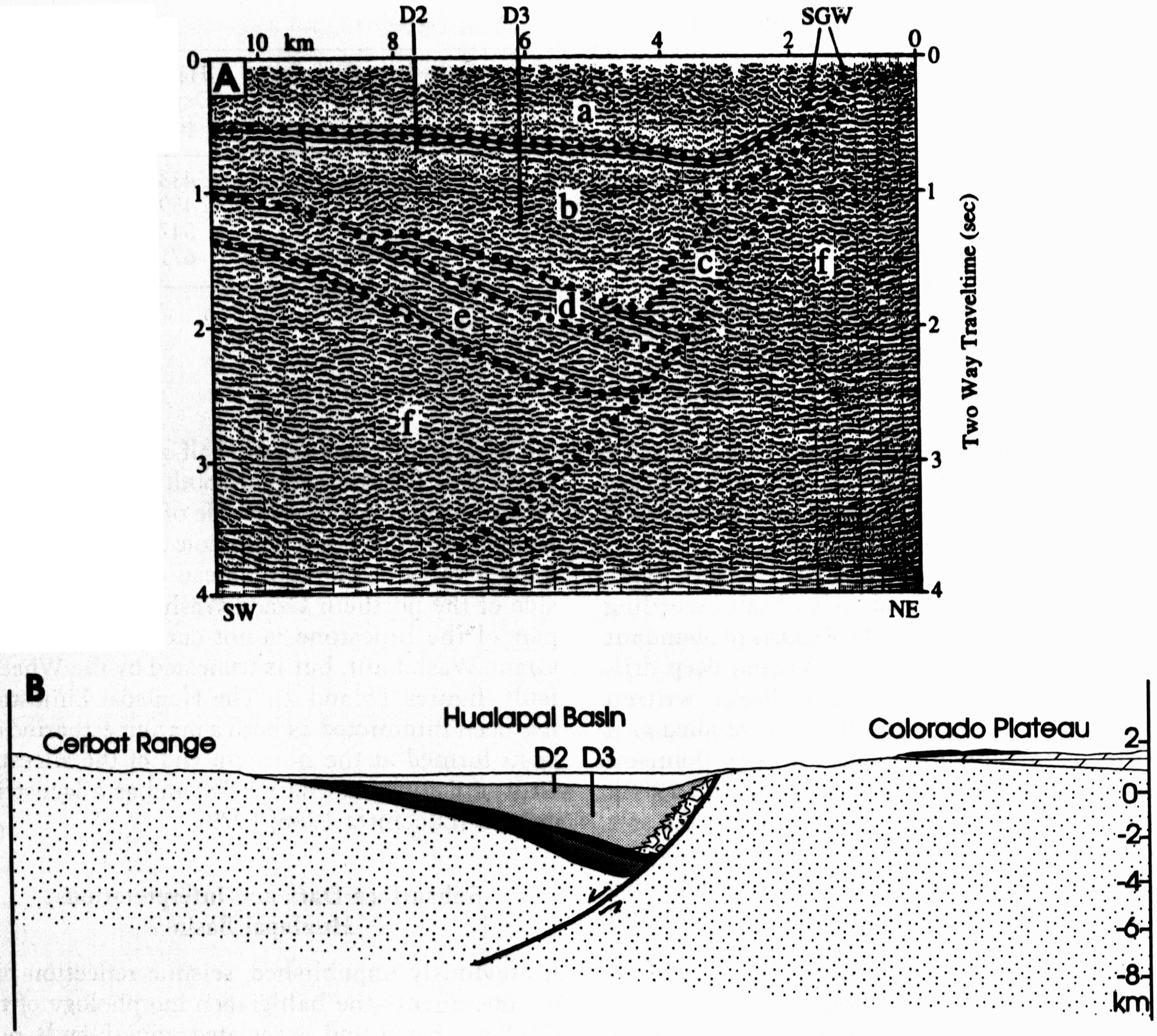

Figure 3. *(a)* Migrated seismic reflection profile of the Hualapai basin collected using a dynamite source, 48 channel off-end array with 67 m receiver spacing, and shotpoint spacing of 268 m for a common-depth-point fold of 600%. The profile has been subjected to limited conventional data processing. The original digital format was not available for reprocessing. See text for explanation of stratigraphy and figure 1b for location. D2 and D3 are drill holes (table 1). SGW, southern Grand Wash fault. *(b)* 1:1 cross section parallel to reflection profile. Patterns for Tertiary strata are the same as in figure 4; other patterns are described figure 1*b*.

ties, which permitted accurate estimates of thickness for several units. Gravity data and a second unpublished seismic reflection profile (not shown in this paper) indicate that the Hualapai basin essentially ends to the north at the Cerbat Range–northern Grand Wash fault (figure 1*b*). To the south, the Hualapai basin breaks into several smaller basins where the southern Grand Wash fault splays and displacement on its main strand decreases appreciably.

In descending order, the inferred stratigraphy of the Hualapai basin includes: ~600 m of late Miocene-Quaternary shale and lesser amounts of gypsum, anhydrite, and conglomerate (unit a), up to 2500 m of middle-to-upper Miocene halite intercalated with minor shale (5–10%) and anhydrite (unit b), fanglomerates along the margins of the basin (unit c) that interfinger with unit b, ~335 m of middle Miocene volcanic and sedimentary rock (unit d), ~750 m of lower-to-middle Miocene volcanic and sedimentary rock possibly resting on Cambrian strata (unit e), and Proterozoic gneiss, granite, and diabase (unit f) (figures 3*a* and 4). Drill holes penetrate units a and b. Unit d is inferred

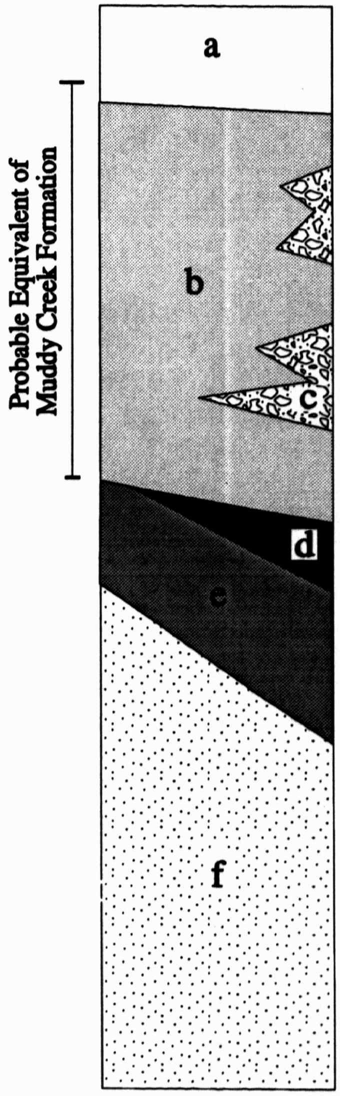

Figure 4. Generalized stratigraphic column of the Hualapai basin, as inferred from the seismic reflection profile and regional relations. a, Holocene–Upper Miocene shale, conglomerate, gypsum, and anhydrite, which are probably correlative with the Muddy Creek Formation (Lucchitta, 1979) in the Grand Wash trough; b, Upper Miocene (probably ~9–13 Ma) halite and lesser shale and anhydrite, temporally correlative with the evaporites (limestone and dolomite) and clastic sediments in the upper members of the Horse Spring Formation (Bohannon 1984) in the Lake Mead area, as well as with the Muddy Creek Formation in the Grand Wash trough; c, locally derived upper Miocene fanglomerate; d, Middle Miocene (~13–16 Ma) volcanic and sedimentary rock, which may correlate with the Mount Davis Volcanics and volcanics of Red Gap Mine in the Black Mountains (e.g., Faulds et al. 1995*b*) or the Thumb Member of the Horse Spring Formation (Bohannon 1984) in the Lake Mead area; e, Lower to Middle Miocene (~20–16 Ma) volcanic and sedimentary rock similar to the Patsy Mine Volcanics (Anderson et al. 1972) and volcanics of Dixie Queen Mine (Faulds et al. 1995b), possibly resting on a thin section of Cambrian strata; f, Proterozoic gneiss, granite, and diabase.

based on reflection character and the slight angular unconformity and onlap relationship with unit e. Gently (15–20°) northeast-tilted, 17.8–19.2 Ma mafic flows, conglomerate, and tuff in the Cerbat Range (J. Faulds unpub. data) project into the basin and merge with unit e. A southwestward thickening sequence of lower Miocene (e.g., 17.4 Ma; Lucchitta and Young 1986), subhorizontal basalt flows atop the Grand Wash Cliffs also correlates with unit e. Widely spaced, subhorizontal diabase intrusions, ranging up to 30 m in thickness cut the early Proterozoic granite and gneiss (unit f) at the base of the Grand Wash Cliffs (Albin and Karlstrom 1991) and may account for some of the discontinuous subhorizontal reflectors beneath the Miocene and Cambrian nonconformities (figure 3*a*).

Growth-fault relations, including eastward-thickening wedge shapes, progressive upward decreases in tilt (25° to near 0°), and onlap unconformities, are well developed in units a, b, and d (figure 3*a*). The true thickness of the Miocene section is ~3.9 km. All units, except the upper part of unit a, are truncated by the southern Grand Wash fault. In the central part of the basin, the southern Grand Wash fault accommodated ~5 km of throw. The fault has a listric geometry, as indicated by greater tilting of the hanging wall (25°), as compared to the footwall (near 0°), and the eastward increase in east-tilting of hanging-wall strata (figure 3). The westward dips of strata along the eastern margin of the basin probably resulted from normal drag, compaction, and possibly incipient flow of salt into the southern Grand Wash fault zone.

The wedge-shaped halite deposit is clearly not domed (figure 3). Drill core and estimated velocities for unit a indicate that the prominent east-dipping, double reflector (0.5–0.8 sec) is the top of the salt. The halite reflection package (unit b) continues down to 1.85 sec in the deeper part of the basin. Drill core observations show that unit b consists of 90–95% halite, 5–10% interbedded shale, and traces of anhydrite. Gamma ray logs indicate a density of ~2.06 g/cc for the halite and ~2.24 g/cc for the shale, which suggest velocities of 4.5 km/sec and 2.5 km/sec, respectively, using the velocity-density relations of Gardner et al. (1974). The layering within unit b is generally defined by thin beds of shale intercalated within thick horizons of poorly bedded halite. Seismic reflections and drill core observations indicate an average dip of 5° for the salt layers. Thus, the thickness of the little-deformed salt is as much as ~2.5 km in the central part of the basin. Gravity data

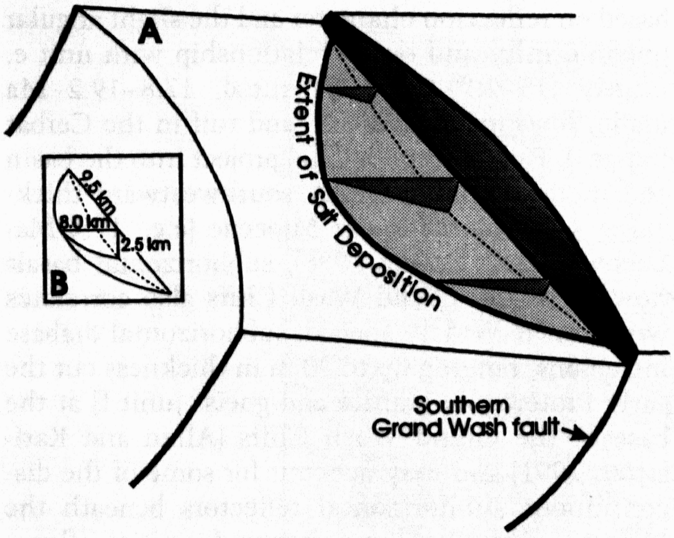

Figure 5. (*a*) Schematic block diagram of the Hualapai basin. (*b*) Lenticular, wedge-shaped salt deposit modeled as one-quarter of an ellipsoid.

(figure 1*b*) imply that the salt pinches out away from the central part of the basin commensurate with decreasing offset on the southern Grand Wash fault.

The seismic reflection and Bouguer gravity data indicate that the three-dimensional geometry of the salt resembles a lenticular wedge, which can be modeled as one-quarter of an ellipsoid (figure 5). Based on inferred ellipsoidal radii of 2.5 km (thickness), 8.0 km (width), and 9.5 km (length parallel to southern Grand Wash fault), the total volume of salt may approach ~200 km³ (volume = (1/4)4/3πabc; a, b, c = radii of ellipsoid).

Halite and Anhydrite, Hualapai Basin

Composition. The salt primarily consists of poorly bedded, displacive masses of large (up to 8 cm long), interlocking subhedral to euhedral crystals of clear halite (figure 6*a*). Small pockets or inclusions of reddish brown clay occur between or within most halite crystals and, in some cases, completely envelop crystals (figure 6*b*). The salt also includes some finer-grained beds of relatively pure halite. Fluid inclusions are small and sparse. X-ray diffraction analysis shows that the thin (<1 m thick) "shaly" layers intercalated within the halite typically consist of 65% anhydrite and 35% kaolinite. Desiccation cracks are common in the "shaly" layers, but no fossils were observed. Many of the "shaly" beds also contain isolated euhedral crystals of displacive halite (figure 7). The bromine content of six samples of halite from drill hole D3 did not exceed 2.5 ppm (table 2; courtesy of L. Walter and T. Huston, written comm. 1995).

Up to 50 m of bedded, nodular anhydrite and lesser amounts of gypsum cap the halite (figure 8). In addition, thin beds of anhydrite (<1 m thick) occur within the halite. One intercalated anhydrite layer yielded $\delta^{34}S$ and $\delta^{18}O$ isotopic values of 6.84 (‰ vs. CDT) and 5.86 (‰ vs. SMOW), respectively. The anhydrite cap has $\delta^{34}S$ and $\delta^{18}O$ isotopic values of 11.31 (‰ vs. CDT) and 11.54 (‰ vs. SMOW), respectively (table 3).

Age. Regional relations are applied to bracket the age of the halite. Growth-fault relations in nearby ranges and half grabens (Anderson et al. 1972; Bohannon 1984; Beard 1993; Faulds 1993; Faulds et al. 1995*b*) suggest that the angular unconformity above unit e, which records the onset of major tilting and basin subsidence is ~16 Ma, and synextensional unit d is ~16–13 Ma. Unit d is probably temporally correlative with thick synextensional mafic and felsic volcanic sequences in the White Hills and Black Mountains (e.g., Anderson et al. 1972; Faulds et al. 1995*b*; McDaniel 1995), as well as with clastic sedimentary rocks and gypsum that compose the lower part of the Horse Spring Formation in the Lake Mead area (e.g., Bohannon 1984). The magnitude of tilting relative to lower parts of the section (≤10° versus 25°), upward decrease in tilt of the salt layers (10° to 2°), and truncation by the Grand Wash fault indicate a relatively late synextensional origin for the salt. Gently tilted (<5°) to flat-lying 11 Ma basalt flows 30 km west of the Hualapai basin (Conrad et al. 1990; Faulds 1993; Faulds et al. 1995*b*) and gently east-tilted 9–11 Ma basalt flows in the southern White Hills (Calderone et al. 1990; McDaniel 1995) directly west of the basin (figure 1*b*) are considered to be coeval with the salt. Upper Miocene (~6–9 Ma) basalt lavas, which locally overlie halite deposits near Lake Mead (Feuerbach et al. 1993), and the 9–4 Ma Bouse Formation are not faulted or tilted in the region. Thus, the age of the Hualapai basin halite is firmly constrained between ~16 and 6 Ma but is most likely ~13 to 9 Ma. This suggests that the halite is slightly older than both the Bouse Formation and Grand Canyon, but overlaps in age with the upper Miocene–lower Pliocene Muddy Creek Formation in the Grand Wash trough (Lucchitta 1979), including the 10.8–3.8 Ma Hualapai Limestone Member. The halite is also roughly equivalent in age with upper members of the Horse Spring Formation described by Bohannon (1984) in the Lake Mead area, including (a) the 13.5–13.0 Ma Bitter Ridge Limestone, (b) the 13.0–11.9 Ma Lovell Wash Member that consists of dolomite, limestone, tuff, and sandstone, and (c) the 11.9–10.6 Ma Red Sandstone.

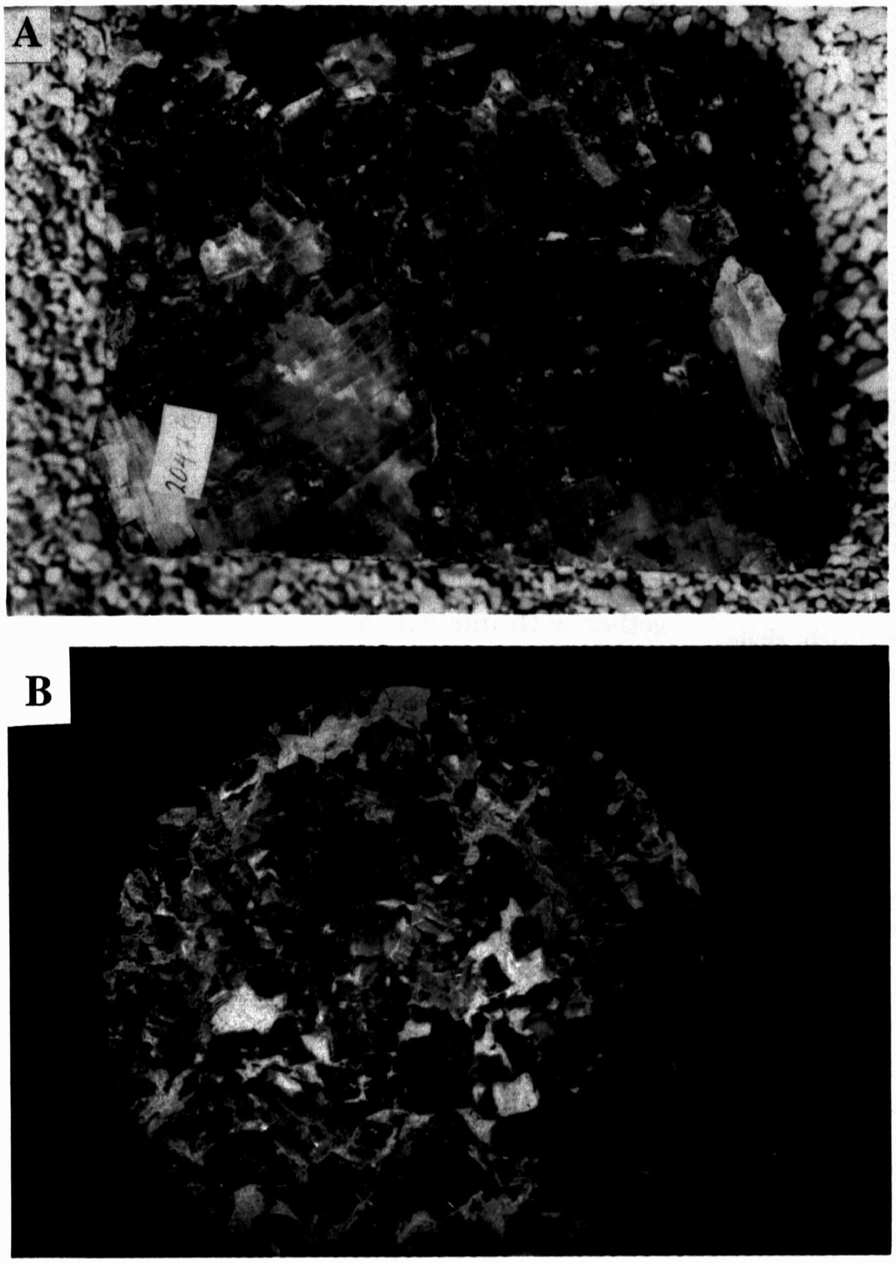

Figure 6. Massive, nearly clear halite in the Hualapai basin core (drill hole D3; table 1): (*a*) interlocking, subhedral to euhedral halite crystals with only a small amount of matrix (624 m); (*b*) bedding plane view of displacive, grayish euhedral crystals of halite in a white shale/anhydrite matrix (1248 m). Core diameter is ~7.65 cm.

Limestone, Grand Wash Trough

The Hualapai limestone consists primarily of impure micritic carbonate (marl) containing variable amounts of silt-sized detrital grains of quartz, chert, and feldspar. Travertine (tufa) deposits have been reported by Blair and Armstrong (1979). Textures vary considerably according to variations in the carbonate component. In samples in which carbonate content is greatest, oncolites and/or pisoliths are locally abundant, and ostracodes are common. Non-carbonate detrital grains can constitute up to 20% of the carbonate-rich rocks. Caliche crusts are commonly developed on oncolite bearing samples. Where fossil content is minimal, intraclasts are common, and clastic grains can compose as much as 30–40% of the sample. In these samples, vuggy porosity is high, and vugs resemble casts of decayed plant roots and fragments. The $\delta^{13}C$ (PDB) and $\delta^{18}O$ (% vs. SMOW) values from the Grapevine Mesa area of the Grand Wash trough range from −0.26 to −2.86 and 18.78 to 20.54, respectively (table 4).

Discussion

Origin of Halite, Hualapai Basin. Several features, including the overall composition of the evaporite sequence and regional stratigraphic-structural relations, strongly suggest that the evaporites in the Hualapai basin have a nonmarine origin and accumulated within an intracontinental lake/playa (cf., Rosen 1994) rather than within a

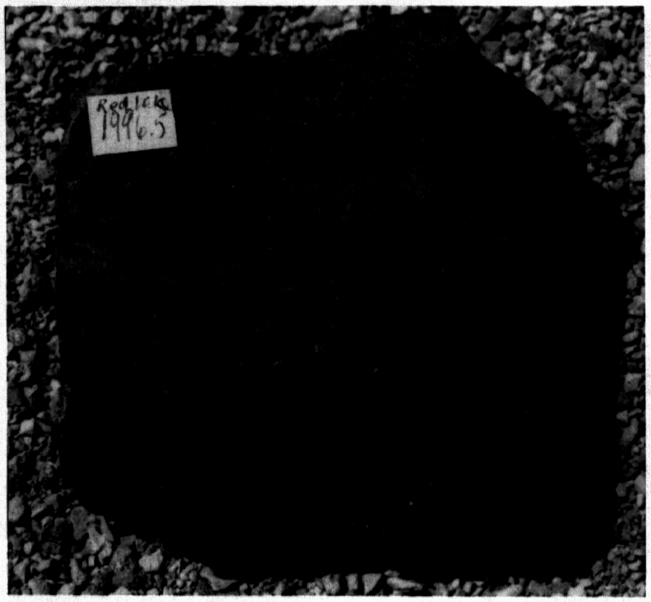

Figure 7. Displacive halite in anhydrite-rich shale. Note faint traces of disrupted bedding. From the Hualapai basin core at 609 m (drill hole D3; table 1). Core diameter is ~7.65 cm.

marine-fed proto-Gulf of California. For example, thick deposits of halite, with negligible anhydrite and gypsum, are unlikely by-products of the evaporation of sea water (Hardie 1984). More important, the bromide content of the halite (≤2.5 ppm) (table 2) is far below the 75 to 500 ppm range expected for seawater derived halite (Hanor 1987; Braitsch 1971) or the 5 to 20 ppm range expected from halite derived by a first-cycle dissolution-precipitation of marine-derived halite (Holser 1979). In addition, the $\delta^{34}S$ values of the intercalated and capping anhydrite (table 3) are significantly lower than those documented for Tertiary (17 to 21‰) or other Phanerozoic (>12‰) marine sulfate deposits (Claypool et al. 1980). The depleted $\delta^{18}O$ of the sulfate (table 3) also indicates a nonmarine, fresh water source for the evaporites in the Hualapai basin. Thus, neither Miocene seawater nor recycling of older marine derived sulfate was a source for the evaporites within the Hualapai basin. The sulfur in the sulfatic evaporites of the basin may have been derived from the oxidation of sulfide in Cretaceous mineral deposits of the region (e.g., Theodore et al. 1982), including perhaps a large porphyry copper deposit (Eidel et al. 1968) that currently resides on the west flank of the Cerbat Range just outside of the present catchment area of the basin.

The halite in the Hualapai basin originated primarily through intrasedimentary displacive growth in desiccated pans (playa mudflats), together with intervals of deposition in flooded saline pans (e.g., Gornitz and Schreiber 1981; Rosen 1994; Curial and Moretto 1996; Schubel and Lowenstein, 1997), as evidenced by the poorly developed bedding, coarse interlocking halite crystals, abundance of intercrystalline shale within the halite, and isolated displacive halite crystals and desiccation cracks in the associated shale. Subaqueous growth in a shallow hypersaline lake probably produced the relatively pure beds of finer-grained halite, although subsequent desiccation and development of dissolution surfaces and puffy halite crusts in sporadically exposed mudflats may have obliterated much of the typical, original chevron pattern of fluid inclusions (e.g., Shearman 1970). The extreme thickness of the halite, dominance of displacive growth textures, and relative lack of interlayered clastics suggest that most of the halite was

Table 2. Bromine Content for Upper Miocene Halite, Hualapai Basin (Drill Hole D3)

Depth (m)	Sample Type	ug Br/g of rock	mg Na/g of rock	Percent NaCl	ug Br/g NaCl
597	Acetone Wash	<2.2	394	100	<2.2
597	Whole Rock	<2.4	375	95	<2.5
609	Acetone Wash	<2.3	354	90	<2.5
609	Whole Rock	<2.3	288	73	<3.2
624	Acetone Wash	<2.2	369	94	<2.4
624	Whole Rock	<2.3	351	89	<2.6
1237	Acetone Wash	<2.2	363	92	<2.4
1237	Whole Rock	<2.5	387	98	<2.5
1248	Acetone Wash	<2.5	331	84	<3.0
1248	Whole Rock	<2.4	357	91	<2.7
1828	Acetone Wash	<2.0	390	99	<2.1
1828	Whole Rock	<2.2	399	102	<2.2

Note. Whole rock samples include fluid inclusions. Samples ground and rinsed in acetone exclude fluid inclusions. Nominally 0.5 g of sample was dissolved in 25 ml of H_2O. Br was analyzed by Ion chromatography; Na by ICP. Br values are 3-sigma limit of detection (0.05 mg Br/l); Na values are ±3%. Data provided courtesy of L. Walter and T. Huston at the Department of Geological Sciences, University of Michigan.

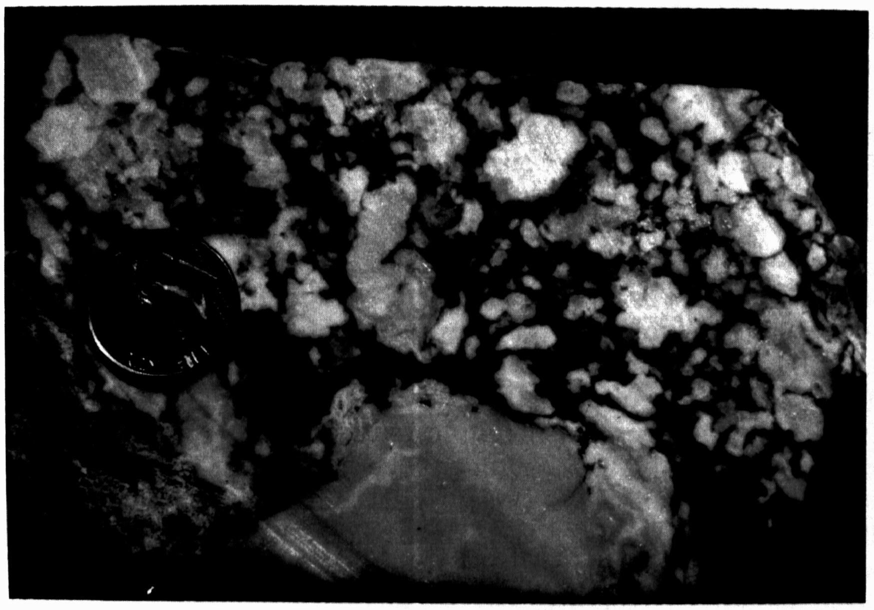

Figure 8. Displacive nodular anhydrite in a coarse sandy matrix near the top of the evaporite section. From the Hualapai basin core at 427 m (drill hole D1; table 1). Core diameter is ~5 cm.

derived from salt-bearing groundwater solutions (e.g., Neev and Emery 1967; Smoot and Lowenstein 1991) and that the playa served as a prolonged, regional discharge zone for large volumes of saline groundwater. The high influx of groundwater, with little accompanying surface water, and arid climate account for the dearth of clastic sediments. A similar depositional environment presently characterizes the Dead Sea (Neev and Emery 1967).

Possible sources of sodium chloride for the Hualapai basin include Permian redbeds (Supai Formation) in the Colorado Plateau, which are rich in chloride salts (Lucchitta 1966; Eaton et al. 1972), thick Miocene calc-alkaline volcanic piles in the Basin and Range, and hydrothermal waters. The Permian redbeds are the most likely source of the Na^+ and Cl^-, because the nearby Colorado Plateau provides a large, topographically elevated catchment area from which to derive appreciable volumes of ground water and surface runoff. However, similar to the central Andes, where unusually thick nonmarine salt deposits were derived from volcanic source areas (Ericksen and Salas 1989; Alonso et al. 1991), 3–4 km thick volcanic piles in the central part of the extensional corridor and associated hydrothermal activity may have also provided a significant source of Na^+ and Cl^- for the Hualapai basin. It is noteworthy that modern hypersaline and soda lakes are most commonly associated with active volcanic regions typically in rift settings (Kempe and Degens 1985). Cessation of halite deposition within the Hualapai basin during late Miocene time may have resulted from (a) initial cutting of the western Grand Canyon (e.g., Lucchitta 1989), which would have largely removed Permian redbeds from the catchment area of the basin, and/or (b) waning magmatism and

Table 3. Isotopic Data, Upper Miocene Anhydrite, Hualapai Basin

Drill Hole[a]	Depth (m)	$\delta^{34}S$ (% vs. CDT)[b]	$\delta^{18}O$ (% vs. SMOW)[c]
D2	447	11.31	11.54
D3	625	6.84	5.86

[a] Drill hole data shown in Table 1.
[b] The $\delta^{34}S$ values are relative to troilite in the Canyon Diablo meteorite (CDT).
[c] The $\delta^{18}O$ values are relative to standard mean ocean water (SMOW).

Table 4. Isotopic Data for the Miocene-Pliocene Hualapai Limestone, Grand Wash Trough

Sample #	$\delta^{13}C$ (PDB)[a]	$\delta^{18}O$ (% vs. SMOW)[b]
1	−2.84	20.54
2	−2.86	19.88
3	−.52	18.78
4	−.26	20.17

Note. All samples were limestone (marl), collected from the Hualapai Limestone Member of the Muddy Creek Formation at Grapevine Mesa within the Grand Wash trough.
[a] $\delta^{13}C$ values are relative to PDB standard, which is based on belemnites from the Cretaceous Peedee Formation, South Carolina (Faure, 1986).
[b] The $\delta^{18}O$ values are relative to standard mean ocean water (SMOW).

tectonism (e.g., Faulds et al. 1995*b*) and a probable corresponding decrease in hydrothermal activity.

Deposition of great thicknesses of evaporites in a short time interval is well documented. High evaporation in arid regions permit optimum accumulation of sulfates at rates of 1–40 m/1000 yrs and halite at 10–100 m/1000 yrs (Schreiber and Hsu 1980). These high values have been observed in modern marine-sourced basins. For example, deposition of the 2 km thick upper Miocene section on the floor of the Mediterranean probably took no more than 0.25–0.40 m.y. (Hsu et al. 1978; Rouchy and Saint-Martin 1992; Gautier et al. 1994). In continental basins with sufficient accommodation space, evaporite deposition may be as rapid as in marine-fed basins. Assuming the ionic input into a continental-sourced basin is only one-tenth that of marine sources, the time interval available for deposition in the Hualapai basin (~3–4 m.y.) is entirely sufficient for the accumulation of the entire evaporite section.

Origin of Limestone, Grand Wash Trough. On the basis of fossil assemblages, oxygen isotopic data, and petrography, we conclude that the upper Miocene–lower Pliocene limestone within the Grand Wash trough is also a freshwater deposit. Blair (1978) and Blair and Armstrong (1979) utilized fossils, mineralogy, petrography (calcite cements), and isotope chemistry ($\delta^{13}C$) to assign a marine origin to the limestone. However, none of the fossils (e.g., algal stromatolites, diatoms, gastropods, ostracodes) analyzed by Blair and Armstrong (p. 5–8, 1979) are unique to marine environments. In addition, the association of the most abundant macrofossil, plant molds of reeds and rushes, with travertine is indicative of freshwater carbonate environments (Julia 1983). Blair and Armstrong (1979) did recognize some freshwater fossils within the limestone (e.g., ostracodes and some diatoms), but attributed them to fluvial input by an ancestral Colorado River. Based on the work of Kendall and Tucker (1973), the presence of radiaxial fibrous calcite was also used by Blair and Armstrong (1979) as an indicator of marine origin. However, these fabrics were later found to occur in non-marine freshwater settings (Kendall and Broughton 1978). It is now recognized that no single calcite cement fabric is diagnostic of any particular environment (e.g., Chafetz et al. 1985) and that calcite saturation (e.g. Given and Wilkinson 1985) or hydrodynamic conditions (e.g., González et al. 1992) play a greater role in determining cement fabrics. Petrographic and textural properties are consistent with a lacustrine origin in which shoreline environments have a higher carbonate content, more abundant fossils, and features indicative of subaerial exposure (e.g., caliche and travertines), whereas the farthest and deepest portions have a lower carbonate content and sparse fossils (Dean and Fouch 1983). The carbon isotopic composition of limestone is highly variable, because various processes, such as CO_2 consumption during algal blooms (Herczeg and Fairbanks 1987), can lead to ^{13}C enrichment; thus carbon isotopes alone cannot differentiate environments of formation. In contrast, the $\delta^{18}O$ composition of a carbonate can be diagnostic of the fluids from which the carbonates formed. The $\delta^{18}O$ values of marine carbonates have exceeded 24‰ (SMOW) through Phanerozoic history and 29‰ (SMOW) since Cretaceous time (Lohmann and Walker 1989). The oxygen isotopic composition of the carbonates in the Grand Wash trough (<21‰) (table 4) clearly demonstrates that they did not form from marine water, but instead indicates formation from freshwater derived from high elevations. Values of $\delta^{18}O$ and $\delta^{13}C$ similar to those of the carbonate in the Grand Wash trough have been observed in many lacustrine carbonates (e.g., Dean and Stuiver 1993; Palacios-Fest et al. 1993; Stuiver 1970).

Regional Implications. The nonmarine origin of both the halite in the Hualapai basin and limestone in the adjacent Grand Wash trough suggests that middle Miocene to lower Pliocene evaporite deposits throughout the Lake Mead region, including the limestone and dolomite deposits within the Horse Spring Formation (e.g., Bohannon 1984) and halite deposits in the Detrital and Virgin basins (e.g., Holser 1970), originated in a series of shallow saline lakes and continental playas and do not represent the northern extent of the ancestral Gulf of California. Consequently, these deposits cannot be used as evidence for significant uplift of the southwestern Colorado Plateau and northern Colorado River extensional corridor since late Miocene time. If lacustrine in origin, as the Sr isotopic values imply, the Bouse Formation is also irrelevant to late Miocene-to-Recent uplift of the lower Colorado River region and southwestern Colorado Plateau (Patchett and Spencer 1995). Transport by birds may account for the presence of some of the apparent marine fossils (e.g., Buising 1990) within the Bouse Formation (Patchett and Spencer 1995). Some marine invertebrates (e.g., some diatoms and foraminifera) can locally prosper in lakes so long as saline conditions prevail (G. Truc personal comm. 1995).

On the basis of the lack of Miocene-Pliocene marine deposits in the Lake Mead region and relatively negligible faulting since late Miocene time, we conclude that major extension between ~16 and 9 Ma (e.g., Duebendorfer and Wallin 1991; Beard 1993; Faulds et al. 1995*b*) produced most of the differential relief between the southwestern Colorado Plateau and northern Colorado River extensional corridor. Excavation of the western part of the Grand Canyon may have begun with the headward erosion of small streams during the early phases of extension ~16 Ma and was probably well underway by ~9 Ma. Rapid downcutting of the Grand Canyon since 6 Ma (Lucchitta 1989) may not be due entirely to coeval epeirogenic uplift of the southwestern Colorado Plateau and adjoining regions (Lucchitta 1979; Parsons and McCarthy 1995), but may instead be largely the result of the capture of an upper Colorado River by headward eroding streams along the southwestern margin of the Colorado Plateau and/or a lowering of base level as interior-drained basins in the Lake Mead and lower Colorado River regions were integrated with the Gulf of California, the extent of which may have changed little since latest Miocene time.

An intriguing possibility is that an ancestral Colorado River may have excavated much of the Grand Canyon and emptied into a series of lakes in the Lake Mead region by late Miocene time (e.g., Hunt 1969; Lovejoy 1980). If this were the case, a very large source of Na^+ and Cl^- would be available from the large Permian salt deposits within the Colorado Plateau, particularly the Paradox Basin of eastern Utah and the Holbrook basin of eastern Arizona (e.g., Peirce and Gerrard 1966). However, Lucchitta and Young (1986) discounted an ancestral Colorado River in the Lake Mead region, because (a) the evaporites are consistently associated with poorly sorted fanglomerates and have not been observed anywhere to interfinger with river gravels, and (b) the provenance of much of the fanglomerate that interfingers with the Hualapai Limestone in the Grand Wash trough precludes an ancestral Colorado River at least near its present course. Although these features do not completely rule out an ancestral (>6 Ma) Colorado River, the Great Salt Lake in northern Utah demonstrates that large saline lakes do not require a single major river system as a source.

We suggest that the Great Salt Lake (e.g., Spencer et al. 1984) may represent a modern-day counterpart to the middle Miocene to early Pliocene system of lakes and playas within the Lake Mead region. The Great Salt Lake lies near the margin of the Basin and Range province adjacent to a broad regional uplift, which includes the Wasatch Range and parts of the Colorado Plateau. Similar to the contemporary Great Salt Lake, a series of relatively small streams, as opposed to a major river system, and substantial amounts of ground water probably fed the Miocene-Pliocene playas and lakes in the Lake Mead region. The thicker accumulations of halite in the Lake Mead region, as compared to northern Utah, may have resulted from greater aridity and associated higher evaporative rates, as well as perhaps a more plentiful supply of Na^+ and Cl^-.

Broader Implications. Although thicker nonmarine salt has been found in the transtensional regime of the Dead Sea (Bentor 1968) and convergent setting of the central Andes (Alonso et al. 1991), the 2.5 km thick Hualapai basin salt is one of the thickest known, nonmarine halite deposits in a continental rift. Most of the major evaporite deposits in the Basin and Range, including the Miocene-Pliocene deposits near Lake Mead, probably originated in nonmarine, interior-drainage basins (e.g., Peirce 1976). Considering the regional extent of the Basin and Range evaporites and the great thickness of some of these deposits, it is important to discuss the combination of features and events that induced halite deposition in the Hualapai basin and whether such conditions are common within continental rifts.

Several tectono-hydrologic events conspired to produce the unusually thick nonmarine halite in the Hualapai basin. Appreciable movement on and the listric geometry of the southern Grand Wash fault were both critical, because they accommodated the tilting of the Cerbat Range, which generated the relatively deep half graben of the Hualapai basin and accommodation space for evaporite deposition. The maximum fault displacement coincides with the deepest part of the basin and apparent maximum thickness of salt. The angular unconformities in the basin and great thickness of salt imply rapid basin subsidence and relatively fast slip rates on the fault. Most of the slip probably occurred 15–12 Ma, which coincides with high rates of extension and subsidence in the region (Anderson et al. 1972; Bohannon et al. 1993; Beard 1993; Faulds 1993; Faulds et al. 1995*b*). The rapid subsidence and arid climate prevented integration of the Hualapai basin into a regional drainage net and led to a protracted history of interior drainage that continues to this day. Initially, volcanic and clastic sedimentary rocks accumulated in the half graben. Halite deposition probably did not begin until ~13 Ma, which may signal the time when (a) significant topographic relief had developed between the Colorado Plateau and major basins within the northern Colorado River extensional corridor, (b) the configuration of the drainage net permitted the influx of large volumes of saline ground water, and/or (c) climatic conditions were at an optimum for evaporite deposition. The broad uplift of the Colorado Plateau provided a large catchment area with an abundant source of nonresistant, chloride-rich Permian redbeds (the Supai Formation) from which to derive large volumes of saline ground water, while the newly developed basins within the corridor afforded regional sinks for the groundwater. Thus, the major ingredients that led to voluminous deposition of nonmarine halite in the Hualapai basin include (1) the rapid development of a deep basin, (2) arid climate, (3) interior drainage, (4) proximity to a large uplifted region from which to derive ample ground water, and (5) a readily available source of salt.

Such conditions are common in many continental rifts. The thick nonmarine evaporites in several other basins in Arizona (Peirce 1976), including other unusually thick halite deposits (Eaton et al. 1972), suggest that similar conditions prevailed all along or proximal to the southern and southwestern margin of the Colorado Plateau. It is noteworthy that were it not for problems with saline ground water, the unexposed Hualapai basin salt may never have been discovered. This implies that additional deposits of unusually thick, Cenozoic evaporites are yet to be found in the Basin and Range province, particularly near its eastern and western margins adjacent to the broad uplifts of the Colorado Plateau and Sierra Nevada, where the thickest Cenozoic evaporites have thus far been documented.

Documented Cenozoic evaporite deposits within the Basin and Range already provide large quantities of valuable mineral resources such as halite, gypsum, potash, and borate (e.g., Kyle 1991; Kistler and Smith 1983). The unexposed, 2.5-km-thick Hualapai basin salt suggests that the extent of these resources may be much greater than previously thought. Some of the deposits may also be useful for storage of natural gas and/or nuclear wastes (e.g., Johnson and Gonzales 1978; Netherland and Sewell 1977; FERC 1982; Dean and Johnson 1989). In addition, in less arid parts of the Basin and Range, or those with a greater catchment area, lacustrine depositional phases may provide a source of hydrocarbons that may feed reservoirs in marginal clastic alluvial deposits that are, in turn, sealed by evaporites.

Saline groundwater within the Hualapai basin demonstrates, however, the negative impact of thick, near-surface salt. Due in large part to this problem, ranching and urban development has been greatly limited within the Hualapai basin. The likelihood that the Basin and Range contains many other thick salt deposits poses a potentially serious problem to some of the large metropolitan areas in the region. For example, the Hualapai basin and most other basins in the Lake Mead region probably could not provide nearby Las Vegas, currently the fastest growing major city within the USA, with an adequate resource of potable ground water. Thick halite deposits and attendant saline groundwater may eventually limit the growth of many of the currently burgeoning cities within the "sun-belt" of the Basin and Range.

The widespread occurrence of thick Cenozoic nonmarine evaporites in the Basin and Range suggests that the depositional setting of the Hualapai basin is not unusual for extended terranes. Because widespread crustal extension precedes the eventual breakup of continental masses, it seems intuitive that depositional environments similar to those in the Basin and Range would characterize the early history of many of the world's passive margins. Thus, the known extent of the Basin and Range nonmarine evaporites implies that a nonmarine origin should not be overlooked for thick, synrift salt deposits on passive continental margins. The thickest nonmarine evaporite deposits on passive margins would probably be found in large, relatively deep basins near the margins of major platforms or plateaus. However, the thicker salt deposits on passive continental margins have commonly been appreciably deformed, making interpretation of their origin difficult. An important question is whether the deformation of the salt bodies is in some way linked to their primary depositional geometries.

As exemplified by the Hualapai basin, lenticular-wedge shapes probably characterize the original geometry of many synrift salt deposits. A thick wedge-shaped salt body would be unstable, as greater loading may induce migration of salt away from a basin depocenter. The appreciable westward tilt of the upper part of the Hualapai basin salt along the southern Grand Wash fault (figure *3a*) may reflect incipient flow of the salt into the fault zone. Migration of salt into the fault as an upward-tapering, linear sheath may have even accommodated some extension in the Hualapai basin, as has also been noted on the passive margin of eastern North America (e.g., Balkwill and Legall 1989). Although not expressed in the Hualapai basin, large salt diapirs may have a tendency to form near the originally thickest parts of synrift salt deposits, which would generally be spatially associated with the displacement maxima on major normal faults. This would result from a combination of greater loading on the deeper central part of the basin and enhanced migration of salt into the segment of the fault accommodating the greatest displacement and extension. Thus, the distribution of slip on major normal faults may be fundamentally linked to the development of the thickest, synrift salt deposits as well as to the processes and positioning of diapiric intrusion. If the shape of both the primary depositional wedge and final deformed diapir can be defined or modeled, it may also be possible roughly to quantify the magnitude of strain that a salt body has undergone.

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