The origin and significance of groundwater-seepage gypsum from Bristol Dry Lake, California, USA

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ABSTRACT

Gypsum and anhydrite fabrics observed in trenches and deep (500 m) cores from Bristol Dry Lake, California, USA, exhibit a vertical alignment of crystals similar to the fabric seen in bottom-nucleated brine pond gypsum. However, geochemical and sedimentological evidence indicate that the gypsum formed in Bristol Dry Lake precipitated displacively within the sediment where groundwater saturated with respect to gypsum recharges around the playa margin (groundwater-seepage gypsum). Evidence for displacive growth of gypsum is: (i) the geometry of the deposit, (ii) stable isotopic data and the water chemistry of the brine, and (iii) inclusions of matrix which follow twin planes and completely surround crystals as they grow.

The bulk of the gypsum precipitated in the playa occurs around the edges of the playa in the playa-margin facies and completely rings the lake. Sulphate concentrations in the groundwater increase toward the gypsum zone in the playa margin. Basinward of this zone, sulphate concentrations decrease sharply to trace element levels in the basin centre brine. Authigenic gypsum is rare in the centre of the playa. Stable $^18O$ values measured for gypsum waters of crystallization (GWC) are similar to the values calculated for groundwater in the playa margin and alluvial fan sediments ($\sim -6\%$), whereas measured brine $^18O$ values range from $+0.5$ to $+3.7\%$. Deuterium values measured for groundwater are $\sim -70\%$, GWC are $\sim -60$ to $-65\%$, and brine values are $\sim -57\%$. The geometry of the deposit and the chemical data suggest that the water precipitating the gypsum is more closely associated with the groundwater than the brine. However, some mixing between groundwater and brine is likely.

Within 100 m of the surface, the gypsum dehydrates to anhydrite, although the same vertically aligned fabric is retained through the diagenetic process. The similarity of displacive vertically aligned gypsum and anhydrite fabrics seen in Bristol Dry Lake to subaqueously deposited gypsum in modern brine ponds indicates that the criteria used to define subaqueous fabrics must be better constrained.

INTRODUCTION

The vertical alignment of gypsum and anhydrite fabrics has been well documented in both Holocene and ancient examples (see references in Schreiber, 1988; Warren, 1989). Vertically aligned gypsum crystallizes in Holocene coastal lakes (salinas) in southern and western Australia (Arakel, 1980; Warren, 1982a, b). These modern examples indicate that the vertically aligned fabric is produced during subaqueous gypsum growth from an evaporating brine pond. Vertically aligned gypsum and anhydrite fabrics found in Bristol Dry Lake, California, USA, do not follow the accepted criteria for primary subaqueous gypsum growth (Table 1). Field and geochemical evidence indicate that the gypsum formed from groundwater resurfacing around the margins of the playa, precipitating gypsum as a diagenetic mineral within the near-surface sediments of a continental playa.
The purpose of this paper is to document the occurrence, fabric, and geochemistry of vertically aligned gypsum in Bristol Dry Lake so that these groundwater-produced fabrics can be compared with subaqueous and subaerial gypsum fabrics. The documentation of gypsum/anhydrite fabrics will enable more precise determinations of gypsum depositional environments.

**GEOLOGICAL SETTING**

Bristol Dry Lake, a closed-basin playa, is situated in the Mojave Desert region of southeastern San Bernardino County, California (Fig. 1). It is the largest (155 km²) in a system of three NW–SE-trending dry lakes (playas) located in a structural trough between mountain ranges in the Basin and Range physiographical province of North America. Bristol Dry Lake is the terminus of a large (4000 km²) closed-drainage basin. The climate is arid (average < 100 mm rainfall per year) and there are many years when there is no rain at all (Thompson, 1929).

Field-work was conducted on six separate occasions in Bristol Dry Lake over a 3-year period during the months of October–May. Around the margins of the playa seven trenches along two transects perpendicular to the basin margin were excavated, one transect on the north and the other on the south edge of the playa (Fig. 1). These trenches were cut perpendicularly through the entire length of the gypsum zone in the playa-margin facies. Each trench is approximately 2 m deep. The length of each trench is close to 20 m except one continuous trench on the south side of the playa which is 300 m long.

One core (CAES No. 1; Fig. 1), taken by Southern California Edison Utility Company in 1985, contains playa-margin sediments from 150 to 540 m. This core, which has virtually 100% core recovery, is open to public viewing and is permanently stored at the core storage facility of the Bureau of Economic Geology, University of Texas at Austin. The core was logged and selected samples were used for petrographical and chemical analyses.

Representative gypsum samples from the surface and core were cut in oil-based lubricants, impregnated with blue epoxy, and made into 75 x 130-mm thin-sections. Thin-sections were studied to determine mineralogy, fabric and diagenetic alterations in the sediment. The determination of mineralogies was aided by X-ray diffraction analyses. Five-hundred points were counted on four gypsum slides to determine quantitative mineralogies.

Eighteen gypsum samples were sent to Arizona State University for deuterium analysis of gypsum water of crystallization (GWC). Two of these samples were also analysed for 18O (error of the analysis is ± 0-2‰). Two blind duplicates were also sent for deuterium analysis. One sample was within the reported error (± 2‰), and the other was 7‰ lighter than the original value. Heterogeneities caused by
Origin of groundwater-seepage gypsum

Multiple growth episodes in the gypsum can account for this discrepancy. Deuterium values for rainwater (G. I. Smith, pers. comm.), groundwater, and brines (I. Friedman & J. Gleason, pers. comm.) were made available from the United States Geologic Survey (USGS). The isotope data are presented in the standard δ notation relative to SMOW.

Water from three brine samples were analysed for trace elements and δ18O. Major and minor element chemical analyses were taken from various sources in the literature. Charge balance calculations were determined for each analysis to determine their accuracy. Although the charge balance calculations indicate that the analyses are not very accurate (up to 20% imbalance), the analyses are adequate for some important conclusions to be drawn from these data. These water data can be found in Rosen (1989, 1991).

SULPHATE OCCURRENCE

General facies relationships

The overall facies relationships in Bristol Dry Lake have been worked out by Handford (1982) and modified by Rosen (1989, 1991). In general, Bristol Dry Lake has a bull's-eye distribution of evaporite minerals and sedimentary units (Fig. 1). Low-gradient alluvial fans ring the playa. Extensive calcrete and pedogenic calcite associated with halophyte plants cement the mid- to distal-fan gravels and sands. Basinward of the distal-fan facies is the playa-margin facies containing gypsum in a playa-fringing zone more than 300 m wide.

Within the gypsum zone, celestite forms decimetre-sized nodules which may coalesce into metre-sized patches. Basinward of the playa-margin facies, halite hopper crystals up to 0.5 m in diameter form in muds of the saline mudflat facies. Finally, in the basin-centre a 0.2-m-thick chevron halite crust forms from evaporation of ponded ephemeral water. For the purposes of this study, the observation that the bulk of the gypsum in the playa is situated around the margin of the playa is the most important aspect of basin facies relationships (Fig. 1).

Playa-margin siliciclastic sediments, sparsely covered by halophytes, pass gradually into the barren saline mudflat. Playa-margin sediments beneath the vegetation zone vary from silty sands to sandy muds that contain calcite-cemented nodules surrounding root holes of former halophyte shrubs.

Basinward of the vegetation-covered playa margin is a zone, approximately 30 m wide, where large centimetre-sized gypsum blades are cemented by fine-grained calcite. The calcite in places voids produced by decayed roots or dissolution of gypsum. This zone represents a mineralogical transition area from calcite-cemented sediment to gypsum-cemented sediment. Further into the basin, the calcite becomes less abundant and vertically aligned gypsum and nodular celestite dominate. The remainder of the playa-margin facies (approximately 300 m wide) is dominated by vertically aligned gypsum growth (Fig. 2).

Geometry and textures of the gypsum zone

A continuous trench 2 m deep and 300 m long (see Fig. 1), excavated across the gypsum zone of Bristol Dry Lake, reveals that at the alluvial fan end of the trench (proximal playa-margin facies) the gypsum forms as stringers in a mud and sand matrix. Further into the lake basin (medial playa-margin facies), the stringers coalesce into a single unit that is over 2 m thick and composed of stacked beds composed of almost pure gypsum (Fig. 2). Further basinward (distal playa-margin facies), the gypsum in the bed gradually returns to stringers in a mud matrix, but with localized occurrences of celestite (SrSO₄) nodules enclosed by vertically aligned gypsum or growing displacively in gypsum-free muds.

Individual gypsum crystals in Bristol Dry Lake beds are, in general, vertically aligned and up to 80 mm in the longest dimension. Gypsum can form >70% of the sediment, although in places, the sediment may contain up to 90% gypsum (Fig. 3; Table 1). No sedimentary structures or evidence of mechanical reworking is present within the gypsum, yet intercalated beds of mud and sand exhibit both organic (burrowing) and inorganic (dewatering) reworking. Individual gypsum horizons may be up to 0.3 m thick and are underlain and overlain by additional gypsum beds. Some horizons have an undulatory upper contact with the overlying gypsum and dissolution and karsting of the beds is apparent in the proximal end of the trench.

Gypsum crystal size is variable in a single vertical sequence and both upward-finings and upward-coarsening units are present. Crystal size increases from the proximal to the distal end of the playa-margin facies. Morphology of the crystals varies widely from biconcave (lenticular) lens-shaped discs to 'swallow-
Fig. 2. Detail of the 300-m trench wall from the south side of Bristol Dry Lake (Fig. 1) showing the geometry of the vertically aligned gypsum deposit. Notice the lenticular geometry of the gypsum zones and the almost pure area of gypsum in the middle of the trench. In places, the sediment is over 90% gypsum. This thick accumulation of gypsum is due to the present stability of the discharge zone. Celestite nodules (SrSO₄) are concentrated to the basinward portion of the trench. Vertical exaggeration = × 60.

Fig. 3. Vertically aligned gypsum fabric from the 300-m trench. The crystals are between 0.02 and 0.04 m in length. There are no well-defined bedding surfaces or growth laminations in the Bristol Dry Lake deposits and there is no bedding in the matrix inclusions. The lens cap is 50 mm in diameter.

tail' twinned blades, with discs as the dominant morphology. However, almost all of the twins are $d\{101\}$ twins rather than the more common $a\{100\}$ twins (Cody & Cody, 1989). In many cases, matrix inclusions completely outline crystal growth surfaces within individual gypsum crystals. Siliciclastic green muds and red sands, intercalated between gypsum accumulations, show centimetre-thick laminations of burrowed sediments. Because the colours are lithologically controlled (i.e. green mud and red sand) and do not cut across from mud to sand, it is likely that the colours indicate alternations between oxidizing and reducing conditions due to alternations between shallow water and subaerial exposure, and are not due to post-depositional chemical reactions. Original depositional fabrics within the muds and evaporites in gypsum accumulations have been completely destroyed by subsequent displacive growth of the gypsum.

CAES No. 1 (see Fig. 1) penetrates the distal end
Table 1. Comparison of Bristol Dry Lake groundwater-seepage and subaqueous gypsum (after Rosen, 1989; Warren, 1989).

<table>
<thead>
<tr>
<th>Groundwater-seepage gypsum</th>
<th>Salina-subaqueous gypsum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporite units are subaerial, sulphate-dominated, can be &gt;70% sulphate with individual units typically less than 0.3 m thick</td>
<td>Evaporite units are subaqueous, sulphate-dominated, often &gt;70% sulphate with individual depositional units up to 10 m thick</td>
</tr>
<tr>
<td>Evaporite crystals are displacive and grow in a near-surface thixotropic matrix</td>
<td>Evaporite crystals are deposited on a sediment substrate at the sediment–water interface</td>
</tr>
<tr>
<td>Displacive and replacive pyramidal gypsum as vertically aligned aggregates. Inclusions of matrix typically follow twin planes and completely surround crystals as they grow. Lenticular habit is dominant and crystal size increases into the basin. Laminated beds and prismatic gypsum crystals are rare. Crystals fit together tightly as space will accommodate but lack a common nucleation surface.</td>
<td>Bottom-nucleated prismatic crystal textures; often beds are laminated. Inclusions typically define bedding surfaces although subordinate inclusions can outline crystals. Lenticular crystals subordinate to growth-aligned prismatic morphologies which are the dominant crystal type. Aligned crystals typically nucleate on a common surface (bedding plane).</td>
</tr>
<tr>
<td>Gypsum is deposited as playa-margin facies that parallel the strandline. Gypsum units are separated from basin-centre halite facies by gypsum-free mechanically reworked muds and silts. Rarely intercalated with halite units and if occurring in same core will be separated by a gypsum-free mud. Carbonate is typically deposited as a pedogenic facies in alluvial fan and sheetflood sands. Minor carbonate is formed in the halite facies as bacterially induced nodules. Hydrology dominated by capillary evaporation of resurging meteoric groundwaters. Isotopic signature shows affinities to ambient rainwater/groundwater.</td>
<td>Gypsum beds often occur in near basin-centre or basin-centre positions and are commonly transitional into basin-centre halite facies. Gypsum units are typically interlayered with subaqueous halite facies. Carbonate facies are typically laminated to cryptalgal-crenulated subaqueous mudstones. Hydrology dominated by ponded evaporating brines. Isotopic signature shows strong affinities to evaporated brine.</td>
</tr>
</tbody>
</table>

GEOCHEMICAL RESULTS

Deuterium and oxygen

The range of δD values for 18 GWC is −95 to −67‰, the average is −81‰ and the standard deviation is ±8‰ (Table 2). The rain water samples for 4 years of precipitation are strongly dependent on the season. Samples collected after winter storms have an average δD of −73‰ and samples collected during the summer have an average δD of −48‰ (Table 2). The overall average of the δD in Bristol Dry Lake is approximately −60‰. Two δD values for the basin-centre brine are −56 and −58‰ (Table 2). Two δ18O values for the GWC are −0.8 and −2.6‰, and three values for the basin-centre brine are somewhat variable and range from +0.5 to +3.7‰ (Table 2).

Water analyses

The chemistry of groundwater from Cadiz and Bristol Dry Lake and brines from Bristol Dry Lake come from a number of sources (primarily from R. Shafer, unpublished observations, 1964, and J. Calzia, 1979) and three analyses of trace elements of the basin-centre brine (data in Rosen, 1989, 1991). Figure 5 demonstrates that the concentration of sulphate increases toward the basin centre until it reaches the playa margin where it sharply decreases into the centre of the basin. Calcium increases toward the
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Fig. 4. (a) Photograph of a core slab from Bristol Dry Lake (depth 350 m). All gypsum has been converted to anhydrite, yet the vertically aligned fabric seen at the surface is retained. (b) Detail of the texture seen in (a). Notice that the matrix outlines the shape of the former gypsum crystals. Pyrite (P) and abundant calcite (C) can be seen within the crystals and the matrix indicating that bacterial sulphate reduction was involved in the conversion of gypsum to anhydrite. Individual pseudomorphs are about 3 mm long.

Sedimentological and geochemical evidence for displacive growth

The observation that the gypsum is concentrated around the margins of the playa separated from the basin-centre halite is, by itself, a strong indication that the gypsum formed displacively rather than from a brine pond. If a subaqueous brine pond model is applied, the relative lack of gypsum in the basin centre could only be explained by a stratified water body which is precipitating halite in the basin centre and gypsum around the margins. This scenario is similar to the barred-basin model of Schmalz (1970). However, this model is untenable in a relatively small hydrologically closed basin such as Bristol Dry Lake because, unless the water body was relatively deep (on the order of tens of metres), the water would not stratify but would instead be homogeneous and precipitate gypsum in the basin centre. If the water was deep it would require some relief on the margins of the basin. There is no evidence of relief greater than approximately 0.5 m around the margins of the playa and there is also no sedimentological or geochemical evidence of deep water in the basin (Rosen, 1989, 1991).

In addition, the facies distribution of gypsum–mud–halite in Bristol Dry Lake does not fit the facies postulated for the barred-basin model. The lateral and vertical separation of gypsum and halite by a thick detrital mud unit would require a chemical gap in a subaqueous brine pond between gypsum and halite precipitation which is not possible in a free-standing brine. Instead, the geometry of the deposit suggests that the gypsum is forming where groundwater supersaturated with respect to gypsum is resurging around the playa margin. The separation of the gypsum within the sediment from the brine-pond halite at the surface indicates that it is only in the basin centre that free-standing water is present. However, by the time the groundwater has flowed to the brine pond, it has already precipitated gypsum and reduced the sulphate concentration of the groundwater to trace amounts (Fig. 6).

The influence of gypsum precipitation on the reduction of sulphate in the groundwater profile is well illustrated by plotting the concentrations of SO$_4$ and Ca versus Cl or distance from the alluvial fan to the basin centre (Fig. 5). The chloride concentration is seen to increase logarithmically toward the basin centre. The decrease in SO$_4$ is sharp basinward of the gypsum zone of the playa-margin sediments. Calcium has a slight decrease in this zone but then increases toward the basin centre. The continued increase in Ca toward the basin centre indicates that SO$_4$ is the limiting ion in the basin and that Ca is slightly depleted by gypsum precipitation, but is still abundant even in the basin centre.

The co-occurrence of calcite and gypsum in the proximal end of the gypsum zone is probably due to
Origin of groundwater-seepage gypsum

Table 2. Deuterium and oxygen isotope data for gypsum crystallization water and water samples (‰).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (m)</th>
<th>Deuterium</th>
<th>Equivalent water 20‰</th>
<th>Equivalent water 15‰</th>
<th>Oxygen</th>
<th>Equivalent water 4‰</th>
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</thead>
<tbody>
<tr>
<td>Gypsum, north side of playa trench</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TR3 0-2M</td>
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<tr>
<td>TR3 1-4M SINGL</td>
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<td>-57.8</td>
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<tr>
<td>Gypsum, 300-m trench on south side of playa</td>
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<tr>
<td>TRC1 0-9M</td>
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<tr>
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<td>TRC6 1-5M</td>
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<tr>
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<tr>
<td>TRC9 1-3M GYP</td>
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<td>1/11/87 GYP-C</td>
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<td>(3) 6'</td>
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<td>-80.1</td>
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<td>-80.7</td>
<td>-65.7</td>
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Surface basin-centre brine samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (m)</th>
<th>Deuterium</th>
<th>Oxygen</th>
</tr>
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<tbody>
<tr>
<td>Br-1</td>
<td>0.1</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Br-2</td>
<td>0.1</td>
<td>3.7</td>
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</tr>
<tr>
<td>Br-3</td>
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<tr>
<td>Average</td>
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<td>2.3</td>
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Rain water data, Amboy station. Data provided by G. I. Smith, USGS, Menlo Park

<table>
<thead>
<tr>
<th>Summer average 1982-1988</th>
<th>Deuterium</th>
<th>Rainfall (mm)</th>
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<tbody>
<tr>
<td></td>
<td>-50</td>
<td>45</td>
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<tr>
<td>Winter average 1983-1989</td>
<td>-72</td>
<td>62</td>
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<tr>
<td>Annual average*</td>
<td>-63</td>
<td>107</td>
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Subsurface water data, Bristol Dry Lake basin. Data provided by G. I. Smith, USGS, Menlo Park

<table>
<thead>
<tr>
<th>Basin-centre subsurface brines</th>
<th>Depth (m)</th>
<th>Deuterium</th>
<th>Oxygen</th>
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<tbody>
<tr>
<td>34/29 4 115/39-7†</td>
<td>154</td>
<td>-56</td>
<td></td>
</tr>
<tr>
<td>34/28 0 115/41-5</td>
<td>248</td>
<td>-58</td>
<td></td>
</tr>
<tr>
<td>Subsurface alluvial fan groundwater</td>
<td>Depth (m)</td>
<td>Deuterium</td>
<td>Oxygen</td>
</tr>
<tr>
<td>34/46 8 115/36-5</td>
<td>67</td>
<td>-76</td>
<td></td>
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<tr>
<td>34/44 0 115/14-7</td>
<td>183</td>
<td>-83</td>
<td></td>
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<tr>
<td>34/47 1 115/39-7</td>
<td>28</td>
<td>-76</td>
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<tr>
<td>34/25 4 115/33-4</td>
<td>81</td>
<td>-73</td>
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<tr>
<td>34/25 5 115/33-4</td>
<td>75</td>
<td>-73</td>
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<td>34/25 5 115/33-4</td>
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<td>34/54 8 115/04-2</td>
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</tr>
<tr>
<td>Average</td>
<td></td>
<td>-78</td>
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</tr>
</tbody>
</table>

* Cumulative D weighted by precipitated amounts.
† Latitude/longitude.

fluctuating saturation states of the groundwater over time. During periods of reduced rainfall, the groundwater would be more concentrated at this point in the basin and so precipitate gypsum. During wetter periods, the groundwater would not reach gypsum saturation until it was further into the centre of the basin. Thus, the gypsum formed in the sediment would be overprinted with calcite cements precipitated at a later time.

Evidence of this type of fluctuation can be seen in the proximal end of the 300-m trench. Just basinward of the transitional area from calcite to gypsum, there
are large blocks of gypsum that are not supported in the trench wall. Inspection of the material indicates diagenetic recrystallization of the gypsum into large poikilitic crystals overprinting the original fabric as well as veins of gypsum cement orientated perpendicular to the earlier fabric-filling voids (Fig. 7). This portion of the trench is essentially a gypsum karst area. The present near-surface groundwater system is apparently undersaturated with respect to gypsum at this point in the playa-margin sediments and so is dissolving and reprecipitating gypsum with an overall net loss in this area over time. This ‘cannibalized’ calcium sulphate may then be precipitated in a more basinward area of the playa. This gypsum karst is important because it implies that the present chemistry of the groundwater is not in equilibrium with the observed position of the mineral phases in the facies.

**Fabric relationships**

Many of the mesoscale fabrics also indicate a displacive origin for the bulk of the gypsum in Bristol Dry Lake. For example, there are no common surfaces from which the gypsum crystals nucleated. Crystals are fitted together as space will accommodate, but the tops and bottoms of the crystals are not aligned. This can be seen in the surface gypsum and in the core anhydrite (Figs 3 & 4a). If the gypsum had precipitated from the bottom of a brine pond, then the nucleation of a particular layer of crystals should follow a plane. This type of nucleation surface is a dominant feature of modern and ancient brine-pond gypsum (Warren, 1982a; Schreiber, 1988).

In addition, the siliciclastic matrix completely surrounds gypsum crystals in many cases in Bristol Dry Lake. On the micro-scale, inclusions of matrix also completely surround the growing surface of gypsum crystals and are enclosed by the next phase of growth (Fig. 8). Again, if the gypsum was forming from the bottom of a brine pan, neither matrix nor matrix inclusions could surround the entire growing crystal.

**Gypsum morphologies**

Environmental conditions controlling gypsum nucleation and crystal morphology have been studied

![Graph showing log molar concentrations of Ca, SO₄, and HCO₃ ions plotted against the log molar concentration of Cl.](image)
Origin of groundwater-seepage gypsum

Fig. 6. Model of groundwater gypsum precipitation. Groundwater flows through the alluvial fan and begins to seep back to the surface by capillary action during evaporation. Vertical alignment of the crystals is due to this upward component to the groundwater movement. Comparison with Fig. 5 shows how sulphate is depleted as gypsum precipitation progresses toward the basin centre. Once sulphate is sufficiently depleted, gypsum precipitation is greatly reduced or stopped. Isotopically, δD values for the gypsum crystallization waters reflect evaporated groundwater with possibly some brine influence. Oxygen values indicate a definite groundwater source and cannot have been solely derived from the present brine. The size of the points indicates variability of the average values. Rainwater and groundwater alluvial fan values for δ18O are calculated (see text). Both δD and δ18O values for the gypsum have been corrected for fractionation.

Fig. 7. Cross-polarized photomicrograph of large, clear gypsum crystals lining and filling vertical fractures (F). Original matrix of smaller vertically aligned gypsum crystals is still present. Small fracture on left is about 2 mm across.

Gypsum occurs in many morphologies, but there are three basic forms which are used to describe gypsum in the literature: (i) prismatic (bladed, spears); (ii) pyramidal (hemi-bipyramidal, lenticular, disc, lozenge, or lens-shaped); and (iii) pinacoid. The names in parentheses are common descriptive terms used for these crystal habits; however, the terms bladed and spears may also be used to describe some pyramidal forms. Pinacoidal forms are rare in nature (Magee, 1988) and so are not included in the following discussion.

Acicular prismatic crystals grow dominantly in pure aqueous solutions supersaturated with respect to gypsum. Edinger (1973) suggested that this is due to the selective adsorption of H⁺ and OH⁻ on to the 110 and 010 faces of the crystal caused by the arrangement of atoms in the crystal. The adsorption on to these faces inhibits growth in these directions and promotes growth of the 111 face and elongation in the c-direction. These prismatic crystals grow mostly in sediment-free solutions such as bottom-nucleated brine-pond gypsum at the sediment-water interface and as free crystals at the brine–air interface (Cody & Shanks, 1974; Cody, 1976).
Pyramidal forms grow when the 111 face is selectively inhibited. Cody (1976, 1979) and Cody & Cody (1988a) have shown that organic additives commonly present in terrestrial muds inhibit growth and promote development of the 111 face. Thus, the crystals are flattened perpendicular to the c-axis. Pyramidal forms are common in muds which are supersaturated with respect to gypsum. These muds generally contain the types of organic matter which inhibit the growth of the 111 face. Therefore, most displacive gypsum growing in mud is pyramidal or lenticular in form. Magee (1988) has used this data and field observation from an Australian inland lake to conclude that, as a rule of thumb, subaqueously deposited gypsum is dominantly prismatic in form and displacive groundwater-seepage gypsum is pyramidal in form. In general this conclusion is valid for Bristol Dry Lake. The playa-margin gypsum zone is dominated by gypsum growing in muds and sands that have pyramidal gypsum crystals flattened perpendicular to the c-axis. Prismatic gypsum does occur, but is rare.

Although the Bristol Dry Lake crystals are very similar to crystals grown with polytannate ions, the general lenticular habit does not appear to be diagnostic of any particular organic habit modifier chemical. However, all the twinning observed appears to be $d\{101\}$ twins (R. D. Cody, pers. comm. 1989). Cody & Cody (1989) showed that $d\{101\}$ twinning in gypsum crystals is found almost exclusively in deposits from saline lakes and secondary alterations. Experiments showed that this unusual twinning was induced by the presence of $\alpha$-amylase, an enzyme excreted into soil and water by bacteria, fungi, algae, and plant roots (Cody & Cody, 1989). Therefore, it is possible that the Bristol Dry Lake gypsum crystals grew under the influence of this organic habit modifier, or alternatively, that there is a complex assortment of organic compounds that control gypsum crystallization.

In further support of a bacterially controlled morphology of the gypsum, Eardley & Stringham (1952) have postulated that sulphate-reducing bacteria play an important role in the formation of vertically aligned pockets of gypsum crystals forming in the bottom muds in Great Salt Lake, Utah. These deposits are not well described, but they do appear to be similar to the vertically aligned gypsum in Bristol Dry Lake. However, Eardley & Stringham (1952) also recognized the need for elevated temperatures and pH to initiate precipitation of gypsum.

Alternatively, Kushnir (1980) has shown in laboratory experiments that gypsum growth habits may be controlled by the Ca/SO$_4$ ratio in the solution. Essentially, Kushnir (1980) has shown that high Ca/SO$_4$ ratios in an aqueous solution produce small lenticular crystals flattened along the c-axis and at low Ca/SO$_4$ ratios prismatic crystals are formed. As was shown above, Bristol Dry Lake is characterized by extremely high Ca/SO$_4$ ratios and is dominated by lenticular gypsum crystals. However, most of the lenticular gypsum crystals in Bristol Dry Lake are quite large (>10 mm). Small lenticular discs do occur in the basin-centre muds and in some areas of the playa margin. The basin-centre discs show obvious current reworking and may actually have been transported into the basin centre from the playa margin. Alternatively, they may have precipitated from the water column of a basin-centre brine with a high Ca/SO$_4$ ratio and been subsequently reworked.

With the present state of knowledge, it is not possible to determine whether all the lenticular crystals at Bristol Dry Lake are organically or inorganically controlled. What is important is that both field and experimental data indicate that large (>10 mm) gypsum crystals with a lenticular habit are produced within the sediment column and not from free-standing brine solutions. The gypsum in Bristol Dry Lake is overwhelmingly dominated by large lenticular morphologies. This implies that the major mechanism of gypsum growth is displacement within the sediment.

Another important aspect of the experimental work on gypsum formation is the determination of the
parameters that control the nucleation density of crystals. Cody & Cody (1988a) determined that, with increased NaCl content in the brine, nucleation density decreased producing larger, slower growing crystals. In a 5% NaCl solution the nucleation density was 10 times less than that in an NaCl-free solution. The NaCl effect may explain why the gypsum crystals in the playa-margin sediments of Bristol Dry Lake become larger towards the basin centre where the NaCl concentrations increase. In the NaCl-dominated saline mudflat, gypsum growing in the sediment is rare. This is probably due to a shortage of sulphate ions, but where gypsum does occur in the saline mudflat, it always forms as large (0.1–0.3 m) widely dispersed crystal aggregates suggesting a low nucleation density perhaps enhanced by the amount of NaCl present in the solution.

**Vertical alignment of gypsum**

The final morphological question to consider is why displacive gypsum would be vertically aligned. This question cannot be answered directly; however, from the geochemical evidence and field relations it is likely that the vertical alignment is due to a combination of an overall upward capillary movement of groundwater as evaporation proceeds (Fig. 6), and to faster crystal growth along the minimum stress direction. A slow upward movement of gypsum-saturated water through the capillary zone will tend to allow crystal growth to proceed fastest vertically. This flow direction coupled with a vertical (upward to the surface) minimum stress direction will enhance the ability of crystals to grow more quickly towards the surface, and will, in general, out-compete crystals growing in other directions.

If the gypsum is precipitated during capillary evaporation, this implies that the gypsum must be growing relatively near the surface. The presence of thin, oxidized red sand zones directly overlying vertically aligned gypsum also suggests that the gypsum was formed near the surface probably only 0.05–0.2 m below the surface. The red sand zones in the trench walls are identical to the present surface of the playa which is composed of a thin reddened sand. The buried red sands are therefore interpreted to represent periods of subaerial exposure.

The volume of gypsum versus matrix suggests that growth takes place in water-saturated thixotropic mud which is easily moved to accommodate new gypsum growth. Limited areas of thixotropic muds are present just below the modern playa surface but are not precipitating gypsum at this time.

The vertical alignment is thus the product of a relatively strong vertical component to the groundwater evaporation path coupled with faster crystal growth along the minimum (upward) stress direction. The vertical alignment may be enhanced by competition for space while crystals are growing, similar to the competition for space in subaqueously formed crystals.

**Isotopic evidence for displacive growth**

The stable isotopic compositions of the gypsum crystallization water, rainwater/groundwater, and brine can be used to determine whether basin-marginal groundwater or basin-centre brines are responsible for the precipitation of the gypsum. If the gypsum has a groundwater stable-isotopic signature then it can be inferred that the gypsum was precipitated within the sediment. Figure 6 plots isotopic values against position in the basin to illustrate these relationships.

Analyses of δD and values of GWC average about −80‰ (Table 2). The fractionation of deuterium from the water precipitating the gypsum to the water included in the crystal structure is between −15 and −20, that is the GWC will be 15–20‰ lighter than the water from which it precipitates (Fontes & Gonfiantini, 1967). This implies that Bristol Dry Lake gypsum precipitated from water with an isotopic value of between −60 and −65‰. The 4-year average δD value for rainwater in the basin ranges from −48 to −73‰; depending on the season, the δD for seven groundwater samples averages −78‰. Thus, the values for the GWC of around −60 to −65‰ are within the range for gypsum to have been precipitated from evaporated rainwater and groundwater with values of around −70‰.

Conversely, the δD measured for two samples of the basin-centre brine is ~−56‰. This value is heavier than the value calculated for the GWC and could not have precipitated the gypsum in the playa margin. Therefore, the most likely source of water for gypsum precipitation in the playa-margin sediments is slightly evaporated groundwater rather than basin-centre brine. However, some mixing of groundwater and brine may occur. Partial mixing may explain some of the scatter in the isotopic data.

Similar techniques can be used to determine the origin of the water precipitating the gypsum using stable oxygen isotopes. The values for oxygen isotopes of the GWC are about −1.5‰. However, the fractionation for oxygen is +4‰ (Fontes, 1965) so
that the water from which the gypsum precipitated should have a $\delta^{18}O$ of about $-5.5\%$.

The precise $\delta^{18}O$ values for rainwater in Bristol Dry Lake have not been measured, but in regional reconstructions of water analyses for the central Mojave region the $\delta^{18}O$ should be between $-4$ and $-8\%$, relative to SMOW (Yurtsever, 1975). The stable oxygen isotopic composition of pedogenic calcite from around the playa margin can be used to determine the $\delta^{18}O$ value for the groundwater. Using the equation of Friedman & O'Neil (1977) for determining the oxygen isotopic fractionation between inorganically precipitated low-Mg calcite and water, the water from which the pedogenic calcite precipitated should have an isotopic composition of between $-4$ and $-9\%$ for the temperature range of 10–30°C. This calculated range is within the range of regional rainwater values suggesting that the bicarbonate in pedogenic calcite is derived mainly from a rainwater source. The calculated value for the oxygen in the GWC is also within this range. This suggests that rainwater/groundwater sources are responsible for gypsum precipitation. In addition, the $\delta^{18}O$ for the basin-centre brine ranges from $+0.5$ to $+3.7\%$. These values are much heavier than those calculated for the GWC, suggesting that these brines have not been the major source of fluid for the precipitation of the gypsum.

**Geological significance**

When gypsum is buried it is transformed to anhydrite which often has a nodular and enterolithic texture. The process is complete by a depth of 1000 m. When the pore fluids are saline, the transformation may occur at depths as shallow as 1–2 m (Holser, 1979; Shearman, 1985; Hovorka, 1988). The conversion of gypsum to anhydrite (or back to gypsum again from anhydrite) may make the determination of the original depositional environment of diagenetically altered gypsum difficult in many ancient calcium sulphate deposits. Gross morphological outlines of the originally subaqueous gypsum crystals may be preserved as pseudomorphs or simply as a vertical orientation of nodular sulphate fabrics (Schreiber, 1988; Warren, 1989).

Vertically aligned brine-pond gypsum typically indicates a topographically low position, close to or directly at the centre of the evaporite basin (Warren & Kendall, 1985). However, vertically aligned groundwater gypsum may indicate a gypsum facies position closer to the margin of the basin or it may indicate an overprint of a later hydrological system (i.e. diagenesis). The similarity of the vertical alignment between brine-pond and groundwater-seepage gypsum means that in some cases the criteria of crystal or nodule alignment may not be enough to define a subaqueous setting. Hence the distinction between groundwater-seepage and subaqueous aligned fabrics is of depositional significance in palaeoenvironmental interpretation (Table 1).

If the geometry of the anhydrite/gypsum deposit is known it can be helpful in distinguishing the two types of deposit. If the geometry of the deposit is not known, the vertical relationships which can be seen in a single core may be useful. In Bristol Dry Lake and other intermontane basin playas such as Panamint Valley, California, the brine-pan halite is laterally separated from the groundwater gypsum by an extensive saline mudflat. There is little room for progradation in these settings because of the geometry of the basins, so that brine-pan halite is never associated with extensive groundwater gypsum in cores. Throughout the depositional history of this lake the groundwater-seepage gypsum facies has maintained its basin-margin position—a direct result of its groundwater origin. Even if progradation or retrogradation did occur, gypsum and halite would be separated by a mud-rich interval which would contain increasingly abundant displacive halite towards the top of the mud-rich interval just below the brine pan halite (Rosen, 1989, 1991). This makes the vertical sequence very different from a brine-pong gypsum sequence where halite deposition is intimately associated with gypsum (see Warren, 1982a, 1989, for a summary of the literature).

**CONCLUSIONS**

The sedimentological, stratigraphical, and geochemical data from Bristol Dry Lake all indicate that the vertically aligned gypsum fabrics precipitate within the sediment as an early, dominantly displacive diagenetic mineral. Gypsum precipitates where groundwater saturated with respect to gypsum recharges around the playa margin (groundwater-seepage gypsum). The vertically-aligned fabric is probably due to a relatively strong vertical capillary component to the groundwater evaporation along the horizontal flow path coupled with faster crystal growth along the minimum (upward) stress direction.

Because the vertically aligned fabric in a brine pond may be similar to groundwater gypsum, a close
examination of gypsum textures, associated beds, and basin position, are necessary to distinguish between the two environments, particularly for cases where there is limited core, or after gypsum has been converted to anhydrite (Table 1). Accurate identification of gypsum fabrics will help indicate proximity to the basin centre and the diagenetic history of the deposit. Therefore, the recognition of vertically aligned groundwater gypsum is important in distinguishing vertical and lateral depositional sequences (as well as diagenetic signatures) of any given modern or ancient evaporite basin.

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