Paleoenvironmental interpretation of the Messinian Kalavasos Formation in Gypsum Canyon, Kato Moni, Cyprus

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INTRODUCTION

The Messinian Salinity Crisis manifests itself in Cyprus on both the northern and southern margins of the Troodos massif in the form of thick gypsum units ranging from tens of to several hundred meters in thickness (Robertson et al., 1995). Gypsum Canyon, near Kato Moni, was chosen for a detailed paleoenvironmental analysis because of its wide range of different gypsum morphologies and for the relationships between the gypsum and other sediments revealed in the outcrop. From these relationships, a history of gypsum deposition in the area can be devised suggesting that gypsum previously interpreted as deep-water deposits may have accumulated in shallower waters in tectonically active basins. In addition, the presence of some carbonate impurities, most notably *Globigerinid* fossils, suggests detrital reworking also played a role in shaping the Kalavasos Formation.

GEOLOGIC SETTING OF GYPSUM CANYON

Gypsum Canyon is located in the Mesaoria Basin on the north side of the Troodos ophiolite, approximately 2 kilometers northeast of Kato Moni village. The canyon, which is presumed to have been carved by a presently ephemeral river, provides excellent exposures of the Kalavasos Formation with its range of gypsum morphologies, as well as sediments of the underlying Pakhna and Lefkara Formations. The Miocene Pakhna Formation, which is directly beneath the Kalavasos Formation stratigraphically, consists mainly of pelagic chalks, marls, calcarenites, and conglomerates (Robertson et al., 1995). The Pakhna Formation also contains the Koronia Member, which consists of reefal and bioclastic limestone. These limestones crop out at a higher topographic level than the gypsum, at distances of ca. 2 km to the north and south of the canyon. The Pakhna Formation is in turn underlain by the Maastrichtian to Oligocene Lefkara Formation, which is a much more uniformly fine-grained pelagic chalky marl with occasional planktonic foraminifera fossils.

Cyprus is located atop the subducting northern margin of the African plate which subjected it to widespread rollback-driven extensional faulting from the mid-Miocene through the mid-Pliocene (Robertson et al., 1995). This tectonic activity created both the Mesaoria and other major sedimentary basins of Cyprus as well as topographic highs on which the Koronia Member reefs were deposited via tilting of fault blocks (Figure 1). In addition, the area was affected by the Messinian Salinity Crisis, during which the connection between the Mediterranean and the world ocean was severed tectonically. This led to significant and repeated changes in Mediterranean water level via large-scale evaporative draw-down and subsequent inflow through the Straits of Gibraltar.

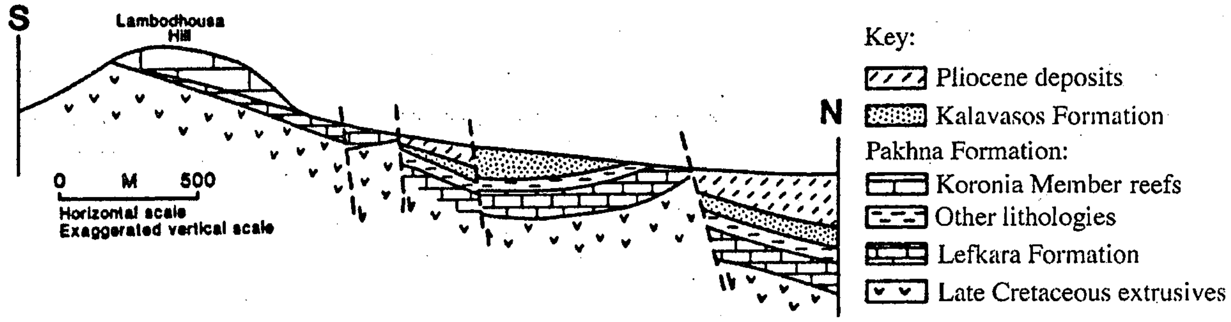

Figure 1: **North-south cross section from Gypsum Canyon area (after Robertson et al., 1995)**

Lithologic column of Kalavasos Formation present in Gypsum Canyon, Kato Moni, Cyprus

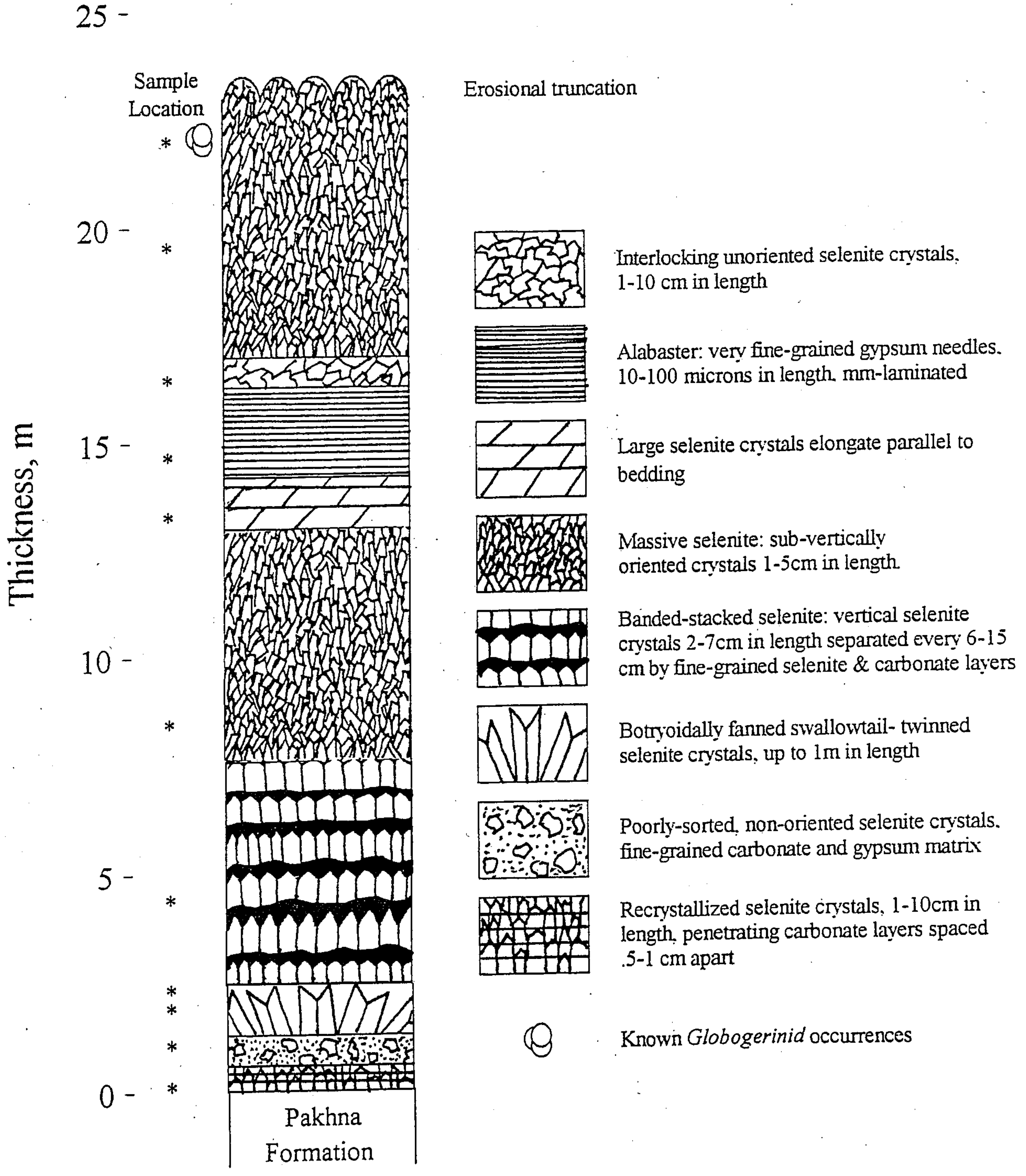

Figure 2: Lithologic column of gypsum present in Gypsum Canyon

GYPSUM AND CARBONATE MORPHOLOGIES OF GYPSUM CANYON

The bulk of the strata exposed in Gypsum Canyon consist of selenitc gypsum, i.e., coarse gypsum crystals ranging from less than a centimeter to a full meter in length. Eight distinct types of gypsum were differentiated on the basis of variations in crystal size, presence or absence of twinning, consistency of crystal orientation, presence of carbonate inclusions, and/or the presence of thin laminations (Figure 2). Recrystallization is evident in some of the morphologies, where large replacive selenite crystals can be seen crosscutting the original layering, but most of the gypsum retains its primary structure. Three of these types, banded-stacked selenite, swallowtail-twinned selenite, and massive selenite, collectively constitute ca. 75% of the section and exhibit vertical orientation of selenite crystals. They differ in that the banded-stacked selenite contains fine-grained carbonate/gypsum laminations spaced at 6-15 cm intervals, whereas the carbonates in the massive selenite are relatively evenly dispersed between the selenite crystals rather than being segregated into discrete layers. The swallowtail-twinned selenite is relatively free of carbonate impurities. One of the eight types of gypsum, known as alabaster, consists of thinly laminated fine gypsum crystals, 10-100 μm in length, that are highly elongated with their long axes parallel to bedding. The laminations, ca. a millimeter thick, arise from an alternation between layers of finer and coarser gypsum crystals with average lengths 10 and 100 μm respectively. Although alabaster comprises less than 10% of the column (Fig. 2), its presence is noteworthy for its paleoenvironmental implications.

Carbonate impurities are a minor but widespread constituent of all the gypsum types except alabaster. Well-sorted peloids are seen in several different samples, and occur in either oblate or spherical forms, depending on their location in the column. The massive selenite crystals that stratigraphically overlie the alabaster layer contain a diverse assemblage of carbonate inclusions quite different from those elsewhere in the column, including fossils, angular lithoclasts, and mud. Fossils are numerous and consist of unreplaced whole *Globigerinid* tests. X-ray diffraction revealed that the carbonates here and elsewhere in the section are mostly if not entirely calcite, with little evidence of dolomite.

PALEOENVIRONMENTAL INTERPRETATION OF KALAVASOS FORMATION

The different types of gypsum described above require precipitation via several different mechanisms. The vertical orientation of the swallowtail-twinned, banded-stacked, and massive selenite suggests bottom nucleation of crystals, leading to crystal impingement and preferential vertical alignment as growth continued (Warren, 1989). This could only happen on the bottom of a shallow supersaturated brine where there was continuous water replenishment to provide the large solute supply needed to allow uninterrupted large crystal growth (Kendall, 1992). Bottom supersaturation is believed to happen only in water <10 m deep (Robertson et al., 1995) with little clastic input, most likely a restricted lagoonal setting. In the case of the banded-stacked selenite, where fine-grained carbonate/gypsum partings interrupt selenite growth at 6-15 cm intervals, upward crystal growth was periodically halted by either an influx of less saline water, permitting $CaCO_3$ precipitation, or by an erosional event responsible for breaking up and reworking the selenite and carbonate, redepositing it in a laterally continuous layer.

The alabaster, on the other hand, requires a much different origin. The alignment of long crystal axes parallel to bedding suggests that the crystals settled to, instead of nucleated on, the bottom of the basin, collecting as cumulates. This in turn implies the crystals precipitated at the air-water interface via supersaturation of surface waters due to high evaporative rates. The fine crystal size, paucity of impurities, and thin, continuous laminations with no sign of erosion indicates that they accumulated in very quiet water with little clastic input.

The presence of the alabastrine layer sandwiched between two layers with vertically oriented selenite (Fig. 2) clearly signals a change in the nature of gypsum precipitation during the life of the basin. Precipitation of gypsum needles at the air-water interface and subsequent settling on the bottom suggests that the entire brine was no longer supersaturated, but saturated at the substrate, allowing the gypsum precipitated to collect, but not grow, on the bottom of the basin. This indicates a change in the saturation regime of the basin, as the surrounding layers contain vertical selenite crystals grown from supersaturated bottom waters. The conventional interpretation of this alabaster deposit has been that it formed in a much deeper basin (Robertson et al., 1995) than the swallowtail and other vertically-oriented selenites because its formation required a quiet environment (with little clastic input) to permit particles 10-100 μm in size to settle out and remain undisturbed. However, well-defined brine stratification can develop in saline lakes when they are deeper than about 10 m, thereby inhibiting wave motion and allowing fine-grained sediments unaffected by currents to accumulate (Kendall, 1992). Based on the fact that the alabaster in Gypsum Canyon is a fairly thin layer (2 m) sandwiched between units that were clearly deposited in very shallow water, I suggest that it is likeliest that the alabaster is indicative of deposition in a shallow stratified brine pool rather than a deep-water environment. This would allow a change from bottom-nucleated growth to precipitation at the air-water interface and back to bottom-nucleated growth again without a major change in water depth.

The presence of *Globigerind* fossils in the massive selenite layer near at the top of the section indicates a departure from the carbonates seen elsewhere in the column. *Globigerinid* are planktonic foraminifera that only live in open-ocean environments with normal marine salinities. Their presence in the midst of gypsum implies they were physically transported into the environment after death. Older units in the area, notably the Pakhna and Lefkara Formations, contain similar *Globigerinid* remains, so the *Globigerinids* could have been reworked from those units into the Kalavasos Formation. The lithoclasts likewise resemble lithologies in the Lefkara Formation, again suggesting detrital reworking. The intact nature of many of the tests and the angular nature of many of the lithoclasts also implies that they were transported for relatively short distances.

CAUSES OF PALEOENVIRONMENTAL CHANGE

The likeliest explanation for both the environmental shift that allowed the alabaster to precipitate and the detrital reworking of planktonic foraminifera into an evaporite basin lies in the active tectonics of the area and in the fluctuations of water level in the Mediterranean associated with the Messinian Salinity Crisis. The reefs of the Koronia Member, which are located topographically above nearby Gypsum Canyon, serve as a good proxy for sea level at the time the top of the Pakhna Formation was deposited, i.e., just prior to deposition of the Kalavasos. As evaporative draw-down occurred in conjunction with the Messinian Salinity Crisis, a relatively small drop in water level would be needed before the depressions in the seafloor between the reefs, where most gypsum deposits are found (Robertson et al., 1995), were restricted or completely isolated from the rest of the Mediterranean hydrologic system. It thus appears that a barred-basin to closed-basin model of evaporite precipitation was operating in the area, whereby the basin was partially to completely isolated from influxes of Mediterranean water during times of lowered water level. This allowed evaporation to proceed more rapidly than reflux of new waters and resulted in net precipitation of evaporitic sediments. Times of greater basin quiescence, represented by alabaster formation, could signify times when extensional faulting was active in the area, dropping the floor of gypsum-precipitating basins with respect to mean water level such that water depth increased past the 10 m cutoff for complete brine supersaturation. Once tectonic activity diminished, evaporative draw-down would proceed to once again lower the water column and bottom-nucleated crystal growth could recommence. Alternatively, minor fluctuations in the overall hydrologic balance of the Mediterranean basin could account for the inferred changes in water level.

The location of the gypsum deposits at a topographically lower position than older stratigraphic units in the area also provides an explanation for the detritally reworked carbonates found in the upper few meters of Gypsum Canyon's massive selenites. Differential uplift has caused the Pakhna and Lefkara Formations, which stratigraphically underlie the Kalavasos formation, to crop out topographically higher than the gypsum in some areas (Figure 1). The Lefkara Formation contains foraminifera fossils, mainly *Globigerinid* tests, in addition to its dominant fine-grained carbonate muds. Its fossils are identical to those seen intact in the upper reaches of the Kalavasos Formation, and the angular carbonate lithoclasts which accompany them resemble the bulk of the muds in the Lefkara. Thus, physical processes transported some detritus basinward from the topographically higher Lefkara Formation during later gypsum precipitation. The Kalavasos Formation itself is erosionally truncated in the Gypsum Canyon area (Fig. 2), so the evidence of tectonic activity in the upper gypsum unit could simply be the first manifestation of the uplift which eventually brought Cyprus out of the sea and ended marine sedimentation altogether.

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