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Comparative Sedimentology of Lake Bonneville and the Great Salt Lake

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ABSTRACT

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Ooids of Great Salt Lake, Utah (GSL) have been studied periodically by geologists since the 1960's. These studies have documented the locations of ooid deposits, bulk composition, mineralogy, and internal structural variations of GSL ooids. Ooids have also been identified in sediment cores from lakes predating the Great Salt Lake, but similar descriptions have not been made for these ooids. Samples of ooids from cores in Pilot Valley, UT/NV and Knolls, UT have been obtained, along with samples from the Great Salt Lake at Bridger Bay and Rozel Point. The cortical fabrics and crystal morphologies of these ooids were studied in thin section and under scanning electron microscopy. Examples of cortex morphologies previously documented in GSL ooids were observed, to some degree, in ooids from Pilot Valley and Knolls. Knolls ooids had unique cortical layers that were resistive to acid and appeared to be dominantly comprised of clays. Bulk dissolution ages were obtained for ooids from each location. Ooids form both Pilot Valley and Knolls had average ages that pre-date Lake Bonneville, whereas GSL ooids from Bridger Bay had an average age of roughly 3,500 years before present (yr BP) and Rozel Point ooids had an average age of 500 yr BP. Along with a bulk age, ooids from Bridger Bay at the Great Salt Lake were subjected to serial dissolutions during which a split of gas was taken from each stage and an age was obtained. Ages spanned 7,000 years with the final dissolution stage delivering an average age of 9,000 yr BP. Based on this data it is likely that GSL ooids at Bridger Bay have been forming since the cessation of Lake Bonneville and that many of the nuclei in Bridger Bay ooids are remnant peloids from the Gilbert level of Lake Bonneville.

Keywords: Ooids, Great Salt Lake, microbialites, Nannobacteria, serial dissolution

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INTRODUCTION

Great Salt Lake (GSL), a hypersaline remnant of Pleistocene Lake Bonneville, has been noted to contain oolitic beaches around many of its shorelines (Pedone & Norgauer, 2002). The nature and origin of these ooids have been of great interest to the scientific community (Eardley, 1938; Kahle, 1974; Sandberg, 1975; Halley, 1977; Folk, 1993). GSL ooids played an important role in helping scientists distinguish between original and diagenetic cortical fabrics in ancient calcite ooids (Kahle, 1974). Their study has also improved understanding of factors affecting cortical fabric morphologies. More recently, Rey (2012) discovered ooids in Lake Bonneville and pre-Lake Bonneville sediment cores taken from Pilot Valley, which straddles the Utah-Nevada border (a sub-basin within the Lake Bonneville basin). These ooids remain unstudied and generally unknown to the scientific community. However, an increased understanding of these carbonate grains combined with the existing knowledge of GSL ooids has the potential to increase our overall understanding of factors effecting the growth and morphologies of lacustrine ooids. This study aims to describe the ooids of the Lake Bonneville Basin and to compare/contrast them with their modern GSL counterparts.

GEOLOGIC HISTORY

Scientific interest in Lake Bonneville began in the late 1800's with G.K. Gilbert's reconstruction of the lake's history (Gilbert, 1890). The four main lake levels that he elucidated are still commonly recognized (Table 1), although numerous distinct shoreline levels (wave-cut and wave-built terraces) are visible on the mountains surrounding the basin. The earliest stage of Lake Bonneville is referred to as the Stansbury level, which is considered to have begun roughly 23,000 years before present (yr BP). The final stage of the lake has been named the Gilbert level, ending only 10,000 yr BP. The shrinkage of Lake Bonneville led to the formation of the

Great Salt Lake. Evidence of large lakes pre-dating Lake Bonneville has also been found (Eardley et al., 1973). Cores drilled throughout the Bonneville Basin have demonstrated a fluctuation between three dominant environments over the last 280,000 years: 1) shallow saline and hypersaline lakes, 2) marshes, and 3) freshwater lakes (Balch et al., 2005). Brief dry periods also occurred sporadically within the basin during this period.

The Great Salt Lake is significant in the study of factors that affect ooid growth, morphology, etc. because such drastically different environments occur within the same lake and geographic area. These differences were accentuated in 1959 when the Southern Pacific Railroad constructed a causeway from Promontory Point to the west side of the lake. The only communication currently between the northern and southern arms occurs through two 5 meter-wide culverts in the causeway. Minimal communication may occur through the causeway due to the limited porosity of the structure or its foundational materials. The south arm receives fresh water input from the Bear, Weber, and Jordan rivers along the Wasatch Front. Its salinity was approximately 11% in 1998. The northern arm receives little freshwater run off. Its salinity was approximately 27% in 1998 (Gwynn, 2002).

PREVIOUS RESEARCH

Modern GSL ooids were first noted by Eardley (1938). Eardley described coarse radial fabrics in many ooid cortices. He inferred that the cortices were currently comprised of calcite and that their radial fabric and calcitic composition resulted from recrystallization of precursor aragonitic ooids. This interpretation prevailed for decades until Kahle (1974) demonstrated that GSL ooids are in fact aragonitic in composition and that the cortical fabric was depositional rather than diagenetic. However, for reasons that remain unclear, Kahle (1974) concluded that the GSL ooids had undergone aragonite-to-aragonite inversion. Unaware of Kahle's as yet unpublished work, Sandberg (1975) began his own re-evaluation of Eardley's (1938) work on GSL ooids. He confirmed the aragonite composition and depositional origin of the radial fabric, but found no evidence of aragonite-aragonite inversion. In yet a third paper of 1970's vintage, Halley (1977) focused on the processes of GSL ooid growth, concluding that radial fabrics are characteristic of hypersaline and freshwater environments. Folk (1993) reported possible remnants of nannobacteria in GSL ooids. Most recently, Pedone and Norgauer (2002) examined variation in grain size, mineralogy, and cortical fabric with respect to a range of geochemical and physical environments in GSL. They demonstrated that ooids formed in high-energy sites had large, clear radial crystals, few concentric growth bans, and little inter-ray micrite (micrite forming between the large aragonite crystallites in the cortex). Low-energy settings led to the formation of ooids that had small radial crystals, many growth bands, and abundant inter-ray micrite (Pedone and Norgauer, 2002).

Even after the extensive research of these and other authors, five questions remain unanswered concerning GSL ooids: (1) Are the ooids of the GSL actually forming today? (2) What is the frequency of cortex formation at GSL? (3) Have ooids formed at other times in the GSL/Lake Bonneville basin? (4) If so, how do ooids from Lake Bonneville and pre-Lake Bonneville deposits compare with modern GSL ooids? (5) Are nannoballs, as described by Folk (1993) present in GSL ooids, and are they a biologic artifact?

The aim of this paper is to answer these questions and to apply many of the methods used by previous researchers in examining GSL ooids to the study of ooids of different time periods and lake stages within the Lake Bonneville Basin.

METHODS

Field Work

Ooids were collected from two modern and two ancient deposits for purposes of this study (Fig. 1). Modern ooids were collected from Rozel Point on the north side of the GSL and from Bridger Bay, located on the north end of Antelope Island. Ancient ooids were collected from the shallow subsurface in Pilot Valley, situated due north of Wendover, NV. The fourth population of ooids is from the shallow subsurface (1.5 meters) at Knolls, UT located along Interstate 80 approximately 40 miles east of Wendover. This sample is 1.5 meters below the surface of the shoreline deposits that sit at the same approximate elevation as the Gilbert level of Lake Bonneville (Currey, 1984).

Ooids from Rozel Point were collected using a hand–driven percussion corer with a 5 cm diameter plastic liner (Fig. 2a). Samples were collected from a 30 to 70 centimeter-thick blanket of ooids that covers a15 km^2 area of recently exposed lake floor. The blanket of unconsolidated ooids shows no evidence of bedding and overlies a layer of dark organic mud of unknown thickness. The contact between the organic mud and ooids is sharp (Fig. 2b). Ooids from Bridger Bay were collected by hand from the lower foreshore of the Bridger Bay beach in approximately 15 centimeters of water (Fig. 3). Sediment samples in Pilot Valley and at the Knolls site were collected using a hand auger with a 15 centimeter-long bucket. Sediment was extracted in 15-centimeter intervals and logged in the field. Intervals containing ooids were bagged and logged for later examination (Fig. 4). Total depth was reached when the sediment could no longer be kept in the bucket and extracted due to water saturation decreasing the cohesion of the sediment. Stratigraphic columns of three cores in Pilot Valley are shown in Figure 5.

Laboratory Methods

All ooids were cleaned using deionized water and dried in an oven at 60 degrees Celsius prior to analysis. Multiple thin sections of grain mounts were made of samples from each of the four localities. 350 ooids from each locality were classified according to their cortical fabric. Percentages were recorded and the dominant cortex morphology was documented for each location.

Ooids were also examined using a scanning electron microscope. Some samples were etched for three to eight seconds using ten percent formic acid. Samples were coated with a 4.8 nanometer-thick layer of chromium using a Quorum Q150T ES coater. A sample from Upper Knolls was initially over-coated with a 25 nanometer-thick layer of chromium, resulting in production of “nannoballs”. This sample was examined and it was determined that a second sample would need to be properly coated and examined (for comparison purposes). A discussion of this comparison follows later in this paper.

Isotopic Analysis

Two types of radiocarbon ages were obtained during this study: composite ages and serial dissolution ages. Composite ages were obtained by dissolving an entire sample of ooids from a location and sending the gas off for ^{14}C analysis. The age obtained represents a mixture of all the gasses generated from every corticle layer dissolved. Due to a greater percentage of the volume of calcium carbonate residing in the outermost corticle layers it is assumed that the composite ages are generally on the younger end of the average age. Serial dissolution ages were obtained by dissolving a sample of ooids from a single location in steps. Gasses were trapped at each dissolution step and analyzed individually. These ages are a much more precise representation of the age of the corticle layers involved. All samples were processed for composite ages, whereas only a sample from Bridger Bay was processed for serial dissolution ages. Gasses were analyzed for ^{14}C at the Center for Applied Isotope Studies at the University of Georgia (CAIS-UG). Carbon-13 stable isotope analysis was performed at Brigham Young University's (BYU) Hydrogeochemistry Laboratory using a Finnigan Delta^{plus} Isotope ratio mass spectrometer. Any ratios reported are with respect to Pee Dee Belemnite (VPDB) using reference gasses calibrated to NBS-19.

Composite Ages.-For each location, approximately 4 milligrams of ooids were completely dissolved in a sealed vessel at room temperature using one hundred percent phosphoric acid. Gasses were generated and sealed in borosilicate glass tubes. The gas samples were then sent to The University of Georgia for ^{14}C analysis.

Serial Dissolution Ages.-Ten grams of Bridger Bay ooids were added to fifty milliliters of deionized water in a reaction vessel. A stirring rod was also added to aid in agitating the ooids to allow for uniform dissolution. The mass was then recorded for the vessel, water, stirring rod, and ooids. Atmospheric oxygen was removed from the vessel and all other vessels along the gas line. While stirring, two milliliters of six-molar hydrochloric acid (HCl) were added to the ooids and water and allowed to fully react. The gas was trapped in a sealed vessel. One split was taken and sent for ^{14}C analysis and the other split was prepared for stable isotope analysis following the methods of Swart et al. (1991). The ooids were then rinsed in deionized water and a small sample was retained to allow for scanning electron microscope (SEM) examination of the extent of dissolution. Fifty milliliters of deionized water was added to the glass vessel and the atmospheric oxygen was removed by vacuum. Five milliliters of HCl were added to the ooids and water while stirring and allowed to completely react. The gas was trapped in a glass vessel following the same methods used in previous steps. This process was repeated two more times until the ooid cortices were entirely dissolved. The mass was recorded before and after each dissolution phase in order to calculate the mass lost in each reaction (Table 2).

The entire partial dissolution process was duplicated a second time with Bridger Bay ooids and a sample of ooids was retained from each dissolution phase allowing for thin sections to be made. The thin sections were compared with SEM images to allow for a better understanding of the character of dissolution that occurred.

RESULTS

Physical Description

Both spherical and rod-shaped ooids occur at all locations as a function of grain size. Ooids less than 0.177 millimeters in diameter are rod-shaped while those with diameters larger than 0.177 millimeters are increasing spherical. The size difference is dominantly related to larger ooids having a larger nucleus. Round ooids predominantly have quartz nuclei, which are often larger than the pellets in rod-shaped ooids. This size difference effectively partitions the rod-shaped ooids into the smaller size ranges leading to the concentration of spherical ooids in the larger sizes.

Observed cortical morphologies include radial, tangential, and superficial ooids (coated grain with a single cortical layer). Cortical fabrics are made up of variably oriented arrangements of small, blade-like or needle-like crystallites of aragonite. Kahle (1974) and Halley (1977) used the terms “grain” and “nannograins”, respectively to refer to these cortical building blocks of physicochemically precipitated aragonite. We prefer the term "crystallite" to either of these terms (grain or nannograin) to characterize the fundamental building blocks of the cortex because the term *grain* is commonly used in reference to sedimentary carbonate allochems such as a skeletal grains or coated grains.

Tangential fabrics are composed of layers of randomly or tangentially oriented crystallites (Sandberg, 1975) (Fig. 6a). Spherical grains lacking any interior structure were categorized as peloids. The number of cortices varies within each sample. The number of cortical layers observed ranges from one to eight.

Radial fabrics are composed of aragonite rays of various sizes that are arranged in a radiating pattern away from the nucleus (Fig. 6b). Rays are sometime arranged in spherulitic fans or in bundles of crystals.

Nuclei consisted of peloids (likely fecal pellets), random grains bound by calcium carbonate mud (referred to as intraclastic pelsparite by Pedone and Norgauer, 2002), and quartz grains.

With the exception of sample S3 (a sample from the Pilot Valley core GC-1.), all samples are chiefly comprised of whole ooids (53 to 89 percent, average=73 percent)(Table 3), with lesser amounts of peloids and broken ooids. Sample S3 from Pilot Valley was predominantly peloidal (70% peloids).

Great Salt Lake Ooids- GSL ooids range in size from 0.053 mm to 0.991 mm with the most prevalent ooid diameter falling between 0.177 mm and 0.25 mm for Rozel Point and 0.25 mm and 0.42 mm for Bridger Bay (Table 4). Ooids from Bridger Bay (cortex widths from 0.008-0.03 mm) and Rozel Point (cortex widths from 0.003- 0.015 mm) displayed largely radial morphologies (Sandberg, Fig. 8). Sandberg (1975) made similar observations when he noted three main crystal fabrics in GSL ooids: type 1. random and tangentially arranged fine crystals (Fig. 6a), type 2. intermediate crystals arranged in spherulitic fans or bundles of crystals (Fig. 6b), type 3. large (100-200 microns long) aragonite rays oriented radially (Fig. 8). Bridger Bay ooids are generally more coarsely crystalline than ooids from Rozel Point and contain smaller amounts of inter-ray micrite.

Great Salt Lake samples had the fewest percent of superficial ooids with a ratio of just 12% superficial to mature ooids (Table 3). The dominant nuclei of Bridger Bay ooids were quartz grains, presumably due to the quartzite cliffs and boulders surrounding the bay (Pedone & Norgauer, 2002)(Fig. 3)(Table 5).

Upper Knolls Ooids- Ooids from Upper Knolls cover the slightly smaller range of 0.053 mm to 0.42 mm, and most frequently fall into the range of 0.177 mm to 0.25 mm (Table 4). They are also dominantly tangential with cortex widths ranging from 0.005 mm to 0.03 mm. Similar to Pilot Valley and the Great Salt Lake, tangential fabrics are made up of randomly oriented needle- and blade-like aragonite crystallites of a similar size range (about 2 to 8 micrometers) (Fig. 7). Knolls ooids are unique in that they have bands of what appear to be clays that are resistant to dissolution and therefore, are easily visible using SEM due to their relative relief compared to surrounding layers (Fig. 7). One sample from Knolls was etched for two minutes, effectively dissolving the ooids, leaving non-reactive nuclei and resistive layers as the only remnants (Fig. 9). It is notable that the outermost cortical layers of many ooids from Upper Knolls are badly pitted, and therefore have distinctive undulating perimeter referred to by Sandberg (1975) as a cerebroid surface (Fig. 10). The surface undulations do not appear to be attributed to crystal terminations or intercrystalline clays that fill in between some of the aragonite bundles. Pitting is significantly greater in samples from Upper Knolls than any of the other sample locations. Knolls ooids are also brown in color unlike their milky white counterparts at the other locations. Roughly 30% of the Upper Knolls sample comprised of superficial ooids (Table 3) with peloids as the dominant nuclei of all coated grains (Table 5).

Pilot Valley Ooids- The ooids from Pilot Valley, with the exception of ooids from the deepest sample (S3), span the same diameter range from 0.053mm to 0.42 mm. The dominant ooid diameter is slightly smaller ranging from 0.124 mm to 0.177 mm, when compared to Upper Knolls and Rozel Point (Table 4). Ooids from sample S3 have the same dominant ooid diameter as the other Pilot Valley samples, but have a smaller size distribution from 0.053 mm to 0.25 mm. They have predominately tangential cortex fabric. Cortex thicknesses ranges from 0.005 mm to 0.025 mm. Grains making up the cortex vary in size from three to eight micrometers. The smaller grains are generally randomly oriented, whereas the larger grains tend to exist as bundles of individual crystals with orientations of up to 30 degrees from perpendicular to the ooid nucleus (Fig. 6b). Larger crystals also exist as interfering spherulitic fans (Sandberg, 1975) that radiate away from the nucleus. Bands can be seen as concentric layers within continuous radiating crystals, but there is no optical or physical change in the crystal across these boundaries (Fig. 6b). The few radial ooids that were observed in Pilot Valley samples were finely crystalline and contained the highest percentage of inter-ray micrite of any of the samples containing radial ooids. Ooids from Pilot Valley had the highest percent of superficial ooids (average=33.6%.). The dominant nuclei of Pilot Valley ooids were peloids (Table 2).

Ages

Composite ages for the Pilot Valley samples and for the sample from Upper Knolls pre-date Lake Bonneville (Table 6). The oldest composite ages from this study belong to ooids from Pilot Valley (32,288 radiocarbon years). Upper Knolls ooids are younger (25,134 radiocarbon years) than any of the ooids from samples obtained in Pilot Valley. As discussed previously, composite ages are generally thought to represent an age younger than the average age of the cortex. Therefore, it is likely that initial precipitation began even earlier than the documented composite ages in this study.

As expected, radiocarbon ages for Bridger Bay ooids were youngest for the outer cortex and grew older with subsequent dissolution stages. The age of the cortical layers in Bridger Bay ooids spans a period of roughly 6,000 radiocarbon years (from 8144 to 2024 yr BP)(Fig. 12)(Table 7). Splits of ooids were reserved from each dissolution stage and examined using a scanning electron microscope and thin sections. It is clear that dissolution of the ooids was not always uniform and that some pitting did occur in each stage. It was also clear after a visual comparison between the first and last dissolution stage that some peoloidal nuclei were dissolved in the dissolution stages (Fig. 11).

DISCUSSION

The bulk age of the innermost cortical layers of Bridger Bay ooids corresponds to roughly 1,000 years after the Gilbert Level of Lake Bonneville. It is clear that, at a minimum, at least some of the nuclei of ooids found at Bridger Bay are products of Lake Bonneville. It is not clear that ooids found at Bridger Bay have been forming since the closing stages of Lake Bonneville. In many locations around the world where ooids are known to form, the nuclei are often comprised of skeletal fragments from the local biota (Duguid et al., 2010). There was a complete absence of skeletal or shell fragments in any of the nuclei of ooids in this study, which suggest that ooids did not begin to form until after the water from which they precipitated had become uninhabitable for species other than brine shrimp. This evidence suggests that the earliest GSL ooids at Bridger Bay could have begun precipitating is at the latest stages of the Gilbert level when salinity began to rapidly increase in the lake as lake level fell. This model would still depend on ooid formation occurring over a span of roughly 6,000 radiocarbon years. Similar serial dissolution experiments have been performed on ooids from different locations throughout The Bahamas (Duiguid et al., 2010). Age spans of ooids from The Bahamas ranged from 1,000 to 2,700 years. The vastly different environments of formation must account for the differences in age spans. A fluctuation model was recently developed by Dr. Summer Rupper and Dr. Steven Nelson of Brigham Young University. The model demonstrated that lake level can fluctuate from 7.5 to 15 meters based only on inter-annual variability of weather cycles. As the size of the lake increases, so does the magnitude of the fluctuations. These conditions are immensely different from those at a modern shoal in The Bahamas. With large-scale fluctuations occurring frequently, ooids at Bridger Bay would have spent only a portion of their existence in a zone that is conducive to precipitation of aragonite. Another portion of time would have likely been spent stranded on dry ground where precipitation would cease and erosion would dominate, while another would have been spent below the wave base that would suspend precipitation for that period of time. Previous SEM observations of GSL ooids support this formation model. Sandberg (1975) noted the existence of angular unconformities between corticle layers that represent periods of erosion.

Ooids from both Pilot Valley and Upper Knolls have composite ages pre-dating Lake Bonneville. Eardley et al. (1973), after their examination of the Burmester Core (a 307 m deep core through Bonneville Basin sediments at the south shore of the Great Salt Lake), indicated that 17 deep-lake cycles had occurred during the last 780,000 years. These deep-lake cycles were separated by soil-forming periods and shallow-lake periods. Charles Oviatt et al. (1999) re-examined the Burmester core and proposed that only four deep-lake cycles existed in the basin's history (correlated to the most extensive glaciations in the Northern Hemisphere). Due to the pivotal role that high salinity water plays in ooid formation in the basin, the presence of ooids that pre-date Lake Bonneville is further evidence in support of Oviatt et al. (1999) as to the dominance of smaller, saline to hyper-saline lakes antedating Lake Bonneville.

Some form of Sandberg's (1975) three cortical fabric descriptions could be applied to ooids from each of the locations in this study. Great Salt Lake ooids (particularly those from Bridger Bay) display well-developed type 3 radial fabrics (Fig. 14). Large aragonite rays were easily visible in thin section and distinct growth bands were prevalent. Sandberg noted that a crystal fabric succession often occurred within GSL ooids that graded from smallest crystals and their associated type 1 fabric (tangentially or randomly oriented crystals) to largest crystals. These sequences could repeat themselves within a single ooid in some instances (Fig. 8). These successions, allowing for slight modifications, are also present in ooids from Pilot Valley and Upper Knolls. Ooids from Pilot Valley and Upper Knolls rarely contained crystals longer than twenty microns, and therefore infrequently exhibit type 3 fabrics like those of GSL ooids. Ooids from Upper Knolls dictate the need for the creation of a new fabric classification. Unlike the fabric types defined by Sandberg (1975), this fabric is dominantly composed of clay minerals. Aragonite crystals from preceding cortices terminate into these clay bands. Subsequent cortical layers appear to nucleate from the outer surface of the clay. When compared with tangential GSL ooids, Upper Knolls ooids, in general, have poor definition between cortical layers and growth bands are difficult to distinguish in many instances (Fig. 14a and 14b).

Ooids from Pilot Valley differ most dramatically from the other samples in that they are predominately superficial and are smaller on average than ooids from the other locations. They are predominately rod-shaped in all but their largest sizes. This might be linked to the fact that the samples from Pilot Valley contained the highest percentages of peloids (average= 51%). Radial cortex fabrics from Pilot Valley ooids were typified by high concentrations of inter-ray micrite and finer, poorly developed aragonite crystals (Figs. 14c and 15c). Ooids with tangential fabrics often had very thin cortical layers with well-defined boundaries between those layers (Figs. 14d, 15a, 15b, and 15d).

Ooids from Bridger Bay and Rozel Point have radial cortices and few growth bands (generally). These characteristics are indicative of ooids formed in high-energy environments (Pedone and Norgauer, 2002). Of the two locations, Bridger Bay ooids are more coarsely crystalline and have less inter-ray micrite than ooids from Rozel Point. Ooids from Upper Knolls and Pilot Valley appear to be most similar to the low-energy description of Pedone and Norgauer (2002). Pilot valley samples showed an increase in radial ooids as depth of sample decreased (S3= 0.9%/ S1= 2.5%). Both locations contained very few radial ooids (Pilot Valley= 2.5%/ Upper Knolls= 1.9%). Radial ooids from Pilot Valley appeared to have slightly less inter-ray micrite than those from Upper Knolls.

During preparation for SEM analysis, a sample from Upper Knolls was accidentally over coated with a 25 nanometer-thick coat of chromium. Examination of the sample showed an abundance of features previously described as nannoballs by Folk (1993) and Folk and Lynch

(2001)(Fig. 16). These features tended to reside along crystal edges, fractures, or in other areas where there was a contact along which nucleation could occur. Another sample from Knolls was prepared and coated with the standard 5 nanometer-thick chromium coating. “Nannoballs” previously seen in abundance were no longer present.

CONCLUSION

Great Salt Lake ooids have been forming, at least intermittently, for over 9,000 years. Any real percentage of radial fabric in ooid samples does not appear until the time of Great Sale Lake ooids. Large-scale lake level fluctuations typical of the Great Salt Lake cause the ooids to form over significantly longer periods of time than their counterparts in the marine shoals of The Bahamas.

Salinity appears to be a major factor influencing ooid formation for all ooids in this study. At times when large fresh water lakes were present in the basin, ooids are absent from the sedimentological record.

After re-visiting the idea of nannobacteria in GSL ooids for the first time since Folk (1993), it is apparent that the nannoballs earlier identified in GSL ooids are in fact purely a remnant of improper coating of the sample.

Sample locations have been ranked by highest to lowest energy based on corticle characteristics outlined by Pedone and Norgauer (2002): Bridger Bay, Rozel Point, S1, Upper Knolls, S2, and S3.

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FIGURES

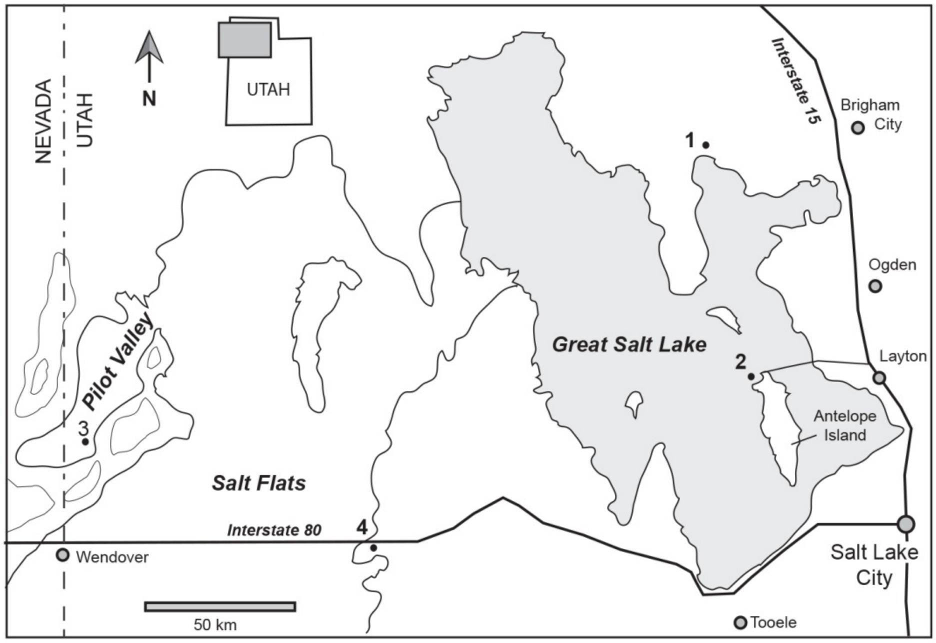

Figure 1.- Index map of sample locations in the Bonneville Basin, Ut. 1. Rozel Point. 2. Bridger Bay. 3. Upper Knolls. 4. Pilot Valley.

Figure 2.- Location 1. A) Field assistant using the hand-driven percussion auger at Rozel Point, Great Salt Lake. B) Excavation pit dug at Rozel Point displaying thickness of ooids and sharp contact between ooids and lake muds.

Figure 3.- Location 2. Image of Bridger Bay at the Great Salt Lake. Sediment was collected in 15 cm of water along the foreshore and from subaerially exposed shoreface.

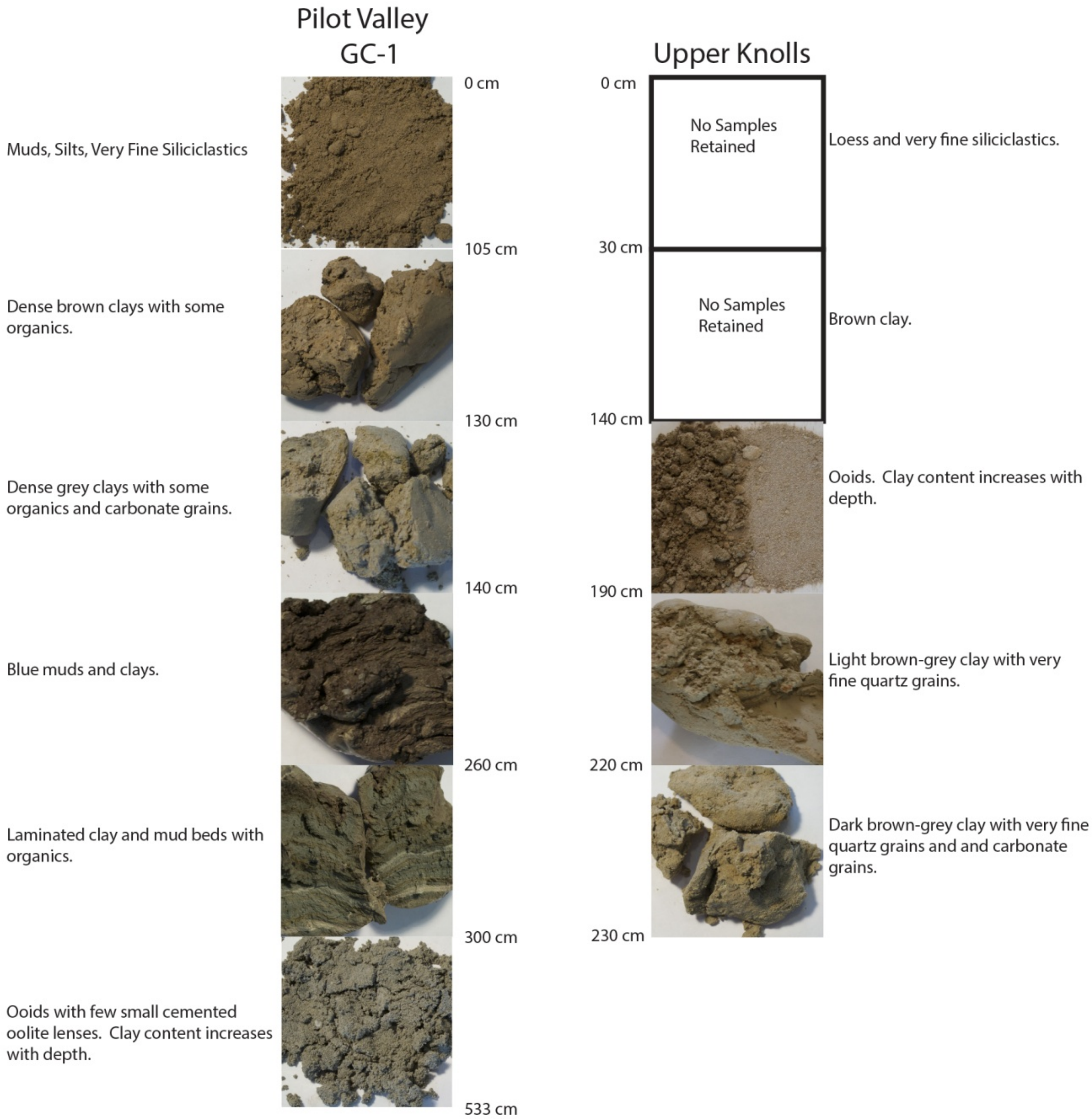

Figure 4.- Generalized stratigraphic columns from core GC-1 in Pilot Valley and Upper Knolls. Intervals are not to scale.

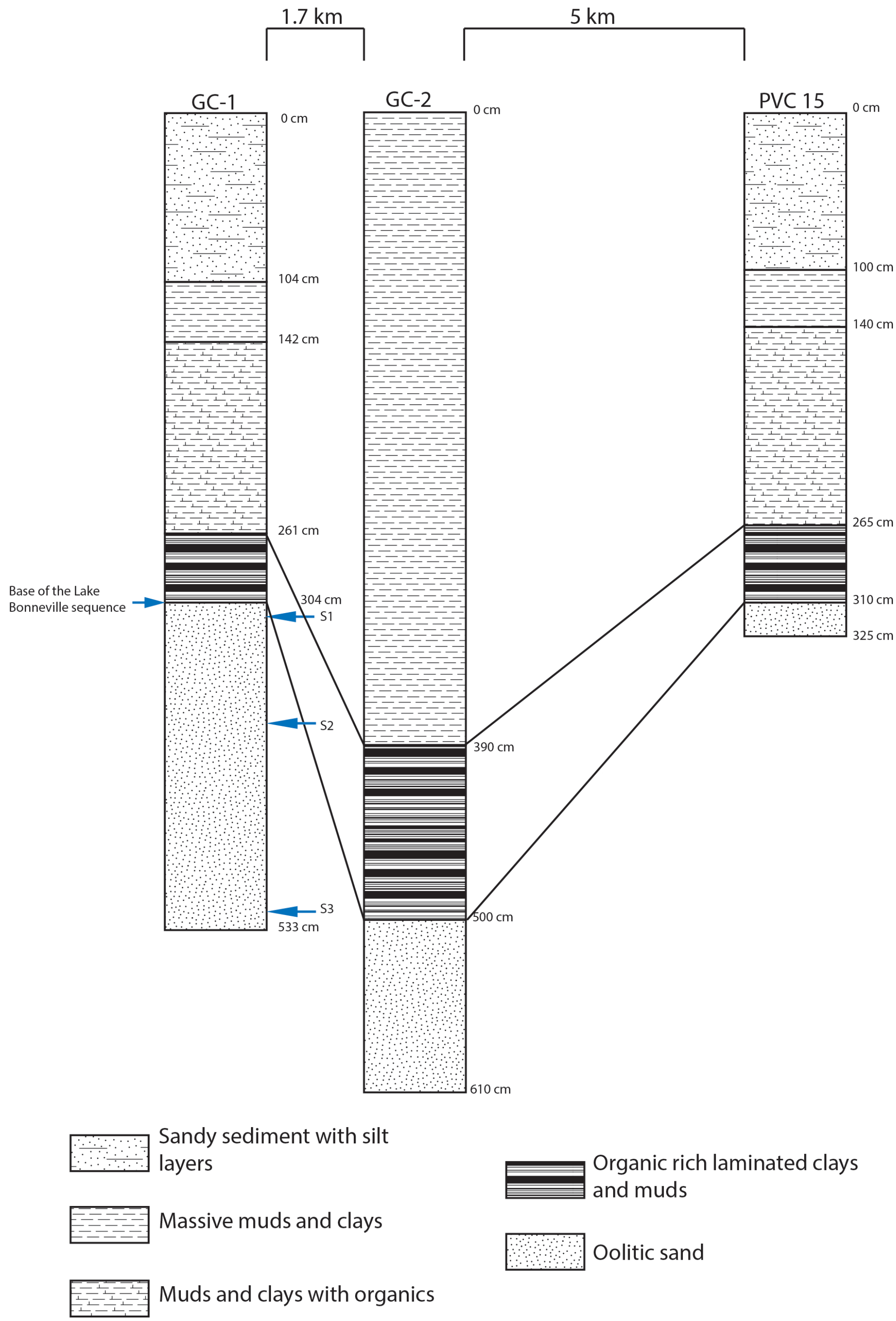

Figure 5.- Stratigraphic columns from cores GC-1, GC-2, and PVC 15 (from Rey, 2012) in Pilot Valley. Sample locations, as well as the base of the Bonneville sequence are noted on GC-1. Cores were correlated by the top of the laminated organic-rich clays and the top of the ooids.

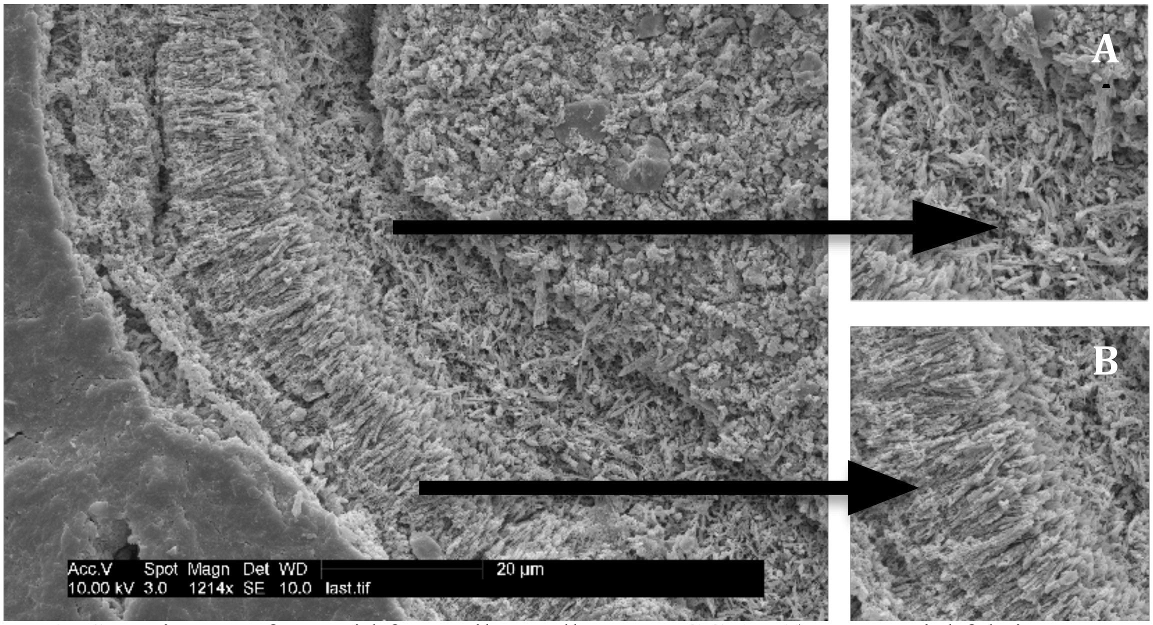

Figure 6.- SEM image of an ooid from Pilot Valley core GC-1. A) Tangential fabric composed of small, randomly oriented aragonite crystals. B) Radial fabric composed of spherulitic bundles of medium aragonite crystals.

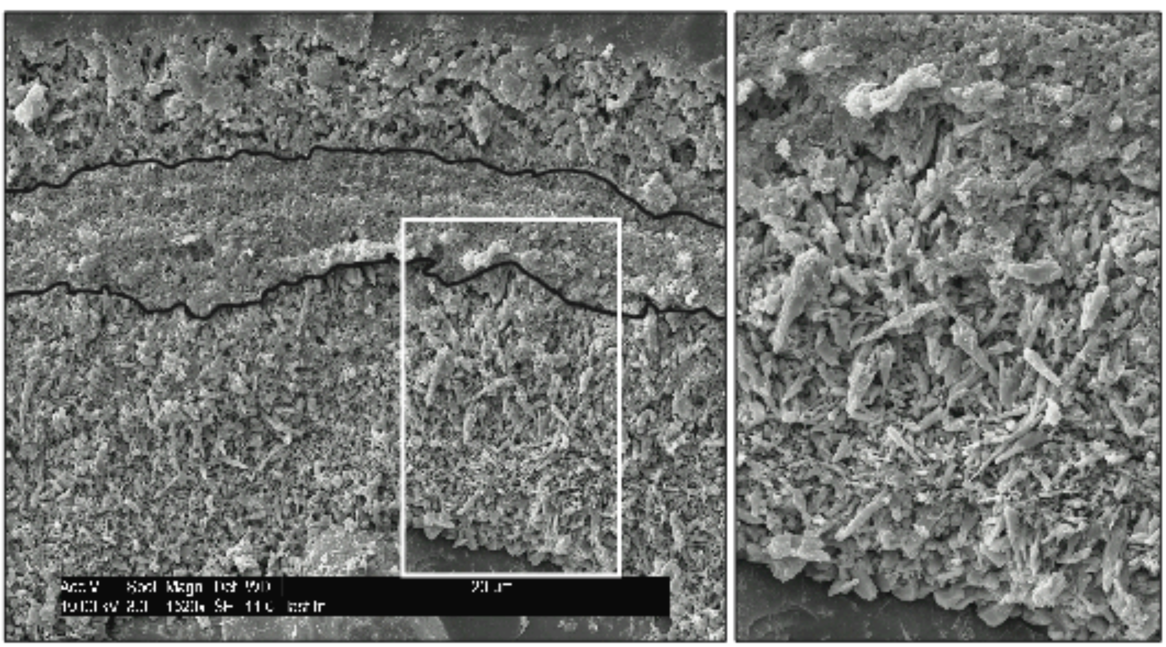

Figure 7.- SEM image of an ooid from Upper Knolls. Resistive layer is outlined in black. A) Tangential cortex fabric composed of randomly arranged aragonite crystals that increase in size away from the nucleus (bottom of image).

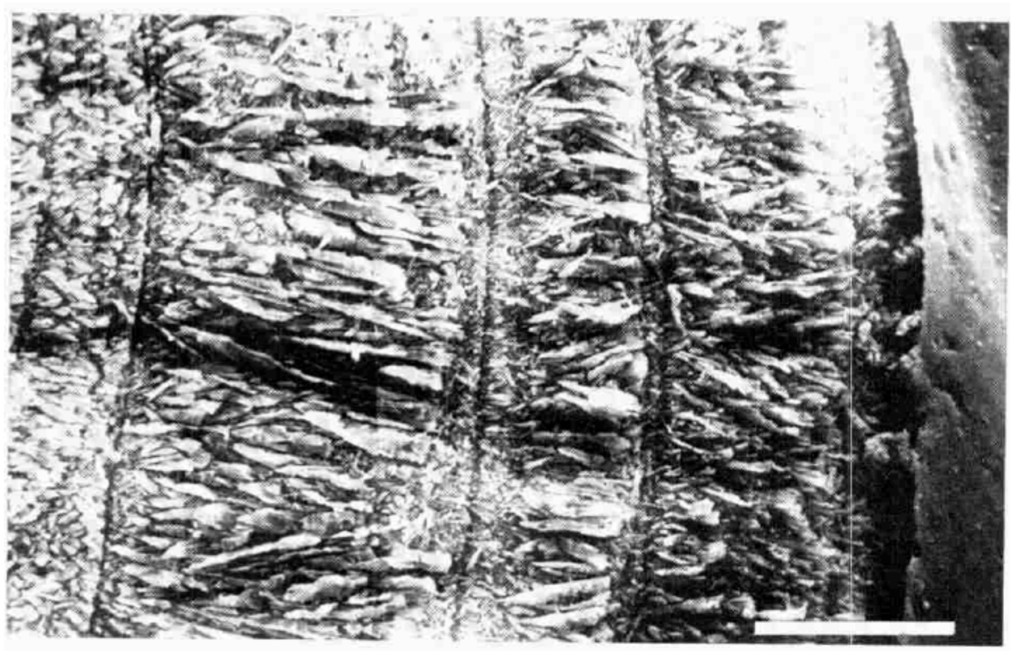

Figure 8.-SEM image of Great Salt Lake ooid with radial fabric (Sandberg, 1975).

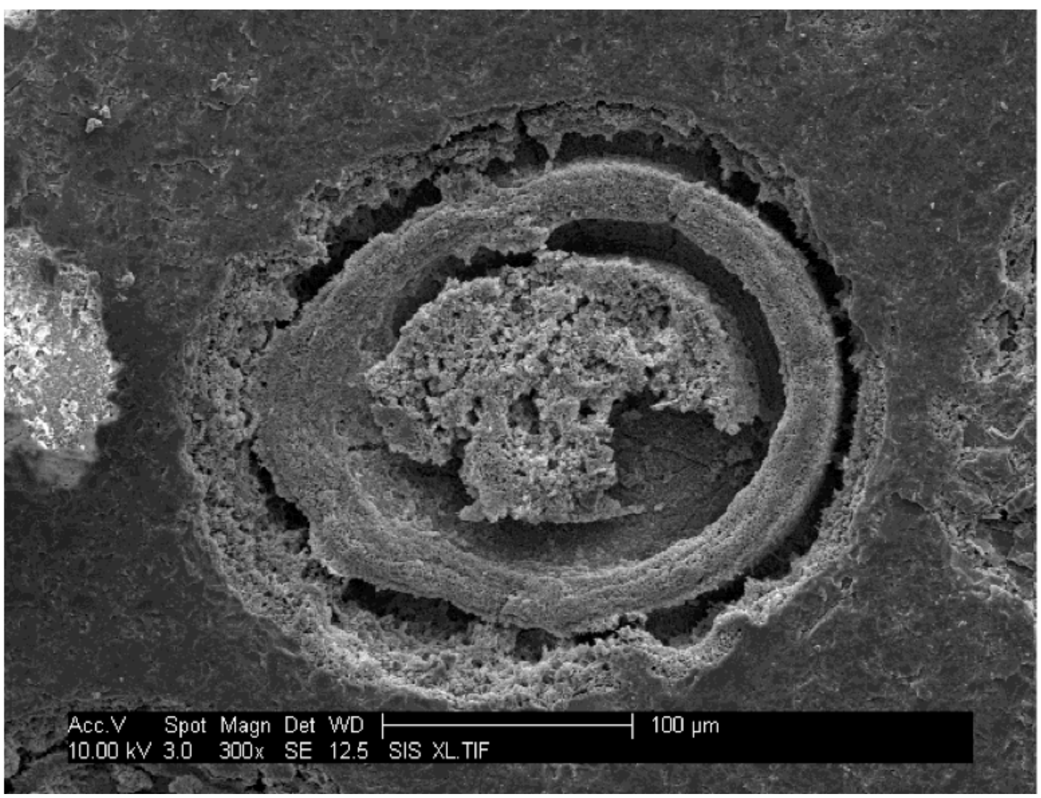

Figure 9.-SEM image of remnants of an ooids from Upper Knolls after being exposed to acid for two minutes. The only remnants are the clay mineral-rich nucleus and the resistive layer from the center of the cortex.

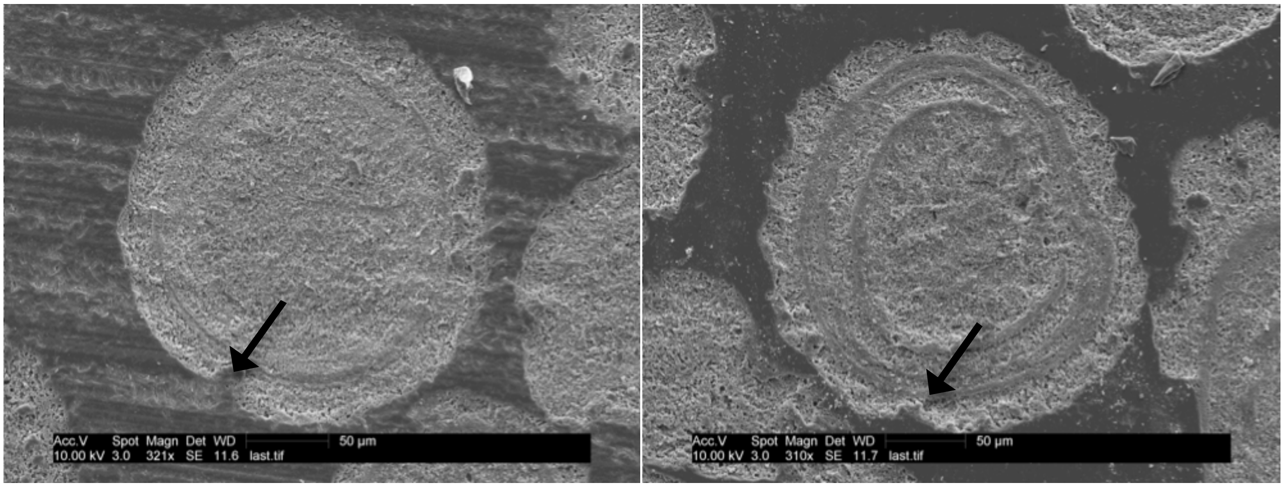

Figure 10.-SEM images of cerebroid ooids from Upper Knolls. Arrows denote pitted areas along the outer cortexes.

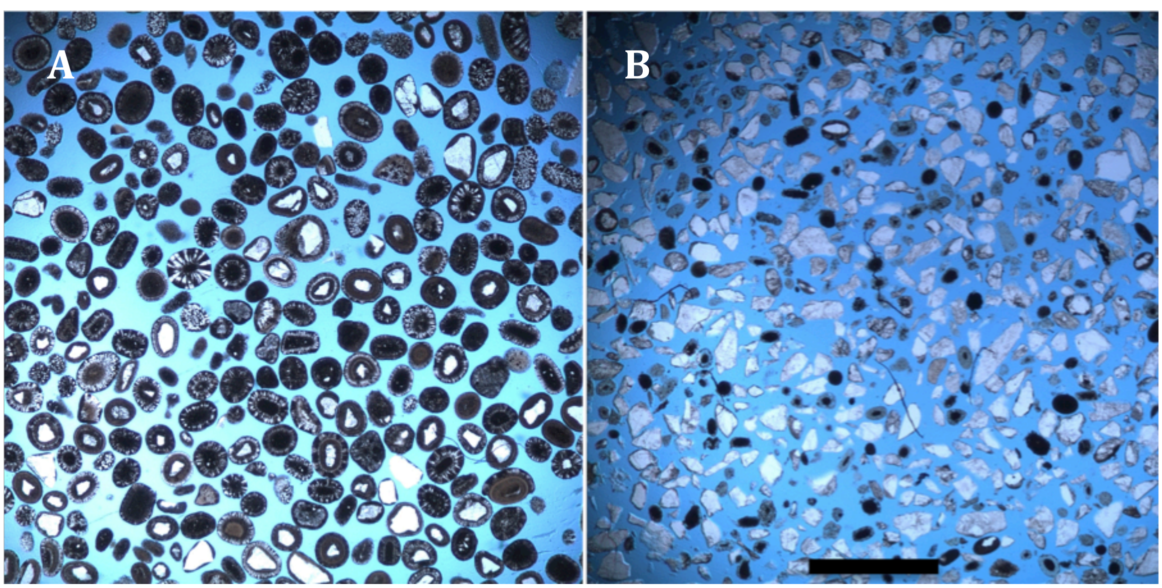

Figure 11.-Photomicrographs of ooids from Bridger Bay taken as splits during partial dissolutions. A) Ooids after the first dissolution stage. B) Ooids after the fourth stage of dissolution. Note the relative increase in the ratio of quartz to peloid nuclei.

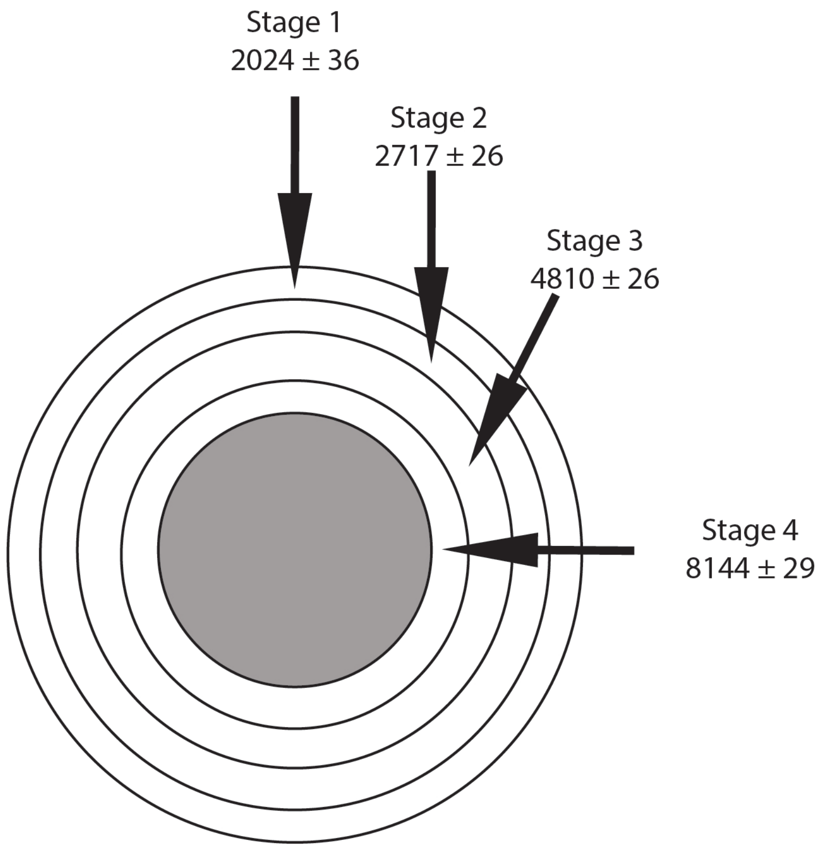

Figure 12.-Radiocarbon ages for reaction intervals from Bridger Bay ooids. Values represent an average of all cortical layers involved in the reaction interval. Gray shaded circle represents the nucleus. All ages are listed in radiocarbon years.

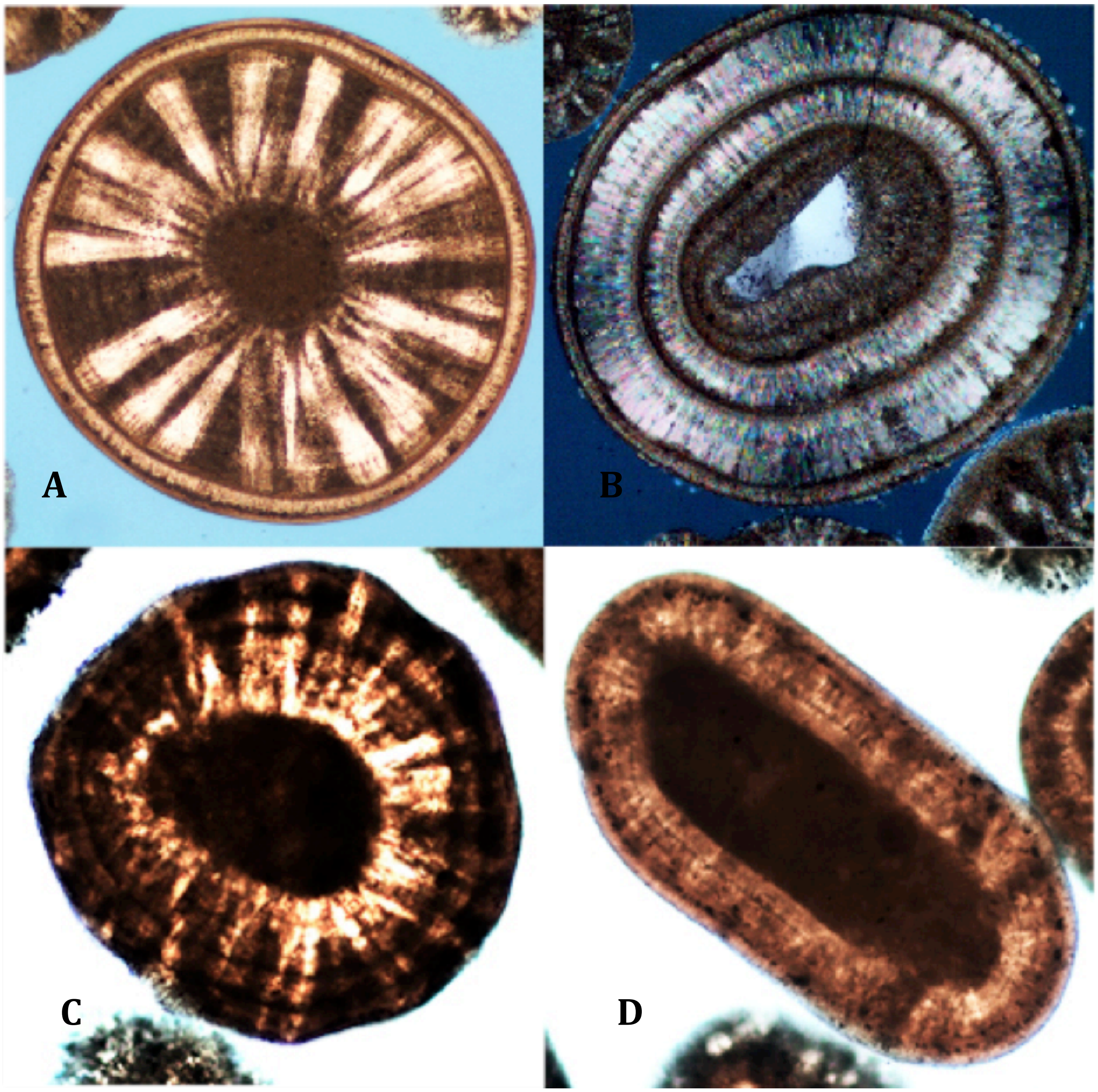

Figure 13.-Photomicrographs of ooids from the Great Salt Lake. A) Radial ooid from Bridger Bay with a peloidal nucleus. B) Tangential ooid from Bridger Bay with a quartz nucleus. C) Radial ooid from Rozel Point. D) Elongate tangential ooid from Rozel Point.

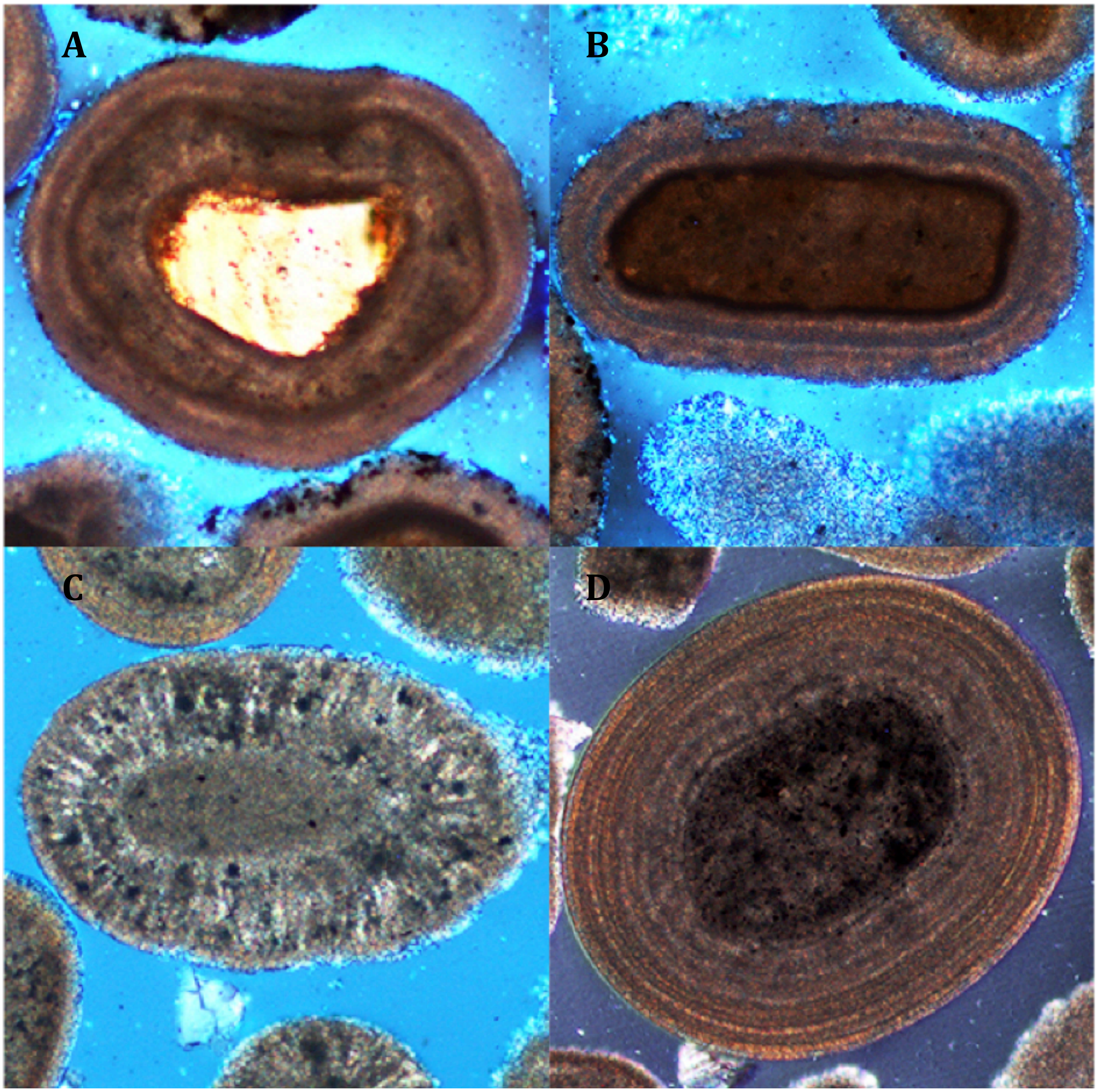

Figure 14.-Photomoicrographs of ooids from Upper Knolls and Pilot Valley. A) Tangential ooid with a quartz nucleus from Upper Knolls. B) Elongate tangential ooid from Upper Knolls. Outer cortical layers appear to have been altered or degraded. C) Radial ooid from sample S1 in Pilot Valley. D) Tangential ooid from sample S1 in Pilot Valley.

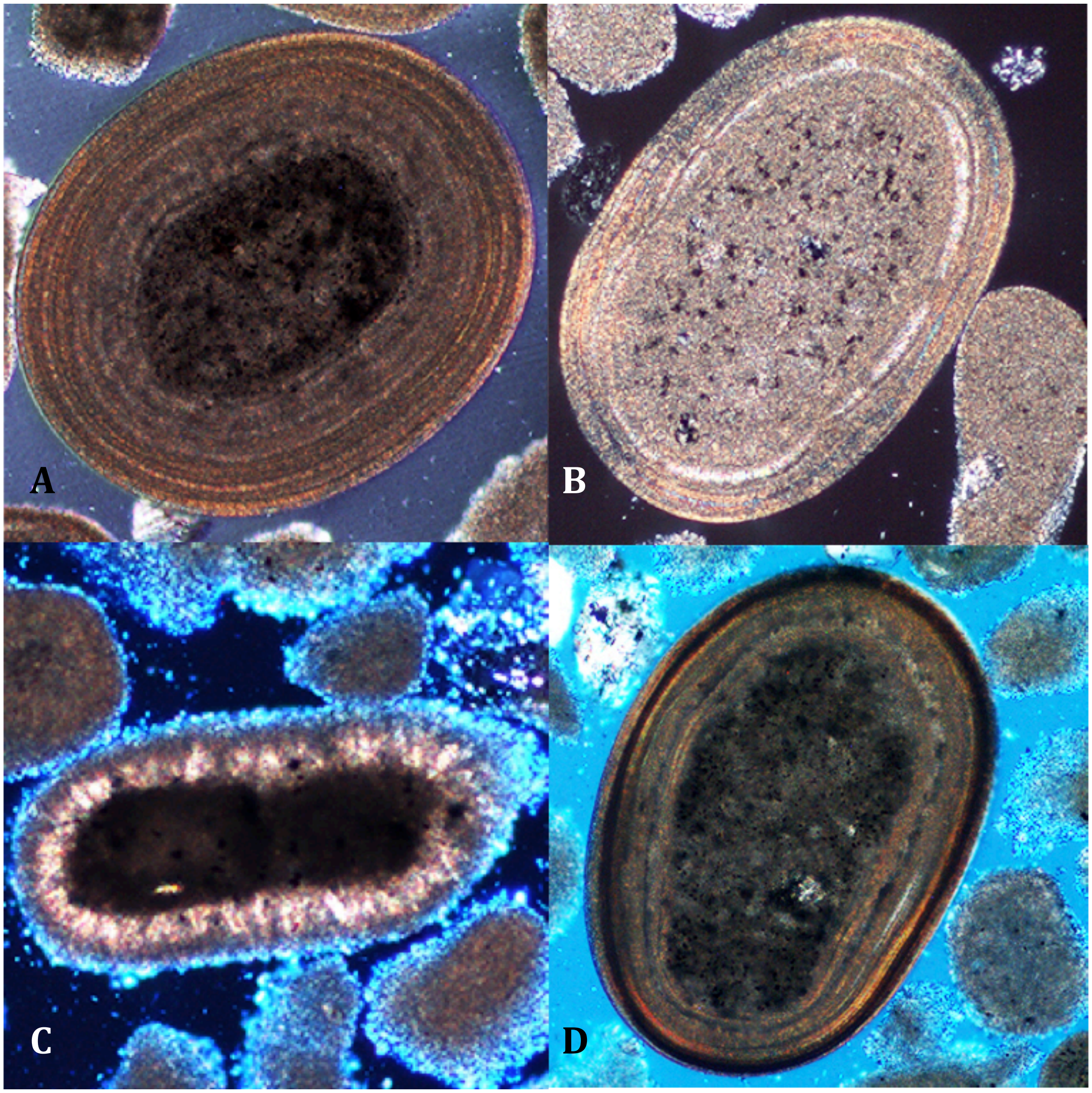

Figure 15.-Photomoicrographs of ooids from Pilot Valley. A) Tangential ooid from sample S2 in Pilot Valley. B) Slightly elongate tangential ooid from sample S2 in Pilot Valley. C) Radial elongate ooid from sample S3 in Pilot Valley. D) Slightly elongate tangential ooid from sample S3 in Pilot Valley.

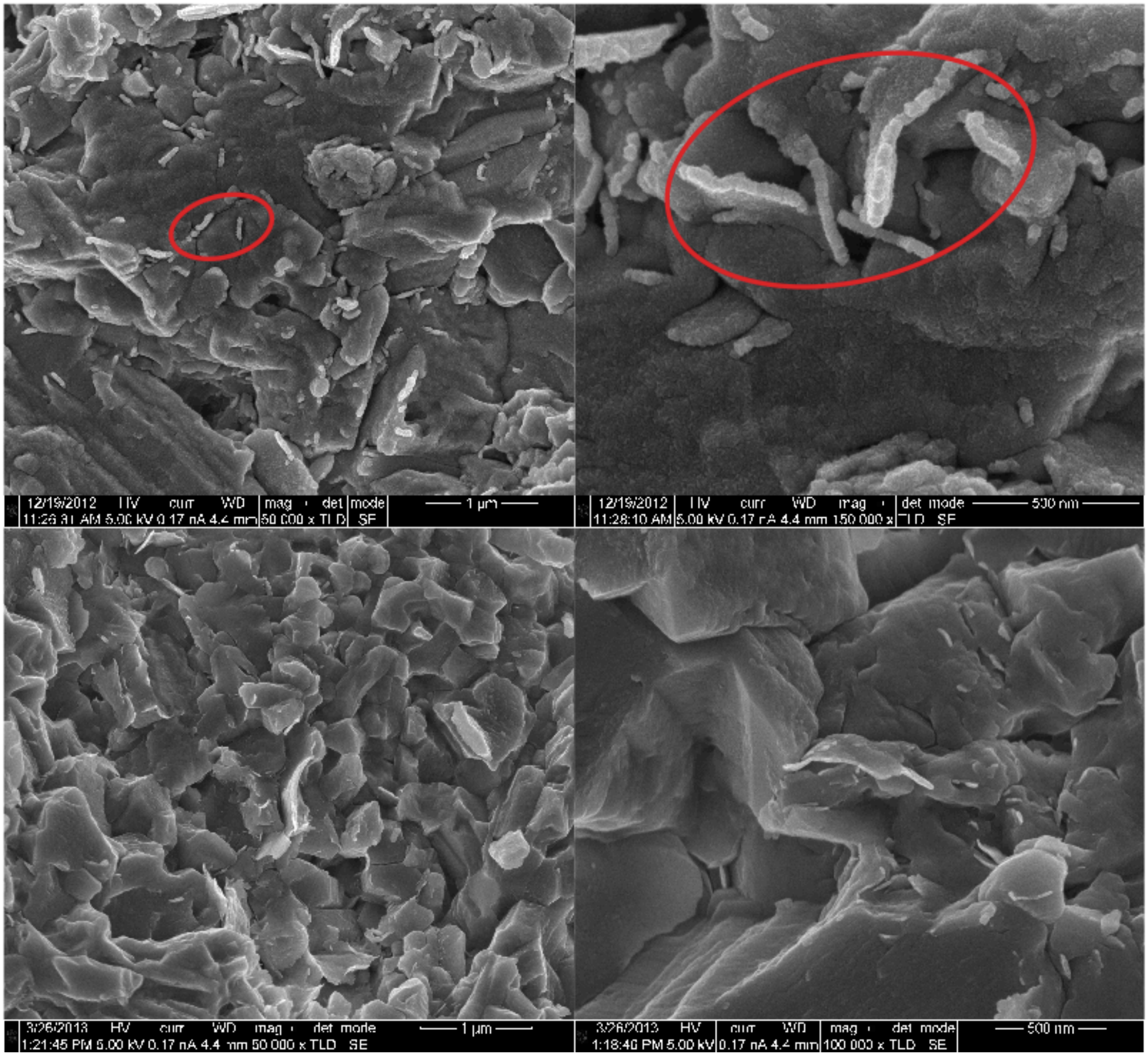

Figure 16.-SEM images of two ooids coated with different thicknesses of chromium from Upper Knolls. A) Ooid with a 25 nm chromium coating. Many chains of “nannoballs” (one example is circled in red) can be seen along edges of crystals. B) Magnified view of “nannoballs” from 25 nm-coated ooid. C) Ooid with 5 nm chromium coating. An absence of “nannoballs” when properly coated. D) Magnified view of properly coated ooid.

TABLES

Shoreline/ Level	Approximate age (years before present)	Elevation (feet above sea level)	Approximate surface area (square miles)	Salinity
Stansbury	23,000-20,000	4,500	9,300	Moderately saline
Bonneville	16,000-14,500	5,090	19,800	Relatively fresh, hard water
Provo	14,500-13,500	4,740	14,400	Relatively fresh, hard water
Gilbert	11,000-10,000	4,250	6,600	Saline

Table 1.-Table from Currey, et al., 1984 of significant shorelines and lake levels of the Great Salt Lake and Lake Bonneville.

	Mass Lost (g)
Stage 1	1.001
Stage 2	0.972
Stage 3	1.510
Stage 4	1.191

Table 2.-Mass lost from each partial dissolution stage.

	Ooid	Superficial Ooid	Peloid
Bridger Bay	74.8%	15.3%	9.9%
Rozel Point	77.9%	10.9%	9.0%
Upper Knolls	63.4%	26.1%	9.9%
Pilot Valley S1	18.9%	43.2%	37.0%
Pilot Valley S2	20.4%	32.3%	46.4%
Pilot Valley S3	4.4%	25.3%	70.1%

Table 3.-Grain type distributions for all ooid samples.

	.42mm<x<.991mm (#40)	.25mm<x<.42mm (#60)	.177mm<x<.25mm (#80)	.124mm<x<.177mm (#115)	.053mm<x<.124mm (#270)
Bridger Bay	6.4%	46.9%	33.9%	12.3%	0.5%
Rozel Point	23.4%	18.8%	22.6%	18.4%	2.3%
Upper Knolls		9.2%	42.8%	28.7%	18.7%
Pilot Valley S1		2.5%	25.0%	49.6%	15.6%
Pilot Valley S2		7.4%	21.1%	34.9%	20.3%
Pilot Valley S3		2.4%	8.3%	45.0%	30.9%

Table 4.-Grain size distribution for all ooid samples. Some samples contained varying percentages of cemented oolite that was not included in the table.

	Peloid	Intraclastic Pelsparite	Quartz
Bridger Bay	5.8%	44.5%	49.7%
Rozel Point	63.9%	22.2%	13.9%
Upper Knolls	90.5%	7.3%	2.2%
Pilot valley S1	92.9%	0.0%	7.1%
Pilot valley S2	92.1%	2.6%	5.3%
Pilot valley S3	82.6%	0.0%	17.4%

Table 5.-Table of ooid nucleus distributions by location.

Locality	Sample Depth	Dominant Corticle Fabric	Age (Radiocarbon Years)	Error	Grain Size Range	Dominant Grain Size Range
Great Salt Lake						
Bridger Bay	5 cm	Radial	3,172	26	.991mm-.053mm	.42mm-.25mm
Rozel Point	5-25 cm	Radial	431	23	.42mm-.053mm	.25mm-.177mm
Lake Bonneville						
Upper Knolls	142-152 cm	Tangential	25,134	73	.42mm-.053mm	.25mm-.177mm
Pre Bonneville						
Pilot Valley S1	312-322 cm	Tangential	28,118	80	.42mm-.053mm	.177-.124mm
Pilot Valley S2	381-389 cm	Tangential	28,848	90	.42mm-.053mm	.177-.124mm
Pilot Valley S3	498-513 cm	Tangential	32,288	103	.42mm-.053mm	.177-.124mm

Table 6.-table of cortex fabrics, composite ages, and grain size distributions for ooids from each location.

Dissolution Stage	Age (radiocarbon years)	+	-
Stage 1	2053	25	-25
Stage 2	2717	26	-26
Stage 3	4810	26	-26
Stage 4	8144	29	-29

Table 7.-Dissolution stages with their associated average ages. Ages are given in years before present (yr BP).