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# ISOTOPIC VARIATION IN AQUATIC GASTROPODS FROM THE CONTINENTAL LATE CRETACEOUS KAIPAROWITS FORMATION, SOUTHERN UTAH, U.S.A.

By

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**Committee Approval**

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Amy V. Hudson find it satisfactory and recommend that it be accepted.

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**ABSTRACT**

Base level exerts a fundamental control on continental sedimentary architecture, affecting the vertical and lateral deposition of sediments along the coastal plain. In the Late Cretaceous Kaiparowits Formation of southern Utah, coastal and alluvial plain deposition is recorded in a continuous ~2.1 myr section, with abundant and well-preserved continental fossils, of which mollusks are the dominant fauna. This study examines $\delta^{13}C$ and $\delta^{18}O$ stable isotopes in primary aragonite shell material from aquatic gastropods in pond and river deposits to evaluate the impact of changes in fluvial architecture, such as changes in pond stability and increased overbank flooding.

Analysis of 67 gastropod shells from three morphotaxa display similar carbon and oxygen values, and show no significant variance attributed to vital effect differences among species. Primary aragonite shell material is distinguished from diagenetically altered calcite and dolomite bearing samples by X-ray diffraction methods. Samples composed of more than 75% aragonite are inferred to record close to primary $\delta^{13}C$ and $\delta^{18}O$ isotope signatures, while those containing less than 50% aragonite reflect a significant increase in $\delta^{13}C$ and $\delta^{18}O$ shell isotopic values. Mixed carbonate shell $\delta^{18}O$ values are corrected to original aragonite isotopic composition using isotopic mixing equations.

Pond gastropods record a distinct shift in the mean $\delta^{18}O$ values between each unit. The lower unit records a mean $\delta^{18}O$ value of -12.7±4.3‰, while the marine influenced portion of the middle unit has a heavier mean $\delta^{18}O$ value of -9.8±4.2‰. The post marine influenced middle unit records a similar mean $\delta^{18}O$ value to the marine influenced portion, with a value of -10.9±1.8‰, while the upper unit returns to $\delta^{18}O$ values more

similar to the lower unit with a mean of -12.3±4.4‰. This increase in $\delta^{18}O$ values and return to lighter $\delta^{18}O$ values correspond to changes in the fluvial geometry between meandering and anastomosing style rivers, and an incursion of marine waters up the river channels.

Average values for pond unionoids (-9.5±1.6‰ $\delta^{18}O$) and pond gastropods (-10.3±3.8‰ $\delta^{18}O$) are statistically similar. In most units, the range of values recorded by the pond gastropods overlaps the range recorded by the pond unionoids. Occasionally, the range of pond gastropods overlaps with the fluvial unionoids as well. The consistent small offset of heavier $\delta^{18}O$ and lighter $\delta^{13}C$ values between gastropods and unionoids suggests these two mollusks record a similar environmental signal, but may record slightly different positions within the Late Cretaceous microenvironments, such as shallow vegetated areas versus deeper non-vegetated areas. These relationships suggest that aquatic gastropods promise to be an additional archive for geochemists, sensitive to both local and regional environmental changes, with the potential to expand our understanding of basin scale processes on the flora and fauna living in the Western Interior Basin.

## 1. INTRODUCTION

The diversity of the fossil record in the Kaiparowits Formation has prompted extensive research over the last 25 years, which has led to a multitude of paleontological and paleoclimatic discoveries concerning the terrestrial flora and fauna preserved in the Late Cretaceous strata along the Western Interior of North America. Discoveries in the areas of biostratigraphy (Eaton, 1991), dinosaur paleobiology (Zanno and Sampson, 2005; Gates and Sampson, 2007; Sampson et al., 2010), reptile diversity and biogeography (Hutchison et al., 2013; Irmis et al., 2013; Farke et al., 2014; Lively, 2015), distribution of mammalian taxa (Cifelli, 1990; Eaton and Cifelli, 2013), plant diversification (Miller et al., 2013), precipitation and climate patterns through modeling (Fricke et al., 2010; Sewall and Fricke, 2013), tectonics and sediment provenance (Lawton et al., 2003; Lawton et al., 2014), invertebrate diversity and taphonomy (Roberts et al., 2008; Tapanila and Roberts, 2013), and early bird relatives (Farke and Patel, 2012) have illustrated the potential for high-resolution investigations into the evolution of the Campanian ecosystem and its inhabitants. However, the most numerous and perhaps most diverse fossil group are mollusks, of which Tapanila and Roberts (2013) documented 52 morphotaxa from the Kaiparowits Formation, dominated by aquatic gastropods and bivalves. Yet these invertebrates have been comparatively ignored in favor of paleoecological studies focused on their larger vertebrate contemporaries. However, these mollusks contain within their shells a chemical archive with the potential to track Late Cretaceous climate and environmental change.

In the terrestrial sedimentary record, unionoid bivalve shell and pedogenic soil carbonates are the usual targets for stable isotopic investigations. Pairing mollusks and

pedogenic soil carbonates has provided insight into paleoclimatic conditions, such as the $\delta^{18}O$ of local precipitation, and alluvial deposition processes, with support for an uplift event that shaped the Western Interior environments during the Campanian (Fricke et al., 2010; Foreman et al., 2015). Building upon these investigations and the relationship between sedimentary facies and gastropod species diversity (Kelly, 2014), this study employs $\delta^{13}C$ and $\delta^{18}O$ stable isotopes from aquatic gastropods and pedogenic soil carbonates to expand upon the existing isotopic record from unionoid bivalve shell. Further, we evaluate the impact of changes in fluvial architecture on the stable isotopic signals recorded between pond and river ecosystems in the Kaiparowits Formation as a result of changes in pond stability and increased overbank flooding.

To our knowledge, this is the first attempt to investigate stable isotopes in aquatic gastropods from as deep in time as the Cretaceous Period. Several Cenozoic paleoclimate studies show that gastropod shell has the potential to track small-scale environmental changes related to marine and freshwater mixing (Latal et al., 2006), can be indicators for paleoaltimetry (Garzione et al., 2004), and record changes in temperature and humidity related to seasonal variation in precipitation distribution (Schmitz and Andreasson, 2001).

The Kaiparowits Formation presents an ideal location in which to test these new chemical archives. Paleoclimate reconstructions based on paleoflora (Wolfe and Upchurch, 1987; Miller et al., 2013) and unionoid bivalves (Fricke et al., 2010; Foreman et al., 2015) will allow us to evaluate the ability of aquatic gastropod to characterize the chemistry of the formation. If the aquatic gastropods record stable isotopic values that correspond to values recorded by the unionoid bivalves, they will be considered viable geochemical archives.

**Considerations for using aragonite from gastropods**

Stable isotopic analysis using $\delta^{13}C$ and $\delta^{18}O$ in biogenic carbonates is widely used to reconstruct past climate and conditions in freshwater environments. Generally, the organisms used for these investigations are bivalves, and gastropods (Schmitz and Andreasson, 2001; Garzione et al., 2004; Latal et al., 2006; Kohn and Dettman, 2007; Spiro et al., 2009) from aquatic terrestrial settings. Mollusks represent a particularly useful geochemical archive because they grow their shells almost continuously over their lifetime (Kaplan and Selleck, 2008). Additionally, most mollusks are considered to precipitate their shell carbonate $\delta^{18}O$ in near equilibrium with their environment (Fritz and Poplawski, 1974; Grossman and Ku, 1986; Dettman et al., 1999), although some species display vital or kinetic effects causing non-equilibrium (Shanahan et al., 2005; McConnaughey and Gillikin, 2008). Isotopic composition of shell material is therefore related to the environmental conditions in which the mollusk lived, and is sensitive to changes in these environments over time.

For aquatic mollusks, shell $\delta^{18}O$ is a function of temperature and the $\delta^{18}O$ signal of the ambient water in which the mollusk lives. In freshwater environments the $\delta^{18}O$ composition of the water is ultimately related to climate through precipitation, evaporation, water residence time, upstream source elevation, and river and floodplain interaction (Schmitz and Andreasson, 2001; Shanahan et al., 2005; Latal et al., 2006). Shell $\delta^{13}C$ is related to the dissolved inorganic carbon (DIC) of the ambient water, which can be influenced by surrounding vegetation, mollusk growth and metabolic rates, and respired $CO_2$ from their diet (Dettman et al., 1999; Schmitz and Andreasson, 2001; Shanahan et al., 2005; Latal et al., 2006; McConnaughey and Gillikin, 2008).

Although the main contributing factors for shell isotopic composition are known, using shell material to accurately reconstruct past environments requires a well constrained relationship between the equilibrium values of the $\delta^{18}O$ from the shell carbonate and the temperature at which it was precipitated (Shanahan et al., 2005). Calculated fractionation factors, which differ significantly based on the methods used to calculate them (Grossman and Ku, 1986; Kim and O'Neil, 1997; Zheng, 1999; Kim et al., 2006; Kohn and Dettman, 2007), could potentially be applied to the problem, but not without significant complications in the presence of vital effects and additional constraints on their validity for the particular mollusk species of interest. For this reason, determining if vital effects are causing the mollusks to be out of equilibrium with their surroundings is essential.

Vital effects occur when an organism's isotopic composition fractionates away from the equilibrium conditions of its environment due to physiological processes (McConnaughey and Gillikin, 2008). The magnitude and direction in which the fractionation occurs is variable between species, as it relies on each of their unique calcification physiologies (Kim et al., 2006). The presence or absence of vital effect, however, does not preclude the effects that external influences, such as microenvironment, may have on the isotope fractionation (Fritz and Poplawski, 1974; Leng and Marshall, 2004; Shanahan et al., 2005; Latal et al., 2006).

Although Kim et al. (2006) suggests that vital effects are species dependent, the effect can be demonstrated in any mollusk if $\delta^{13}C$ and $\delta^{18}O$ covary (McConnaughey, 1989; Shanahan et al., 2005), as light $\delta^{13}C$ values are generally paired with light $\delta^{18}O$ values (Grossman and Ku, 1986). The lack of covariance however, does not rule out vital

effects completely, but may indicate that larger environmental differences are the primary cause for distinct groups of values (Shanahan et al., 2005).

## 2. GEOLOGIC SETTING

### Western Interior

Subduction of the Farallon oceanic plate beneath the western margin of North America began in the Late Jurassic (~155 Ma) forming the north-south trending Cordilleran Orogenic Belt and foreland basin system. The Cordilleran Orogenic Belt stretches over 6000 km, from parts of Alaska and the Canadian Arctic down through the continent to southern Mexico, with the Western Interior Foreland Basin on the eastern side (DeCelles, 2004). Flexural subsidence caused by the eastward advancement of thrust sheets from the Sevier Orogenic Belt in the area of what is now southern Nevada and California caused the Western Interior Basin to be inundated by marine waters in early Late Cretaceous time (Figure 1). The resulting inter-continental seaway received a continuous supply of synorogenic sediments transported by north- northeast flowing fluvial systems that cut across the Sevier hinterlands and thrusts (Goldstrand, 1994) depositing material in alluvial to marine settings (DeCelles, 2004).

During the Late Jurassic to Late Cretaceous (around 75 Ma), pulses of volcanism from an advancing and retreating magmatic arc, episodes of metamorphism, shortening in the orogeny interior and hinterland, and eustatic fluctuations, led to the deposition of a relatively low-relief, high elevation hinterland region. At the same time foredeep to wedge-top deposition occurred in the frontal thrust zone (Dickinson, 1983; DeCelles, 2004), which was subsequently uplifted and divided into smaller basins by Laramide style deformation as the subduction angle of the Farallon plate decreased during late Campanian to Maastrichtian time (DeCelles, 2004).

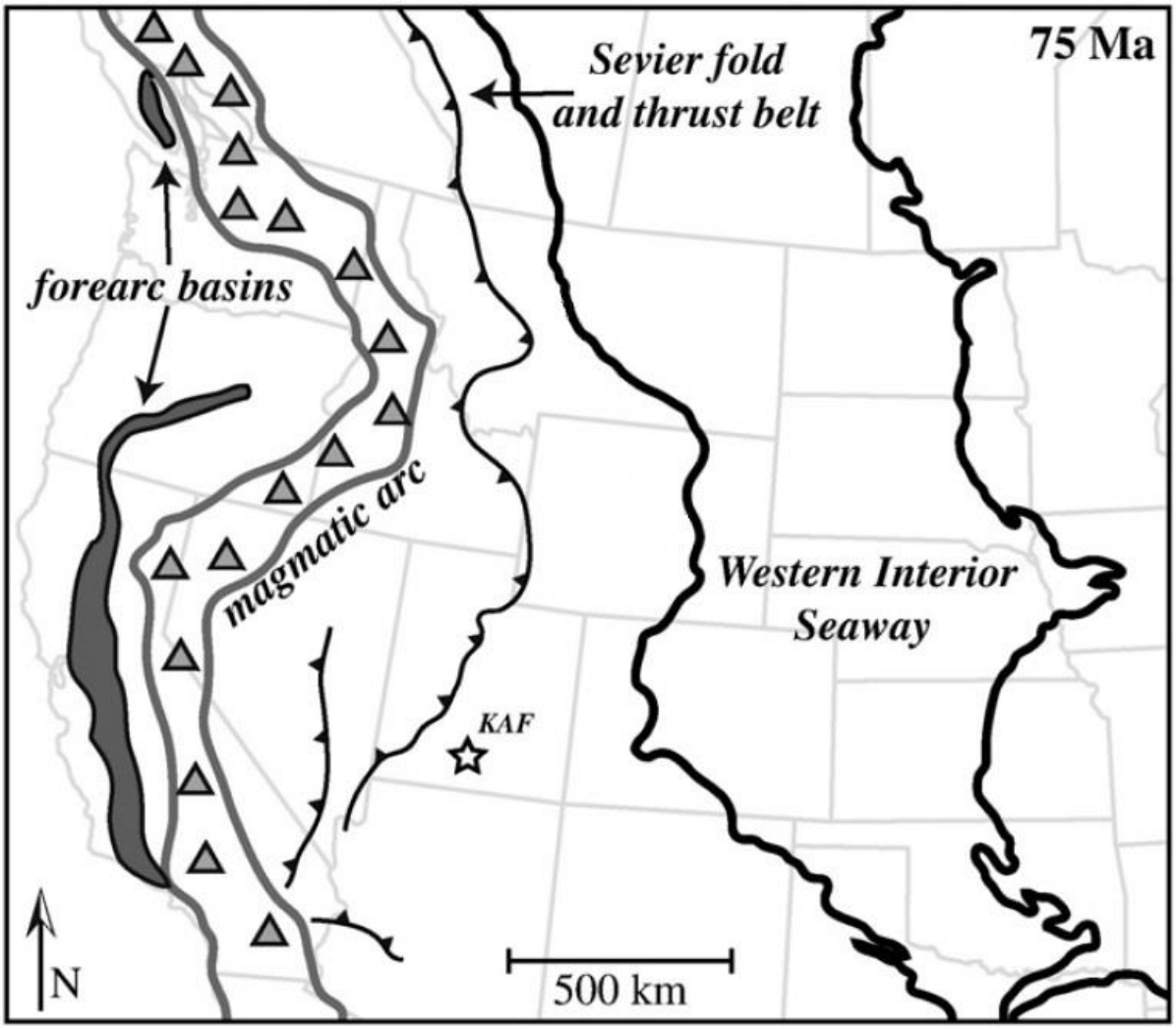



**Figure 1:** Paleogeographic map of the Western Interior Seaway and surrounding geologic features during the Campanian (75 Ma). Star denotes the location of the Kaiparowits Formation relative to the thrust belt and seaway margin. Modern state boundaries superimposed in light grey. Modified from Fricke et al. (2010).

Warmer conditions than exist today characterized the greenhouse climate of the Cretaceous period. The increased global temperature resulted in warm high latitudes as a result of greatly reduced ice volumes at the poles (Miller et al., 2003), shallower latitudinal temperature gradients (Wolfe and Upchurch, 1987), higher concentrations of atmospheric $pCO_2$, around 1200 ppm (Nordt et al., 2002), and higher global sea level and sea surface temperatures (Pearson et al., 2001). In the Western Interior Basin, subhumid megathermal conditions with moderate precipitation (< 1.6 m) were interpreted for nearly all of the basin during Campanian time. The exception was a zone from paleolatitude 44-50° N, which experienced a slight increase in precipitation. Lack of seasonal freezing is inferred for much of the basin, based on the foliar physiognomy of woods (Wolfe and Upchurch, 1987). More recent paleofloral investigations and climate modelling have suggested the presence of seasonal monsoons (Fricke et al., 2010) and a more humid climate, equating the basin's Late Cretaceous climate to conditions similar to the Mississippi Delta region along the modern Gulf of Mexico (Miller et al., 2013).

**Kaiparowits Formation**

The Kaiparowits Formation represents approximately 2.1 million years of continuous alluvial and coastal plain deposition along the western margin of the Western Interior Seaway (Roberts, 2007) (Figure 2). Located at 46.2° N paleolatitude (Miller et al., 2013) during deposition in the Late Cretaceous, the formation now outcrops from the Table Cliffs Plateau to the Kaiparowits Plateau as ~70 km of badland-style exposures within the Grand Staircase-Escalante National Monument (GSENM) of southern Utah (Goldstrand, 1994). The roughly 860 m thick formation conformably overlies the early to

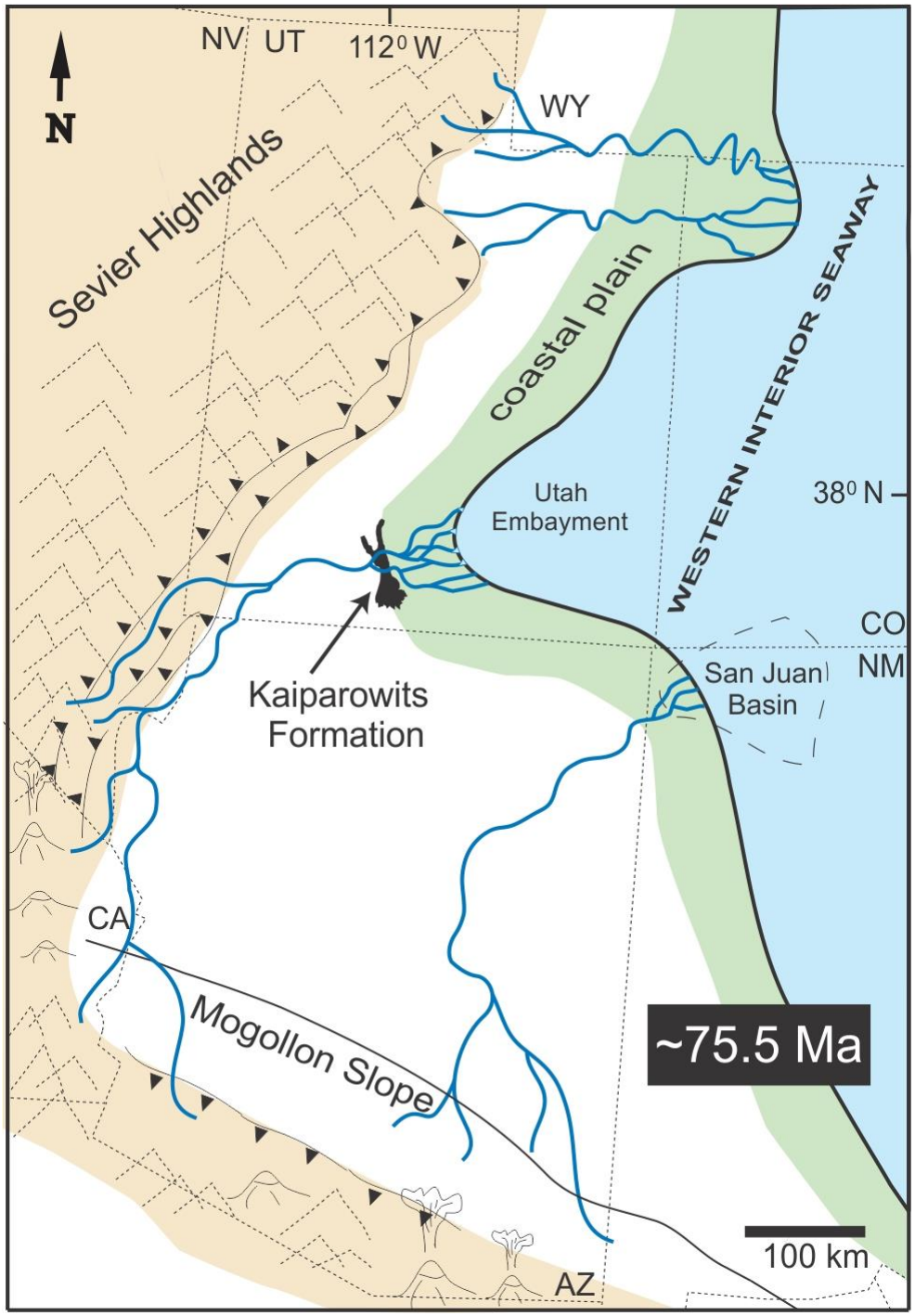



**Figure 2:** Paleogeographic map of the western margin of the Western Interior Seaway, sediment source areas to the west and south. The rivers represent the general trend of the fluvial systems. Outcrop location of the Kaiparowits Formation is marked in black. Modern state boundaries are overlain with dotted lines. Modified from Roberts et al. (2008).

middle Campanian fluvial Wahweap Formation (Jinnah et al., 2009), and is unconformably overlain by the latest Cretaceous- early Paleogene braided fluvial to lacustrine Canaan Peak Formation (Goldstrand, 1994).

A middle to late Campanian age of ~76.6 to 74.5 Ma was calculated for the formation by Roberts et al. (2013) using $^{40}Ar/^{39}Ar$ and U/Pb from sanidine and zircon crystals collected from five bentonite horizons and correlation across at least 12 bentonite ash beds present in the underlying Capping Sandstone Member of the Wahweap Formation and throughout the Kaiparowits Formation. Fossil evidence from biostratigraphic studies in the formation also support a Campanian age (Eaton, 1991). Regional fossil and stratigraphic comparisons have led to correlation of the Kaiparowits Formation to other contemporaneous fossil rich deposits along the Western Interior, including the Fruitland Formation in New Mexico, Two Medicine Formation and Judith River Formation in Montana, and Dinosaur Park Formation in southern Alberta (Wolfe and Upchurch, 1987; Fricke et al., 2010; Miller et al., 2013; Roberts et al., 2013)

The Kaiparowits Formation records a sediment accumulation rate of up to 570 m/Myr, higher than any other Late Cretaceous continental sedimentary basin in the Western Interior (Roberts et al., 2013). Such a high sedimentation rate was possible due to the eastward advancement of thrust sheets from the Sevier Orogenic belt, and by subsequent Laramide basement uplifts. The thrust loading caused lithospheric flexure and rapid subsidence which led to a continuous sediment supply from the surrounding highlands to the south and west (Goldstrand, 1994; Lawton et al., 2003).

The Kaiparowits Formation is divided into three informal units. Divisions are based on fluvial architecture and relationships between the nine facies associations of

Roberts (2007), particularly concerning thickness and occurrence of fluvial versus overbank deposits and channel stacking density. The lower unit (0 to ~125 m) consists of mainly closely spaced single and multi-story channel sandstones separated by thin overbank deposits, and has a channel/overbank ratio of 75/25. Fossil preservation in this unit is generally poor compared to the rest of the formation (Roberts, 2007). The lower unit is interpreted as deposits of meandering rivers which flowed north east, longitudinally along the foredeep (Lawton et al., 2003). The middle unit (~125 to ~550 m) is dominated by regionally extensive overbank deposits. The unit records a significant decrease in the channel/overbank ratio to 45/55, and a switch to single story channel deposits. Paleoflow direction changed to the east, transverse across the foredeep (Roberts, 2007) marking the change to anastomosed rivers (Lawton et al., 2003), and an increase in sediment accumulation rates and quality of fossil preservation (Roberts, 2007). In the lower portion of the middle unit (~125 to ~320 m) a zone of marine influence or brackish conditions is recognized due to the presence of the trace fossil *Teredolites,* and encrusting bryozoans on unionoid shells. The *Teredolites* trace fossil lives in marine to brackish conditions, and suggests that shorelines were proximal enough to allow marine mixing 10s-100s of km up river (Roberts et al., 2008). The presence of lenticular bedding, clay draped foresets, and inclined heterolithic strata also supports this interpretation by Roberts (2007). In the upper unit (~550 to 860 m), a return to dominantly multi-story channel sandstones with slightly reduced overbank deposits is reflected by the channel/overbank ratio of 60/40 (Roberts, 2007). The upper unit is interpreted as a return to the meandering style river, and records another shift in paleoflow direction to the south east. Fossil preservation is generally worse than either the lower or middle units. Despite

paleocurrent shifts, sediment source areas for the Kaiparowits Formation remained fairly constant throughout the formation, with sediments eroding off the thrust sheets, and from arc related sediments in southeast California, the Sevier hinterlands of south-central Nevada (Goldstrand, 1994), and the regionally high Mogollon Highlands in Arizona (Roberts, 2007).

Throughout this study, units are divided as lower (0 to ~125 m), middle-marine influence (~125 to 320 m), middle-post marine influence (320 to 550 m), and upper (550 to 860 m).

Climate reconstructions from Miller et al. (2013) are based on terrestrial and aquatic fossil plants collected from the middle unit of the Kaiparowits Formation, which suggest a subtropical, wet, megathermal climate. A mean annual temperature (MAT) estimate of 20.2 ±2.3°C and a mean annual precipitation (MAP) estimate of 1.78 m (1.24 to 2.55 m) were calculated using leaf physiology from the dominant and most diverse flora, the dicotyledonous angiosperms. Angiosperms typically represented 60-90% of the species diversity in floodplains during this time. These include the first occurrence of widespread palm plants as dominant floor cover, accompanied by a diverse group of aquatic plants. Platanoids dominate channel environments in the middle unit, but are accompanied by conifers, cycads, and ferns. The aquatic plants from the middle unit represent the most diverse assemblage known from the Late Cretaceous, consisting largely of ferns and angiosperms. Of the species found in pond deposits, the angiosperm *Quereuxia* is the most dominant, while the fern *Hydropteris* is more often found in ponds that experienced periodic flooding. The high diversity of aquatic plants present in the middle unit mirrors the high diversity of aquatic vertebrate and invertebrate faunas

present, and supports the interpretation of the landscape as a large floodplain with large low-gradient rivers and substantial ponds (Miller et al., 2013).

## 3. MATERIALS AND METHODS

### Species of Interest

Three morphotaxa of aquatic prosobranch gastropods (*Lioplacodes nebrascensis*, *Lioplacodes subtortuosa* and *Viviparus sp.*) from pond and river deposits (Tapanila and Roberts, 2013) were selected for this investigation (Figure 3). These morphotaxa are ideal for a stable isotopic analysis because of their overwhelming abundance and diversity throughout the most of the formation, frequent primary aragonite preservation, and exclusive assimilation of carbon and oxygen through water. Additionally, extant species of aquatic gastropods from the same family, Viviparidae, are known to live for an average of 2-5 years (Jakubik and Lewandowski, 2007; Browne, 1978) suggesting these gastropods represent a fairly complete annual record for the years these specimens represent.

### Field Sampling

Sample collection focused on intervals of green-grey mudstone, representing pond and floodplain facies, and tan sandstones of the channel facies (Roberts, 2007) within the informal middle unit, and to a lesser extent the lower and upper units of the Kaiparowits Formation. Sample locations follow stratigraphy up section from approximately 40 m above the contact with the Wahweap Formation to 670 m in the Blues section of the formation, north of Highway 12 in the GSENM. Height in section (within 5 m) was determined by the presence of distinct marker beds and bentonite horizons using the lectostratotype column (Figure 4) from Roberts (2007). At each sample interval, bulk sampling of well-preserved whole and partial gastropods and pedogenic soil carbonates

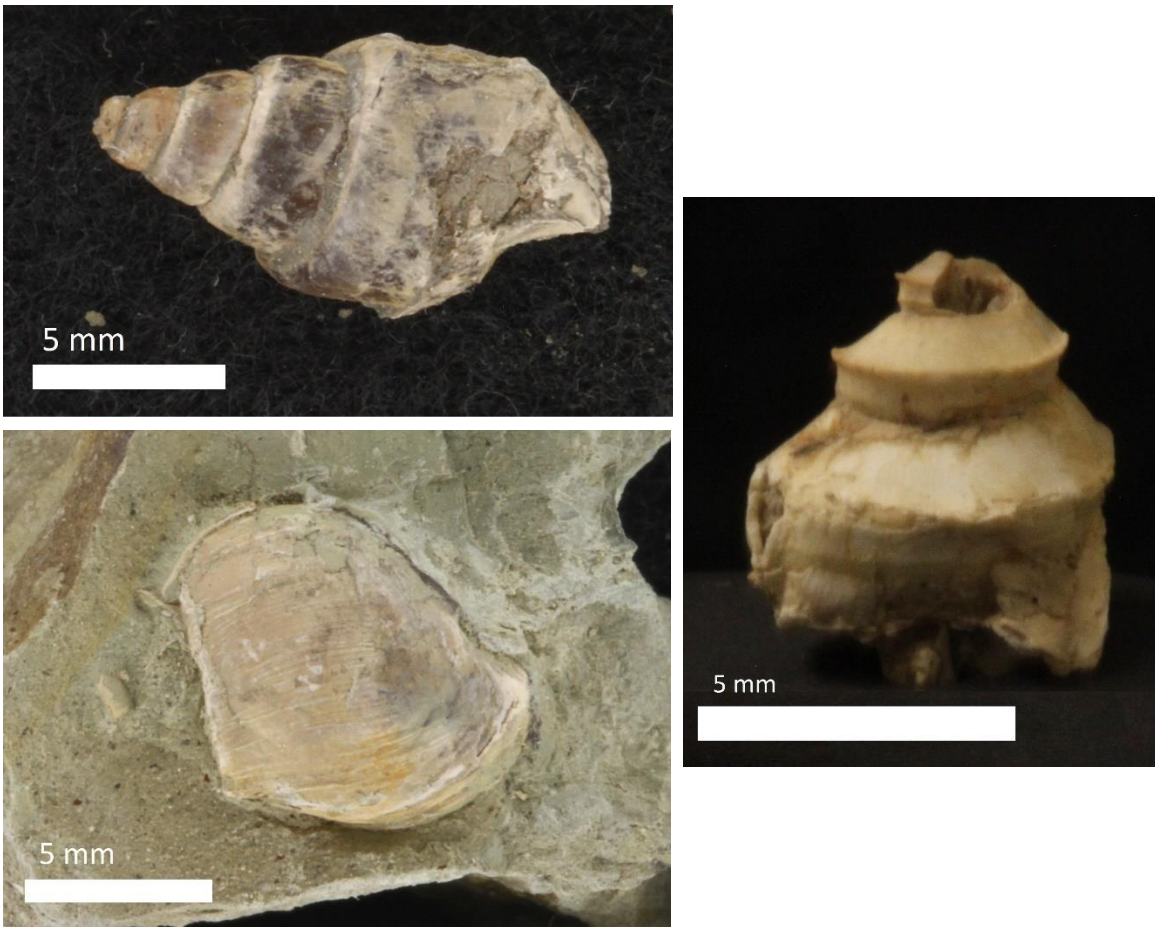



**Figure 3:** The three aquatic gastropod morphotaxa selected for this study. From top to bottom: *Lioplacodes nebrascensis* (top), *Lioplacodes subtortuosa* (right) and *Viviparus sp.*(bottom). Specimens are easily differentiated based on distinct shell morphologies, all of which are characteristic of the family Viviparidae.

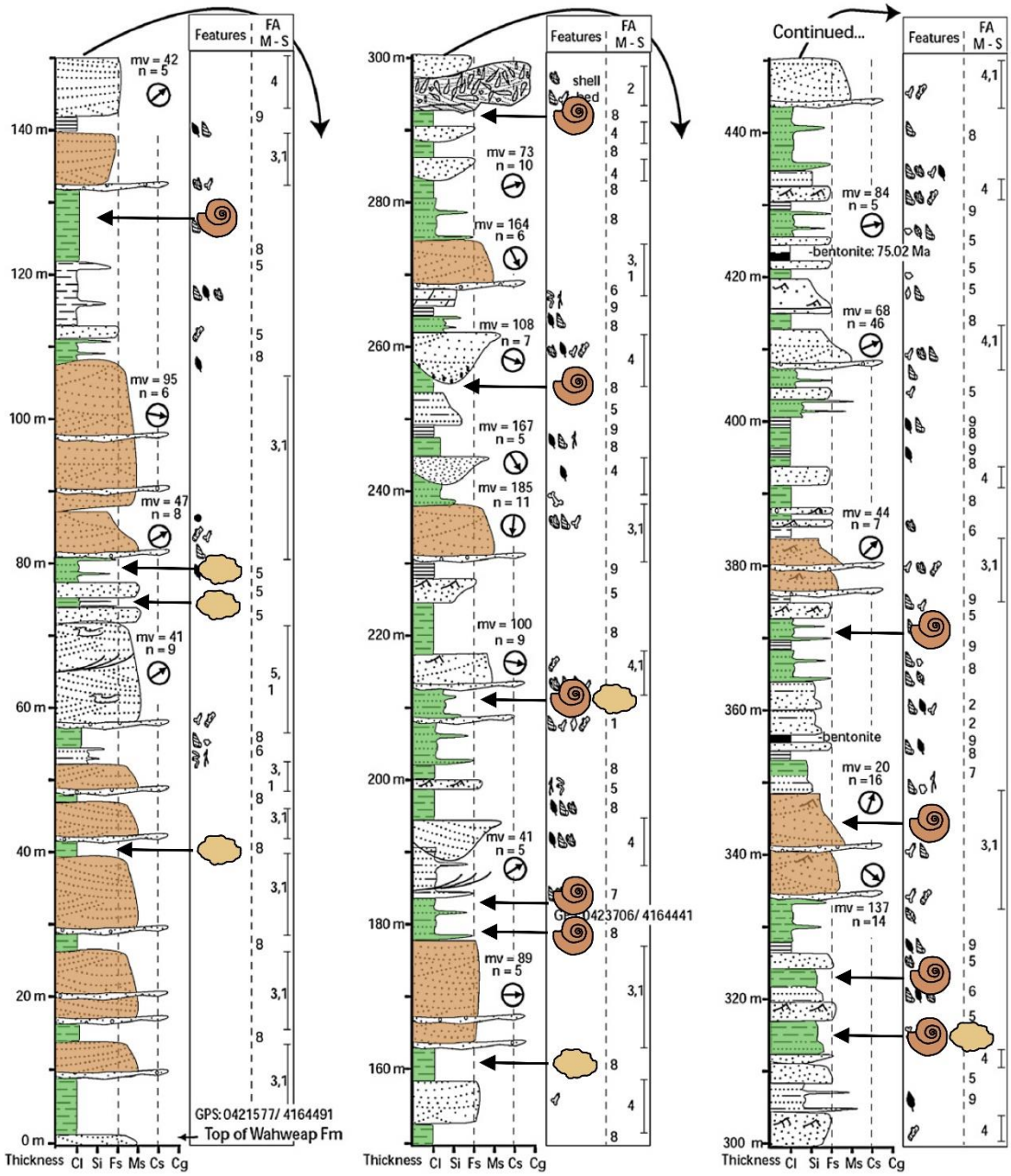



**Figure 4:** Lectostratotype column of the Kaiparowits Formation. Pond deposits (Facies Association 8) are colored in green, fluvial deposits (Facies Association 3) are colored in tan. Sample intervals are marked with arrows and the type of material collected there according to their height in section. Modified from Roberts (2007).

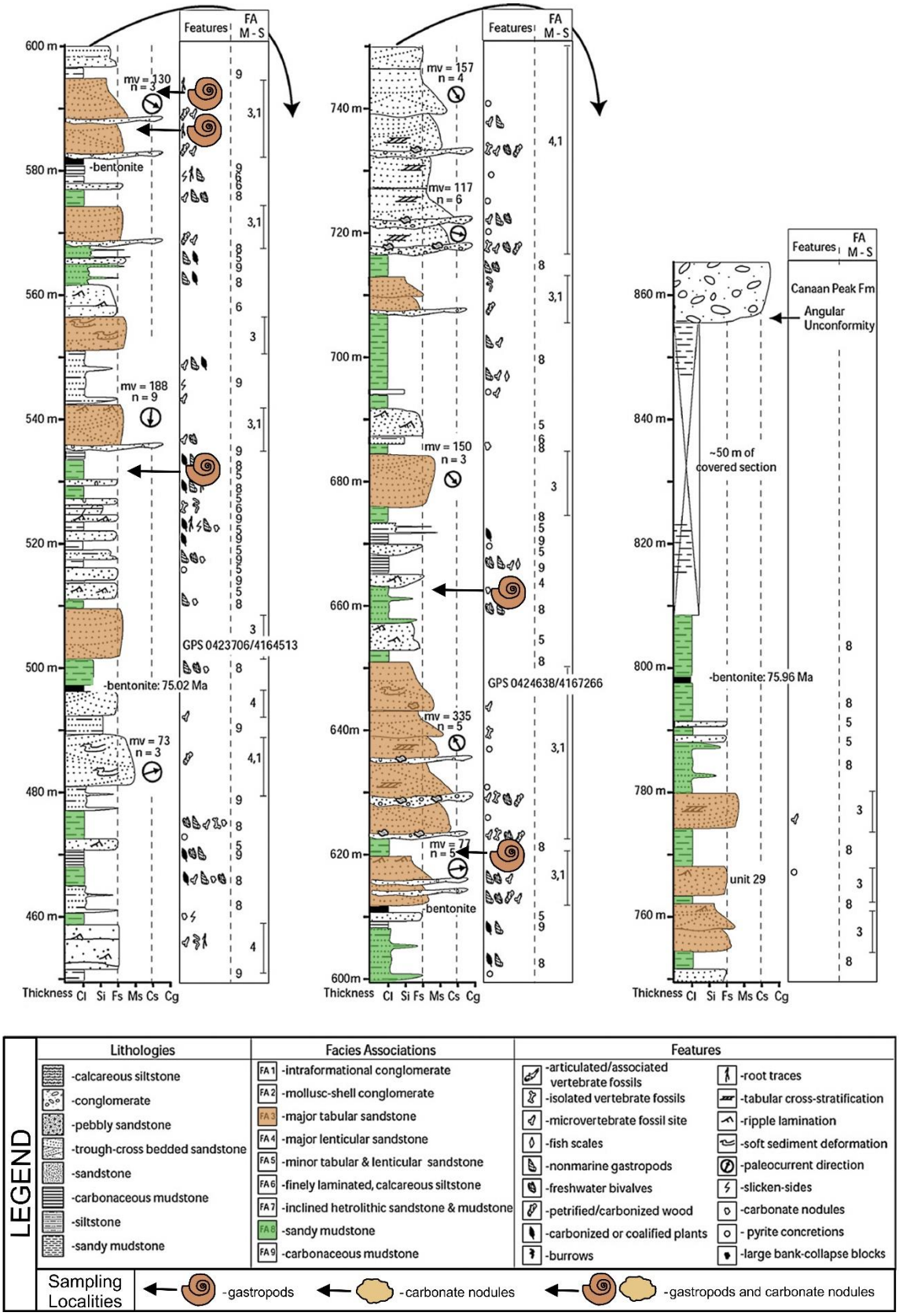



**Figure 4** continued.

were collected from small trenches dug through regolith into fresh outcrop at least 40 cm below the surface.

Of the 150+ individual gastropod and pedogenic soil carbonate samples collected, 41 aquatic gastropods belonging to the three morphotaxa and 15 pedogenic soil carbonates contained enough calcium carbonate material to be useable for the stable isotopic investigation. An additional 26 aquatic gastropod samples were analyzed from collections made by Kelly (2014), which are stratigraphically well defined.

Shell remnants and steinkerns from the 67 gastropods used in the study, and all unused materials from bulk sampling are catalogued and housed in the Earth Sciences Invertebrate Paleontology Collection at the Idaho Museum of Natural History.

***Depositional Environments Sampled***

Gastropods and pedogenic soil carbonates are sampled from pond and floodplain mudstones, siltstones and fluvial sandstones. Pond deposits classified as Facies Association 8 by Roberts (2007) are composed of grey-green sandy mudstone, silty mudstone, and siltstones with the clay fraction composed of roughly 90% smectite and 10% illite. An abundant mix of bentonite beds, carbonized plant material, vertebrate bone and teeth, mollusk shells, and pedogenic soil carbonates are present in most beds. Individual beds can extend laterally for 10-100s of meters, and are between 0.7 m and 12 m thick. The presence of gleyed soils and pedogenic soil carbonates in these beds are indicators of wet conditions with elevated water tables that may have been subject to minor seasonal aridity or variable floodplain drainages (Roberts, 2007).

Gastropod shells from these intervals range from moderately compressed partial whorls to fully preserved specimens with visible aragonite shell material. Shells and other fossilized material are generally disseminated throughout the beds, with no indication of stratigraphic horizons, or preferred orientations.

Fluvial deposits, classified as Facies Association 3 by Roberts (2007) are composed of multi- and single-story fine to medium grained tan-grey tabular sandstone channel fills. Channels are at least 1.5 to 2 m thick, but generally have thicknesses of over 5 m, and extend laterally for 100s of meters. These channels are commonly incised and contain intra-formational conglomerates at their base, which fine upwards to siltstone, and can include inclined bedforms and minor bioturbation. Macroforms interpreted as point-bar lateral accretions are also abundant. Preservation of vertebrate macrofossils is rare, while carbonized and petrified trees, mollusks and pedogenic soil carbonates are locally abundant. Paleo-channel reconstructions of bankfull depth and width, suggest typical channel depths were between 3 to 10 m, with more variable widths of 19.5 to 81 m, indicative of meandering and anastomosing rivers (Roberts, 2007).

Gastropods sampled from these intervals generally maintained their unbroken original shape, but showed more obvious signs of calcite recrystallization on shells, with less than 10% maintaining any usable shell material. In most cases, shell material had been completely replaced by calcite or dissolved, leaving casts of the gastropods.

**X-ray Diffraction Analysis**

To investigate the mineralogical composition of the samples, as a basis for determining any diagenetic effects, gastropod shell material was tested using powder

X-ray Diffraction (XrD). Shell material was separated from the matrix using dental picks, and ground to a fine powder of roughly uniform grain size using a glazed porcelain mortar and pestle. In the initial 10 samples, whole shells were crushed before grinding into a powder. This method resulted in some incorporation of interior matrix material. Visual inspection of the crushed material found the interior matrix to be composed of dominantly clay and sparry calcite, therefore contaminating the shell composition for analysis. X-ray diffraction analyses confirmed the presence of calcite for 8 out of the 10 samples. The remaining 57 samples were separated from the matrix before grinding into a powder. A list of which samples were prepared using each of the above methods can be found in Appendix I. Manual separation was necessary due to the presence of a bentonite clay matrix, and the general fragility of shell material, which would have been lost to traditional ultrasonic cleaning methods used on most mollusk shells. When possible, multiple whorls or whole shells were sampled to ensure a heterogeneous and lifelong average chemical signal for each ground specimen.

Specimen powders were hand divided, half for XrD analysis, and half for isotopic analysis. XrD powders were aspirated onto glass slides using a slurry of powdered sample and either acetone (initial 10 crushed samples only) or isopropyl alcohol. Occasionally, shell material was so minimal that there was barely enough to coat the slides and still have enough for isotopic analysis. Analysis was conducted on a Bruker model D8 Advance x-ray diffractometer housed in the Idaho State University Department of Geosciences Laboratory for Environmental Geochemistry. Mineral phases and relative abundances were analyzed using Match! 3 Software (www.crystalimpact.com/match/, March 2016).

**Pedogenic Soil Carbonates**

In addition to fossils, pedogenic soil carbonate nodules were checked for signs of alteration before stable isotopic analysis. The pedogenic soil carbonate nodules were sliced in half, polished, and examined under the microscope to check for alteration from micrite to sparry calcite. Samples were then micro-sampled using a diamond tipped 2 mm bit in at least two locations per nodule. Nodules that were found to have a sparry component were sampled in areas that maintained a micritic texture and in areas of recrystallization, where a sample of spar was taken for comparison. Images showing sample locations on all pedogenic soil carbonates included in this investigation are in Appendix VI.

**Stable Isotopic Analysis**

Oxygen and carbon stable isotope analysis was performed on all gastropod shell material and pedogenic soil carbonate micrite on a ThermoFinnigan Gas Bench II coupled to a Delta Plus Isotope Ratio Mass Spectrometer (IR-MS) by the SIRFER Lab at the University of Utah. For each analytical run, two different primary laboratory reference materials of known isotopic composition are included, as well as at least one secondary laboratory reference. There is a primary reference for every twelve unknowns. Quality assurance is checked using standard uncertainty on the secondary reference, if the standard uncertainty is greater than 0.15‰ ($\delta^{13}C$) or 0.20‰ ($\delta^{18}O$), samples are reanalyzed. Analyses are normalized to internal standards (Carrara Marble and LSVEC-lithium bicarbonate) and international standards using NBS-19 and VPDB. All results are reported in per mil relative to VPDB in δ notation.

Surface water $\delta^{18}O$ estimates are calculated using the temperature-dependent fractionation equation for inorganic calcite from Kim and O'Neil (1997) using the pedogenic soil carbonates,

$$1000 \ln \alpha_{calcite\text{-}water} = 18.03*(10^3T^{-1})-32.42$$

where $\alpha_{calcite\text{-}water} = (1000+ \delta^{18}O_{calcite})/(1000+ \delta^{18}O_{water})$ and T is in kelvins. A mean annual temperature estimate from paleofloral investigations of 20.2°C is used (Miller et al., 2013), with the addition of another 2.5°C due to soil at depth retaining warmer temperatures than the atmosphere from warming in the summer months (Quade et al., 2007). Surface water estimates are reported relative to VSMOW in δ notation. This temperature was also chosen because it is the same value used by Foreman et al. (2015), and will facilitate comparison between the surface water estimates calculated in this study.

***Determination of original $\delta^{18}O$ for shells consisting of mixtures of carbonate minerals***

Stable isotopic mixing calculations are performed on all gastropod shell samples containing the carbonate phases calcite or dolomite to correct measured $\delta^{18}O$ values influenced by diagenetic effects. Given that the carbonate minerals are in isotopic equilibrium with each other, the original shell isotopic composition can be calculated. Calculations are done using one of three different isotopic mixing equations, chosen based on the mineralogy of the sample. These equations are derived from the equilibrium fractionation values between calcite and aragonite (+4.5‰), and dolomite and aragonite (+5.1‰) calculated by Zheng (1999).

For shell samples composed of 100% calcite, or mixtures of calcite and aragonite:

$$A = M - 4.5y$$

where A= original aragonite shell $\delta^{18}O$, M= measured shell $\delta^{18}O$, and y= mass fraction of calcite in the shell measured by XrD; 4.5‰= difference in $\delta^{18}O$ between aragonite (lighter) and calcite (heavier) at 25°C (Zheng, 1999).

Shell samples containing 100% dolomite or mixtures of dolomite and aragonite:

$$A = M - 5.1z$$

where A= original aragonite shell $\delta^{18}O$, M= measured shell $\delta^{18}O$, and z= mass fraction of dolomite in the shell measured by XrD; 5.1‰= difference in $\delta^{18}O$ between aragonite (lighter) and dolomite (heavier) at 25°C (Zheng, 1999).

Shell samples composed of a mixed mineralogy that include aragonite and both calcite and dolomite used one of the two above equations if there was a clear majority mineral with more than a 5% difference in their compositions. Alternatively, if the calcite and dolomite percent compositions were within 5% of each other, a third equation was used. In this equation, the equilibrium fractionation factors of calcite and dolomite are averaged to treat the two mineral phases as one alteration source. This methodology introduces up to about 1.0‰ error, as the equilibrium fractionation between calcite and dolomite is calculated as about 0.6‰ (Zheng, 1999). Shell samples with aragonite and nearly equal amounts of calcite and dolomite use the equation:

$$A = M - 4.8(z+y)$$

where A= original aragonite shell $\delta^{18}O$, M= measured $\delta^{18}O$ value, z= mass fraction of dolomite in the shell measured by XrD, and y= mass fraction of calcite in the shell measured by XrD; 4.8‰= difference in $\delta^{18}O$ between aragonite (lighter) and average calcite-dolomite (heavier) at 25°C.

The measured $\delta^{13}C$ values for the gastropod shells are not corrected in the presence of calcite and dolomite. In a recent study, the $^{13}C$ enrichment of aragonite relative to calcite in mollusks was shown to be less than 1.0‰ (Lécuyer et al., 2012). Similarly, Rubinson and Clayton (1969) measured a mean carbon isotope fractionation factor of 1.8 ±0.2‰ between aragonite and calcite from slow precipitation from a bicarbonate solution at 25°C. Therefore, a recalculation of $\delta^{13}C$ values was not done, as the potential error associated with the different fractionation of calcite and dolomite would have been almost the same as the calculated shifts. Measured values for $\delta^{13}C$ are used for this investigation, while calculated values are used for $\delta^{18}O$.

## 4. RESULTS

### Mineral Assemblages

Shell mineralogy of all gastropod specimens was tested using x-ray powder diffraction to distinguish between the three possible carbonate minerals present (aragonite, calcite, and dolomite). Dolomite and calcite are indicators of diagenetic alteration (Folk, 1974), therefore, the absence of either of those phases is taken as evidence that the shell contains primary aragonite. Gastropod shells were found to contain six possible combinations of carbonate minerals. The most ideal were shells containing only aragonite (Figure 5A). However, the three most common combinations were shells containing variable amounts of calcite or dolomite, or both, in addition to aragonite (Figure 5B). The last two possibilities were shells contain only calcite or dolomite (Figure 5C).

Of the 67 total gastropod samples, 19 had shell material composed entirely of aragonite, while seven had shells that were completely altered to either calcite or dolomite, or a combination of the two. The remaining 41 gastropods contain aragonite as well as the alteration phases of calcite, dolomite, or both. A complete list of carbonate minerals contained in each shell sample, and their relative percentages can be found in Appendix II.

Other minerals from the sandy mudstone matrix (Goldstrand, 1992; Doelling et al., 2000; Lawton et al., 2003) are present in varying amounts in the analysis of almost every sample, including: clays (undifferentiated), quartz, barite, gypsum, kaolinite and possibly calcite. In order of most commonly included matrix minerals, quartz is the most abundant, occurring in 49 out of the 67 samples. Barite and gypsum are found in 18 and

11 samples respectively, and kaolinite is found in one sample. Clays are found in most samples, but have extremely small and variable peaks below 10° 2Θ, and are therefore filtered out with the background signal during data processing.

Only 10 out of the 67 total samples record carbonate minerals with no other non-carbonate included matrix minerals. Of these 10, the only samples with calcite are from the bulk crushed samples, in which the calcite was at least partly sourced from the matrix. In shell samples that were separated from the matrix, calcite does not occur in every sample, but the 15 samples that do contain calcite always contain at least one other non-carbonate matrix mineral. Therefore, any calcite present could be sourced from the either the shell or remnant matrix material. However, non-carbonate matrix minerals occur in purely aragonite samples as well as those with calcite and dolomite. The quantity of included non-carbonate matrix does not correlate with the presence of calcite or dolomite, as shell samples containing >50% matrix material can contain only aragonite, while shell samples with as little as 10% to >75% included matrix material can contain calcite or dolomite. Individual indexed x-ray diffraction spectra can be found in Appendix III. Details of XrD analysis and interpretation methods, and complete XrD data files for gastropod samples are included in Appendix IV.

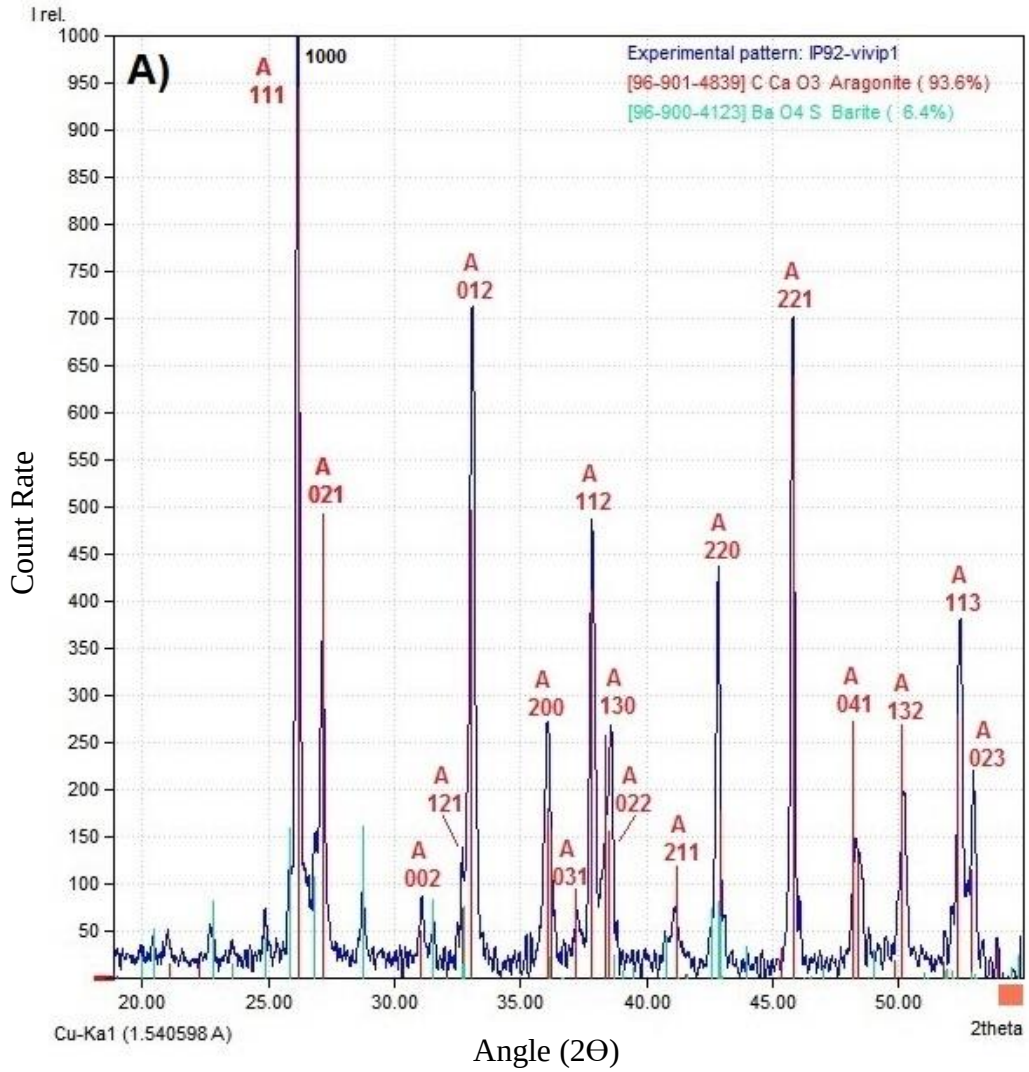



**Figure 5:** Examples of the three most common gastropod shell mineralogies. Figures are indexed to show mineral peak matches and corresponding Miller Indicies {hkl}. The letter and color above indexed peaks corresponds to the mineral phase in the top right corner.

A) aragonite shell; B) mixed mineralogy shell with aragonite, calcite, and dolomite; C) calcite shell.

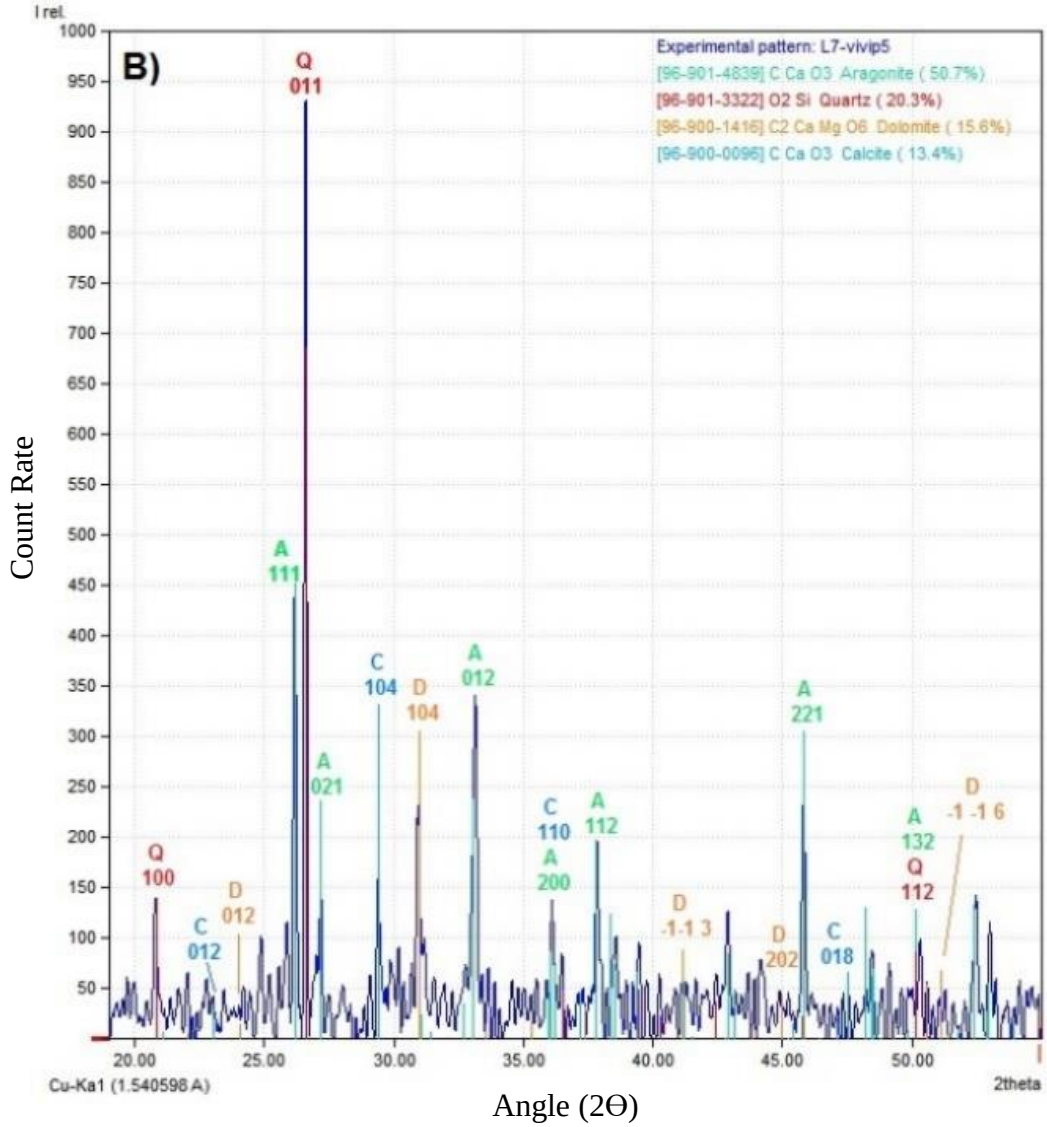



**Figure 5** continued.

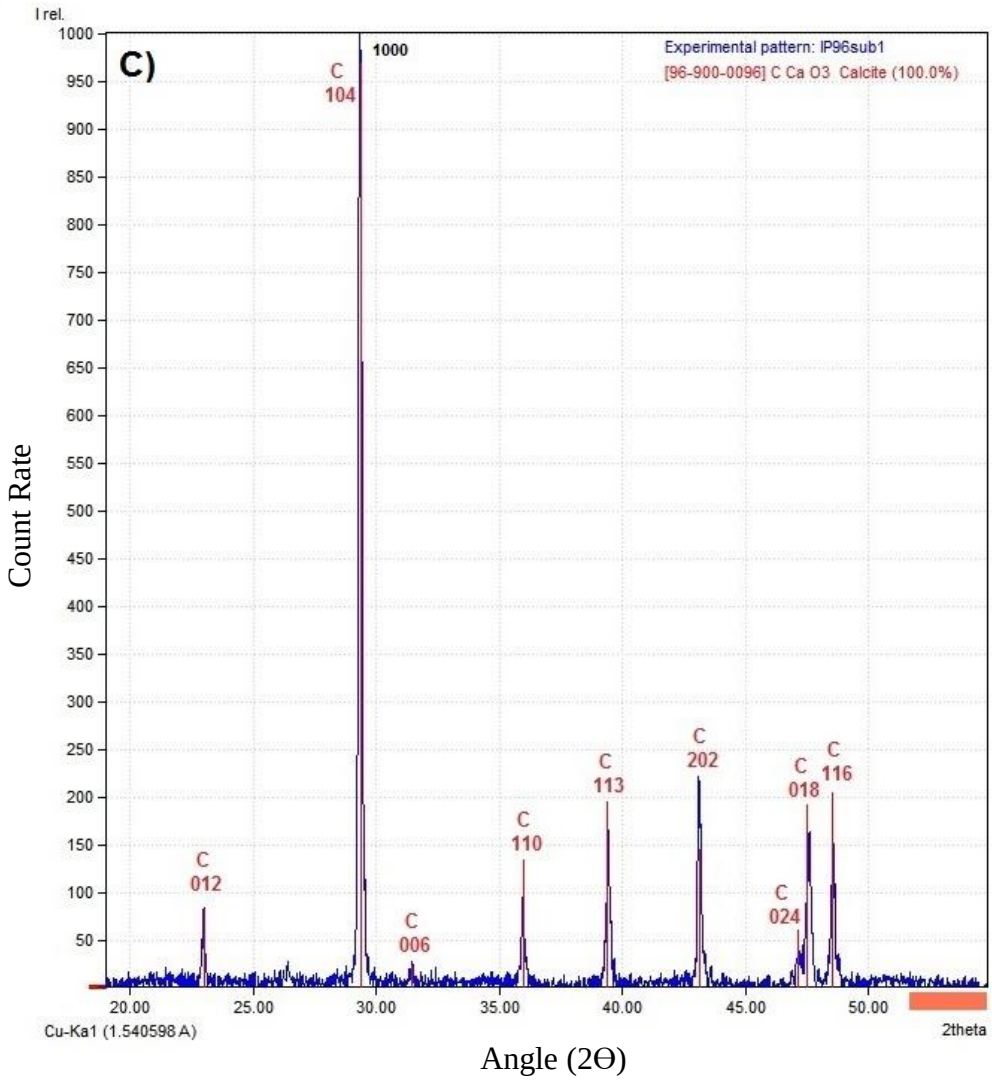



**Figure 5** continued.

**Textural Characterization of Gastropod Shell**

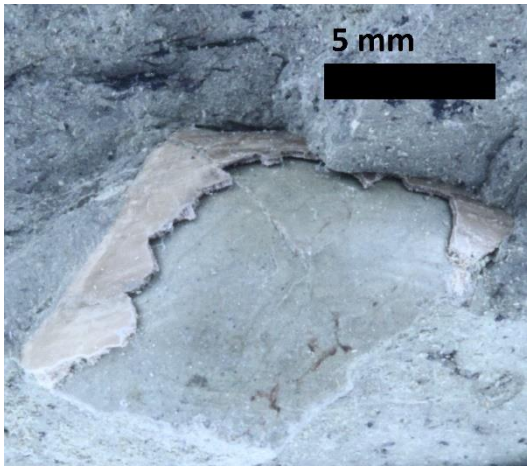
In addition to quantitative analysis, a visual and physical analysis of the gastropod shell material can help to determine the likelihood of alteration from aragonite to calcite or dolomite of the shell material before any chemical analysis. In all cases where soft, pink to pinkish off-white (sometimes nacreous) shell material was present, the shell mineralogy was aragonite. A finding which is consistent with the physical descriptions of gastropod shell material utilized by Garzione et al. (2004). Unfortunately, in this study, a significant amount of the gastropod shells had a brown to reddish-brown coating on the shell which identified as dolomite, and more rarely calcite in addition to dolomite. Examination of the shells in cross section showed that the brown coating does not penetrate into the inner shell layers, rather it resides along the contact between the shell and the surrounding rock matrix. This coating is usually on the external shell surface, but is occasionally present on the inner surface as well. The presence of flaky brown material on the shell surfaces also correlated with a dolomite mineralogy. Shells that contain calcite only are hard on the outside, and have a pale yellow color with a more crystalline than opaque powdery exterior, indicative of replacement. Off-white shells generally contain a mix of aragonite and calcite in the shell material, with the addition of dolomite in the presence of any brown coating. Off-white shells with a calcite signal also generally had harder interior portions of the shell, while the outermost soft layers were more similar to the pink shells. It is possible that the aragonite and dolomite mineralogy in a shell is a result of inclusion of an alteration layer on the outside of otherwise unaltered shell material, which if removed would result in a purely aragonite signal.

**Table 1:** Summary of correlations between shell mineralogy and physical properties.

| **Shell Description** | **Mineralogy** |
|---|---|
| Pale yellow: hard, crystalline look | Calcite |
| Pink to pinkish off-white: soft, occasionally shiny | Aragonite |
| Pinkish off-white with flaky brown coating: soft, thin, whole shell occasionally flaky | Aragonite-Dolomite |
| Off-white with flaky brown coating: soft with harder interior | Aragonite-Calcite-Dolomite |
| Pinkish off-white: hard interior | Aragonite-Calcite |
| Flaky brown and white: hard | Calcite-Dolomite |

** These are general observations that follow with most samples, however it may not always be the case, and XrD analysis is still required to determine shell composition. **

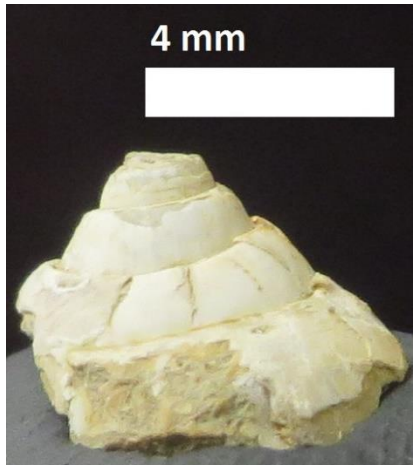

Calcite




Aragonite


Aragonite-Dolomite


Aragonite-Calcite-Dolomite




Aragonite-Calcite


Calcite-Dolomite

**Figure 6:** Examples of characteristic shells and their mineralogy. Accompaniment to Table 1.

Support for this comes from two samples (IP-233-819: L8-Vivip2 and IP-231-796: L6-Vivip3), which had some areas with the brown coating, and others where the pinkish off-white shell was visible. Brown areas were avoided during sampling, and only the underlying pinkish shell was analyzed. In both cases, the samples displayed an aragonite only signal. Due to the fragility and small size of most samples however, removal of the brown coating was not always possible without removing too much shell material to be analyzed in the mass spectrometer. A summary of shell descriptions and mineralogical composition is provided in Table 1, photograph examples in Figure 6.

**Aragonite percentages and isotopic values**

In order to assess the impact of alteration minerals (calcite and dolomite) on the shell $\delta^{18}O$ composition, each sample had the percent of aragonite present calculated relative to the total carbonate minerals in the samples from the x-ray diffraction analysis. Based on the percent of aragonite, samples were divided into 5 groups to evaluate if a certain percentage of aragonite must remain in the shell samples for the $\delta^{18}O$ values to overlap with the pure aragonite samples. The first group is composed of 19 samples that display only aragonite peaks, called the 100% aragonite category. Samples containing aragonite with variable amounts of dolomite or calcite, are divided into three groups; eight samples comprised the 99-75% aragonite group, the 75-50% aragonite group contains 24 samples, and nine samples are represented by the less than 50% aragonite group. The remaining seven samples are composed entirely of calcite or dolomite, with no evidence for remaining primary aragonite, and make up the fifth group, No aragonite.

The $\delta^{18}O$ and $\delta^{13}C$ values demonstrate a large degree of overlap between samples containing only aragonite, and those that contain other carbonate minerals (Figure 7). The

percentage of aragonite present in the sample does not seem to dictate the range of values the shell samples record. Most samples with no aragonite record the same range of values as those that are 100-75% aragonite. Additionally, samples with less than 50% aragonite record a range that overlaps with the majority of the 100% aragonite samples. Samples with 50-75% aragonite have the most offset from the 100% aragonite samples. When the percent of aragonite is the same between samples, shells that have been altered to calcite typically record less of a shift toward heavier $\delta^{18}O$ values than those that have been altered to dolomite. While the range of values are similar in all cases, there is a tendency for samples with calcite and dolomite to record values shifted slightly toward heavier values for both $\delta^{13}C$ and $\delta^{18}O$, resulting in a deflection of values toward the origin of the axes.

Graphing the gastropod shells by their height in section (Figure 8A, 8B) reveals that calcite and dolomite occur in all stratigraphic levels. Several horizons preserve 100% aragonite samples along with samples composed of entirely calcite or dolomite. These altered shell samples record $\delta^{18}O$ and $\delta^{13}C$ values dominantly within the range of the 100% aragonite shells in their horizon.

Calculated $\delta^{18}O$ values, which relied on the percent of aragonite present in the shell samples, show the degree in which the isotopic compositions were shifted by the calcite and dolomite (Figure 9). Calculated shell compositions display a lighter signal relative to the measured composition. The maximum shift was +5.1‰, but most samples shifted less than +2.0‰. A complete list of calculated $\delta^{18}O$ values for all samples is in Appendix II, and a summary of calculated values by depositional environment is in Table 2.

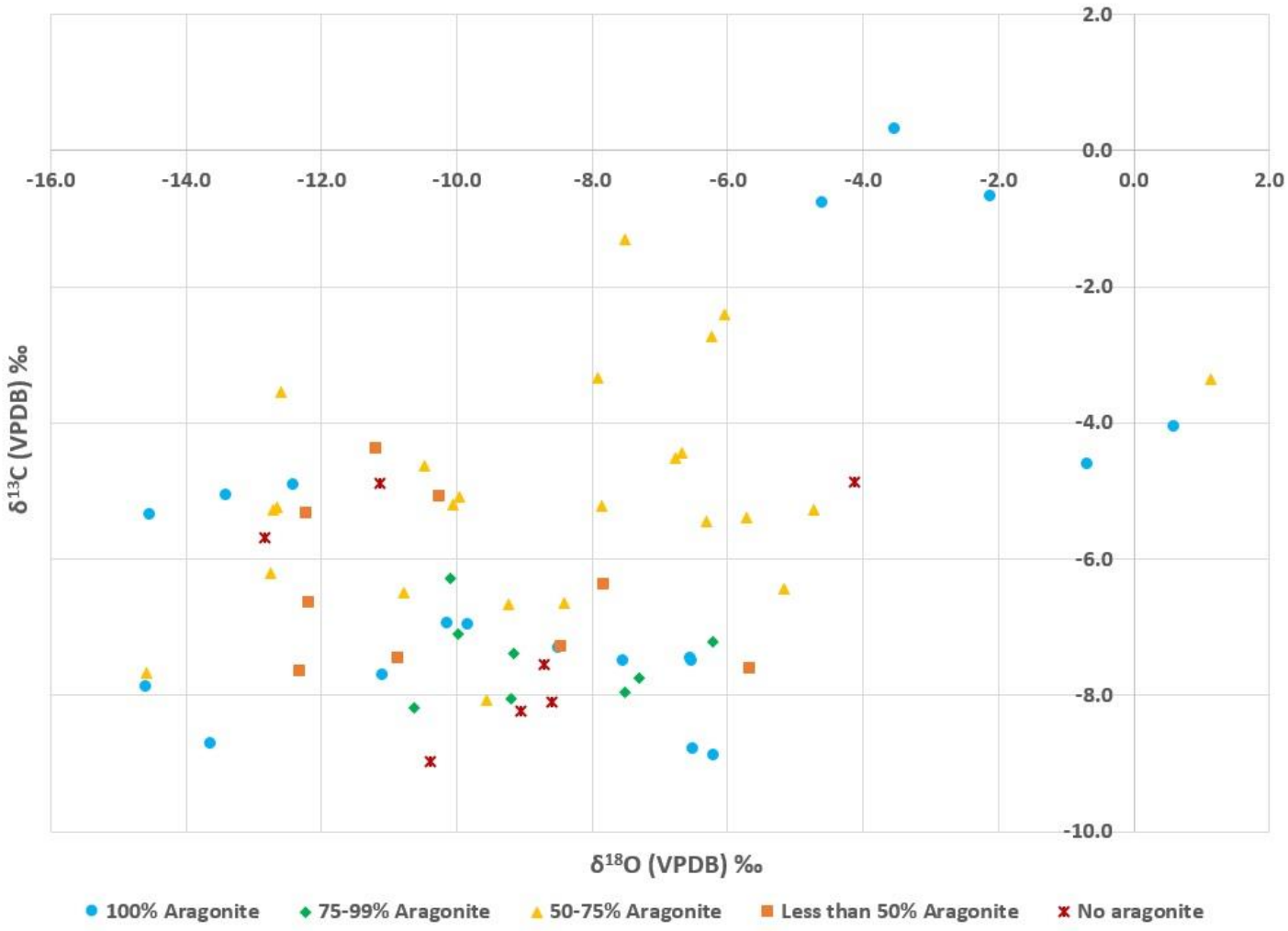



**Figure 7:** $\delta^{18}O$ vs. $\delta^{13}C$ of gastropods according to their percent aragonite composition.

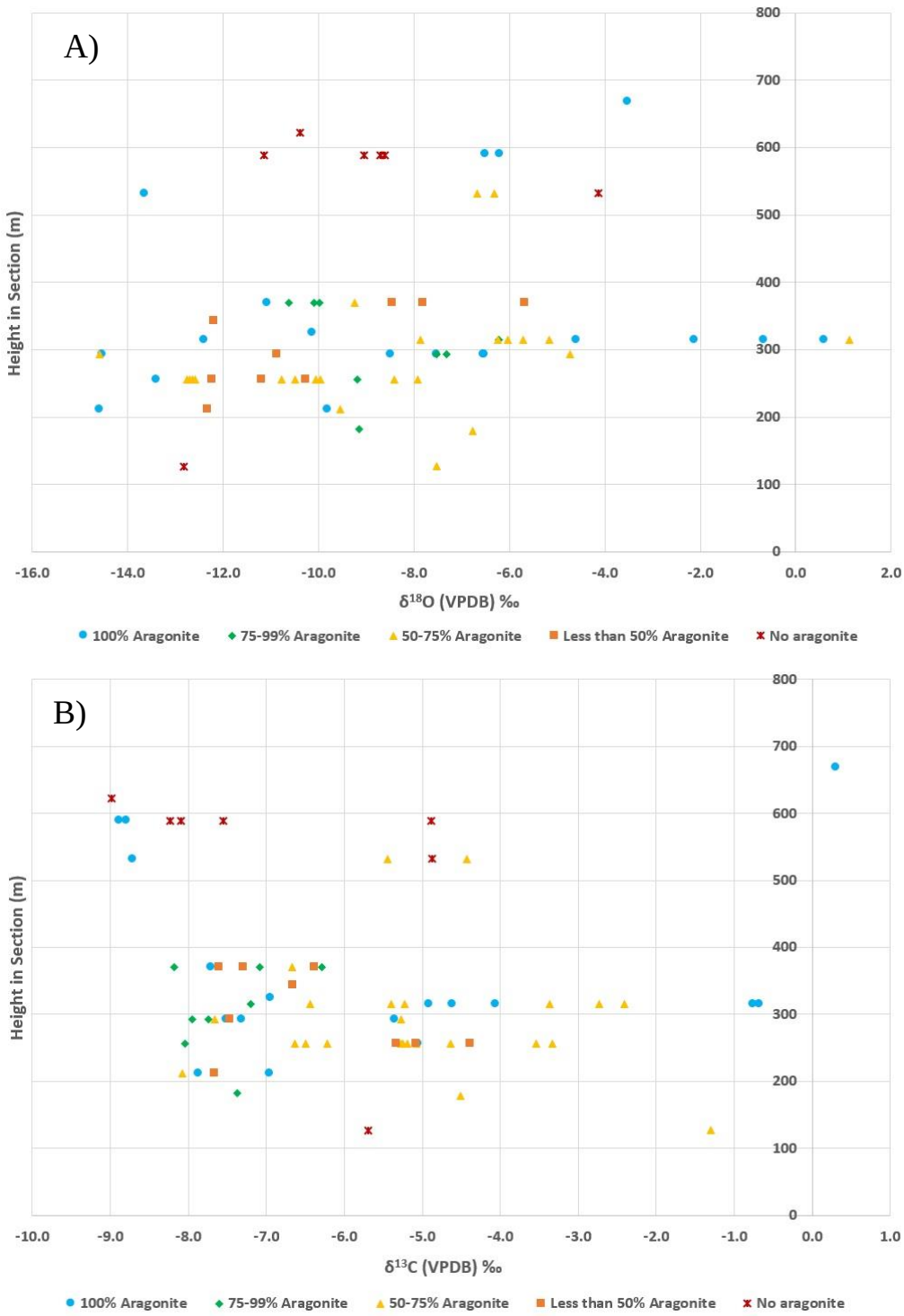



**Figure 8:** Gastropods by percent aragonite according to their height in section, A) $\delta^{18}O$ by sample interval B) $\delta^{13}C$ by sample interval.

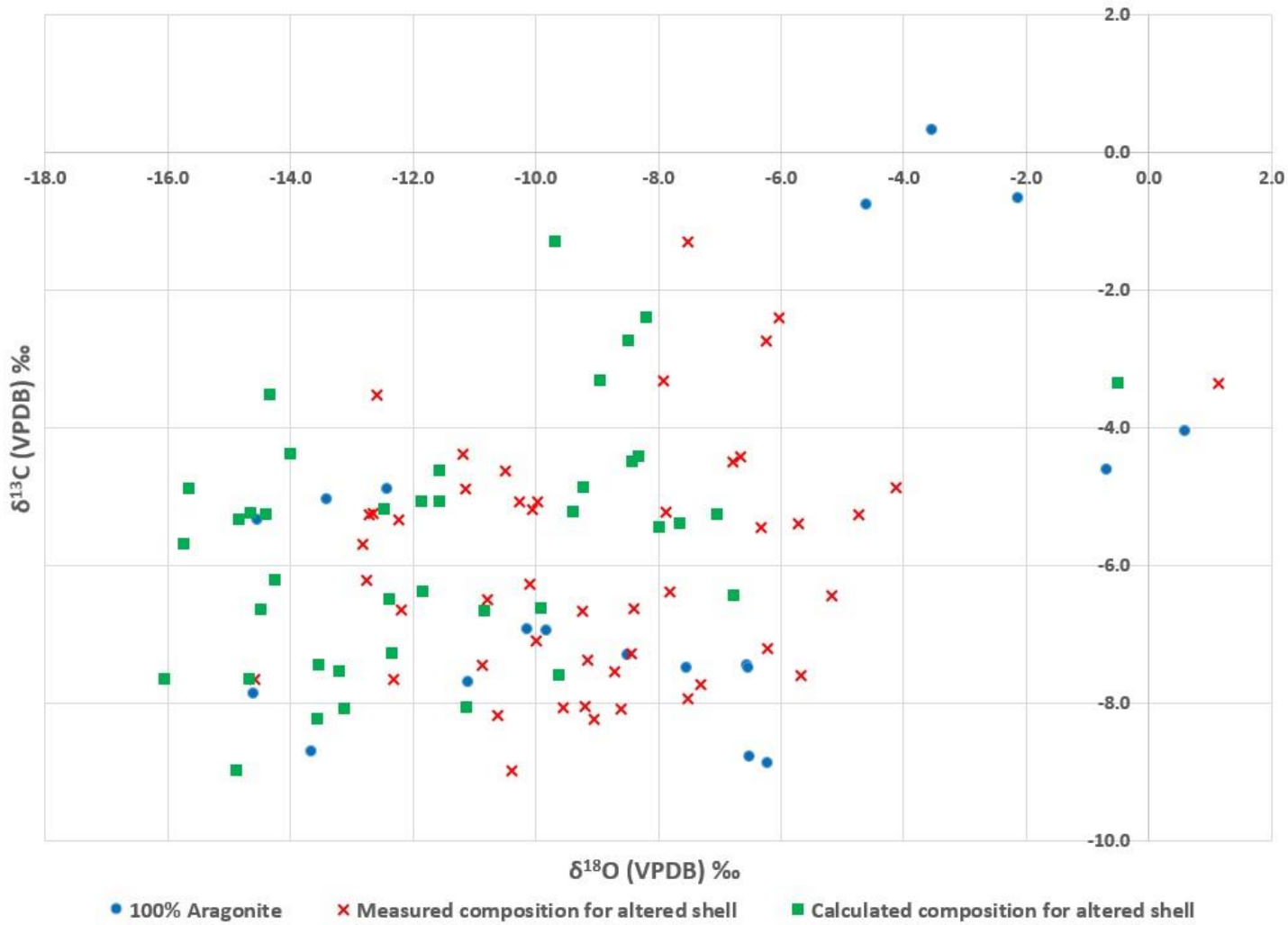



**Figure 9:** Calculated $\delta^{18}O$ values demonstrate a significant shift to lighter values from measured $\delta^{18}O$ values for shells containing mixtures of carbonates. Original 100% aragonite samples included as reference points, since their values are not calculated.

| | | Fluvial Gastropods | Pond Gastropods | Pedogenic Soil Carbonates |
|---|---|---|---|---|
| | n= | 2 | 65 | 31 |
| $\delta^{18}O$ (VPDB) | mean | -6.4‰ | -10.3‰ | -7.6‰ |
| | std. dev. | 0.2‰ | 3.8‰ | 0.9‰ |
| | range | -6.5‰ to -6.2‰ | -16.1‰ to 0.6‰ | -10.5‰ to -4.8‰ |
| $\delta^{13}C$ (VPDB) | mean | -8.8‰ | -5.8‰ | -9.0‰ |
| | std. dev. | 0.1‰ | 2.1‰ | 0.6‰ |
| | range | -8.9‰ to -8.8‰ | -9.0‰ to 0.3‰ | -9.8‰ to -6.9‰ |

**Table 2:** Summary of stable isotopic values by depositional environment.

## Vital Effect

Mean isotopic values are indistinguishable within one standard deviation among the shells of the three morphotaxa (Figure 10; Table 3). However, ranges of $\delta^{18}O$ and $\delta^{13}C$ vary among shells within a single morphotaxon. A two-tailed Student's t-test was performed to compare both $\delta^{18}O$ and $\delta^{13}C$ values between each of the three morphotaxa. There is no significant difference between the $\delta^{18}O$ values of *L. nebrascensis* and *L. subtortuosa* (t=-0.74, p=0.96), and similarly, no significant difference between the $\delta^{18}O$ values of *L. subtortuosa* and *Viviparus sp*. (t=0.05, p=0.96) or *L. nebrascensis* and *Viviparus sp*. (t=0.73, p=0.47). In the same way, the $\delta^{13}C$ values between the three morphotaxa also display no significant difference. *L. nebrascensis* and *L. subtortuosa* have means that are statistically similar (t=-0.99, p=0.34), as do *L. subtortuosa* and *Viviparus sp*. (t=0.93, p=0.37) and *L. nebrascensis* and *Viviparus sp*. (t=0.11, p=0.91). These results demonstrate that the three morphotaxa have statistically similar means, and no significant differences associated with vital effects specific to any one morphotaxon.

## Stratigraphic Analysis

Patterns of $\delta^{18}O$ values in pond gastropods change up-section, with a pronounced shift of nearly +3.0‰ toward heavier values between the average in the lower unit and the marine influenced portion of the middle unit (Table 4). A smaller shift of 1.4‰ back to lighter $\delta^{18}O$ values also occurs between the post marine influenced middle section and the upper unit. The $\delta^{13}C$ values also change up-section, with a shift of about 2.0‰ between the lower unit and marine influenced portion of the middle unit. The majority of $\delta^{13}C$ values however, remain between -9.0‰ and -4.0‰ in all units, with only a few

| | | *L. nebrascensis* | *L. subtortuosa* | *Viviparus sp.* |
|---|---|---|---|---|
| | n= | 26 | 11 | 30 |
| $\delta^{18}O$ (VPDB) | mean | -9.7‰ | -10.6‰ | -10.5‰ |
| | std. dev. | 4.7‰ | 2.4‰ | 3.5‰ |
| | range | -16.1‰ to 0.6‰ | -15.6‰ to -6.5‰ | -15.7‰ to -3.5‰ |
| $\delta^{13}C$ (VPDB) | mean | -5.8‰ | -6.5‰ | -5.8‰ |
| | std. dev. | 2.1‰ | 2.2‰ | 2.1‰ |
| | range | -9.0‰ to -0.8‰ | -8.8‰ to -1.3‰ | -8.7‰ to 0.3‰ |

**Table 3:** Summary of stable isotopic values by morphotaxa.

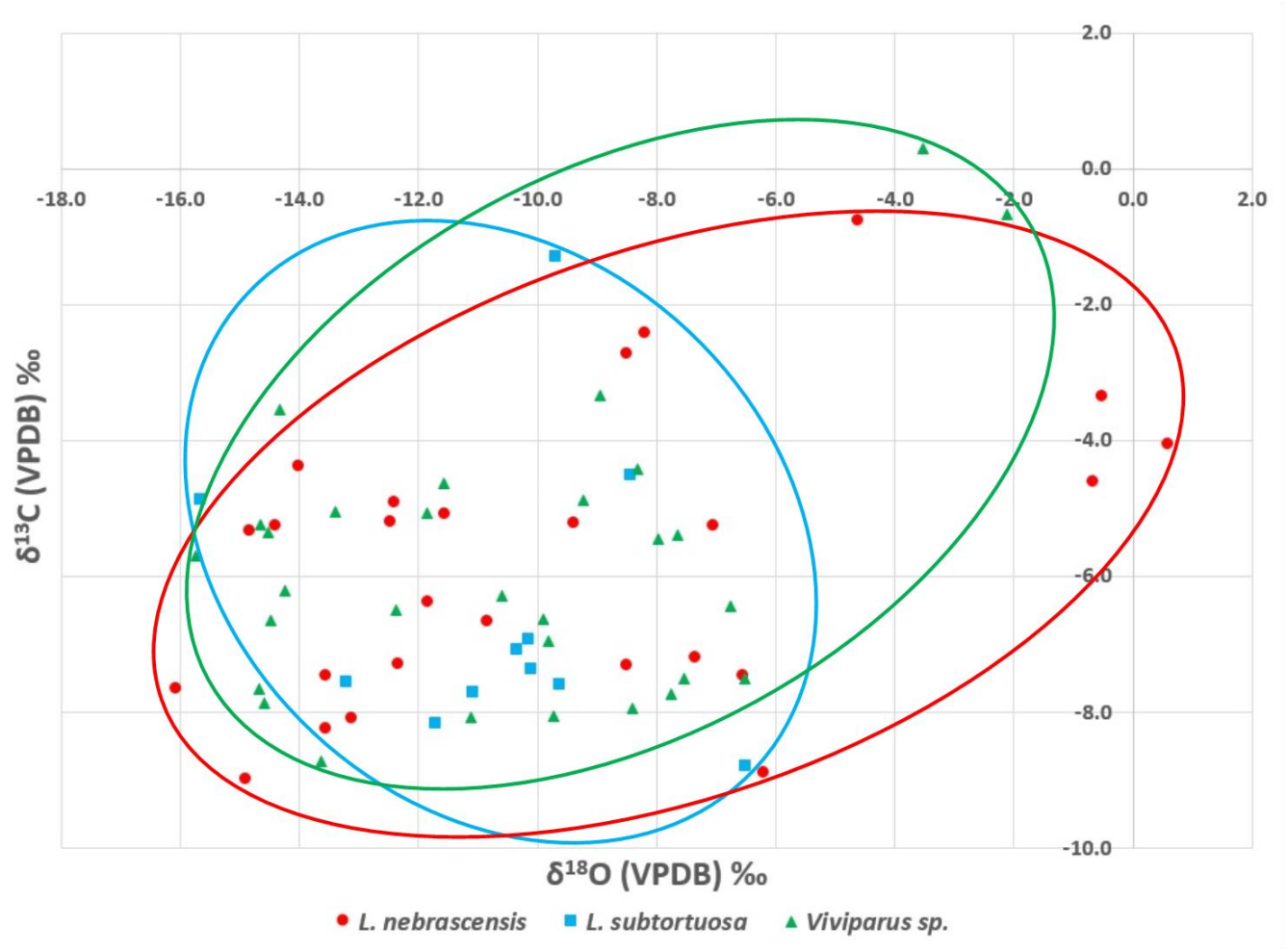



**Figure 10:** $\delta^{18}O$ vs. $\delta^{13}C$ of gastropods by morphotaxa. Colored fields outline the range of values for each morphotaxon.

individuals recording heavier values close to the pedogenic soil carbonates. Additionally, in all units, the majority of pond gastropods record $\delta^{18}O_{shell}$ values within the range of or lighter than the $\delta^{18}O$ values of the pedogenic soil carbonates.

Pond gastropods and pedogenic soil carbonates are well represented in this study. The small number of fluvial gastropods analyzed however, is not representative of their true abundance due to their poor shell preservation in the channel facies. Despite this, the fluvial gastropods record the heaviest average $\delta^{18}O_{shell}$ value, and display the narrowest range of values for both $\delta^{18}O$ and $\delta^{13}C$ by facies. Gastropods from the pond facies display the widest range of $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values, including the highest and lowest $\delta^{18}O$ value, and the highest $\delta^{13}C$ value. Pedogenic soil carbonates display the lowest $\delta^{13}C$ values, generally falling below the range of values displayed by the pond gastropods. Fluvial gastropods also display very low $\delta^{13}C_{shell}$ values, with an average close to that of the pedogenic soil carbonates. Detailed stable isotopic data for all pedogenic soil carbonates is in Appendix V.

***Lower Unit***

The lower unit (0 to ~125 m) produced only two usable pond gastropods with enough intact shell material for stable isotopic analysis (Figure 11). The pond gastropods are from the morphotaxa *L. subtortuosa* and *Viviparus sp*., and are from the same sample horizon. Fifteen pedogenic soil carbonates were recovered from multiple beds with or without other gastropod taxa present. There is a distinct difference between the $\delta^{13}C_{shell}$ and $\delta^{18}O_{shell}$ values of the two gastropods, as one records a $\delta^{18}O_{shell}$ value slightly lighter than the pedogenic soil carbonate $\delta^{18}O$ values, while the other is much lighter.

| | | $\delta^{18}O$ ‰ (VPDB) | | | | $\delta^{13}C$ ‰ (VPDB) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **n=** | **Mean** | **Median** | **Std. Dev.** | **Range** | **Mean** | **Median** | **Std. Dev.** | **Range** | **Fluvial Geometry** |
| **Lower Unit** | 2 | -12.7‰ | -12.7‰ | 4.3‰ | -15.7‰ to -9.7‰ | -3.5‰ | -3.5‰ | 3.1‰ | -5.7‰ to -1.3‰ | Meandering |
| **Middle Unit- marine** | 43 | -9.8‰ | -9.8‰ | 4.2‰ | -16.1‰ to 0.6‰ | -5.6‰ | -5.3‰ | 1.9‰ | -8.1‰ to -0.7‰ | Anastomosing |
| **Middle Unit- post marine** | 14 | -10.9‰ | -10.7‰ | 1.8‰ | -14.5‰ to -8.0‰ | -6.7‰ | -6.8‰ | 1.2‰ | -8.7‰ to -4.4‰ | Anastomosing |
| **Upper Unit** | 6 | -12.3‰ | -13.4‰ | 4.4‰ | -15.6‰ to -3.5‰ | -6.2‰ | -7.8‰ | 3.5‰ | -9.0‰ to 0.3‰ | Meandering |

**Table 4:** Summary of stable isotopic values for pond gastropods by unit.

### *Middle Unit- Marine Influence*

The marine influenced zone in the bottom half of the middle unit contains the most samples of any unit, and gastropods from all three morphotaxa. There are two *L. subtortuosa*, 19 *L. nebrascensis*, and 22 *Viviparus sp*., for a total of 43 pond gastropods and 16 pedogenic soil carbonate samples (Figure 12). Note the presence of five samples with heavy $\delta^{18}O$ values, and mid-range to heavy $\delta^{13}C$ values, and the large number of samples that record very light $\delta^{18}O$ values.

### *Middle Unit- Post Marine Influence*

The remainder of the middle unit contains gastropods from all three morphotaxa, but significantly fewer than the marine influenced portion. In this unit, five *L. subtortuosa*, three *L. nebrascensis*, and six *Viviparus sp*. are present, for a total of 14 pond gastropods (Figure 13). No pedogenic soil carbonates were recovered in this unit.

### *Upper Unit*

The upper unit contains six pond gastropod samples from all three morphotaxa, and is the only unit to contain two gastropods from the fluvial facies (Figure 14). Of the pond gastropods present, two are *L. subtortuosa*, three are *L. nebrascensis*, and one is a *Viviparus sp*. The two from the fluvial facies are represented by one *L. subtortuosa* and one *L. nebrascensis*. No pedogenic carbonate nodules were recovered for this unit. Although sample recovery is weak for this unit, it records the widest range of $\delta^{13}C$ values in the formation.

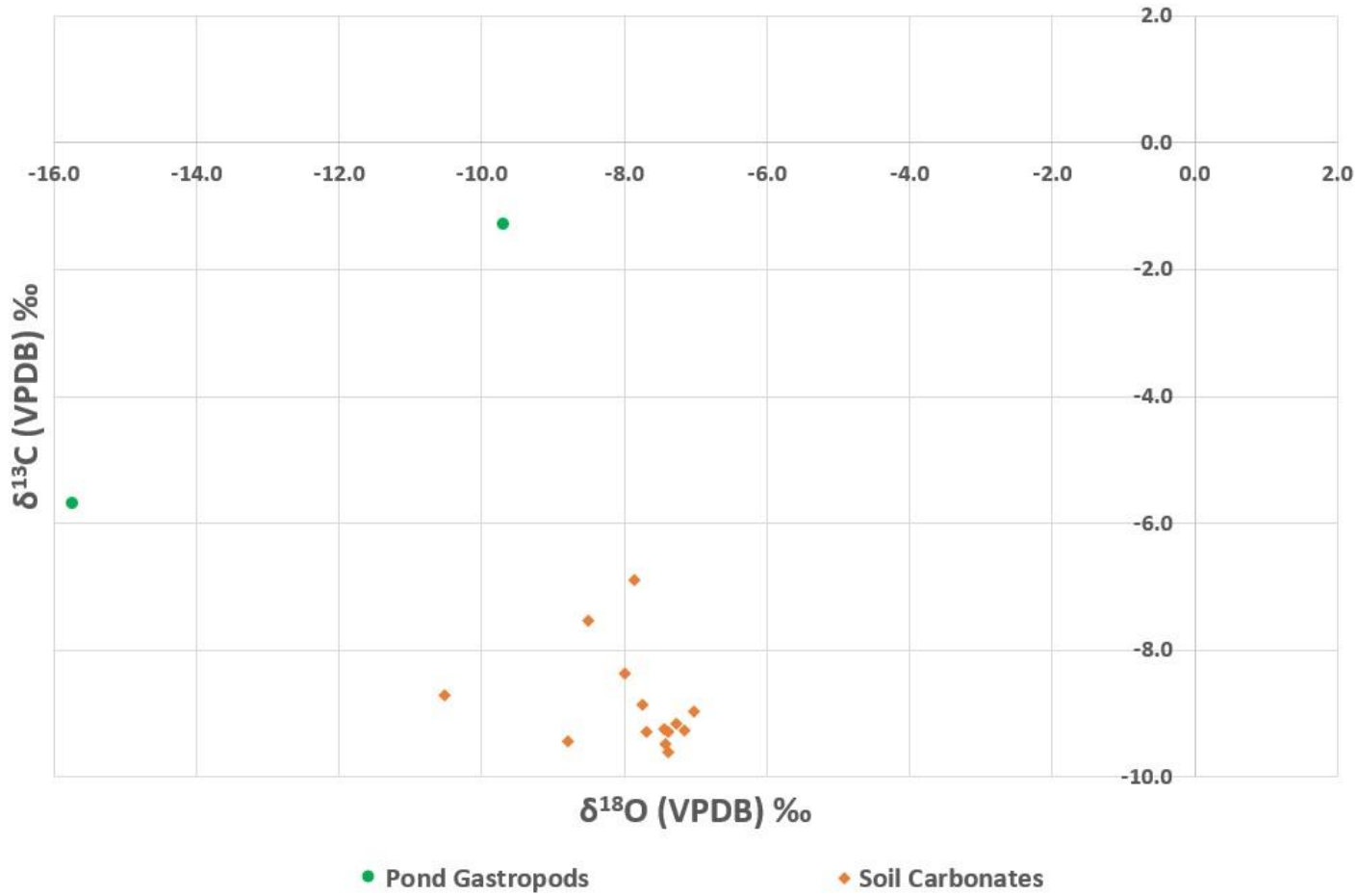



**Figure 11:** Stable isotopic values of pond gastropods and pedogenic soil carbonates from the informal lower unit.

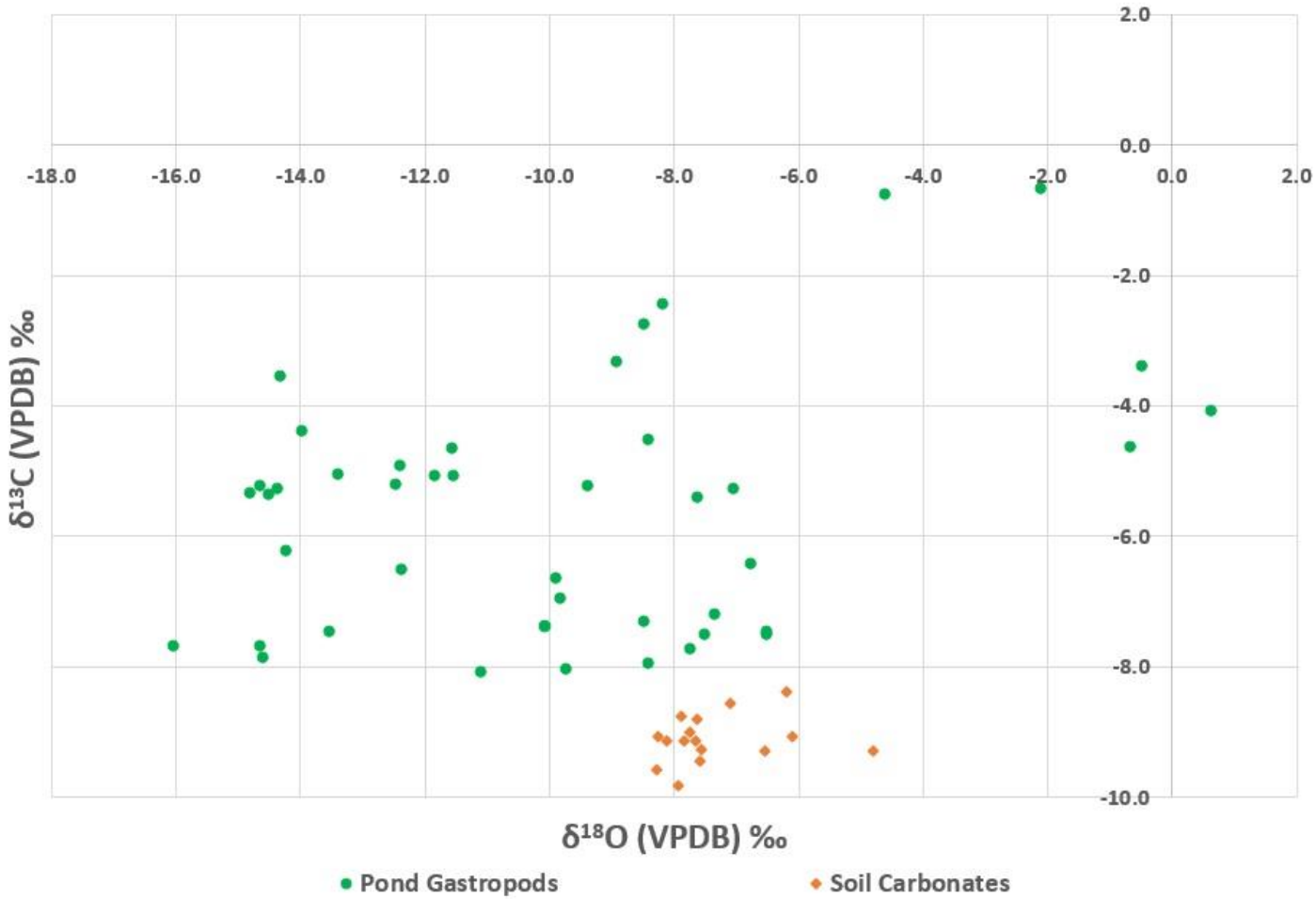



**Figure 12:** Stable isotopic values of pond gastropods and pedogenic soil carbonates from the informal marine influenced middle unit.

***Up Section Trends for $\delta^{18}O$ and $\delta^{13}C$***

The $\delta^{18}O$ values of individual gastropods from each sampled interval according to their height in section display distinct variation between units (Figure 15). Pond gastropods from the lower unit (below ~125 m) record light to mid-range $\delta^{18}O_{shell}$ values. The pond gastropods from the marine influenced area of the middle unit (~125-320 m) record the largest range of $\delta^{18}O_{shell}$ values, from light to extremely heavy. In particular, the 315 m interval, records the four heaviest $\delta^{18}O_{shell}$ values for the entire formation, while still recording some of the lightest values. Above 320 m, in the post marine influence middle unit, the range of $\delta^{18}O_{shell}$ values displayed by the pond gastropods narrows slightly, recording dominantly light to mid-range values between -12.0‰ and -8.0‰. The pond gastropods in the upper unit record $\delta^{18}O_{shell}$ values that are mostly light, with one heavy sample. Fluvial gastropods are only represented in the upper unit, and therefore present no trend. However, the $\delta^{18}O$ values they record are on the heavier side of the average for pond gastropods. Overall, the heaviest $\delta^{18}O$ values are recorded in the marine influenced section of the middle unit, with similar ranges for lighter $\delta^{18}O$ values in the lower and upper units.

For $\delta^{13}C$, individual gastropods for each sampled height interval show a similar pattern of variation to $\delta^{18}O$ (Figure 16). Pond gastropods from the lower unit (below ~125 m) record a light to mid-range values, with one heavier gastropod, and one that records a lighter $\delta^{13}C_{shell}$ value closer to the pond gastropod average. In the marine influenced area of the middle unit (~125-320 m), the majority of pond gastropod samples record light to fairly heavy values between -8.0‰ and -3.0‰ $\delta^{13}C$. However, shell $\delta^{13}C$ values in this unit can extend all the way to some of the heaviest values, such

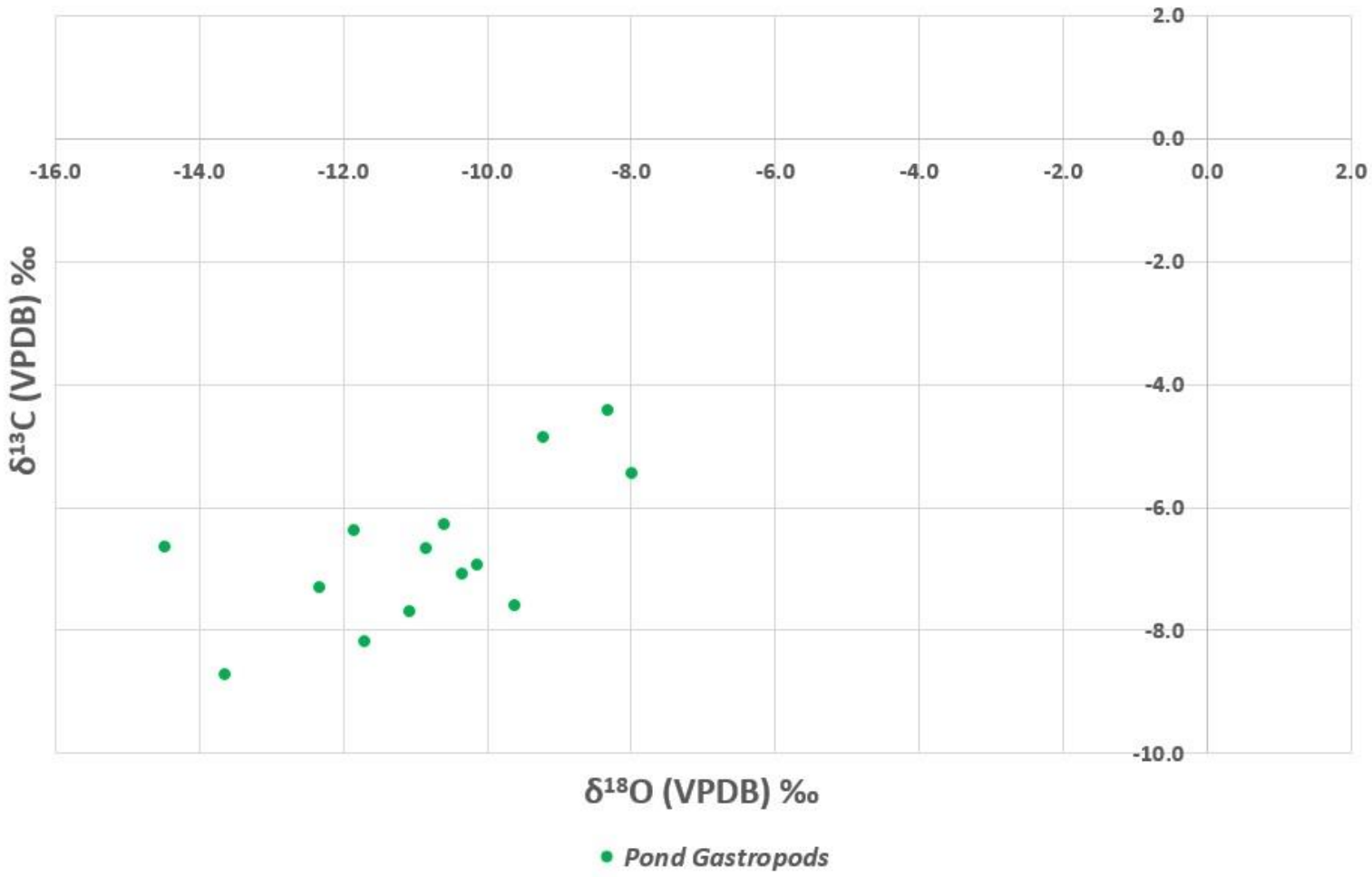



**Figure 13:** Stable isotopic values of pond gastropods from the informal post marine influence middle unit.

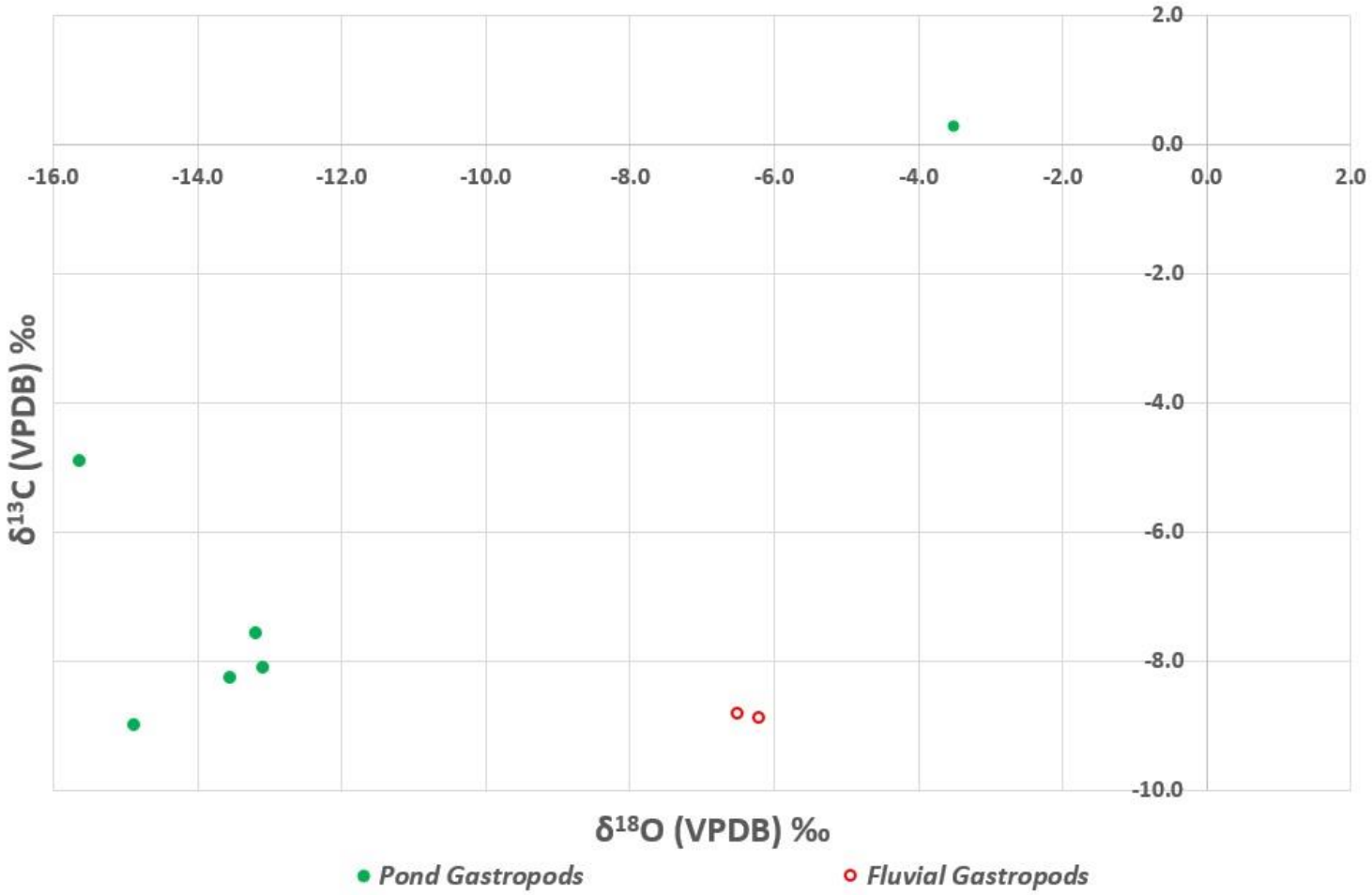



**Figure 14:** Stable isotopic values of pond and fluvial gastropods from the informal upper unit.

as -0.7‰, recording a large range. Pond gastropods from the post-marine influenced area record a much narrower range than the marine influenced area, with most gastropods recording lighter values between -8.0‰ and -6.0‰ $\delta^{13}C$. The upper unit records both the lightest and the heaviest $\delta^{13}C$ values for the entire formation, and the largest range of $\delta^{13}C$ values. The two fluvial gastropods in the upper unit record the second lightest $\delta^{13}C$ values for the entire formation, which is more consistent with where the rest of the upper unit $\delta^{13}C$ values fall. Overall, the $\delta^{13}C$ values tend to be heaviest in the marine influenced area of the middle unit, despite the one heavy pond gastropod from the upper unit that causes a substantial range. The majority of $\delta^{13}C$ values in all units fall between -8.0‰ and -4.0‰.

Conversion of pedogenic soil carbonate signals from $\delta^{18}O_{(VPDB)}$ to $\delta^{18}O_{(VSMOW)}$ is done to estimate the $\delta^{18}O$ of local surface water as it relates to soil water at depth. Soil water $\delta^{18}O_{(VSMOW)}$ values ranged from -2.9‰ to -8.6‰, with an average value of -5.7‰. Uncertainty for the soil water $\delta^{18}O$ estimates is ±0.4‰, which stems from the standard error of ±2.3ºC from the temperature estimate calculated from the paleofloral study by Miller et al. (2013).

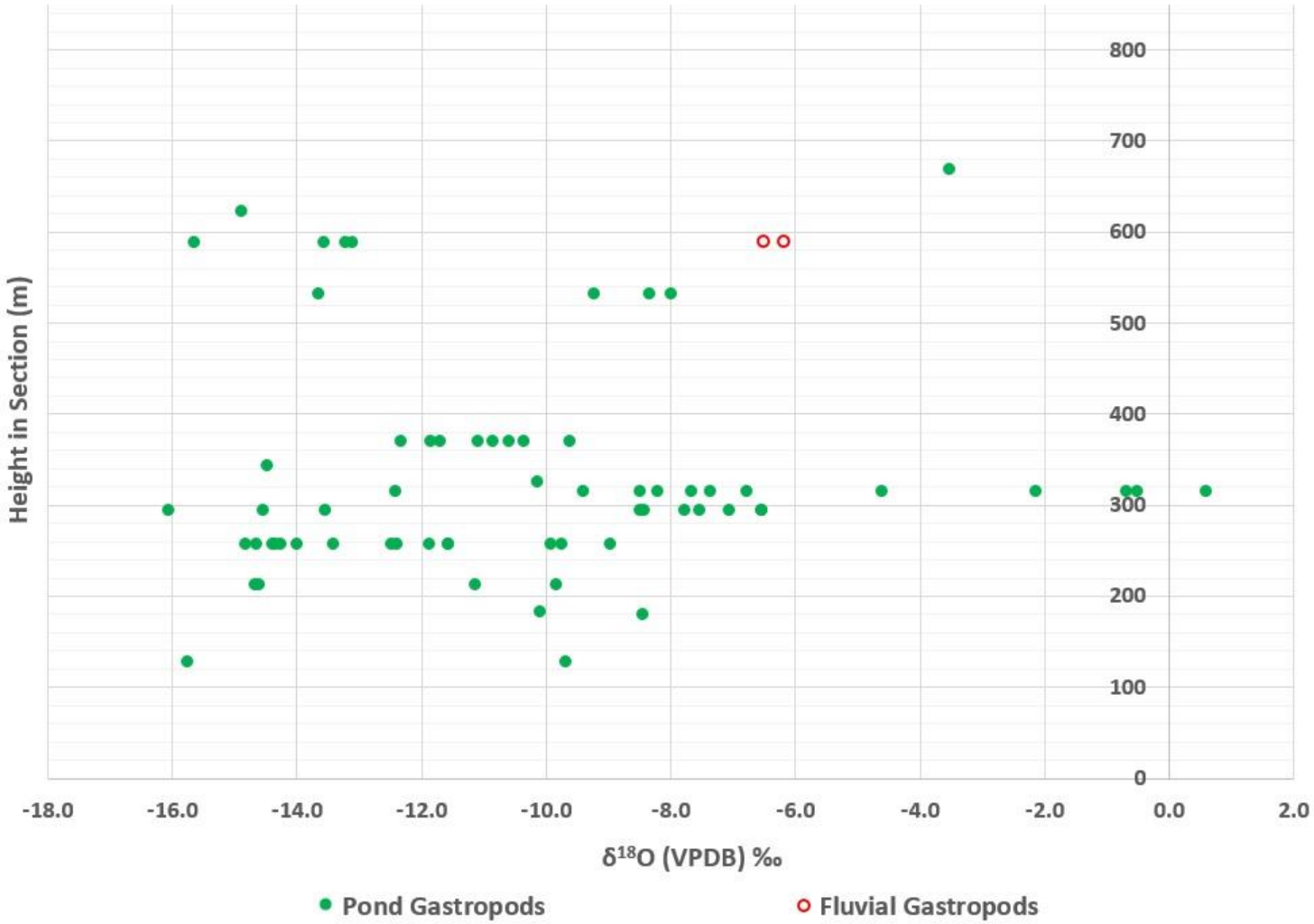



**Figure 15:** $\delta^{18}O$ values of pond and fluvial gastropods according to their height in section.

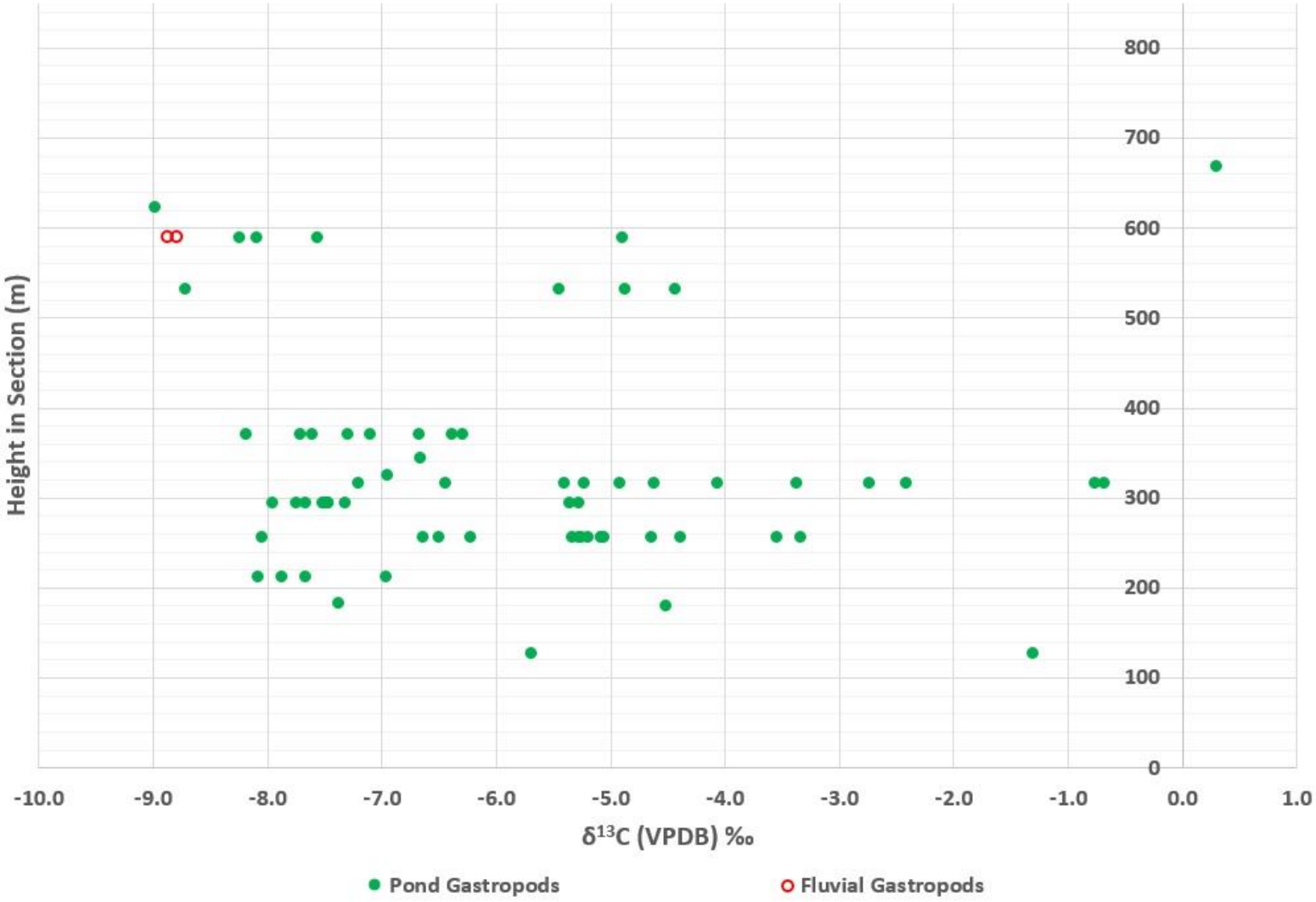



**Figure 16:** $\delta^{13}C$ values of pond and fluvial gastropods according to their height in section.

## 5. DISCUSSION

### Do aquatic gastropod shells record the environmental signal?

By assessing the degree to which vital effects are changing the $\delta^{13}C$ and $\delta^{18}O$ values of the gastropod shells, the influence on each species can be determined, and isotopic values adjusted to more accurately reflect the host water composition.

The three gastropod morphotaxa are statistically indistinguishable (Figure 10). Even though each morphotaxon records a substantial range for both $\delta^{13}C$ and $\delta^{18}O$, the values do not correspond in a predictable magnitude or direction (Kim et al., 2006). The range of $\delta^{18}O_{shell}$ values for each morphotaxon is also significantly larger than the corresponding range of $\delta^{13}C_{shell}$ values, since a single morphotaxon such as *L. nebrascensis* can record a range of $\delta^{18}O_{shell}$ values over 10.0‰, while most of the $\delta^{13}C_{shell}$ values are within 5.0‰ of each other. If a vital effect was significant, $\delta^{13}C_{shell}$ and $\delta^{18}O_{shell}$ values of the morphotaxa are expected to form distinguishable groups (Kim et al., 2006), which they do not. Even at the resolution of single sample intervals, the statistical similarity remains between the three morphotaxa.

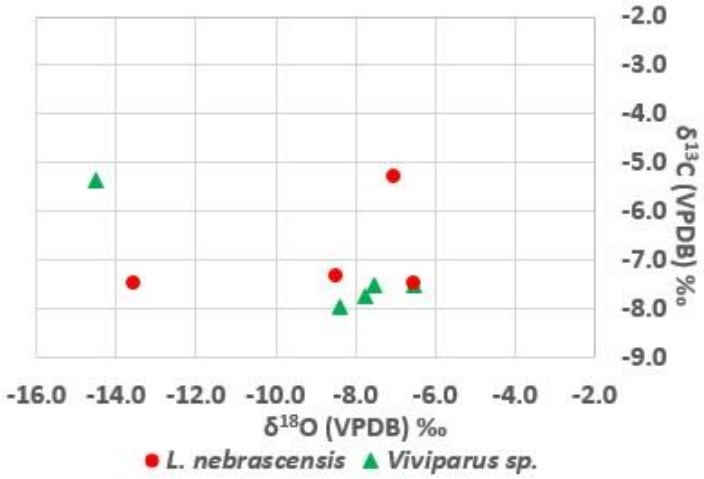
For example, in the 293 m sample interval, two morphotaxa, *L. nebrascensis* and *Viviparus sp*. are present (Figure 17A). Each of the morphotaxon record a nearly identical ~10.0‰ range of $\delta^{18}O_{shell}$ values, while the majority of the $\delta^{13}C_{shell}$ values are within 1.0‰ of each other. This suggests that no covariance trend is present between $\delta^{18}O$ and $\delta^{13}C$, even within a single pond deposit. There are even two individual gastropods that record the same exact $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values, one from each morphotaxa. A two-tailed Student's t-test conducted to compare the *L. nebrascensis* and *Viviparus sp*. in this unit found no significant difference between the two morphotaxa for either $\delta^{18}O$ (t=-0.58,

p=0.58) or $\delta^{13}C$ (t=0.27, p=0.79). Since the values recorded by these two morphotaxa have such a high degree of overlap, and the results of the t-test suggest no significant difference in $\delta^{18}O$ or $\delta^{13}C$, vital effects are not significant between these morphotaxa.

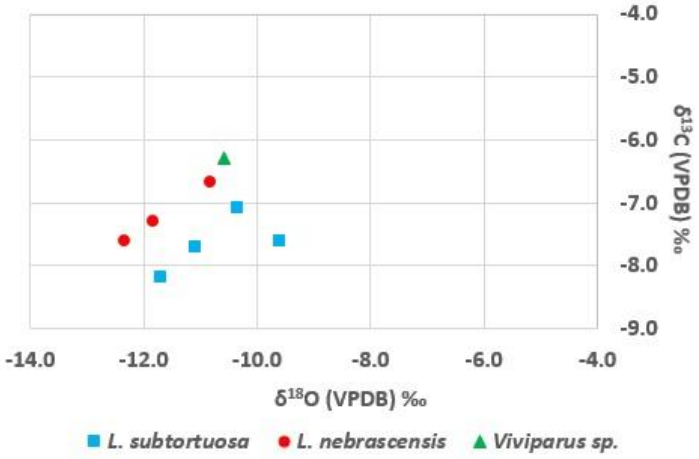
In the 370 m sample interval, all three morphotaxa are present (Figure 17B). Even though there are only a few of the *Viviparus sp*. and *L. nebrascensis* in the interval, their $\delta^{18}O_{shell}$ values overlap almost completely with the range of $\delta^{18}O_{shell}$ values recorded by *L. subtortuosa*. The $\delta^{13}C_{shell}$ values are also quite similar, with overlap between *L. nebrascensis* and *L. subtortuosa*, and all morphotaxa falling within about 2.0‰ $\delta^{13}C$ of each other. A two-tailed Student's t-test comparing *L. subtortuosa* and *L. nebrascensis* in this interval found no significant difference between either the $\delta^{13}C$ values (t=-2.47, p=0.07) or the $\delta^{18}O$ values (t=1.56, p=0.18) of the two morphotaxa, suggesting no significant vital effects. Even though the single sample of *Viviparus sp*. could not be included in the t-test, the overlap with the $\delta^{18}O$ values of other two morphotaxa, and similar $\delta^{13}C$ values suggests that there is no significant vital effect occurring. Further, there are no dramatic directional shifts in either $\delta^{13}C$ or $\delta^{18}O$ causing the morphotaxa to separate.

The 590 m sample interval contains the morphotaxa *L. subtortuosa* and *L. nebrascensis*, which record nearly identical values for both $\delta^{18}O$ and $\delta^{13}C$ (Figure 17C). Although a t-test was not conducted with only two samples in this interval, the $\delta^{18}O_{shell}$ values are within 0.3‰ of each other, and the $\delta^{13}C_{shell}$ values are within 0.1‰ of each other. This degree of similarity suggests that if there are any vital effects present, they are responsible for less than a 0.5‰ shift between the samples. Since the error associated

A)




B)




C)

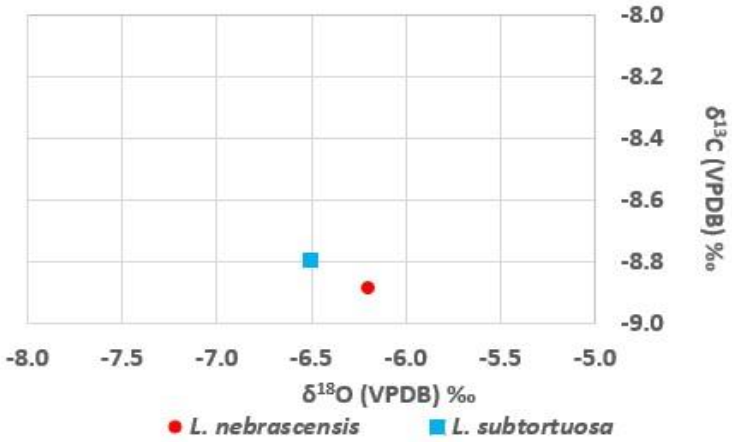



**Figure 17:** A) Stable isotopic values by morphotaxa in the 293 m sample interval; B) Stable isotopic values by morphotaxa in the 370 m sample interval; C) Stable isotopic values by morphotaxa in the 590 m sample interval, note the very different scale for $\delta^{18}O$ and $\delta^{13}C$ here.

with processing the samples in the mass spectrometer up to 0.2‰, it is possible that any shift caused by vital effect is lost in the testing process.

By comparing the morphotaxa across the entire formation and more closely within single sample intervals, it becomes clear that vital effect is not a significant factor controlling the signals in the gastropods shell. Even if the species do have slightly different vital effects acting on them, the environment and sample processing have removed or overprinted the signals, therefore rendering vital effect inconsequential.

The effects of diagenetic alteration can shift the $\delta^{18}O$ values of individual gastropod shells up to 5.1‰ toward heavier values (Zheng, 1999). Therefore, assessing the extent of alteration is crucial to determining how accurately the gastropod shells are recording the original isotopic signal of their environment.

Studies concerning oxygen isotope fractionation in carbonates suggest a noticeable difference (up to a few per mil) between the isotopic composition of aragonite and other carbonate minerals at low temperatures, and support varying degrees of $^{18}O$ enrichment between aragonite, calcite and dolomite (Kim and O'Neil, 1997; Zheng, 1999; Vasconcelos et al., 2005). Comparison of past isotopic studies and experimental calculations performed by Zheng (1999) suggests a consistent enrichment of $^{18}O$ in calcite relative to aragonite at isotopic equilibrium, related to the density of the two phases. In an experimental calculation at 25°C, calcite was found to have increased $\delta^{18}O$ values by 4.47‰ relative to aragonite during equilibrium fractionation. Further, Zheng (1999) suggests that in situations where aragonite transitions into calcite under low temperatures, the oxygen structure of the existing $CaCO_3$ may not reset to the new

isotopic equilibrium conditions of the subsequent water, thus possibly preserving an isotopic composition consistent with the original aragonite composition. Either of these fractionation pathways could explain the range of values displayed by the gastropod shells that contain calcite (No aragonite) or calcite and aragonite. For both No aragonite, and calcite and aragonite samples, the amount of overlap with the 100% aragonite samples suggests they could still be recording $\delta^{18}O$ values similar to the original isotopic composition from not adjusting to a new equilibrium. Alternatively, if we assume a replacement of aragonite by calcite in equilibrium conditions, and increase up to 4.47‰ in the $\delta^{18}O$ value could have occurred during the transition to calcite depending on the mass fraction of calcite in the sample.

Dolomite is considered to always be a result of diagenetic processes, and therefore is replacing the original $CaCO_3$ and its signal. In a similar way to calcite, Zheng (1999) predicted that dolomite has a higher $\delta^{18}O$ value than aragonite. By extrapolating from high temperature laboratory experiments and theoretical predictions, dolomite is expected to display about a 5.1‰ increase in $\delta^{18}O$ values relative to aragonite at 25°C under equilibrium conditions. In nature, dolomite often displays $\delta^{18}O$ values similar to that of coexisting calcite (~0.6‰ heavier than calcite), which may be related to replacement of calcite by a solid-state diffusion reaction which would not completely reset the isotopic composition (Zheng, 1999).

Taking these fractionation factors into account, gastropods containing dolomite in addition to calcite or aragonite should record values that have been affected to some degree by the predicted and measured increase in $\delta^{18}O$. For the one dolomite only sample (heaviest No aragonite sample), a full 5.1‰ increase in $\delta^{18}O$ is expected from the original

aragonite shell, which would place the sample more consistently within the range of pond gastropod $\delta^{18}O$ values, at around -9.2‰. For all of the samples containing dolomite in addition to calcite or aragonite, the degree of the shift toward heavier $\delta^{18}O$ values is likely to be reduced as a result of some of the primary signal remaining, in which case any amount less than 5.1‰ can be expected. Therefore, using the isotopic mixing equations (p. 23 in Materials and Methods) based on Zheng's (1999) fractionation factors, calculated $\delta^{18}O$ values for all altered samples are used, as they represent $\delta^{18}O$ values more likely to reflect the actual environmental signals in the gastropod shells, rather than the measured values influenced by diagenesis.

Although 48 out of the 67 total samples included in this investigation display variable degrees of alteration, the aragonite in the shells is considered to be primary. Aragonite is metastable at the Earth's surface, and can alter to calcite or dolomite in the presence of meteoric water (Folk, 1974; Zheng, 1999). Thus, shells that retain their original aragonite mineralogy likely retain their original geochemical characteristics. Shells that consist of a mixture of aragonite, calcite, and dolomite are likely still recording a primary signal in addition to a weaker secondary alteration signal.

In particular samples with greater than 75% aragonite should maintain signals close to their original composition, as partial alteration accounts for a maximum shift of about +1.0‰, which is not able to overprint the original signal. However, as samples become increasingly replaced by the diagenetic calcite and dolomite, their shells record values shifted further away from the original composition. Samples with greater than 50% aragonite present still record $\delta^{18}O$ values that are fairly close to the original, as their shifts are still less than +2.0-3.0‰. However, once a sample contains less than ~30%

aragonite the shifts are generally greater than +3.0‰, with complete shifts of +4.5‰ and +5.1‰ occurring upon total replacement by calcite or dolomite respectively.

For the seven samples that contain no trace of primary aragonite, calculated values, although possibly closer to the original value, cannot be given much weight in this investigation. There is no way of knowing how many times they have been altered, or if their measured $\delta^{18}O$ values were anywhere near the original aragonite signals prior to recalculation based on the fractionation factors. Therefore, even though they are included, no interpretation is given based solely on those values, particularly since nearly all of their values are recording the lightest $\delta^{18}O$ values in the entire formation.

Despite the variable shifts caused by diagenetic minerals, samples with altered shell material may still be useful, since 32 out of 41shells that display alteration still maintain aragonite as the dominant mineral phase (greater than 50% aragonite). Additionally, in some sample intervals, shells that are 100% aragonite are found in the same beds as the altered shells, often within centimeters of each other. This suggests that the alteration that took place was spatially heterogeneous, and can provide a reference point for a what a reasonable range of $\delta^{18}O$ values would be for samples with altered shell material.

Further, as shown in Figure 7 and Figure 9, the range of values displayed by altered shell samples covers nearly the entire range of values recorded by the 100% aragonite gastropod shells. This suggests that even though the alteration phases are causing the $\delta^{18}O$ values and to a much lesser extent the $\delta^{13}C$ values, to be enriched in the heavier isotopes, as is expected when aragonite alters to either of those phases (Kim and O'Neil, 1997; Zheng, 1999), that the degree in which the values have shifted is generally

not outside of the range in which they would have already fallen. In particular, the lighter calculated $\delta^{18}O$ values are more consistent with values recorded from other studies, which suggest a river water composition around -16.0‰ $\delta^{18}O$ in the formation (Fricke et al., 2010; Foreman et al., 2015). From these adjustments, it is clear that although the diagenetic phases have altered the shell values by as much as +5.1‰ $\delta^{18}O$, the majority of signals recorded are generally not shifted to this degree.

Based on the percentage of aragonite remaining in the shells, it is expected that the samples containing the least amount of aragonite would display the most distinct shift toward heavier $\delta^{18}O$ values. This is often the case, however, occasionally samples containing identical percentages of aragonite display slightly different $\delta^{18}O$ values. In this case, what seems to determine how far the values shift is the result of which alteration mineral they contain, rather than the slight 0.1% difference in the percentages of those minerals. For example, sample 117-Vivip1 contains 49.2% aragonite, and 50.8% calcite, which results in a shift of +2.3‰. Similarly, sample L7-Neb5 contains 49.1% aragonite, and 50.9% dolomite, which results in a shift of +2.6‰. Although not substantial, this difference suggests that the presence of dolomite in a sample controls the signal more than calcite, and can account for why so many of the 50-75% aragonite group samples in Figure 7 appeared to have shifted more than the less than 50% group, as they tend to contain more dolomite.

Even though samples with diagenetic alteration are not the ideal specimens for stable isotopic studies, the presence of alteration phases does not destroy the samples' usefulness. If 100% aragonite samples are present, the inclusion of altered samples can provide additional contextual value without compromising the interpretation of overall

patterns. Additionally, since the 100% aragonite samples displayed repeated but variable signals, altered samples that fall within the same range are most likely recording reasonable values for aquatic gastropods, regardless of the degree of alteration.

**What does gastropod shell indicate about environment?**

Reconstructions of the Late Cretaceous climate in and around the Kaiparowits Formation in the Western Interior Seaway argue for a wet, humid coastal and alluvial plain (Miller et al., 2013), extensive floodplains cut by meandering and anastomosing river systems (Roberts, 2007), and changes in topography related to uplift and base-level fall controlling the influence of high elevation versus local precipitation (Roberts, 2007; Fricke et al., 2010; Foreman et al., 2015). The range of stable isotopic values from pond gastropods in this study broadly support these interpretations, suggesting that changes in the environment are responsible for the variability in $\delta^{18}O$ and $\delta^{13}C$ in the gastropod shell.

***Elevation and Rayleigh distillation effects on surface water $\delta^{18}O$***

The presence of pond gastropods that record isotopically light $\delta^{18}O_{shell}$ values in addition to those with $\delta^{18}O_{shell}$ values that correspond to the range exhibited by the pedogenic soil carbonates suggest two difference sources of water contributed to the composition of the floodplain ponds. The primary source should be local precipitation that fell in and around the ponds directly on the alluvial and coastal plains. Pedogenic soil carbonates are known to record a close approximation of the isotopic composition of local meteoric water, as their formation is not influenced by runoff (Quade et al., 2007). By comparing the average estimated surface water value of -5.7± 0.94‰$_{(VSMOW)}$ for the Kaiparowits Formation to similar modern environments in the continental United States with large river systems that drain into the ocean, $\delta^{18}O$ values are found to be consistent

with local low elevation precipitation, which generally ranges from -6.0 to -2.0‰$_{(VSMOW)}$ (Kohn and Dettman, 2007). Comparison with pedogenic soil carbonates from Foreman et al. (2015) also supports a localized basin recharge signal, as their surface water estimates for the Kaiparowits Formation averaged -6.0± 0.5‰$_{(VSMOW)}$.

The secondary source contributing the much lighter water to the ponds is the river system itself. Large catchments are often isotopically disconnected from local precipitation $\delta^{18}O$ signals (Kohn and Dettman, 2007), due to the decreasing $\delta^{18}O$ of precipitation with increasing elevation (Cerling and Quade, 1993). Since the lightest pond gastropods record $\delta^{18}O_{shell}$ values of -16.1‰$_{(VPDB)}$, the river water contribution into the ponds would be expected to have a $\delta^{18}O$ value the same or lighter than that. Although the two fluvial gastropods from this study do not record light $\delta^{18}O_{shell}$ values, an isotopically light river is supported by the pond gastropods and both Fricke et al. (2010) and Foreman et al. (2015). Fricke et al. (2010) found that water from the large rivers in the Kaiparowits Formation recorded an average $\delta^{18}O$ value of -15.4±0.5‰$_{(VPDB)}$, which is sufficiently depleted in $^{18}O$ to cause the ponds to shift toward the lighter $\delta^{18}O$ values, and almost 1.0‰ lighter than the majority of light pond gastropod. Foreman et al. (2015) reported a similar $\delta^{18}O$ average for the fluvial facies of -13.1±1.9‰$_{(VPDB)}$, with a range from -15.8 to -10.2‰ $\delta^{18}O$, also supporting higher elevation runoff into the river as the source of the lighter water contributed to the floodplain ponds. Therefore, given the large range of $\delta^{18}O_{shell}$ values recorded by the pond gastropods, the Kaiparowits Formation seems to have resided within a large catchment that recorded a mix of high and low elevation precipitation through river and floodplain interaction over the course of its deposition.

***Fluvial Geometry***

The distinct shift in the mean $\delta^{18}O$ values between each unit, and the increase in the range of $\delta^{18}O_{shell}$ values by 10.6‰ from pond gastropods between the lower and middle units suggests a relationship between the dominant fluvial style and the isotopic composition of the ponds related to the frequency of overbank mixing. When the fluvial geometry is classified as a meandering style river, pond gastropods tend to record lighter, less variable $\delta^{18}O_{shell}$ signals. Alternatively, when the fluvial geometry is classified as an anastomosing style river, pond gastropods record high variability in $\delta^{18}O_{shell}$ values. The anastomosing geometry corresponds to the largest range of $\delta^{18}O_{shell}$ values in a single sample interval, and the lightest and heaviest $\delta^{18}O_{shell}$ values for the entire formation (Figure 18).

In the lower unit, pond gastropods record values consistent with both, local precipitation dominated recharge, as well as a pond completely dominated by a fluvial signal. This significant fluvial influence is reflected in the average O value for the unit of -12.7±4.3‰. Despite the small sample size, this may suggest some variability associated with a meandering river that usually stayed in the channel, but could flood catastrophically, dumping a large amount of isotopically light water into the floodplain and completely overprinting the original pond signal. However, the completely altered nature of the light $\delta^{18}O$ sample calls into question the validity of the lighter calculated value. Regardless of the exact light $\delta^{18}O$ composition recorded by that sample, the measured value still suggests a fluvial influence, as the aragonite that originally made up the shell would have to be lighter than the altered material. Given the distinct offset between the two gastropods from the same sample interval, it is possible that a single

flooding event may have changed the isotopic composition of the pond permanently, as it would not have survived long enough to recover from such a large isotopically light freshwater input. Sedimentological evidence also supports fewer and shorter lived ponds in the lower unit, as the average bed thickness is 2.8 m, with ponds occurring approximately every 13 m in section. The pond facies constitute less than 25% of the of the total preserved bed facies (Roberts, 2007) in the lower unit.

Similarly, in the upper unit, most pond gastropods record $\delta^{18}O_{shell}$ values much lighter than those of the pedogenic soil carbonates, with only one that is heavier. This suggests that the water in the main channel of the meandering river mixed with the ponds in the floodplain, but likely not very often as the heavy 100% aragonite sample was able to shift in the opposite direction of a fluvial influence. Despite the presence of a heavy gastropod, the average $\delta^{18}O$ value for this unit is -12.3±4.4‰. Even in a situation where a catastrophic flooding event completely overprints the isotopic composition of the pond it inundated, there should be some shells that record values in between the two end members. All of the light shells that are present in this unit contained no primary aragonite, and therefore the extremely light signals they are recording may not be entirely accurate. However, a fluvial influence is likely based on the fact that the measured $\delta^{18}O$ values were also fairly light.

Sedimentological evidence from the upper unit shows fewer ponds in this unit as well compared to the middle unit. Although there are not as few pond deposits as in the lower unit, the pond facies in the upper unit constitutes only 40% of the total preserved bed facies. Pond facies thickness is slightly greater than it is in the lower unit, with ponds averaging 4.4 m thick. However, the ponds in the upper unit are generally separated by

larger channel deposits in between them than in the lower unit (Roberts, 2007), suggesting their occurrence every 14 m in section was still largely controlled by the meandering river geometry. Overall, this suggests that ponds in the upper unit may have been longer lived than they were in the lower unit, allowing for a potentially wider range of $\delta^{18}O$ values related to evaporation or an unknown marine influence, and a greater chance of mixing with the large meandering river during a large flooding event.

In the middle units, pond gastropods record an extensive range of $\delta^{18}O_{shell}$ values within single pond deposits, as well as in the unit as a whole. The large range of values suggests that the ponds in these units were long lived enough to record many different environmental signals throughout their deposition, which is reflected in the average $\delta^{18}O$ values of -9.8±4.2‰ for the marine influenced portion, and -10.9±1.8‰ in the post marine influenced portion. The number of easily sampled intervals and their proximity within the middle unit also alludes to the increase in the overall number of ponds that are present in the middle unit. The $\delta^{18}O$ values record a gradient of conditions, from ponds dominated by an isotopically light fluvial freshwater signal, to ponds dominated by local meteoric water. Some ponds below 320 m in section record a marine influence as well, since $\delta^{18}O$ values heavier than -2.5‰ are too heavy to be the result of evaporative effects, and sedimentological evidence exists for a marine influence in the lower portion of the middle unit. The variation in $\delta^{18}O_{shell}$ values of the pond gastropods in the middle unit can be quite different between individual pond deposits. Some ponds can record as much as a 16.7‰ difference between the heaviest and lightest $\delta^{18}O_{shell}$ values, while others record as little as 5.0‰. These highly variable signals suggest that the anastomosing

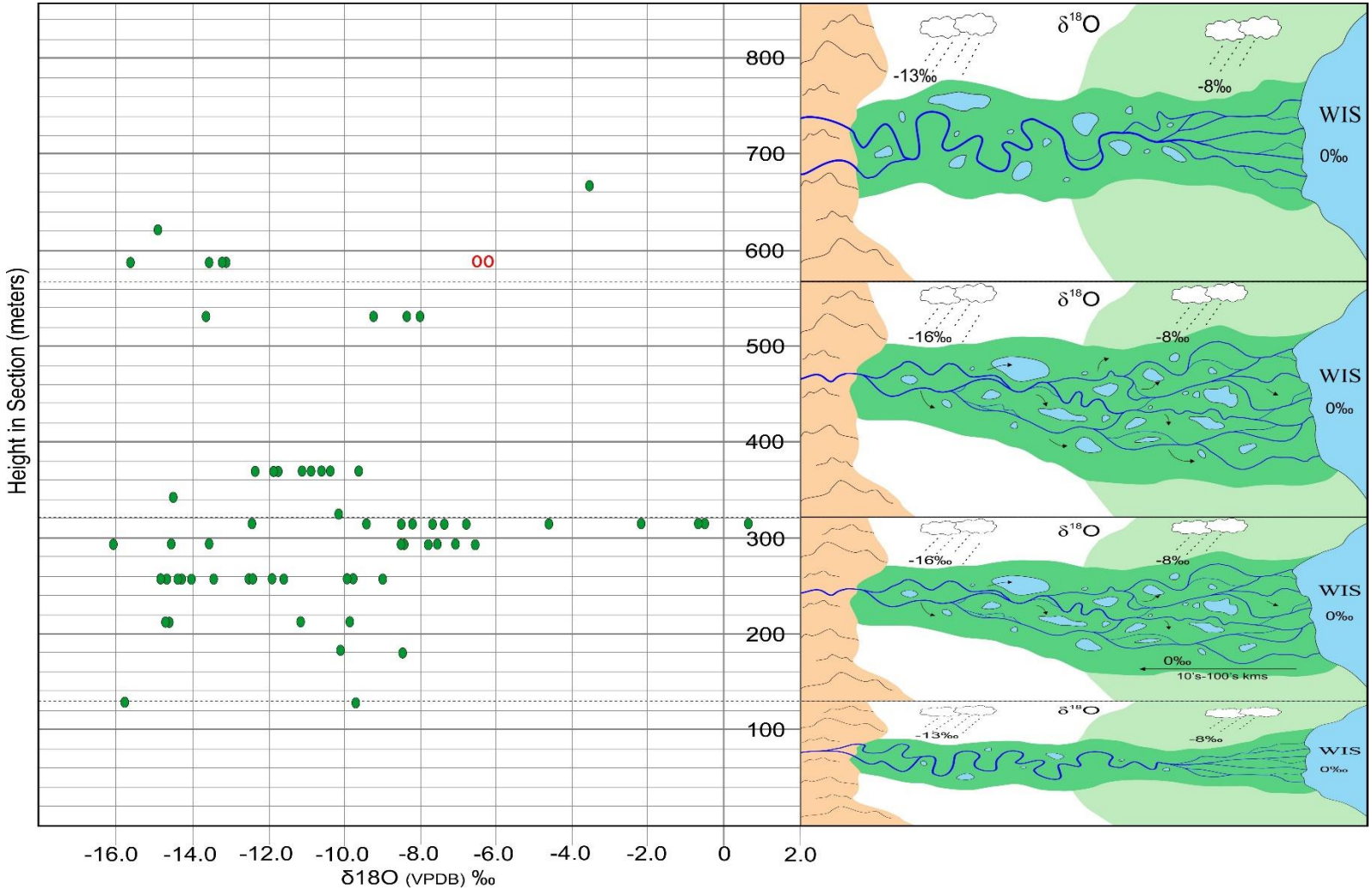



**Figure 18:** $\delta^{18}O$ of pond and fluvial gastropods according to their height in section with corresponding fluvial geometry. Open circles are fluvial gastropods, filled circles are pond gastropods.

style river facilitated extensive mixing between the floodplain ponds and the main channels, as they would have flooded frequently and with varying degrees of severity. It is possible that a single pond could record multiple pulses of isotopically light fluvial input as well as the transition back to a local precipitation dominated source over its lifetime. Even intervals that display a marine influence, such as the 315 m sample interval, had to have been influenced by fluvial mixing prior to the marine incursion. Some of the pond gastropods in the 315 m interval record $\delta^{18}O_{shell}$ values around -16.0‰, which are too light to indicate any marine influence during that mixing event.

Sedimentological evidence supports the increase in the number of preserved pond facies beds, which make up around 55% of the total preserved bed facies in the middle unit. The average pond sediment thickness is 3.5m, with quite a few deposits that are over 5 m, suggesting long lived ponds are characteristic of this unit. The occurrence of numerous ponds less than 2 m thick is also an indication of the increase in the overall number of ponds in in the middle unit, as pond occur about every 11 m in section. Due to the reduction in channel deposits in this unit, the individual pond deposits are often separated by thin beds of sandstone or conglomerate representing a single channel, as opposed to the multistory channels from the upper and lower units (Roberts, 2007).

Based on the way the pond gastropods record the changes in their environments according to source water input, it seems that fluvial geometry was an influential factor determining the composition of the gastropod shell. Further, the similarity between the average $\delta^{18}O$ values of the lower and upper unit, and the shift of around 2.0‰ between them and the middle unit averages suggests noticeable changes in the way the pond and river environments interacted. Additionally, the influence of the change in fluvial style

may be more significant than is represented here. The diagenetic effects on these shell samples may pull the samples closer to heavier values that what was corrected for, and therefore closer the heavier signals of the middle units. To establish if this is the case, more samples are needed, as the small number of samples in the lower and upper units does not allow for more conclusive results. Therefore, by looking for changes in the $\delta^{18}O_{shell}$ values, changes in channel architecture can be tracked through the formation accurately, as the changes in isotopic values are evident from one sample interval to the next moving up-section, and are independently validated by sedimentological evidence.

***Evaporation***

Under evaporative conditions, $^{16}O$ is preferentially removed during vaporization, causing a positive covariance between $\delta^{18}O$ and $\delta^{13}C$ in closed systems such as lakes or ponds, even in humid environments (Leng et al., 2005). If evaporation was a significant factor controlling the $\delta^{18}O$ of the ponds in the Kaiparowits Formation, gastropod shells would be enriched in the heavier isotope. The majority of pond gastropods display no $^{18}O$ enrichment, recording $\delta^{18}O_{shell}$ values lighter than the pedogenic soil carbonates, with values less than -7.5‰ $\delta^{18}O$. Since the pedogenic soil carbonates record soil water $\delta^{18}O$, if any significant evaporation was occurring on the surface waters, $\delta^{18}O_{shell}$ values would be expected to record values heavier than those of the pedogenic soil carbonates. This suggests that evaporation was not a significant factor in controlling the $\delta^{18}O_{shell}$ values, and therefore not significant in the ponds. However, this does not preclude a small amount of evaporation taking place, simply that it is not enough to cause a significant isotopic shift. This evaluation is consistent with reconstructions of a humid environment

similar to the modern Mississippi delta region in the Kaiparowits Formation during Campanian time (Roberts, 2007; Miller et al., 2013; Foreman et al., 2015).

Of the gastropods that record $\delta^{18}O_{shell}$ values heavier than -7.0‰, nearly all of them are from the marine influenced portion of the middle unit. Marine water mixed with the pond water is expected to shift the values dramatically toward the heavier $\delta^{18}O$, as marine water is enriched in $^{18}O$ relative to all freshwater. In the upper unit, only one pond gastropod records a $\delta^{18}O_{shell}$ value heavier than -7.5‰. This pond gastropod has a 100% aragonite mineralogy, and therefore the -3.5‰ values cannot be attributed to a diagenetic shift. However, this individual gastropod is from the highest sample interval, and may record the onset of a slight climatic shift toward the top of the formation where the effects of evaporation are more significant.

Climate and the environment are the driving factors behind aquatic gastropod shell composition. Since gastropods are sensitive to source-water contributing to the ponds, record subtle changes in the amount of high elevation precipitation versus local rainfall contributing to the ponds, changes in fluvial architecture, and marine influence, their shell compositions are able to track environmental change.

**Aquatic gastropods as viable geochemical archives**

Unionoid bivalves are known to precipitate their shell carbonate in equilibrium with the surrounding host water (Dettman et al., 1999). Aquatic gastropods often also do this, making them useful for paleoclimate investigations. If these aquatic gastropods are found to record stable isotopic values that correspond to values recorded by the unionoid bivalves, they will be considered viable geochemical archives.

Comparing the stable isotopes from sampled aquatic gastropods to results from Foreman et al. (2015) suggests that gastropods record a similar range of $\delta^{18}O$ and $\delta^{13}C$ values as the unionoid bivalves, particularly between pond gastropods and pond unionoids. A two-tailed Student's t-test conducted to compare pond gastropods to pond unionoids found no significant difference between their mean $\delta^{18}O$ values (t=-1.58, p=0.12) or their mean $\delta^{13}C$ values (t=-0.40, p=0.69). Fluvial unionoids and pond gastropods also occasionally share similar values, although results from a two-tailed Student's t-test suggest a very large difference between their mean values for both $\delta^{13}C$ (t=-4.90, $p=5.01 \times 10^{-6}$) and $\delta^{18}O$ (t=4.81, $p=5.7 \times 10^{-6}$).

In the lower unit, from 0 to ~125 m (Figure 19), fluvial unionoids record an average value of -12.8±0.8‰ $\delta^{18}O$. The pond gastropods record two $\delta^{18}O_{shell}$ values of -15.7‰ and -9.7‰, suggesting they may have lived in a pond with a host water composition close to local precipitation that was influenced by the river. Pedogenic soil carbonates from Foreman et al. (2015) overlap with values found in this study, with $\delta^{18}O$ averages of -8.0±0.5‰ (Foreman et al., 2015) and -7.7 ±1.1‰. The $\delta^{13}C$ values are variable between the two pond gastropods. However, the pond gastropod with the lighter $\delta^{18}O_{shell}$ value also records a $\delta^{13}C_{shell}$ value close to those of the fluvial unionoids. This suggests that when the pond was inundated with fluvial water, the DIC also changed to reflect a composition similar to the fluvial signal. An increase in the amount of terrestrial matter entering the pond environment may also contribute to these changes.

Since soil carbonates form as a result of groundwater interaction, they record the $\delta^{18}O$ of the local precipitation (Quade et al., 2007). Therefore, based on the pond gastropod with the heavier $\delta^{18}O_{shell}$ composition, it is likely this pond was replenished

primarily by local precipitation, as the one $\delta^{18}O$ value is slightly lighter than the average for pedogenic soil carbonates. Additionally, since the lighter pond gastropod was a sample that contained no primary aragonite, it is unlikely that the original $\delta^{18}O$ value would have been that light. However, the measured $\delta^{18}O$ value for the sample was -12.8‰, so there must have still been a significant contribution of water from the river channel to the pond, as the original aragonite should be lighter than that. A Student's t-test could not be performed on only two data points, but based on the range of $\delta^{18}O$ values for the two gastropods, at least some degree of interaction with the fluvial channel must have occurred. More sampling is needed to fully assess this relationship.

Based on sedimentological data, the dominant fluvial geometry in the lower unit was a meandering style river, characterized by a large main channel that migrated across the floodplain (Roberts, 2007). Although meandering rivers generally remain channelized, a pond adjacent to a large channel could maintain a fairly regular connection to the channel through ground water interaction or from inundation during even minor increased flow events. Ponds located further out in the floodplain are less likely to be inundated on a regular basis, mixing with the waters from the main channel only as a result of a major flood event. These distal ponds would therefore be replenished mainly through local precipitation. In the lower unit however, these two gastropods come from the same pond deposit, suggesting that perhaps on relatively short time scales, a pond that has been replenished mainly by precipitation can have its signal entirely overprinted by a flooding event.

From ~125 m to ~320 m, in the marine influenced portion of the middle unit, the range of gastropod $\delta^{18}O$ and $\delta^{13}C$ values becomes much wider than any other unit,

overlapping almost entirely with the fluvial unionoids, and completely overlapping the pond unionoids (Figure 20). Additionally, both the fluvial unionoids and pond gastropods record lighter $\delta^{18}O$ values here than in the lower unit. Fluvial unionoids record an average of -12.2±1.7‰, with the lightest $\delta^{18}O$ value at -15.5‰. Pond gastropods record values as light as -16.1‰ and as heavy as 0.6‰, with an average of -9.8±4.2‰ $\delta^{18}O$. The increased overlap between the fluvial unionoids and pond gastropods suggests that the pond environments were mixing with the fluvial environments much more than they had previously, particularly since more than half of the pond gastropods in this unit record $\delta^{18}O_{shell}$ values lighter than -9.0‰.

A similar degree of overlap between the range of $\delta^{13}C_{shell}$ values for the pond gastropods and fluvial unionoids may indicate that the DIC of the pond water was influenced by the fluvial system as well. In particular, the range of $\delta^{13}C_{shell}$ values recorded by the pond gastropods with lighter $\delta^{18}O_{shell}$ values is more constrained than the range recorded by those that display a precipitation dominated signal, as most of the $\delta^{13}C$ values are between -8.0‰ and -4.0‰. This suggests that when the gastropods are living in an environment with a similar source-water composition to the unionoids, they will record a similar range of values for both $\delta^{18}O$ and $\delta^{13}C$. Results of a two-tailed Student's t-test however, still suggest a significant difference between the means of pond gastropods and fluvial unionoids in this unit, for both $\delta^{18}O$ ($t=3.20$, $p=0.002$) and $\delta^{13}C$ ($t=-2.60$, $p=0.012$), despite the large degree of overlap.

Pond unionoids in the marine influenced middle unit were all sampled from one pond deposit, and record an average of -8.0±0.4‰ $\delta^{18}O$, consistent with the range of values recorded by the pedogenic soil carbonates, but not very close to the average for the

pond gastropods. A two-tailed Student's t-test comparing the two resulted in similar means for $\delta^{13}C$ (t=-0.07, p=0.94), but no similarity between means for $\delta^{18}O$ (t=-2.68, p=0.01), even with the overlap. This is likely a result of the small number of pond unionoids present in this unit compared to the pond gastropods, coupled with the much wider range the pond gastropods record. Additionally, some pond gastropods display a shift toward heavier $\delta^{18}O$ values, while the majority record $\delta^{18}O$ values that are the same or lighter than the pedogenic soil carbonates. The pond unionoids show no indication of a shift toward heavier $\delta^{18}O$ values. The pond unionoids lack of shifted values suggests that they did not experience the same conditions as the heavier pond gastropods, despite coming from the same height in section at 315 m. Alternatively, the pond unionoids may not be as sensitive to a marine influence as the gastropods.

Although the 315 m sample interval displayed the heaviest $\delta^{18}O$ values in the entire formation, it also contained gastropods that recorded values nearly identical to those of the pond unionoids. This suggests that pond gastropods and pond unionoids collected from the same interval may have lived at vastly different times in the pond's history. Each record different dominant sources of recharge to the ponds during their lifetimes, yet they both record nearly identical values when ponds were recharged dominantly by local precipitation.

In the upper portion of the middle unit, evidence for the marine incursion is gone, and the range of $\delta^{18}O$ and $\delta^{13}C$ values is reduced considerably, despite the river system maintaining an anastomosing geometry (Figure 21). In this post-marine influenced section, there is no longer any overlap between the fluvial unionoids and pond gastropods. However, nearly all pond gastropods record $\delta^{18}O$ values lighter

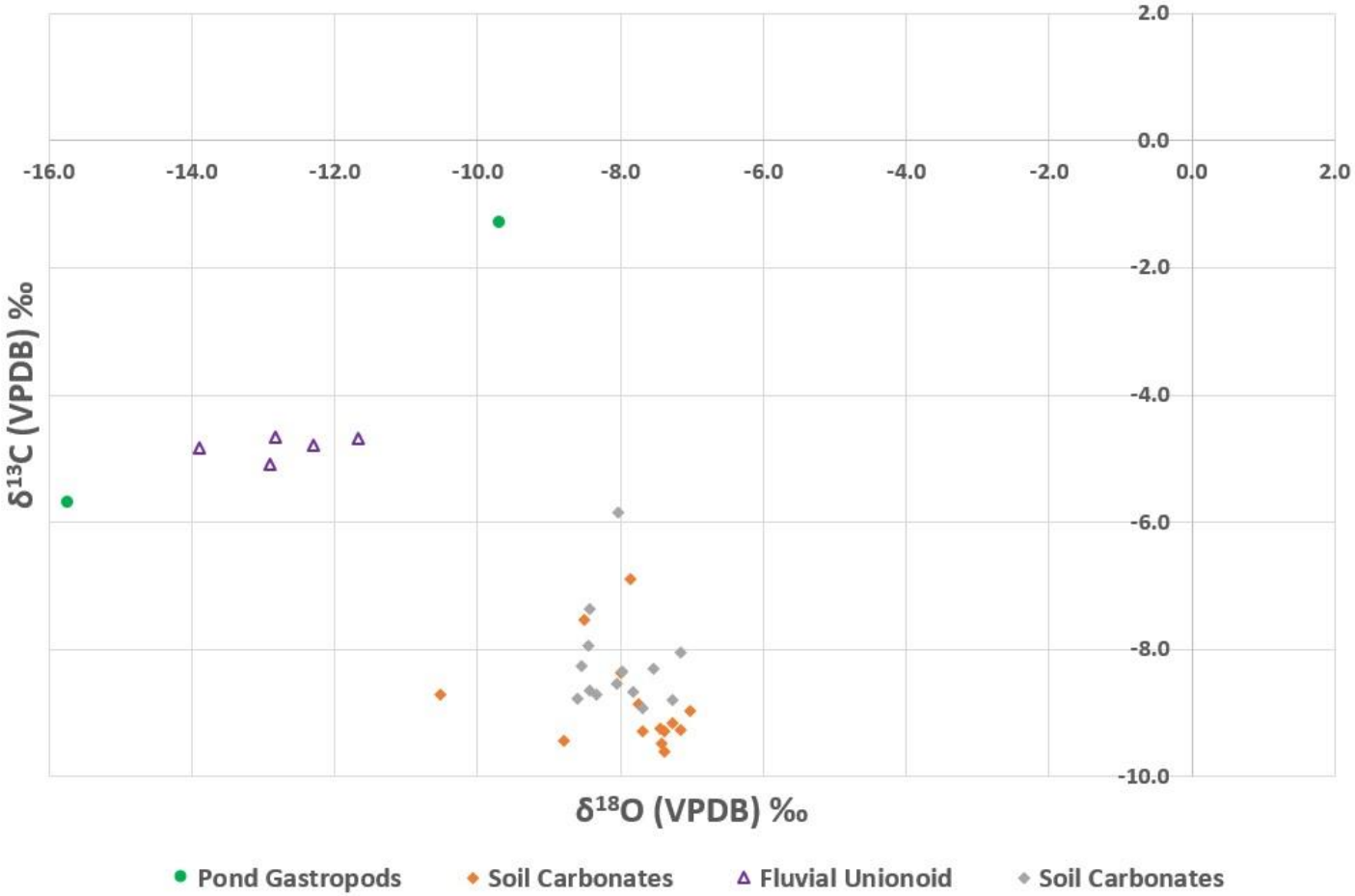



**Figure 19:** Stable isotopic values of pond gastropods and pedogenic soil carbonates from the informal lower unit, with fluvial unionoids and pedogenic soil carbonates from Foreman et al. (2015).

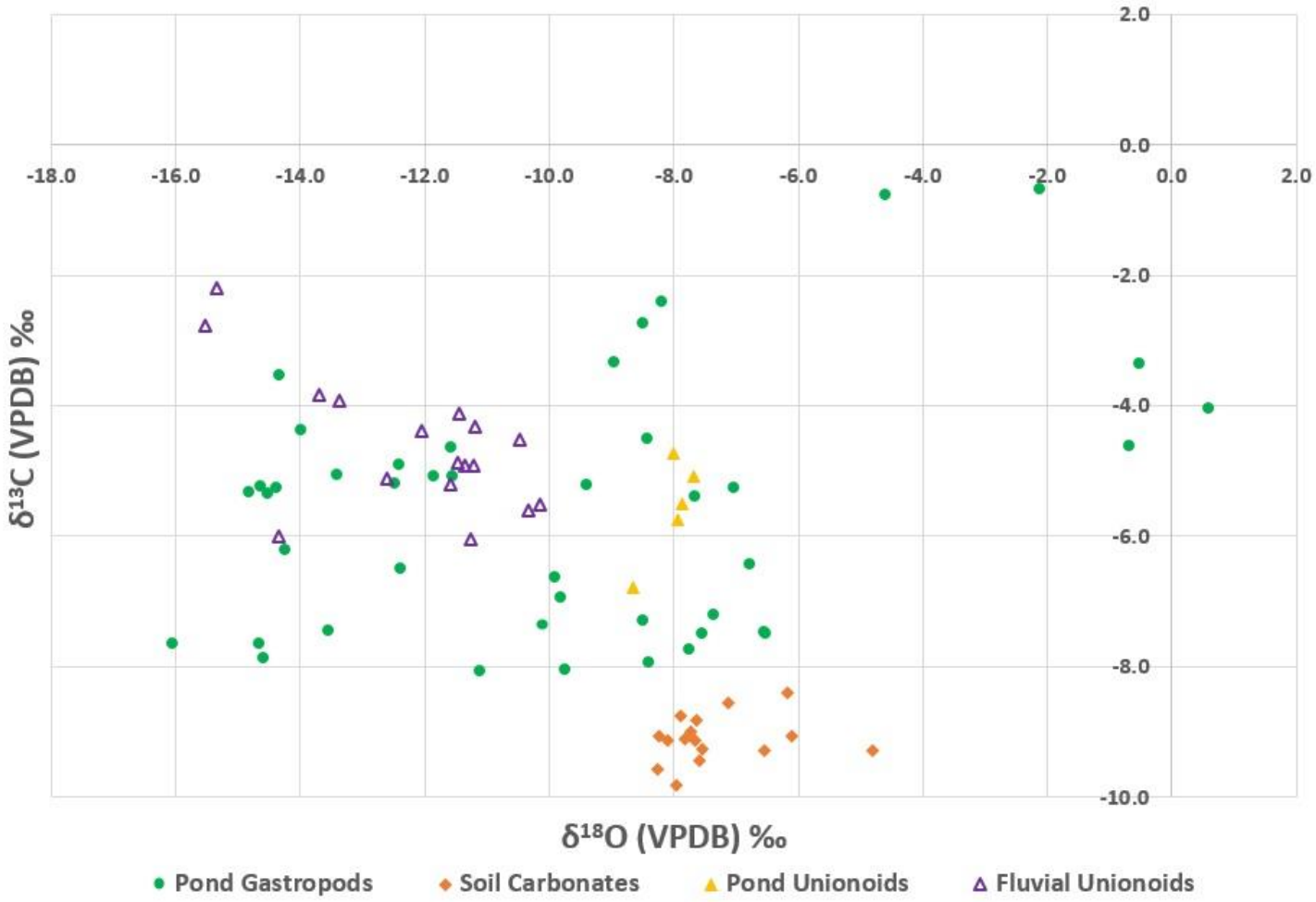



**Figure 20:** Stable isotopic values of pond gastropods and pedogenic soil carbonates from the marine influenced portion of the informal middle unit, with fluvial and pond unionoids from Foreman et al. (2015).

than -9.0‰, suggesting that a significant amount of mixing with the river channels still took place. Pond unionoids and pond gastropods in this unit show a high degree of overlap, with an average of -9.9±1.6‰ $\delta^{18}O$ for pond unionoids and an average of -10.9±1.8‰ $\delta^{18}O$ for pond gastropods. Although the range of $\delta^{18}O$ values for pond gastropods is wider than the pond unionoids, the majority $\delta^{18}O_{shell}$ values for both mollusks fall between -14.0‰ and -8.0‰ $\delta^{18}O$. The $\delta^{13}C$ values for pond unionoids and pond gastropods is also quite similar in this unit. The average for pond gastropods is -6.5±1.3‰, while the pond unionoids' average $\delta^{13}C_{shell}$ value is -6.1±1.9‰. A two-tailed Student's t-test conducted between the pond gastropods and pond unionoids in this unit found no significant difference between the means for either $\delta^{18}O$ ($t=-1.60$, $p=0.12$) or $\delta^{13}C$ ($t=-1.22$, $p=0.23$). This suggests these two mollusks are recording the same environmental conditions within this unit. Further, the amount of overlap displayed by pond gastropods and pond unionoids from the same, and different sample intervals, suggests that without the marine influence ponds were able to maintain their isotopic compositions for longer periods of time, and allow the mollusks to record similar signals. Additionally, the range of $\delta^{18}O$ values recorded by the pond gastropods coupled with the pedogenic soil carbonates consistently recording values around -8.0‰ $\delta^{18}O$, suggests that the isotopic composition of the local precipitation remained nearly constant through the deposition of the formation.

The upper unit marks the transition back to a meandering style geometry around 550 m in section. Despite a reduction in sample size in this unit, pond gastropods still record an extensive range of $\delta^{13}C$ and $\delta^{18}O$ values (Figure 22). The pond gastropods in this unit record values that are significantly heavier and lighter than the small range

displayed by the pond unionoids, but the averages for the two mollusks are -12.3±4.4‰ and -8.5±1.2‰ respectively. Although, the extremely light values recorded by the pond gastropods are likely not that light, as all of these samples contained no primary aragonite. However, similar to the lower unit, the measured $\delta^{18}O$ values for these samples were around -9.0‰ to -11.0‰, which suggests their original aragonite values may have been lighter than that. Despite the wide range of values for pond gastropods, a two-tailed Student's t-test comparing them to the pond unionoids found that $\delta^{18}O$ values (t=-2.03, p=0.09) were not significantly different. Similar to the lower unit, most of the pond gastropods in this unit are recoding $\delta^{18}O$ values much lighter than the pedogenic soil carbonates. However, the one heavier sample contains a 100% aragonite mineralogy, and suggests that most of the pond's main source of water was from local precipitation, rather than the fluvial signal suggested by the lighter altered samples. The lighter values of the altered samples to begin with does suggest that some fluvial mixing may have occurred, although the influence the river water had on the ponds may be less pronounced then they suggest. This unit also displays a larger difference between lightest and heaviest $\delta^{13}C$ values for the majority of the pond gastropods and pond unionoids. Despite the increased range, the average $\delta^{13}C$ for pond gastropods of -6.5±1.3‰ is close to the pond unionoid average $\delta^{13}C$ value of -6.1±1.9‰, and results of a two-tailed Student's t-test confirm no significant difference between the two mollusks (t=-1.67, p=0.13).

Fluvial gastropods are represented for the first time in the upper unit, while fluvial unionoids were not sampled. In spite of this, the expected river signal can still be estimated based on the lightest values recorded by the pond gastropods, which suggests that the rivers $\delta^{18}O$ value should be similar to what was recorded by fluvial unionoids in

the middle units. If that is the case, then the average $\delta^{18}O_{shell}$ values of -6.4±0.2‰ recorded by the two fluvial gastropods in this unit are extremely heavy $\delta^{18}O$ values, even heavier than the pedogenic soil carbonates. Since both fluvial gastropods have aragonite-only mineralogies, a possible explanation for their heavier $\delta^{18}O$ values may be that they lived in a part of the fluvial channel that was either experiencing extreme evaporation, such as a side channel, or they may have lived in part of a channel that became entirely removed from the rest of the fluvial system, such as an oxbow lake. In either case, the water body they were living in must have acted as a closed system with sufficient evaporation to shift the $\delta^{18}O$ values by over +5.0‰. The $\delta^{13}C$ values of the fluvial gastropods are also quite different from the average for all fluvial unionoids, which are never below -5.0‰. The fluvial gastropod's average of -8.8±0.1‰ suggests that the water DIC and amount of terrestrial input was very different than the regular parts of the fluvial channels.

When unionoids and gastropods are compared across the Kaiparowits Formation as a whole, each sample interval displays a significant amount of overlap with the unionoids for both $\delta^{18}O$ and $\delta^{13}C$. From the $\delta^{18}O$ values it is clear that the majority of pond gastropods and pond unionoids are recording similar values when taken from the same interval, but that the pond gastropods generally have wider ranges, particularly in the heavy direction. Even the fluvial unionoids are completely or mostly within the range of the pond gastropods in the middle units. Sparse sampling in the 400-500 m intervals leaves a bit of a gap with only unionoids, but from the values of the pond gastropods above and below, it is likely that the pond gastropods record similar ranges to the pond

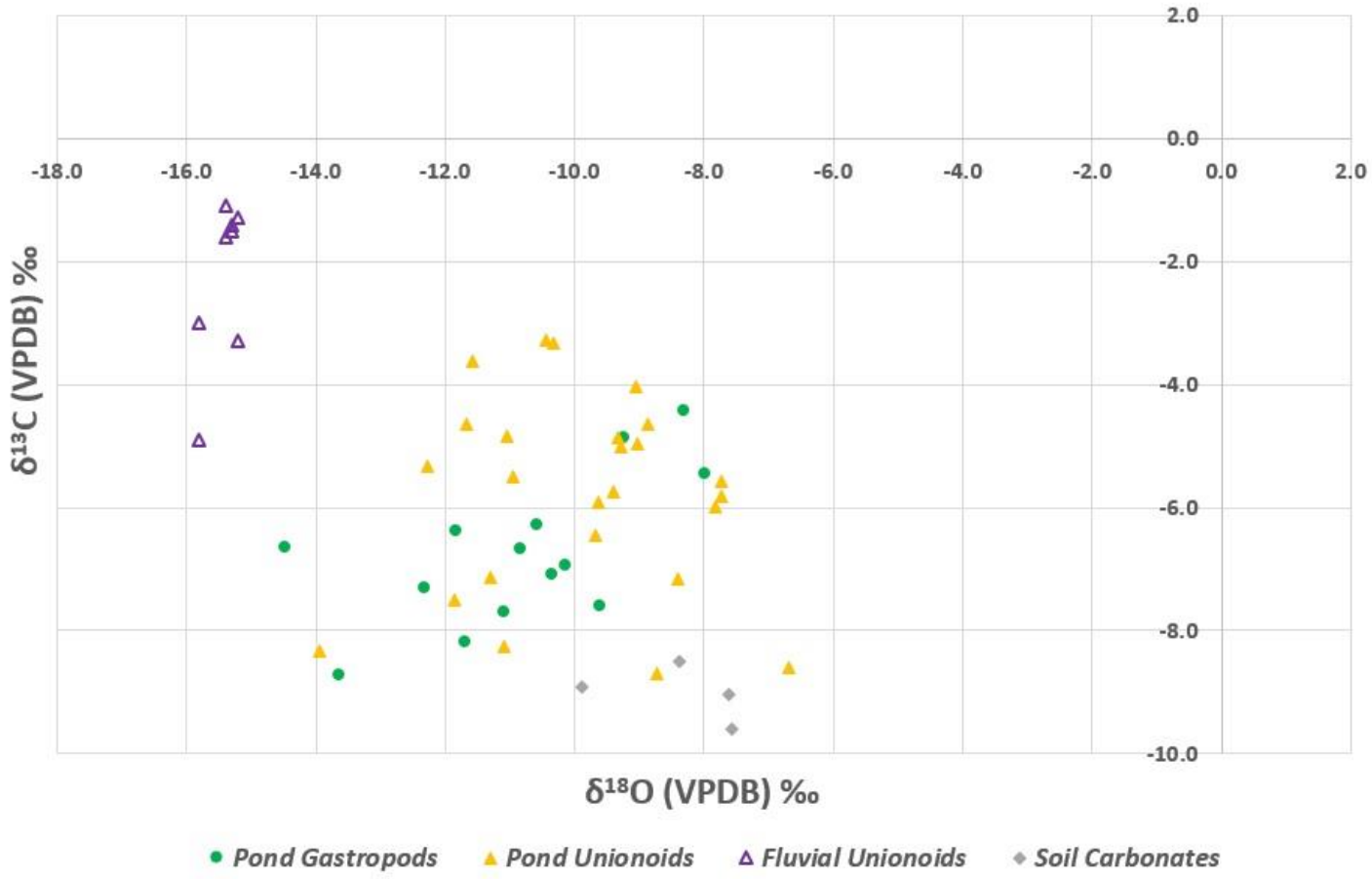



**Figure 21:** Stable isotopic values of pond gastropods from the post marine influenced portion of the informal middle unit, with fluvial and pond unionoids and pedogenic soil carbonates from Foreman et al. (2015).

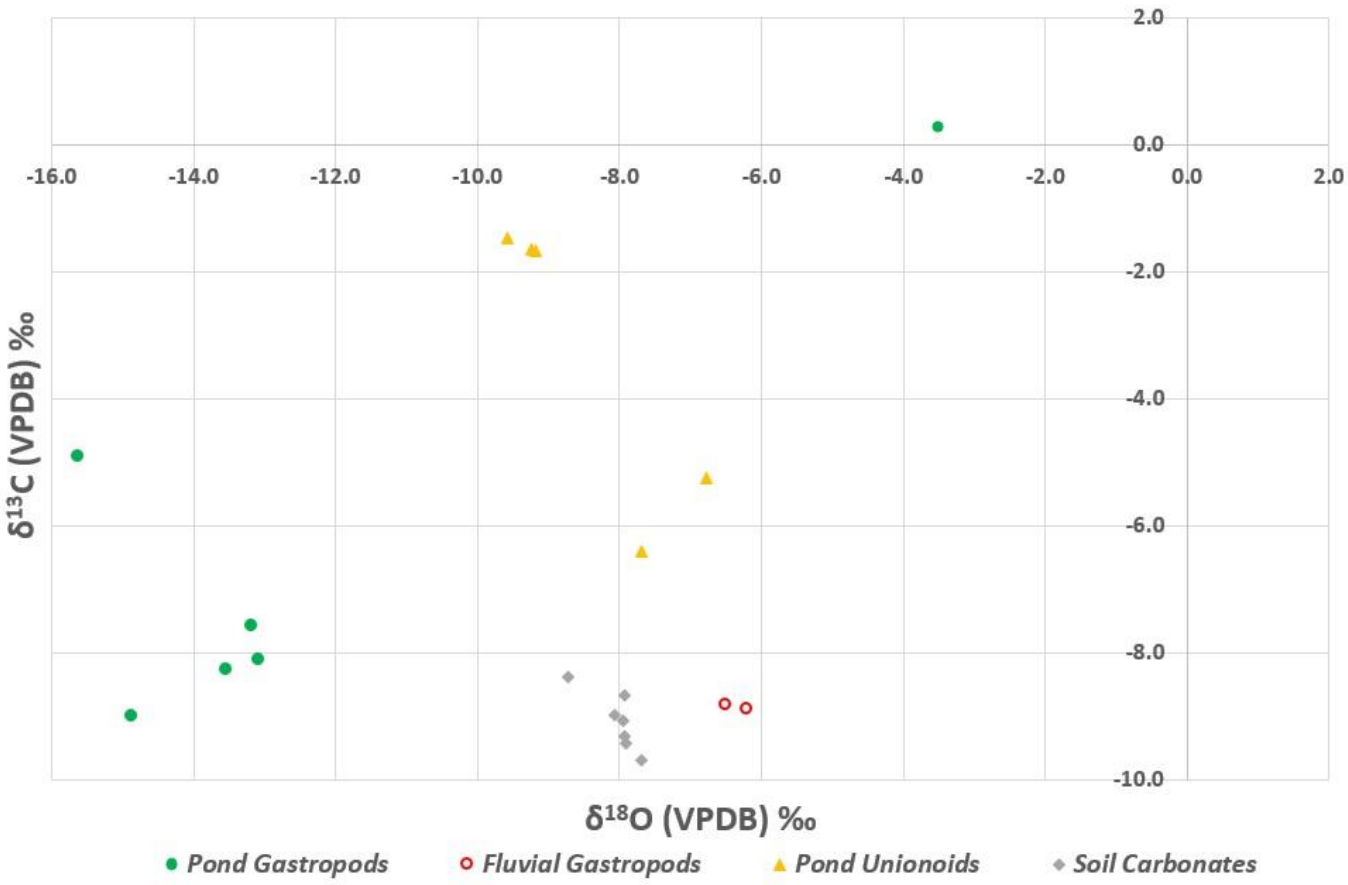



**Figure 22:** Stable isotopic values of pond and fluvial gastropods from the informal upper unit, with pond unionoids and pedogenic soil carbonates from Foreman et al. (2015).

unionoids in those areas too. The $\delta^{13}C$ values are generally consistent throughout the formation as well, but there is a habit for unionoids to be slightly heavier. Most pond and fluvial unionoids record $\delta^{13}C$ values in the mid-range between -8.0‰ and -4.0‰, where the majority of pond gastropods also fall. Therefore, pond gastropods can be considered viable geochemical archives based on their tendency to record $\delta^{18}O$ and $\delta^{13}C$ values that correspond to those recorded by unionoids.

***Factors contributing to the offset between $\delta^{13}C$ and $\delta^{18}O$ of gastropods and bivalves***

Even with the large degree of overlap between the isotopic signals recorded by gastropods and unionoids in all units, when plotted with $\delta^{13}C$ or $\delta^{18}O$ according to their height in section, there is a slight offset between the two mollusks from the same height in section (Figures 23 and 24). For $\delta^{18}O$, the majority of pond gastropods consistently overlap with the ranges of the pond and fluvial unionoids, but also record values greater than 2.0‰ heavier than the unionoids from the same sample height interval. The trend in the $\delta^{13}C$ values, although less pronounced than the $\delta^{18}O$ values, shows that a significant portion of gastropods are recording the same or much lighter $\delta^{13}C$ values than the fluvial or pond unionoids in their corresponding intervals. These offsets could be the result of a number of factors including; unique ponds, timing of seasonal growth, microhabitats, diet, or physiological differences.

Since the gastropods and unionoids are often from the same sample interval, there is a chance they are from the same pond. However, due to the number of years in between the sampling of the unionoids and the gastropods, it is possible that a different pond may have been encountered at the same height in section. In the case of the 668 m sample interval, a slightly different pond seems to be the best explanation for why the pond

unionoids and pond gastropod record values that differ by over 4.0‰, as all the samples are 100% aragonite. For most ponds, if the values recorded by the mollusks are overlapping or within 2.0‰ of each other, attributing the consistent differences to sampling from unique ponds can be discounted as a minor factor. Even though there is no way of knowing how time averaged a single deposit is, or how many hundreds of years of time a single pond could record, signals that are overlapping yet consistently offset are more indicative of a systematic difference rather than as a result of small scale environmental changes.

Timing of shell growth for fossil gastropods and unionoids is expected to be similar. Most extant mollusks have a temperature threshold at which they restrict or cease shell growth. In modern unionoids, shell growth is restricted or absent at temperatures below about 10°C, while the most rapid growth occurs at temperatures from 20-25°C. These temperature restrictions mean that growth occurs mainly in the late spring to early summer (Kohn and Dettman, 2007). Most modern Viviparidae gastropods in North America grow from the months of May to mid-September, and can either have negligible growth during the colder months (Kaplan and Selleck, 2008), or continued winter growth at a reduced rate (Browne, 1978). Since the mean annual temperature in the Kaiparowits Formation is estimated around 20°C (Miller et a., 2013), it is likely that these mollusks grew for the majority of the year, with peak growth during the summer months. Growth may have stopped during the coldest months of the winter, even though the presence of palms and other flora sensitive to frost (Wolfe and Upchurch, 1987; Miller et al., 2013) and winter low temperatures in the highlands around 3°C suggest mild winters (Fricke et al., 2010).

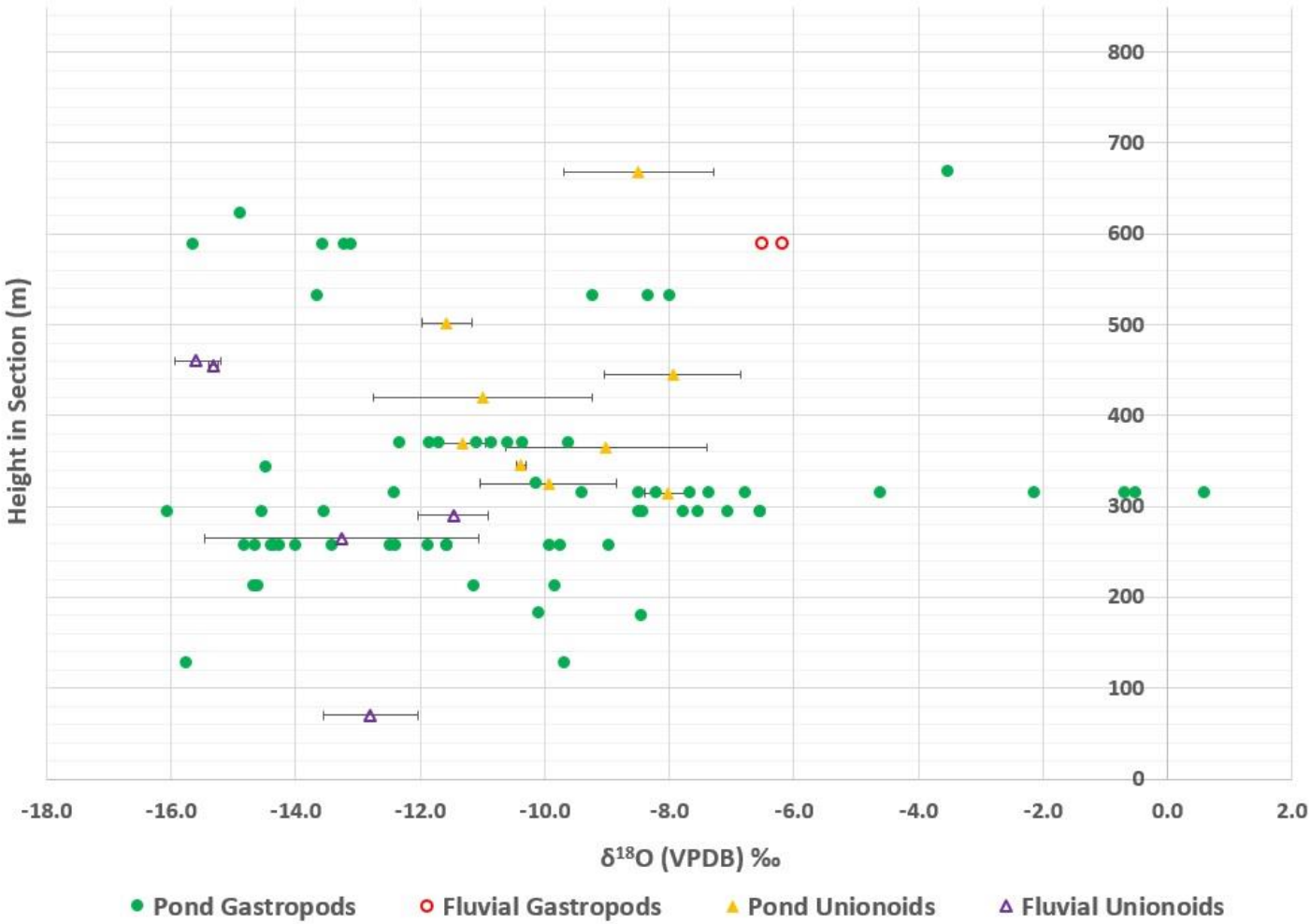



**Figure 23:** $\delta^{18}O$ comparison of pond and fluvial gastropods with pond and fluvial unionoids from Foreman et al. (2015) according to their height in section. Unionoids shown with 1 standard deviation bars.

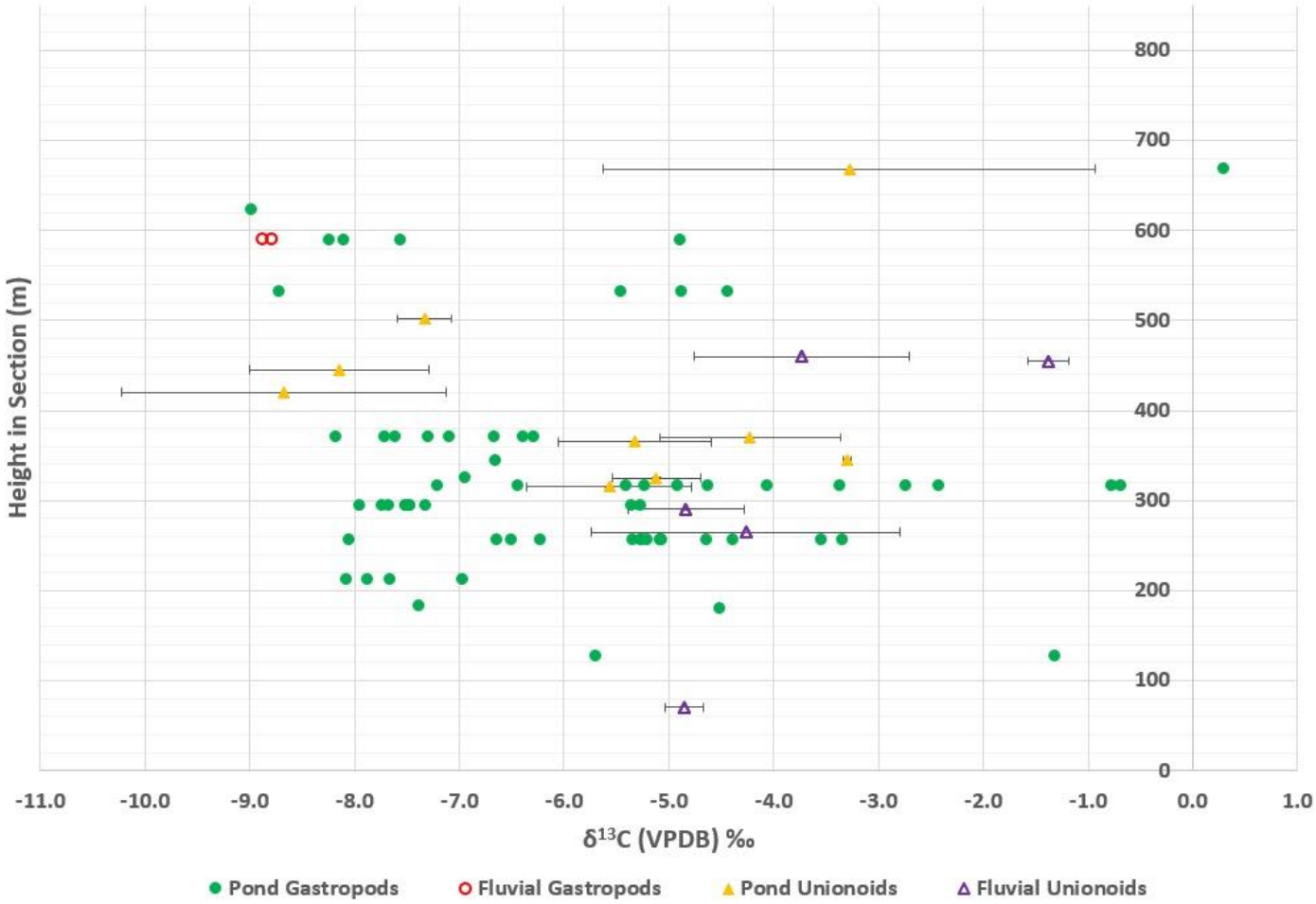



**Figure 24:** $\delta^{13}C$ comparison of pond and fluvial gastropods with pond and fluvial unionoids from Foreman et al. (2015) according to their height in section. Unionoids shown with 1 standard deviation bars.

The most rapid shell growth should have occurred during the warm summer months, which corresponds to the predicted time of peak rainfall (Fricke et al., 2010). Therefore, timing of shell growth in these mollusks is considered not to be a factor in their $\delta^{18}O$ differences, as the current climate model suggests they would have been building the majority of their shells during the same months of the year.

There are five sample intervals in which pond gastropods and pond unionoids were both collected (290/293 m, 315 m, 325 m, 370 m, and 668 m). In every case, gastropods are recording overlapping and heavier $\delta^{18}O$ values. This suggests that there may be slight differences within the same pond environment that could cause these offsets, such as the microhabitats in which these different types of mollusks prefer to live (Figure 25). Extant Viviparidae in North America generally live at water depths of less than 2 m in areas with abundant aquatic plants and a soft muddy substrate (Kaplan and Selleck, 2008). Viviparidae from Europe behave similarly, clustering near food sources in near-shore zones in the summer and moving to deeper parts of ponds and lakes to survive the winter (Jakubik, 2012). In general, Viviparidae will prefer to be as close to the surface as possible, without being disturbed by predators or wave action (Dillion, 2000). In particular, they will concentrate in shallow, stagnant, slow-flow areas of rivers and ponds (Jakubik, 2012). Extant species of unionoid bivalves live in the same types of environments. However, in lentic habitats they will generally have reduced populations above 1 m water depth due to predation, resulting in a maximum abundance from below about 1 m to 2 m depth and decreasing abundance with deeper depths. The composition of the substrate is often the determining factor for populations at depth, suggesting that unionoids can and will live deeper in the water if coarser sediments are present (Dillion,

2000). Riverine environments are quite different, in that unionoids prefer to live close to the center of the river on coarse sediments, and away from vegetation, where they can filter feed on the particles moving through the faster current (Dillion, 2000).

These general habitat strategies seem to hold true in the Kaiparowits Formation. Gastropods are much more abundant in pond environments, often found alongside carbonized plant debris (Roberts, 2007). Alternatively, unionoids in the pond deposits are generally smaller than their riverine counterparts, and are much less abundant than the gastropods. The unionoids in the fluvial facies are abundant and generally found deeper in the center of channel deposits, with much larger and flatter shells (Leif Tapanila and Brady Forman, pers. comm). Additionally, since the pond facies in the Kaiparowits Formation are described as sandy mudstones (Roberts, 2007), it is possible that the unionoids living there would have preferred areas that could have provided the most stable substrate. This was most likely on the bottom, where the larger sediments and terrestrial organic material would have gathered.

Due to pond gastropods favoring areas of ponds closer to the surface water interface than the areas where pond unionoids are generally found, another potential cause for the offset in $\delta^{18}O$ could be evaporation. Even though evaporation in the Kaiparowits Formation is thought to be mild, it's effects may still have influenced the ponds and rivers to some degree. During the warm months, the effects of evaporation would be most influential near the surface of the water, causing a depletion in $^{16}O$. By proximity, pond gastropods living in those areas would form their shells from water slightly enriched in the heavier isotopes compared to deeper portions of the pond. Since there are only two gastropods from the fluvial facies, it is not possible to say whether

they record normal isotopic values for fluvial gastropods throughout the formation. However, the offset between the $\delta^{18}O_{shell}$ values recorded by the fluvial gastropods and fluvial unionoids in different units is extreme. It is possible that the heavier $\delta^{18}O$ values the fluvial gastropods record are a result of living in the calmer pools of the river, or along the edges of banks or point bars. In these areas the effects of evaporation could be more pronounced than in the riffles, and deeper channel areas where unionoids are found.

Gastropod mobility can also be considered a factor in determining their isotopic composition. Gastropods potentially record a combination signal from both shallow and deep areas of the ponds, and thus have the opportunity to encounter a wider variety of conditions and food items. If the gastropods are spending part of their growth periods in the shallow areas of the pond and part in the deeper areas with the unionoids, it is possible that some of them record signals close to the range of the unionoids. In this same way, an individual pond gastropod's movement may explain why some from the same intervals display vastly different signals.

The amount of a gastropod's life that is spent is close proximity to plants can have an influence on shell $\delta^{13}C$. Aquatic vegetation is known to change the $\delta^{13}C$ value of the water DIC in its immediate vicinity (Farquhar et al., 1989; Pedersen et al., 2013), as $C_3$ plants will preferentially fractionate toward $^{12}C$ as they photosynthesize (Farquhar et al., 1989). As a result, the water surrounding the aquatic plants could be depleted in the lighter isotopes. Therefore, prolonged growth in highly vegetated areas could cause a shift in the $\delta^{13}C$ of the gastropod's shell toward much heavier values if they incorporating $^{13}C$ rich $CO_2$ from the DIC pool.

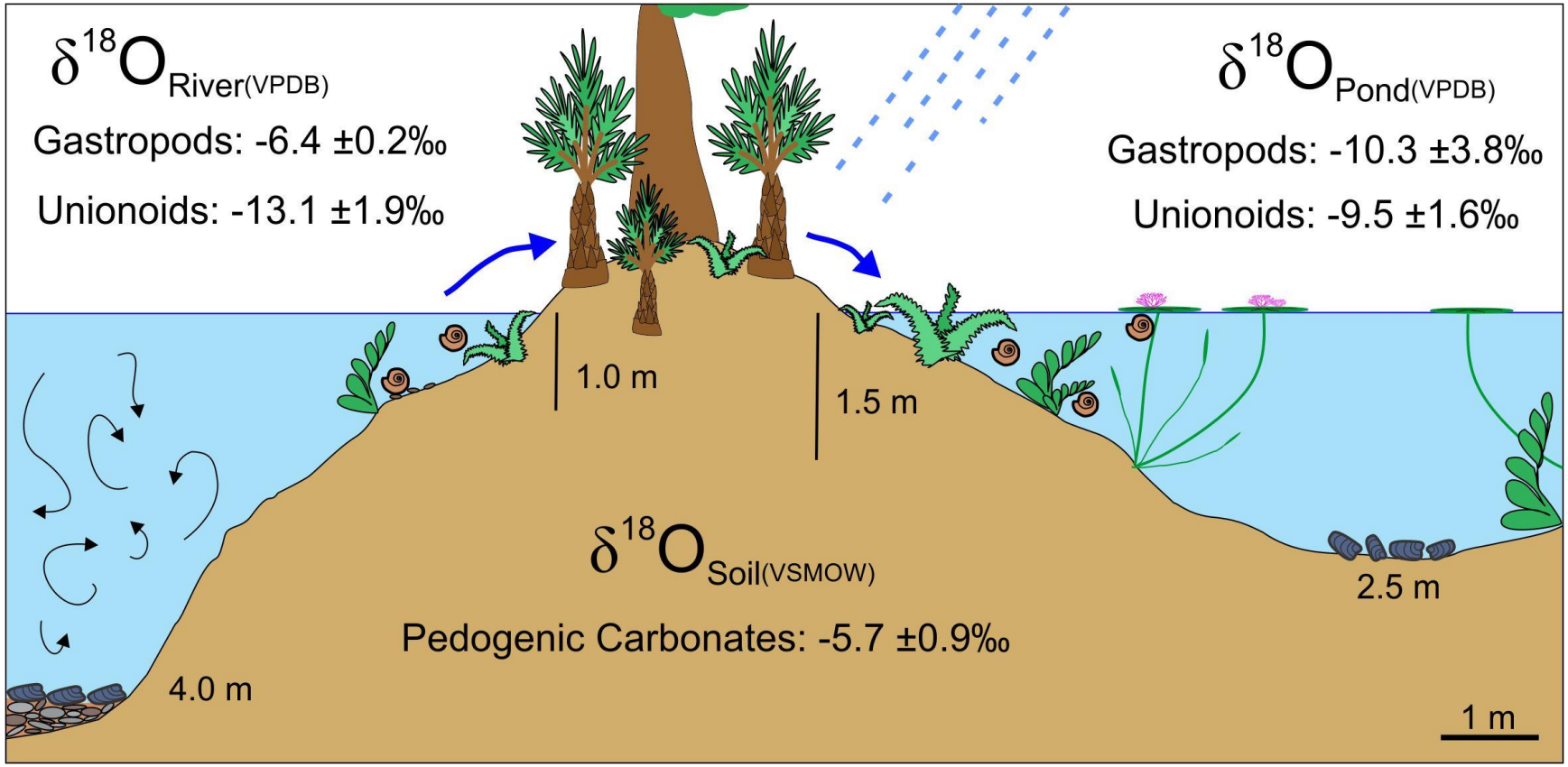



**Figure 25:** Artist recreation of the Kaiparowits Formation river and floodplain environments, with $\delta^{18}O$ summary for each environment by mollusk class. Location of gastropods and bivalves according to locations found when sampling and expected life positions based on extant relatives. Vegetation based on paleoflora found by Miller et al. (2013).

Alternatively, unionoids, which prefer sparsely vegetated areas, may be less affected when building their shells in ambient water that is comparatively removed from these photosynthetic processes. For these reasons, it is possible that where the mollusks were positioned in the ponds and rivers could potentially have an impact their $\delta^{18}O$ and $\delta^{13}C$ values.

In addition to host water DIC, some shell carbonate is influenced by diet. The different feeding strategies of these mollusks therefore have the potential to cause a slight offset in $\delta^{13}C$ values (Antonio et al., 2010). Viviparidae are a unique group of gastropods in that they are able to filter feed as well as graze, often crawling over surfaces and collecting food particles (Dillion, 2000). Although capable of both, feeding preference has been shown to change with species as well as life stage. Extant species *V. georgianus* relies dominantly on filter feeding as an adult (Browne, 1978), while *V. viviparus* remains a grazer for most of its life, filter feeding when the conditions are more favorable (Cook, 1949). The food types eaten by Viviparidae are related to food availability and feeding style preference, but are considered to be composed primarily of diatoms, green and blue-green algae (Dillon, 2000), and detritus from higher aquatic plants. Occasional filtering of bacteria may also contribute to their food sources (Jakubik, 2012). Unionoids rely entirely on filter feeding of small particles, dominantly 1-2 µm in size, composed of the available organic and inorganic detritus in their environment. Generally, this includes filamentous algae and diatoms with a mixture of sand and calcareous debris (Dillion, 2000). From a study by Antonio et al. (2010), terrestrial organics were found to be an important food source for extant mollusks in rivers and floodplain ponds. Additionally, the availability of certain preferred food types was found to result in very different

$\delta^{13}C_{shell}$ values between individuals even over short periods of time. This suggests the gastropods and unionoids in this study have the potential to have very different $\delta^{13}C$ values within the same sample intervals.

Due to the gastropods ability to graze, and their known diet of higher aquatic plants, they likely ingest more $^{12}C$ than the unionoids, since all other food types are similar. However, the relative importance of metabolic $CO_2$ from the diet versus host water DIC in shell carbonate may be more important than the differences in food type. Specifically, aquatic gastropods have been found to rely more on carbon sourced from the host water DIC than from their diets, with only about 10% of total $CO_2$ coming from dietary carbon contributing to shell carbonate (Shanahan et al., 2005). Conversely, the exact contributions of diet and DIC are unknown for freshwater unionoids, marine unionoids have shown that diet and host water DIC are nearly equal contributors to shell carbonate (Dettman et al., 1999), suggesting that diet is more important in bivalves than in gastropods. Therefore, even though gastropods potentially eat aquatic plants enriched in the lighter carbon isotope, because their shell carbonate is built primarily with host water DIC, the values they record may be heavier or lighter than the shell carbonate of unionoid bivalves, which rely more on their diets.

The calcification physiology of gastropods and unionoids should be nearly identical (McConnaughey and Gillikin, 2008). Both mollusks mineralize by extracellular processes that use $CO_2$ from the surrounding water DIC incorporated into the extrapallial fluid that separates the soft mantle tissues from the interior of the shell (Weiner and Dove, 2003; Shanahan et al., 2005; McConnaughey and Gillikin, 2008). Where the processes of shell construction may result in vital effects however, lies in the particular

method of calcification. Whether the gastropod or unionoids follow the kinetic model or carbonate model (Shanahan et al., 2005) during their calcification has the potential to offset their values. In the same way, the relative rates at which these mollusks are precipitating their shells can also be a source of the differences (Kim et al., 2006). Therefore, the offset may be a result of different calcification physiologies causing an inter-species vital effect, but there is no way to definitively test it.

Although there are quite a few potential causes for offset between the gastropod and unionoid $\delta^{13}C$ and $\delta^{18}O$ values, it is clear that they are recording the same overall environmental trend. Individually they may be more or less sensitive to specific local environmental factors, but these differences potentially make them more useful for specialized studies in the future.

## 6. CONCLUSIONS

Aquatic gastropods from the Late Cretaceous Kaiparowits Formation track changes in the fluvial geometry through stable isotopes of oxygen and carbon in their shells, as it relates to the longevity of pond environments, and the amount of fluvial and overbank mixing. The range of $\delta^{18}O$ and $\delta^{13}C$ values, and degree of overlap between pond gastropods and both fluvial and pond unionoids suggests aquatic gastropods are viable geochemical archives. The consistent small offset between the $\delta^{18}O$ and $\delta^{13}C$ values of gastropods and unionoids from the same sample heights in section suggests these two mollusks record largely the same environmental signal, but may record slightly different positions within the pond's microenvironments. The distinct shift toward heavier values in the marine influenced portion of the formation suggests that gastropods are more sensitive in recording marine water mixing than the unionoids.

### Future Work

If aquatic gastropods from the Kaiparowits Formation are used in the future to build on the existing stable isotopic record for the Late Cretaceous Western Interior, the following suggestions may aid those investigations:

- More selective sampling for larger gastropods (>1 cm) with whole shells preserved and minimal discoloration.
- Testing multiple points within a single shell to further constrain seasonality and vital effects.
- Increased collection of fluvial facies gastropods that maintain usable shell material.
- Collection of bivalves from the same units as the gastropods to ensure the same pond deposit.

## REFERENCES


Antonio, E.S., Kasai, A., Ueno, M., Kurikawa, Y., Tsuchiya, K., Toyohara, H., Ishihi, Y., Yokoyama, H., and Yamashita, Y., 2010, Consumption of terrestrial organic matter by estuarine molluscs determined by analysis of their stable isotopes and cellulase activity: Estuarine, Coastal and Shelf Science, v. 86, no. 3, p.401-407.

Bish, D.L., and Reynolds, R.C., 1989, Sample preparation for X-ray diffraction: Reviews in Mineralogy and Geochemistry, v. 20, no. 1, p.73-99.

Browne, R.A., 1978, Growth, mortality, fecundity, biomass and productivity of four lake populations of the prosobranch snail, *Viviparus georgianus*: Ecology, v. 59, no. 4, p.742-750.

Cerling, T.E., and Quade, J., 1993, Stable Carbon and Oxygen Isotopes in Soil Carbonates: Climate Change in Continental Isotopic Records, v. 78, p. 217-231.

Cifelli, R.L., 1990. Cretaceous mammals of southern Utah. I. Marsupials from the Kaiparowits Formation (Judithian): Journal of Vertebrate Paleontology, v. 10, no. 3, p.295-319.

Cook, P. M., 1949, A ciliary feeding mechanism in *Viviparus viviparus* (L.): Journal of Molluscan Studies, v. 27, no. 6, p. 265-271.

DeCelles, P. G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, no. 2, p. 105-168.

Dettman, D. L., Reische, A. K., and Lohmann, K. C., 1999, Controls on the stable isotope composition of seasonal growth bands in aragonitic fresh-water bivalves (Unionidae): Geochimica et Cosmochimica Acta, v. 63, no. 7, p. 1049-1057.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A. and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, no. 2, p.222-235.

Dillon Jr., R. T. ,2000, The ecology of freshwater molluscs: Cambridge, Cambridge University Press, 523 p.

Doelling, H.H., Blackett, R.E., Hamblin, A.H., Powell, J.D. and Pollock, G.L., 2000, Geology of Grand Staircase-Escalante National Monument, Utah: Geology of Utah's parks and monuments: Utah Geological Association Publication, v. 28, p.189-231.

Eaton, J.G., 1991, Biostratigraphic framework for the Upper Cretaceous rocks of the Kaiparowits Plateau, southern Utah: Geological Society of America Special Papers, v. 260, p. 47-64.

Eaton, J.G., and Cifelli, R.L., 2013, Review of Late Cretaceous Mammalian faunas of the Kaiparowits and Paunsaugunt plateaus, southwestern Utah, *in* Titus, A.L., and Loewen, M.A, eds., At the Top of the Grand Staircase: The Late Cretaceous of Southern Utah: Bloomington, Indiana, Indiana University Press, p.319-369.

Farke, A.A., Henn, M.M., Woodward, S.J., and Xu, H.A., 2014, *Leidyosuchus* (Crocodylia: Alligatoroidea) from the Upper Cretaceous Kaiparowits Formation (late Campanian) of Utah, USA: PaleoBios, v. 30, no. 3, p. 72-88.

Farke, A.A. and Patel, P.P., 2012, An enantiornithine bird from the Campanian Kaiparowits Formation of Utah, USA: Cretaceous Research, v. 37, p.227-230.

Farquhar, G. D., Ehleringer, J. R., and Hubick, K. T., 1989, Carbon isotope discrimination and photosynthesis: Annual review of plant biology, v. 40, no. 1, p. 503-537.

Folk, R.L., 1974, The natural history of crystalline calcium carbonate: effect of magnesium content and salinity: Journal of Sedimentary Research, v. 44, no. 1, p. 40-53.

Foreman, B.Z., Roberts, E.M., Tapanila, L., Ratigan, D., and Sullivan, P., 2015, Stable isotopic insights into paleoclimatic conditions and alluvial depositional processes in the Kaiparowits Formation (Campanian, south-central Utah, U.S.A.): Cretaceous Research, v. 56, p.180-192.

Fricke, H. C., Foreman, B. Z., and Sewall, J. O., 2010, Integrated climate model-oxygen isotope evidence for a North American monsoon during the Late Cretaceous: Earth and Planetary Science Letters, v. 289, no. 1, p. 11-21.

Fritz, P. and Poplawski, S., 1974, $^{18}O$ and $^{13}C$ in the shells of freshwater molluscs and their environments: Earth and Planetary Science Letters, v. 24, no. 1, p. 91-98.

Garzione, C.N., Dettman, D.L., and Horton, B.K., 2004, Carbonate oxygen isotope paleoaltimetry: evaluating the effect of diagenesis on paleoelevation estimates for the Tibetan plateau: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 212, no. 1, p.119-140.

Gates, T.A., and Sampson, S.D., 2007, A new species of *Gryposaurus* (Dinosauria: Hadrosauridae) from the late Campanian Kaiparowits Formation, southern Utah, USA: Zoological Journal of the Linnean Society, v. 151, no. 2, p.351-376.

Goldstrand, P.M., 1992, Evolution of Late Cretaceous and early Tertiary basins of Southwest Utah based on clastic petrology: Journal of Sedimentary Petrology, v. 62, no.3, p. 495-507.

Goldstrand, P. M.,1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, no. 1, p. 145-154.

Grossman, E.L., and Ku, T.L., 1986, Oxygen and carbon isotope fractionation in biogenic aragonite: temperature effects: Chemical Geology: Isotope Geoscience section, v. 59, p. 59-74.

Hutchison, J.H., Knell, M.J. and Brinkman, D.B., 2013, Turtles from the Kaiparowits Formation, Utah, *in* Titus, A.L., and Loewen, M.A, eds., At the Top of the Grand Staircase: The Late Cretaceous of Southern Utah: Bloomington, Indiana, Indiana University Press, p. 295-318.

Irmis, R.B., Hutchison, J.H., and Sertich, J.J.W., 2013, Crocodyliforms from the Late Cretaceous of Grand Staircase-Escalante National Monument and Vicinity, Southern Utah, USA, *in* Titus, A.L., and Loewen, M.A, eds., At the Top of the Grand Staircase: The Late Cretaceous of Southern Utah: Bloomington, Indiana, Indiana University Press, p. 424-444.

Jakubik, B., 2012, Life strategies of Viviparidae (Gastropoda: Caenogastropoda: Architaenioglossa) in various aquatic habitats: *Viviparus viviparus* (Linnaeus, 1758) and *V. contectus* (Millet, 1813): Folia Malacologica, v. 20, no. 3, p. 145-179.

Jakubik, B., and Lewandowski, K., 2007, Size structure, age, mortality and fecundity in *Viviparus viviparus* (Linnaeus, 1758) (Gastropoda: Architaenioglossa: Viviparidae): Folia Malacologica, v. 15, no. 3, p. 109-117.

Jinnah, Z. A., Roberts, E. M., Deino, A. L., Larsen, J. S., Link, P. K., and Fanning, C. M., 2009, New $^{40}$Ar-$^{39}$Ar and detrital zircon U-Pb ages for the Upper Cretaceous Wahweap and Kaiparowits formations on the Kaiparowits Plateau, Utah: implications for regional correlation, provenance, and biostratigraphy: Cretaceous Research, v. 30, p. 287-299.

Kaplan, J. and Selleck, B., 2008, Stable Isotopic composition of the Freshwater Gastropod *Viviparus Georgianus*, Central New York State: Evaluation as a Proxy for Summer Climate: Northeastern Geology and Environmental Sciences, v. 30, no. 2, p. 130-139.

Kelly, R.S., 2014, Sequence stratigraphic control on continental biodiversity: A gastropod case study from the Upper Cretaceous Kaiparowits Formation, Southern Utah [Master's Thesis]: Idaho State University, 45 p.

Kim, S. T., Hillaire-Marcel, C., and Mucci, A., 2006, Mechanisms of equilibrium and kinetic oxygen isotope effects in synthetic aragonite at 25 C: Geochimica et Cosmochimica Acta, v. 70, no. 23, p. 5790-5801.

Kim, S. T., and O'Neil, J. R., 1997, Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates: Geochimica et Cosmochimica Acta, v. 61, no. 16, p. 3461-3475.

Kohn, M.J., and Dettman, D.L., 2007, Paleoaltimetry from stable isotope compositions of fossils: Reviews in Mineralogy and Geochemistry, v. 66, no. 1, p.119-154.

Latal, C., Piller, W.E., and Harzhauser, M., 2006, Small-scaled environmental changes: indications from stable isotopes of gastropods (Early Miocene, Korneuburg Basin, Austria): International Journal of Earth Sciences, v. 95, no. 1, p. 95-106.

Lawton, T.F., Eaton, J.G., Godfrey, K.N., and Schellenbach, W.L., 2014, Compositional, paleontological and detrital-zircon data from Cretaceous strata of the Henry Mountains basin and implications for connections with dispersal systems of Wahweap and Kaiparowits Formations in southern Utah, U.S.A., *in* MacLean, J.S., Biek, R.F., and Huntoon, J.E., editors, Geology of Utah's Far South: Utah Geological Association Publication 43, p. 373–396.

Lawton, T.F., Pollock, S.L., and Robinson, R.A.J., 2003, Integrating sandstone petrology and nonmarine sequence stratigraphy: application to the Late Cretaceous fluvial systems of southwestern Utah, USA: Journal of Sedimentary Research, v. 73, no. 3, p. 389-406.

Lécuyer, C., Hutzler, A., Amiot, R., Daux, V., Grosheny, D., Otero, O., Martineau, F., Fourel, F., Balter, V. and Reynard, B., 2012, Carbon and oxygen isotope fractionations between aragonite and calcite of shells from modern molluscs: Chemical geology, v. 332, p.92-101.

Leng, M.J., Lamb, A.L., Heaton, T.H., Marshall, J.D., Wolfe, B.B., Jones, M.D., Holmes, J.A. and Arrowsmith, C., 2005, Isotopes in lake sediments, *in* Leng, M.J., ed., Isotopes in Palaeoenvironmental Research: Netherlands, Springer, p. 147-184.

Leng, M. J., and Marshall, J. D., 2004, Palaeoclimate interpretation of stable isotope data from lake sediment archives: Quaternary Science Reviews, v. 23, no. 7, p. 811-831.

Lively, J.R., 2015, A new species of baenid turtle from the Kaiparowits Formation (Upper Cretaceous, Campanian) of southern Utah: Journal of Vertebrate Paleontology, v. 35, no. 6, p.e1009084.

Makaske, B., 2001, Anastomosing rivers: a review of their classification, origin and sedimentary products: Earth-Science Reviews, v. 53, no. 3, p.149-196.

McConnaughey, T., 1989, $^{13}C$ and $^{18}O$ isotopic disequilibrium in biological carbonates: I. Patterns: Geochimica et Cosmochimica Acta, v. 53, no. 1, p.151-162.

McConnaughey, T.A., and Gillikin, D. P., 2008, Carbon isotopes in mollusk shell carbonates: Geo-Marine Letters, v. 28, no. 5-6, p. 287-299.

Miller, I. M., Johnson, K. R., and Kline, D. E., 2013, A Late Campanian Flora from the Kaiparowits Formation, Southern Utah, and a brief overview of the widely sampled but little-known Campanian vegetation of the Western Interior of North

America, *in* Titus, A.L. and Loewen, M.A, eds., At the Top of the Grand Staircase: The Late Cretaceous of Southern Utah: Bloomington, Indiana, Indiana University Press, p.107-131.

Miller, K.G., Sugarman, P.J., Browning, J.V., Kominz, M.A., Hernández, J.C., Olsson, R.K., Wright, J.D., Feigenson, M.D., and Van Sickel, W., 2003, Late Cretaceous chronology of large, rapid sea-level changes: Glacioeustasy during the greenhouse world: Geology, v. 31, no. 7, p. 585-588

Nordt, L., Atchley, S., and Dworkin, S.I., 2002, Paleosol barometer indicates extreme fluctuations in atmospheric CO2 across the Cretaceous-Tertiary boundary: Geology, v. 30, no. 8, p. 703-706.

Pearson, P. N., Ditchfield, P. W., Singano, J., Harcourt-Brown, K. G., Nicholas, C. J., Olsson, R. K., Shackleton, N.J. and Hall, M.A., 2001, Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs: Nature, v. 413, no. 6855, p. 481-487.

Pedersen, O., Colmer, T.D., and Sand-Jensen, K., 2013, Underwater photosynthesis of submerged plants–recent advances and methods: Frontiers in Plant Science, v. 4, no. 140, 18 p.

Quade, J., Garzione, C., and Eiler, J., 2007, Paleoelevation reconstruction using pedogenic carbonates: Reviews in Mineralogy and Geochemistry, v. 66, no. 1, p. 53-87.

Roberts, E. M., 2007, Facies architecture and depositional environments of the Upper Cretaceous Kaiparowits Formation, southern Utah: Sedimentary Geology, v. 197, p. 207-233.

Roberts, E. M., Tapanila, L., and Mijal, B., 2008, Taphonomy and Sedimentology of Storm-Generated Continental Shell Beds: A Case Example from the Cretaceous Western Interior Basin: Journal of Geology, v. 116, p. 462-479.

Roberts, E.M., Sampson, S.D., Deino, A.L., Bowring, S.A., and Buchwaldt, R., 2013, The Kaiparowits Formation: A Remarkable Record of Late Cretaceous Terrestrial Environments, Ecosystems, *in* Titus, A.L. and Loewen, M.A, eds., At the Top of the Grand Staircase: The Late Cretaceous of Southern Utah: Bloomington, Indiana, Indiana University Press, p. 85-106.

Rubinson, M., and Clayton, R.N., 1969, Carbon-13 fractionation between aragonite and calcite: Geochimica et Cosmochimica Acta, v. 33, no. 8, p.997-1002.

Sampson, S.D., Loewen, M.A., Farke, A.A., Roberts, E.M., Forster, C.A., Smith, J.A. and Titus, A.L., 2010, New horned dinosaurs from Utah provide evidence for intracontinental dinosaur endemism: PLoS One, v. 5, no. 9, p. e12292.

Schmitz, B., and Andreasson, F.P., 2001, Air humidity and lake $\delta^{18}O$ during the latest Paleocene–earliest Eocene in France from recent and fossil fresh-water and marine gastropod $\delta^{18}O$, $\delta^{13}C$, and $^{87}Sr/^{86}Sr$: Geological Society of America Bulletin, v. 113, no. 6, p.774-789.

Sewall, J.O., and Fricke, H.C., 2013, Andean-scale highlands in the Late Cretaceous Cordillera of the North American western margin: Earth and Planetary Science Letters, v. 362, pp.88-98.

Shanahan, T. M., Pigati, J. S., Dettman, D. L., and Quade, J., 2005, Isotopic variability in the aragonite shells of freshwater gastropods living in springs with nearly constant temperature and isotopic composition: Geochimica et Cosmochimica Acta, v. 69, no. 16, p. 3949-3966.

Spiro, B., Ashkenazi, S., Mienis, H.K., Melamed, Y., Feibel, C., Delgado, A., and Starinsky, A., 2009, Climate variability in the Upper Jordan Valley around 0.78 Ma, inferences from time-series stable isotopes of Viviparidae, supported by mollusc and plant palaeoecology: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 282, no. 1, p. 32-44.

Tapanila, L., and Roberts, E.M., 2013, Continental Invertebrates and Trace Fossils from the Campanian Kaiparowits Formation, Utah, *in* Titus, A.L. and Loewen, M.A, eds., At the Top of the Grand Staircase: The Late Cretaceous of Southern Utah: Bloomington, Indiana, Indiana University Press, p. 132-152.

Vasconcelos, C., McKenzie, J. A., Warthmann, R., and Bernasconi, S. M., 2005, Calibration of the $\delta^{18}O$ paleothermometer for dolomite precipitated in microbial cultures and natural environments: Geology, v. 33, no. 4, p. 317-320.

Weiner, S., and Dove, P.M., 2003, An overview of biomineralization processes and the problem of the vital effect: Reviews in mineralogy and geochemistry, v. 54, no. 1, p. 1-29.

Wolfe, J.A., and Upchurch, G.R., 1987, North American nonmarine climates and vegetation during the Late Cretaceous: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 33-77.

Zanno, L.E., and Sampson, S.D., 2005, A new oviraptorosaur (Theropoda, Maniraptora) from the Late Cretaceous (Campanian) of Utah: Journal of Vertebrate Paleontology, v. 25, no. 4, p. 897-904.

Zheng, Y.F., 1999, Oxygen isotope fractionation in carbonate and sulfate minerals: Geochemical Journal, v. 33, no. 2, p.109-126.

**Appendix I:** Gastropod Sample Index

| Locality | IP # | Specimen # | Sample ID | Height in Section (m) | Unit | Facies | Appearance-physical and visual | Preparation Method | Mineralogy | Aragonite % (just carbonates) | $\delta^{13}C$ ‰ (VPDB) | $\delta^{18}O$ ‰ (VPDB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101602-1 | IP-096 | 782 | 96 Sub 1 | 588 | Upper | Pond | pale yellow-hard | Bulk crush | Calcite | 0 | -4.9 | -11.1 |
| 101602-1 | IP-096 | 783 | 96 Sub 2 | 588 | Upper | Pond | pale yellow-hard | Bulk crush | Calcite | 0 | -7.6 | -8.7 |
| 101602-1 | IP-096 | 784 | 96 Neb 3 | 588 | Upper | Pond | pale yellow-hard | Bulk crush | Calcite | 0 | -8.2 | -9.1 |
| 101602-1 | IP-096 | 785 | 96 Neb 4 | 588 | Upper | Pond | pale yellow-hard | Bulk crush | Calcite | 0 | -8.1 | -8.6 |
| 092606-5 | IP-112 | 786 | 112 Sub 1 | 370 | Middle | Pond | white- soft | Bulk crush | Aragonite | 100 | -7.7 | -11.1 |
| 092606-5 | IP-112 | 787 | 112 Sub 2 | 370 | Middle | Pond | white-yellow-hard | Bulk crush | Aragonite-calcite | 12 | -7.6 | -5.7 |
| 092606-5 | IP-112 | 788 | 112 Neb 3 | 370 | Middle | Pond | white-hard inner | Bulk crush | Aragonite-calcite | 13 | -7.3 | -8.4 |
| 092606-5 | IP-112 | 789 | 112 Neb 4 | 370 | Middle | Pond | white-hard inner | Bulk crush | Aragonite-calcite | 11 | -6.4 | -7.8 |
| 051913-1 | IP-196 | 790 | 196 Sub | 179 | Middle | Pond | brown-grey | Bulk crush | Aragonite-Dolomite | 68 | -4.5 | -6.8 |
| 051613-2 | IP-198 | 791 | 198 Sub | 127 | Lower | Pond | brown | Bulk crush | Aragonite-dolomite-calcite | 55 | -1.3 | -7.5 |
| 051613-2 | IP-198 | 792 | 198 Vivip1 | 127 | Lower | Pond | brown and white- hard | Shell separation | Calcite-dolomite | 0 | -5.7 | -12.8 |
| 051513-1 | IP-194 | 793 | 194 Sub1 | 182 | Middle | Pond | off white and brown- hard flaky-softer areas | Shell separation | Aragonite-dolomite | 82 | -7.4 | -9.2 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 052015-1 | IP-231 | 794 | L6 Vivip1 | 212 | Middle | Pond | brown- very thin, flaky | Shell separation | Aragonite-Dolomite | 69 | -8.1 | -9.6 |
| 052015-1 | IP-231 | 795 | L6 Vivip2 | 212 | Middle | Pond | brown to off white- thin | Shell separation | Aragonite-Calcite-dolomite | 37 | -7.7 | -12.3 |
| 052015-1 | IP-231 | 796 | L6 Vivip3 | 212 | Middle | Pond | pinkish off white- soft, light brown areas avoided | Shell separation | Aragonite | 100 | -7.9 | -14.6 |
| 052015-1 | IP-231 | 797 | L6 Vivip4 | 212 | Middle | Pond | pinkish off white to light brown- thin, soft | Shell separation | Aragonite | 100 | -7.0 | -9.8 |
| 052015-2 | IP-232 | 798 | L7 Neb1 | 256 | Middle | Pond | pinkish off white, brown areas-thin, flaky, soft | Shell separation | Aragonite-dolomite | 53 | -5.2 | -10.1 |
| 052015-2 | IP-232 | 799 | L7 Neb2 | 256 | Middle | Pond | off white and brown- flaky, soft | Shell separation | Aragonite-dolomite | 45 | -4.4 | -11.2 |
| 052015-2 | IP-232 | 800 | L7 Neb3 | 256 | Middle | Pond | pinkish off white, slight brown- soft | Shell separation | Aragonite-dolomite | 69 | -5.1 | -10.0 |
| 052015-2 | IP-232 | 801 | L7 Neb4 | 256 | Middle | Pond | pinkish off white-brown, thin flaky, soft | Shell separation | Aragonite-dolomite | 67 | -5.3 | -12.7 |
| 052015-2 | IP-232 | 802 | L7 Neb5 | 256 | Middle | Pond | pinkish brown-thin, soft, slightly flaky | Shell separation | Aragonite-dolomite | 49 | -5.3 | -12.2 |
| 052015-2 | IP-232 | 803 | L7 Vivip1 | 256 | Middle | Pond | pinkish with brown areas-thin and soft | Shell separation | Aragonite-calcite-dolomite | 39 | -5.1 | -10.3 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 052015-2 | IP-232 | 804 | L7 Vivip2 | 256 | Middle | Pond | pinkish lots of brown, thin, soft | Shell separation | Aragonite-dolomite | 69 | -6.5 | -10.8 |
| 052015-2 | IP-232 | 805 | L7 Vivip3 | 256 | Middle | Pond | brownish pink-thin, soft | Shell separation | Aragonite-dolomite | 68 | -6.2 | -12.8 |
| 052015-2 | IP-232 | 806 | L7 Vivip4 | 256 | Middle | Pond | pinkish with brown areas-thin and soft | Shell separation | Aragonite-calcite-dolomite | 63 | -4.6 | -10.5 |
| 052015-2 | IP-232 | 807 | L7 Vivip5 | 256 | Middle | Pond | pinkish off white with brown areas-thin, soft | Shell separation | Aragonite-calcite-dolomite | 64 | -3.5 | -12.6 |
| 052015-2 | IP-232 | 808 | L7 Vivip6 | 256 | Middle | Pond | pinkish brown-thin, soft, slightly flaky | Shell separation | Aragonite-calcite-dolomite | 58 | -5.2 | -12.6 |
| 052015-2 | IP-232 | 809 | L7 Vivip7 | 256 | Middle | Pond | off white- soft outer brown coating on rock | Shell separation | Aragonite-dolomite | 89 | -8.0 | -9.2 |
| 052015-2 | IP-232 | 810 | L7 Vivip8 | 256 | Middle | Pond | pinkish off white, brown area avoided-soft | Shell separation | Aragonite | 100 | -5.1 | -13.4 |
| 052015-2 | IP-232 | 811 | L7 Vivip9 | 256 | Middle | Pond | pinkish with brown areas-thin and soft, flaky | Shell separation | Aragonite-calcite-dolomite | 63 | -3.3 | -7.9 |
| 052015-2 | IP-232 | 812 | L7 Vivip10 | 256 | Middle | Pond | pinkish off white with brown areas-thin, soft | Shell separation | Aragonite-dolomite | 71 | -6.6 | -8.4 |
| 052015-3 | IP-233 | 813 | L8 Neb1 | 293 | Middle | Pond | pinkish off white, brown areas- thin, soft | Shell separation | Aragonite-dolomite | 48 | -7.5 | -10.9 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 052015-3 | IP-233 | 814 | L8 Neb2 | 293 | Middle | Pond | pink, some brown areas-thin | Shell separation | Aragonite-dolomite | 55 | -5.3 | -4.7 |
| 052015-3 | IP-233 | 815 | L8 Neb3 | 293 | Middle | Pond | pinkish to off white- interior only-soft | Shell separation | Aragonite | 100 | -7.5 | -6.5 |
| 052015-3 | IP-233 | 816 | L8 Neb4 | 293 | Middle | Pond | pinkish off white- thin, flaky | Shell separation | Aragonite | 100 | -7.3 | -8.5 |
| 052015-3 | IP-233 | 817 | L8 Neb5 | 293 | Middle | Pond | pinkish off white-thin, flaky | Shell separation | Aragonite-dolomite | 71 | -7.7 | -14.6 |
| 052015-3 | IP-233 | 818 | L8 Vivip1 | 293 | Middle | Pond | pinkish off white- thin, soft | Shell separation | Aragonite **perfect** | 100 | -7.5 | -6.5 |
| 052015-3 | IP-233 | 819 | L8 Vivip2 | 293 | Middle | Pond | pinkish, brown to reddish areas(avoided)-thin | Shell separation | Aragonite | 100 | -5.4 | -14.5 |
| 052015-3 | IP-233 | 820 | L8 Vivip3 | 293 | Middle | Pond | pink-soft | Shell separation | Aragonite | 100 | -7.5 | -7.5 |
| 052015-3 | IP-233 | 821 | L8 Vivip4 | 293 | Middle | Pond | pinkish off white- light brown flaky in places | Shell separation | Aragonite-dolomite | 83 | -7.9 | -7.5 |
| 052015-3 | IP-233 | 822 | L8 Vivip5 | 293 | Middle | Pond | pinkish off-white, thin, flaky | Shell separation | Aragonite-dolomite | 91 | -7.7 | -7.3 |
| 052015-4 | IP-234 | 823 | L9 Neb1 | 315 | Middle | Pond | brownish pink-soft thin | Shell separation | Aragonite | 100 | -4.1 | 0.6 |
| 052015-4 | IP-234 | 824 | L9 Neb2 | 315 | Middle | Pond | brown and off white- thin, flaky | Shell separation | Aragonite-calcite-dolomite | 55 | -2.4 | -6.0 |
| 052015-4 | IP-234 | 825 | L9 Neb3 | 315 | Middle | Pond | brown and off white- thin, flaky | Shell separation | Aragonite-dolomite | 56 | -2.7 | -6.2 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 052015-4 | IP-234 | 826 | L9 Neb4 | 315 | Middle | Pond | pinkish white and brown areas- soft, thin, flaky | Shell separation | Aragonite-calcite | 75 | -7.2 | -6.2 |
| 052015-4 | IP-234 | 827 | L9 Neb5 | 315 | Middle | Pond | pinkish off white and light brown area- thin, soft | Shell separation | Aragonite | 100 | -4.6 | -0.7 |
| 052015-4 | IP-234 | 828 | L9 Neb6 | 315 | Middle | Pond | pinkish white and brown areas- soft, thin | Shell separation | Aragonite-dolomite | 70 | -5.2 | -7.9 |
| 052015-4 | IP-234 | 829 | L9 Neb7 | 315 | Middle | Pond | off white and brownish- shiny, soft | Shell separation | Aragonite | 100 | -0.8 | -4.6 |
| 052015-4 | IP-234 | 830 | L9 Neb8 | 315 | Middle | Pond | pinkish off white and brown areas- soft | Shell separation | Aragonite | 100 | -4.9 | -12.4 |
| 052015-4 | IP-234 | 831 | L9 Neb9 | 315 | Middle | Pond | pinkish off white with brown areas- soft, flaky | Shell separation | Aragonite-dolomite | 68 | -3.4 | 1.1 |
| 052015-4 | IP-234 | 832 | L9 Vivip1 | 315 | Middle | Pond | off white with a reddish brown- soft | Shell separation | Aragonite | 100 | -0.7 | -2.1 |
| 052015-4 | IP-234 | 833 | L9 Vivip2 | 315 | Middle | Pond | pinkish off white with brown areas- thin, soft | Shell separation | Aragonite-dolomite | 62 | -5.4 | -5.7 |
| 052015-4 | IP-234 | 834 | L9 Vivip3 | 315 | Middle | Pond | pinkish off white with brown areas- thin, flaky | Shell separation | Aragonite-dolomite | 69 | -6.4 | -5.2 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 061909-3 | IP-121 | 835 | 121 Sub1 | 325 | Middle | Pond | off white- soft outer | Shell separation | Aragonite | 100 | -6.9 | -10.1 |
| ** | IP-117 | 836 | 117 Vivip1 | 343 | Middle | Pond | pinkish brown- very thin shell | Shell separation | Aragonite-calcite | 49 | -6.7 | -12.2 |
| 092606-5 | IP-112 | 837 | 112 Neb5 | 370 | Middle | Pond | white-soft outer | Shell separation | Aragonite-calcite | 65 | -6.7 | -9.2 |
| 092606-5 | IP-112 | 838 | 112 Vivip6 | 370 | Middle | Pond | pinkish off white- hard inner | Shell separation | Aragonite-calcite | 89 | -6.3 | -10.1 |
| 092606-5 | IP-112 | 839 | 112 Sub7 | 370 | Middle | Pond | light brown pinkish off white- hard inner | Shell separation | Aragonite-dolomite | 93 | -7.1 | -10.0 |
| 092606-5 | IP-112 | 840 | 112 Sub8 | 370 | Middle | Pond | yellowish off white- hard inner | Shell separation | Aragonite-dolomite-calcite | 78 | -8.2 | -10.6 |
| 051413-1 | IP-185 | 841 | 185 Vivip1 | 532 | Middle | Pond | pinkish off white- soft | Shell separation | Aragonite-dolomite | 68 | -4.4 | -6.7 |
| 051413-1 | IP-185 | 842 | 185 Vivip2 | 532 | Middle | Pond | brownish pink off white- soft | Shell separation | Aragonite-dolomite-calcite | 65 | -5.4 | -6.3 |
| 051413-1 | IP-185 | 843 | 185 Vivip3 | 532 | Middle | Pond | pinkish brown- thin shell, soft | Shell separation | Dolomite | 0 | -4.9 | -4.1 |
| 051413-1 | IP-185 | 844 | 185 Vivip4 | 532 | Middle | Pond | brownish pink- thin and soft | Shell separation | Aragonite | 100 | -8.7 | -13.6 |
| 101602-3 | IP-095 | 845 | 95 Neb1 | 590 | Upper | Fluvial | off white- soft outer | Shell separation | Aragonite | 100 | -8.9 | -6.2 |
| 101602-3 | IP-095 | 846 | 95 Sub1 | 590 | Upper | Fluvial | off white- pinkish- soft | Shell separation | Aragonite | 100 | -8.8 | -6.5 |
| 052213-1 | IP-182 | 847 | 182 Neb1 | 622 | Upper | Pond | brown and white- hard | Shell separation | Calcite | 0 | -9.0 | -10.4 |
| ** | IP-092 | 848 | 92 Vivip1 | 668 | Upper | Pond | pink- soft | Shell separation | Aragonite | 100 | 0.3 | -3.5 |

**Appendix II:** Summary of mineral information with relative percentages from XrD analysis and calculated $\delta^{18}O$ values.

| Sample ID | Height in Section (m) | Non-carbonate matrix | Aragonite % | Calcite % | Dolomite % | $\delta^{13}C$ ‰ (VPDB) | $\delta^{18}O$ ‰ (VPDB) Measured | $\delta^{18}O$ ‰ (VPDB) Aragonite (original calculated) |
|---|---|---|---|---|---|---|---|---|
| 96 Sub 1 | 588 | 0 | 0 | 100 | 0 | -4.9 | -11.1 | -15.6 |
| 96 Sub 2 | 588 | 0 | 0 | 100 | 0 | -7.6 | -8.7 | -13.2 |
| 96 Neb 3 | 588 | 0 | 0 | 100 | 0 | -8.2 | -9.1 | -13.6 |
| 96 Neb 4 | 588 | 0 | 0 | 100 | 0 | -8.1 | -8.6 | -13.1 |
| 112 Sub 1 | 370 | Barite | 100 | 0 | 0 | -7.7 | -11.1 | -11.1 |
| 112 Sub 2 | 370 | 0 | 12.4 | 87.6 | 0 | -7.6 | -5.7 | -9.6 |
| 112 Neb 3 | 370 | Barite | 13.7 | 86.3 | 0 | -7.3 | -8.4 | -12.3 |
| 112 Neb 4 | 370 | Quartz | 10.7 | 89.3 | 0 | -6.4 | -7.8 | -11.8 |
| 196 Sub | 179 | Quartz | 67.7 | 0 | 32.3 | -4.5 | -6.8 | -8.4 |
| 198 Sub | 127 | Quartz | 55.1 | 19.8 | 25.1 | -1.3 | -7.5 | -9.7 |
| 198 Vivip1 | 127 | Quartz | 0 | 43.1 | 56.9 | -5.7 | -12.8 | -15.7 |
| 194 Sub1 | 182 | Quartz | 81.7 | 0 | 18.3 | -7.4 | -9.2 | -10.1 |
| L6 Vivip1 | 212 | 0 | 69.4 | 0 | 30.6 | -8.1 | -9.6 | -11.1 |
| L6 Vivip2 | 212 | Quartz | 37.0 | 52.2 | 10.8 | -7.7 | -12.3 | -14.7 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| L6 Vivip3 | 212 | Gypsum+Quartz | 100 | 0 | 0 | -7.9 | -14.6 | -14.6 |
| L6 Vivip4 | 212 | Quartz | 100 | 0 | 0 | -7.0 | -9.8 | -9.8 |
| L7 Neb1 | 256 | Gypsum+Quartz | 52.6 | 0 | 47.4 | -5.2 | -10.1 | -12.5 |
| L7 Neb2 | 256 | Quartz | 44.9 | 0 | 55.1 | -4.4 | -11.2 | -14.0 |
| L7 Neb3 | 256 | Quartz | 68.7 | 0 | 31.3 | -5.1 | -10.0 | -11.6 |
| L7 Neb4 | 256 | Gypsum+Quartz | 67.2 | 0 | 32.8 | -5.3 | -12.7 | -14.4 |
| L7 Neb5 | 256 | Gypsum+Quartz | 49.1 | 0 | 50.9 | -5.3 | -12.2 | -14.8 |
| L7 Vivip1 | 256 | Quartz | 39.5 | 35.6 | 25.0 | -5.1 | -10.3 | -11.9 |
| L7 Vivip2 | 256 | Gypsum+Quartz | 68.6 | 0 | 31.4 | -6.5 | -10.8 | -12.4 |
| L7 Vivip3 | 256 | Gypsum+Quartz | 70.7 | 0 | 29.3 | -6.2 | -12.8 | -14.2 |
| L7 Vivip4 | 256 | Quartz | 62.5 | 24.0 | 13.5 | -4.6 | -10.5 | -11.6 |
| L7 Vivip5 | 256 | Quartz | 63.6 | 19.6 | 16.8 | -3.5 | -12.6 | -14.3 |
| L7 Vivip6 | 256 | Quartz | 58.4 | 22.2 | 19.4 | -5.2 | -12.6 | -14.6 |
| L7 Vivip7 | 256 | Quartz | 89.3 | 0 | 10.7 | -8.0 | -9.2 | -9.7 |
| L7 Vivip8 | 256 | 0 | 100 | 0 | 0 | -5.1 | -13.4 | -13.4 |
| L7 Vivip9 | 256 | Gypsum+Quartz | 62.8 | 22.7 | 14.6 | -3.3 | -7.9 | -8.9 |
| L7 Vivip10 | 256 | Quartz | 70.7 | 0 | 29.3 | -6.6 | -8.4 | -9.9 |
| L8 Neb1 | 293 | Quartz | 47.6 | 0 | 52.4 | -7.5 | -10.9 | -13.5 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| L8 Neb2 | 293 | Quartz | 54.9 | 0 | 45.1 | -5.3 | -4.7 | -7.0 |
| L8 Neb3 | 293 | Quartz | 100 | 0 | 0 | -7.5 | -6.5 | -6.5 |
| L8 Neb4 | 293 | Quartz | 100 | 0 | 0 | -7.3 | -8.5 | -8.5 |
| L8 Neb5 | 293 | Quartz | 71.3 | 0 | 28.7 | -7.7 | -14.6 | -16.1 |
| L8 Vivip1 | 293 | 0 | 100 | 0 | 0 | -7.5 | -6.5 | -6.5 |
| L8 Vivip2 | 293 | Quartz | 100 | 0 | 0 | -5.4 | -14.5 | -14.5 |
| L8 Vivip3 | 293 | Barite+Quartz | 100 | 0 | 0 | -7.5 | -7.5 | -7.5 |
| L8 Vivip4 | 293 | 0 | 82.7 | 0 | 17.3 | -7.9 | -7.5 | -8.4 |
| L8 Vivip5 | 293 | 0 | 91.2 | 0 | 8.8 | -7.7 | -7.3 | -7.8 |
| L9 Neb1 | 315 | Barite+Gypsum+Quartz | 100 | 0 | 0 | -4.1 | 0.6 | 0.6 |
| L9 Neb2 | 315 | Quartz | 55.1 | 19.8 | 25.1 | -2.4 | -6.0 | -8.2 |
| L9 Neb3 | 315 | Quartz | 55.9 | 0 | 44.1 | -2.7 | -6.2 | -8.5 |
| L9 Neb4 | 315 | Quartz | 74.9 | 25.1 | 0 | -7.2 | -6.2 | -7.3 |
| L9 Neb5 | 315 | Barite+Quartz | 100 | 0 | 0 | -4.6 | -0.7 | -0.7 |
| L9 Neb6 | 315 | Barite | 70.1 | 0 | 29.9 | -5.2 | -7.9 | -9.4 |
| L9 Neb7 | 315 | Barite+Gypsum+Quartz | 100 | 0 | 0 | -0.8 | -4.6 | -4.6 |
| L9 Neb8 | 315 | Barite+Quartz | 100 | 0 | 0 | -4.9 | -12.4 | -12.4 |
| L9 Neb9 | 315 | Barite+Quartz | 68.0 | 0 | 32.0 | -3.4 | 1.1 | -0.5 |
| L9 Vivip1 | 315 | Quartz | 100 | 0 | 0 | -0.7 | -2.1 | -2.1 |
| L9 Vivip2 | 315 | Barite+Quartz | 62.2 | 0 | 37.8 | -5.4 | -5.7 | -7.6 |
| L9 Vivip3 | 315 | Barite+Quartz | 68.7 | 0 | 31.3 | -6.4 | -5.2 | -6.8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 121 Sub1 | 325 | Barite | 100 | 0 | 0 | -6.9 | -10.1 | -10.1 |
| 117 Vivip1 | 343 | Quartz | 49.2 | 50.8 | 0 | -6.7 | -12.2 | -14.5 |
| 112 Neb5 | 370 | Barite+Quartz | 64.6 | 35.4 | 0 | -6.7 | -9.2 | -10.8 |
| 112 Vivip6 | 370 | Quartz | 89.0 | 11.0 | 0 | -6.3 | -10.1 | -10.6 |
| 112 Sub7 | 370 | Barite+Quartz | 92.9 | 0 | 7.1 | -7.1 | -10.0 | -10.3 |
| 112 Sub8 | 370 | Barite+Quartz | 77.6 | 12.7 | 9.7 | -8.2 | -10.6 | -11.7 |
| 185 Vivip1 | 532 | Gypsum+Quartz | 67.6 | 0 | 32.4 | -4.4 | -6.7 | -8.3 |
| 185 Vivip2 | 532 | Kaolinite+Quartz | 65.4 | 15.3 | 19.3 | -5.4 | -6.3 | -8.0 |
| 185 Vivip3 | 532 | Quartz | 0 | 0 | 100 | -4.9 | -4.1 | -9.2 |
| 185 Vivip4 | 532 | Gypsum+Quartz | 100 | 0 | 0 | -8.7 | -13.6 | -13.6 |
| 95 Neb1 | 590 | Barite | 100 | 0 | 0 | -8.9 | -6.2 | -6.2 |
| 95 Sub1 | 590 | Barite | 100 | 0 | 0 | -8.8 | -6.5 | -6.5 |
| 182 Neb1 | 622 | Quartz | 0 | 100 | 0 | -9.0 | -10.4 | -14.9 |
| 92 Vivip1 | 668 | Barite | 100 | 0 | 0 | 0.3 | -3.5 | -3.5 |

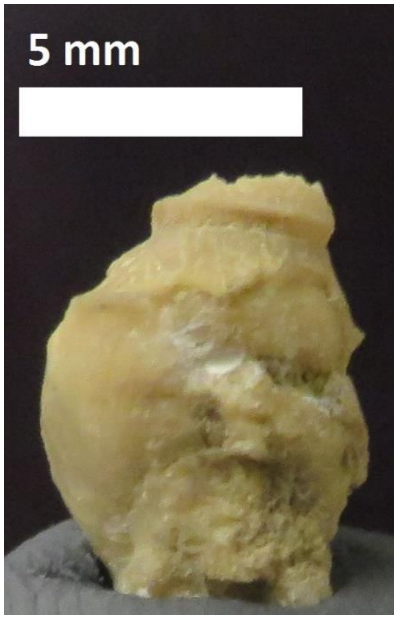
**Appendix III:** X-ray Diffraction Spectra Compendium

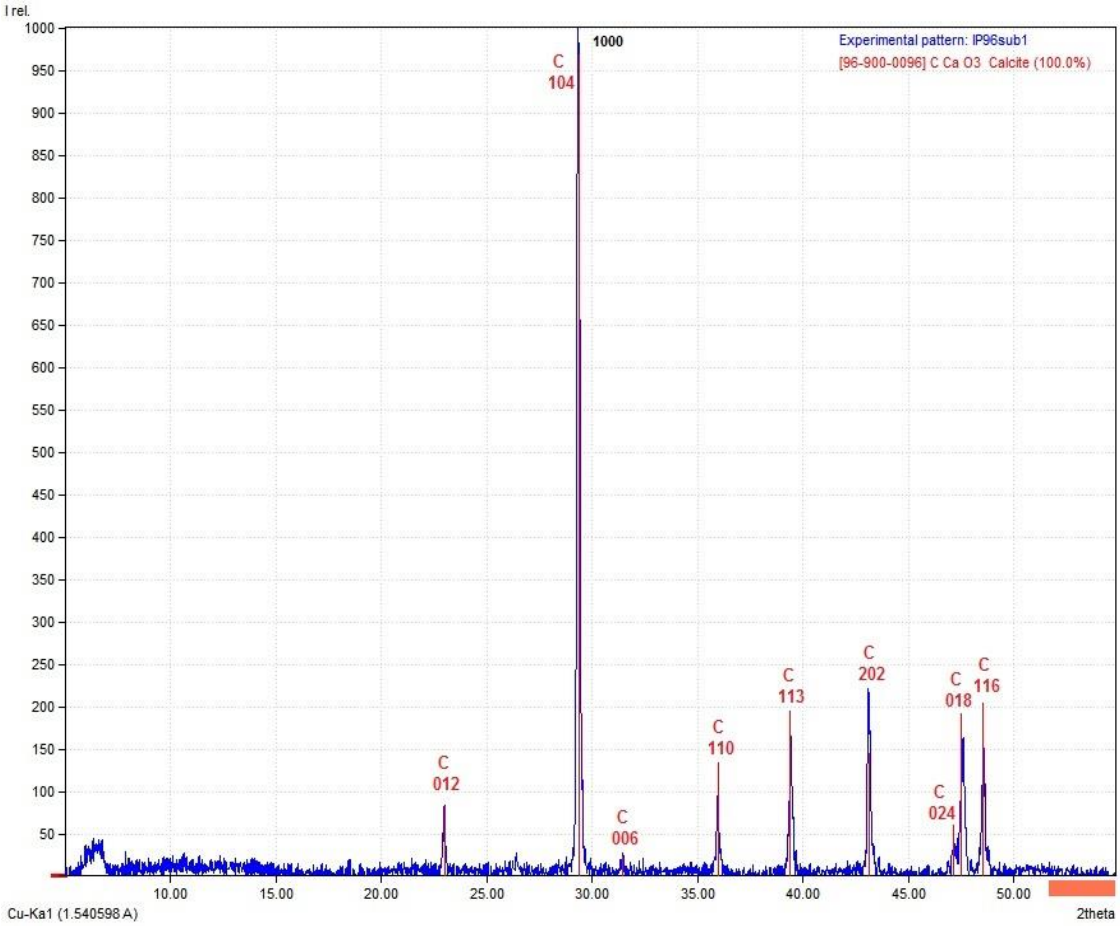
**Sample:** 96-Sub1

**Method:** Bulk Crush

**Height in Section:** 588 m

**Mineralogy:** Calcite



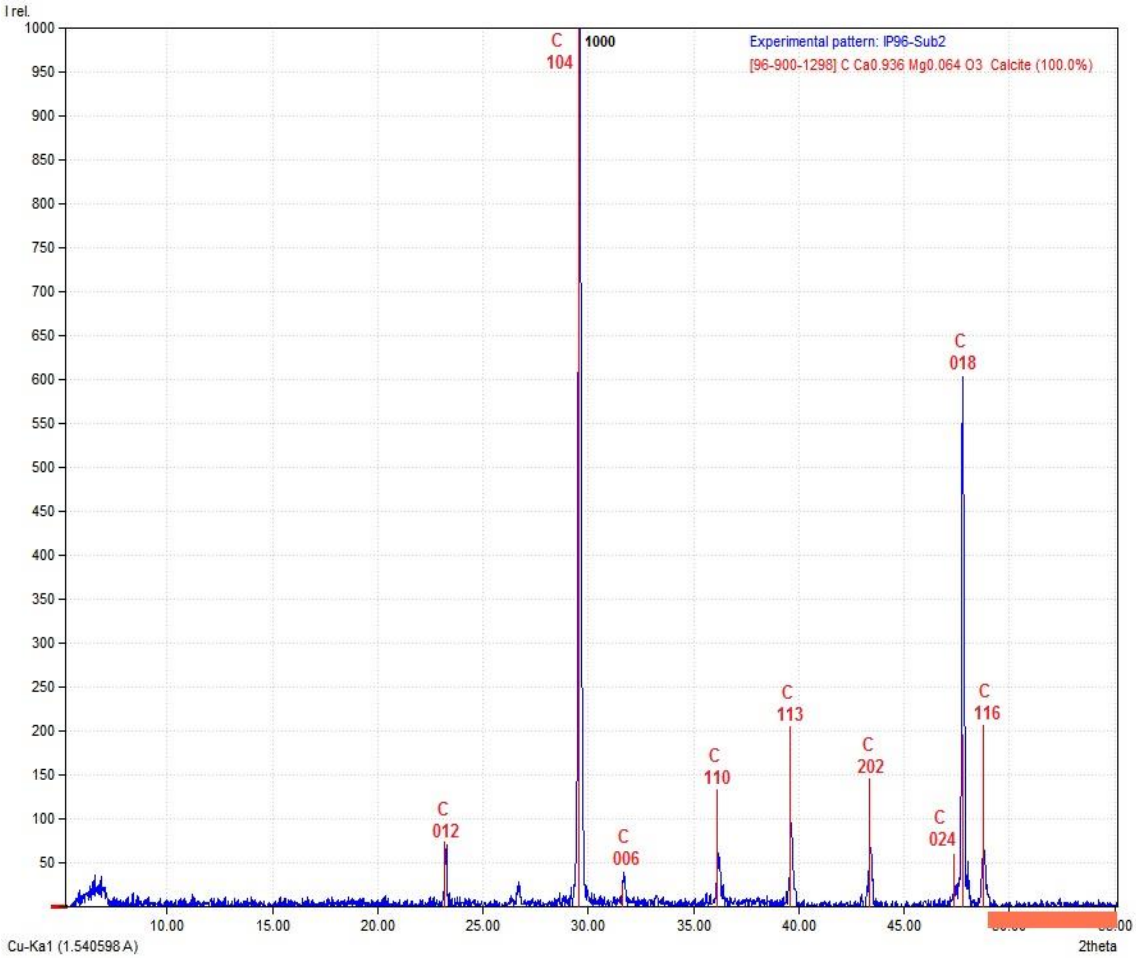



**Sample:** 96-Sub2

**Method:** Bulk Crush

**Height in Section:** 588 m

**Mineralogy:** Calcite

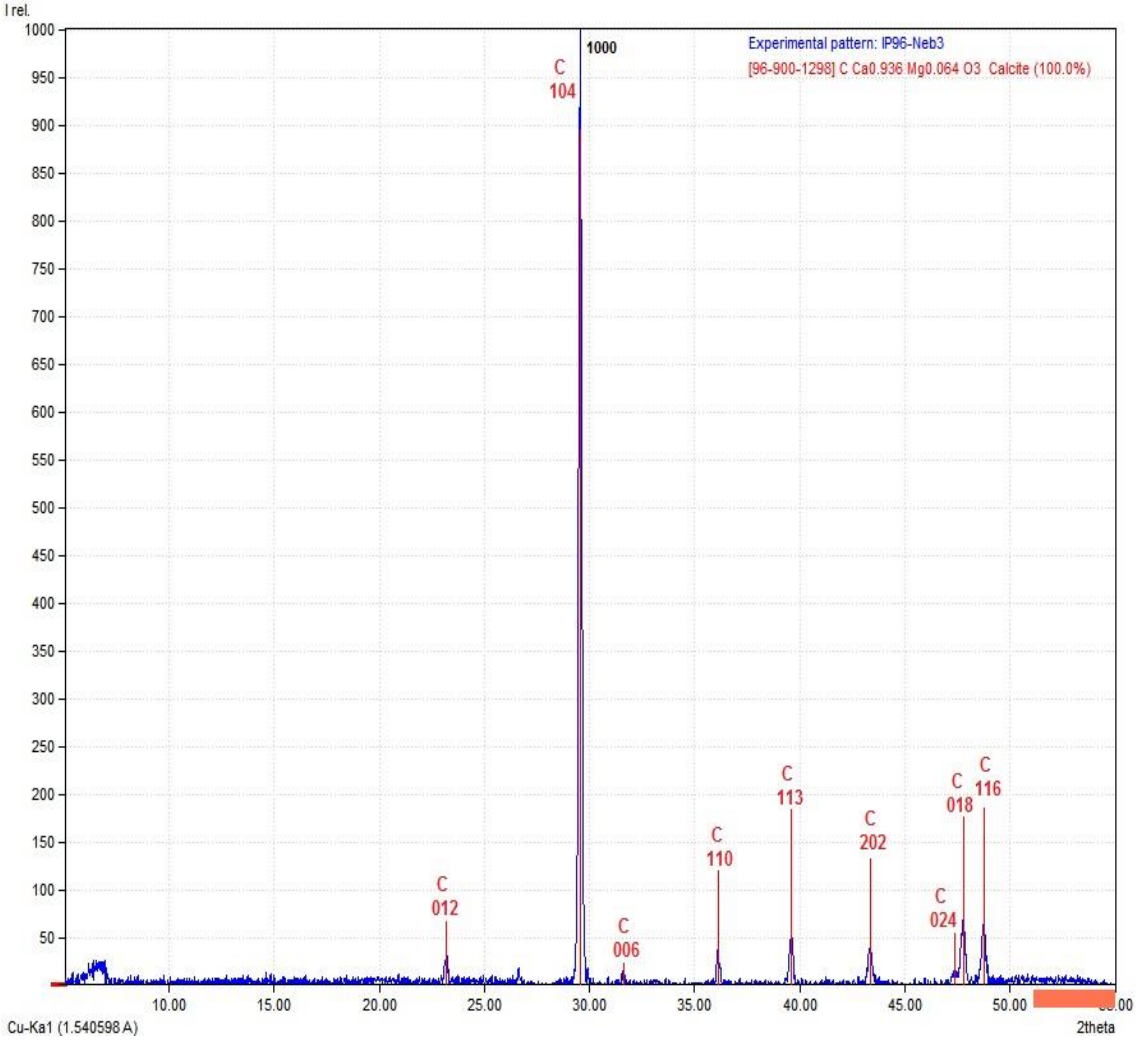



**Sample:** 96-Neb3

**Method:** Bulk Crush

**Height in Section:** 588 m

**Mineralogy:** Calcite

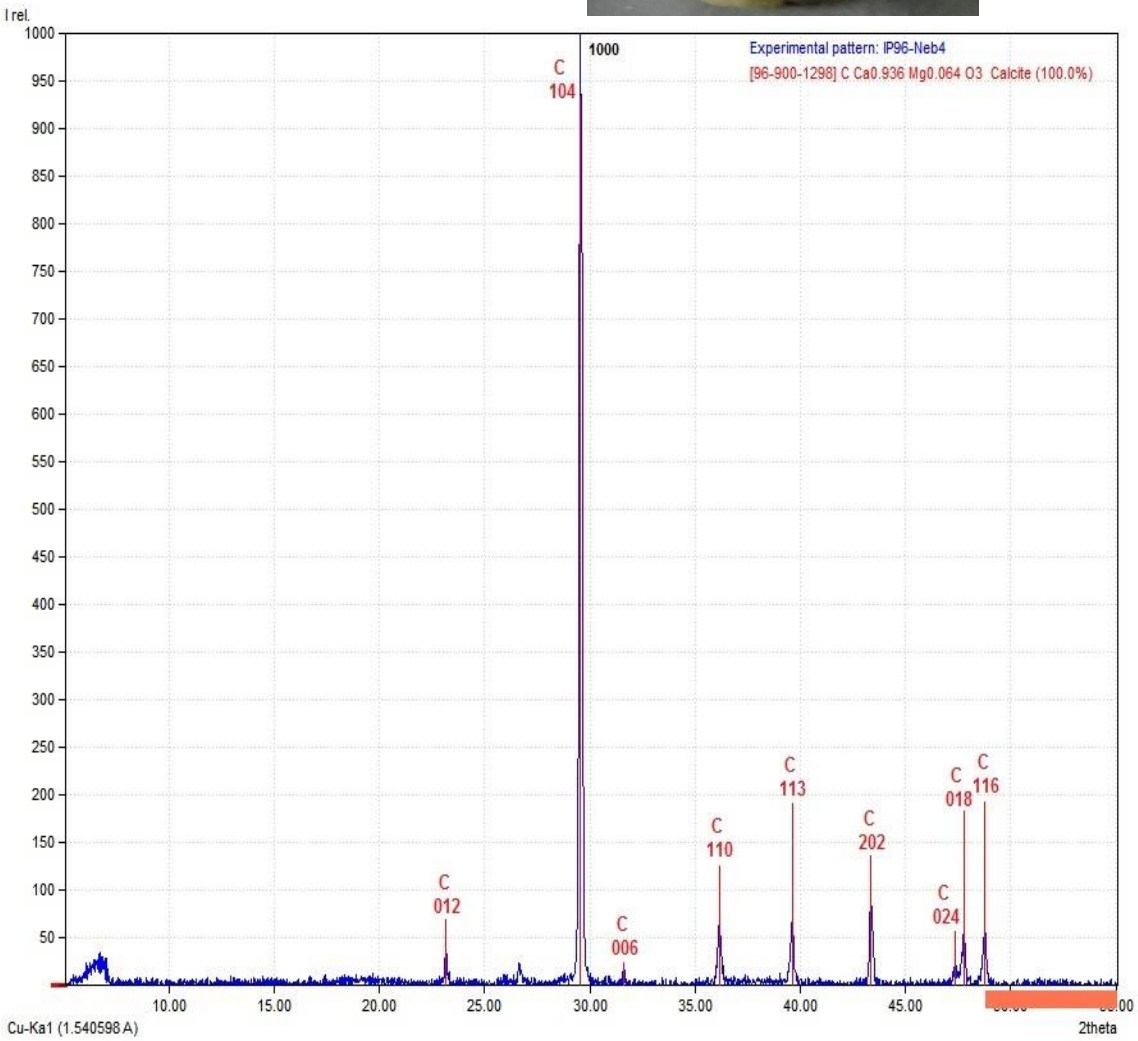



**Sample:** 96-Neb4

**Method:** Bulk Crush

**Height in Section:** 588 m

**Mineralogy:** Calcite

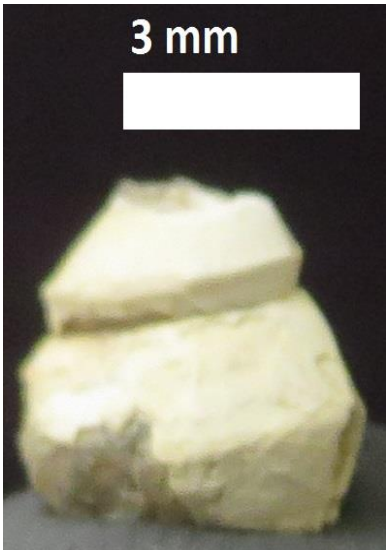



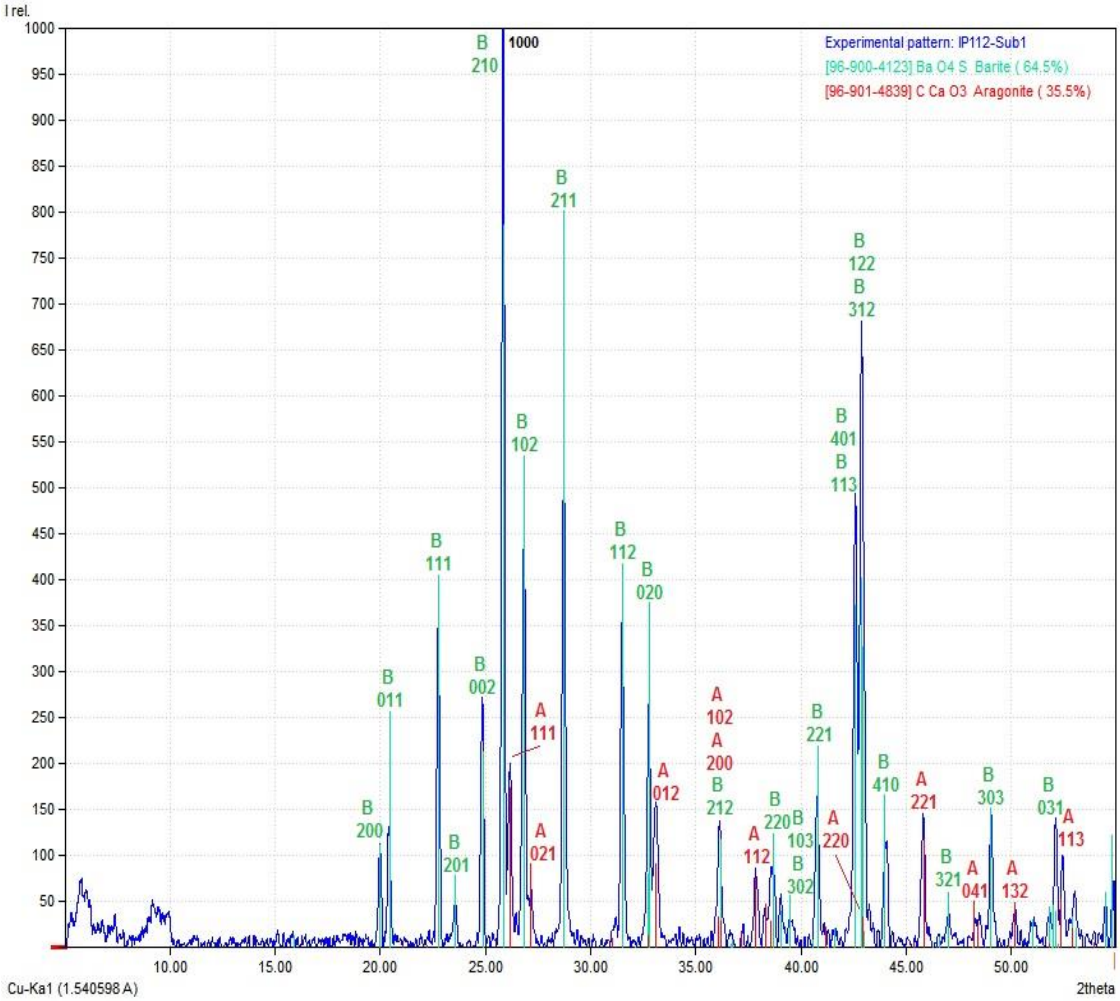
**Sample:** 112-Sub1

**Method:** Bulk Crush

**Height in Section:** 370 m

**Mineralogy:** Barite, aragonite



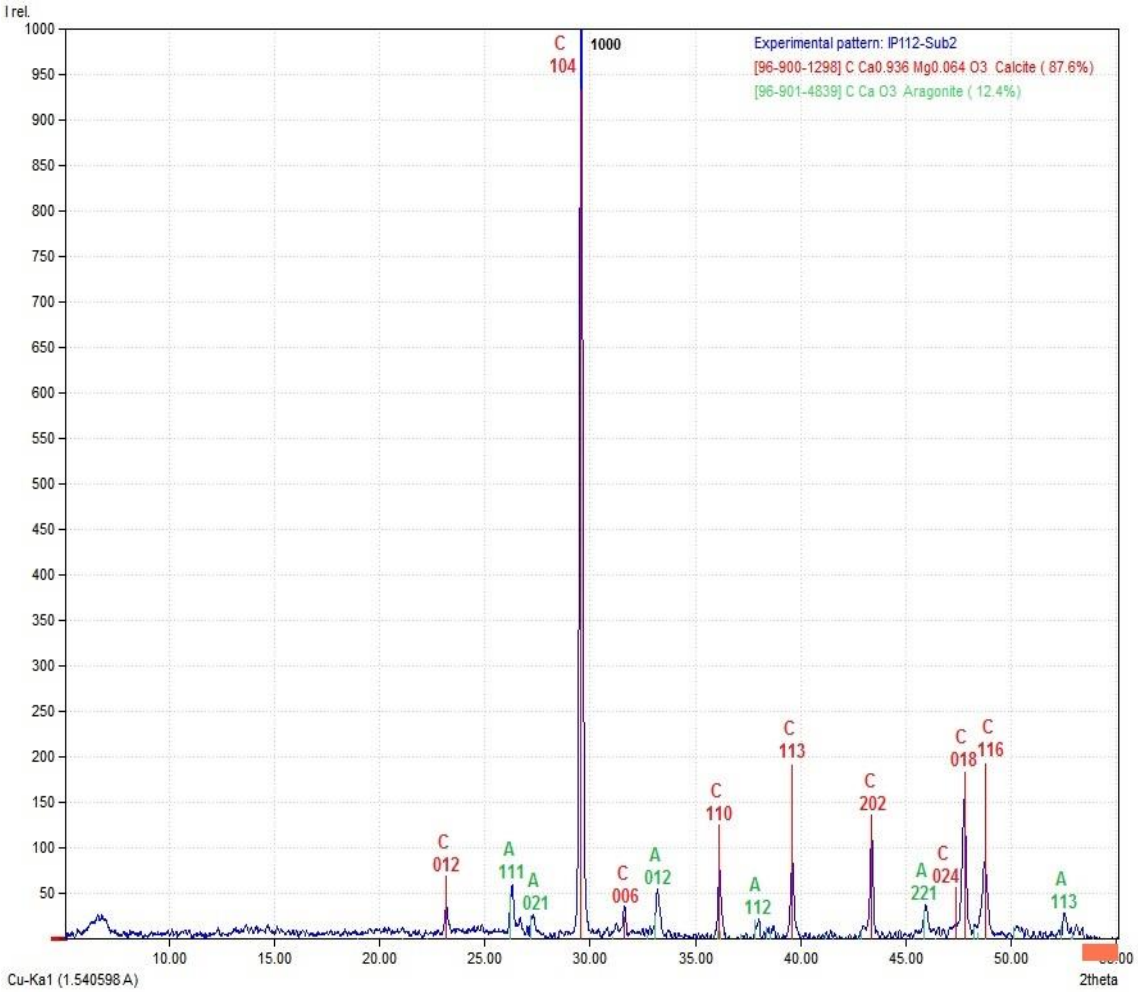



**Sample:** 112-Sub2

**Method:** Bulk Crush

**Height in Section:** 370 m

**Mineralogy:** Calcite and aragonite

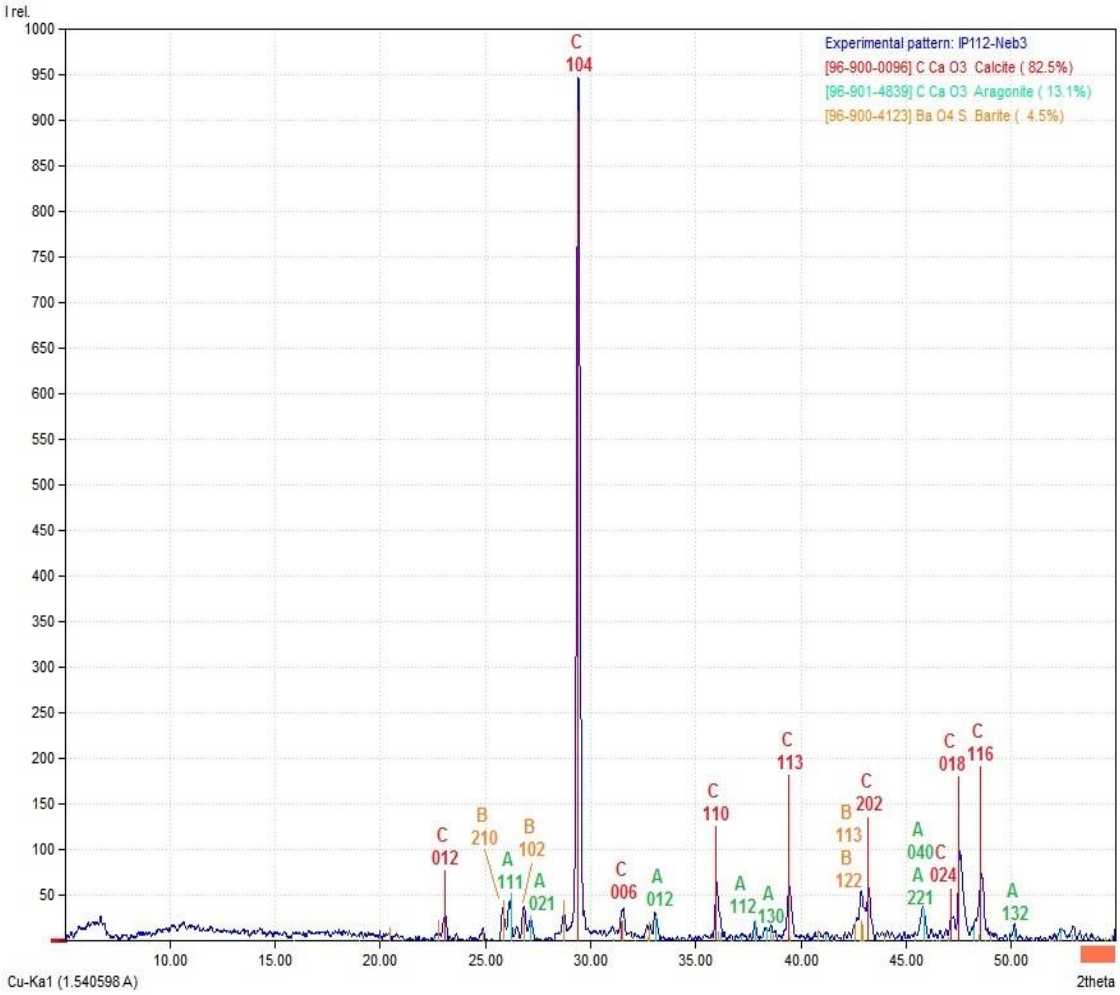



**Sample:** 112-Neb3

**Method:** Bulk Crush

**Height in Section:** 370 m

**Mineralogy:** Calcite, aragonite, barite

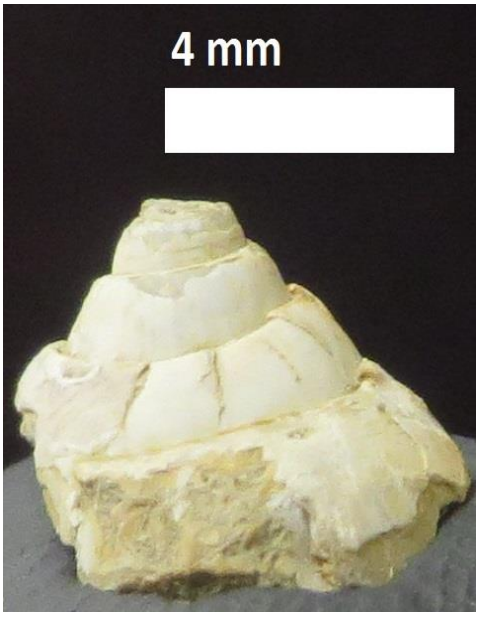



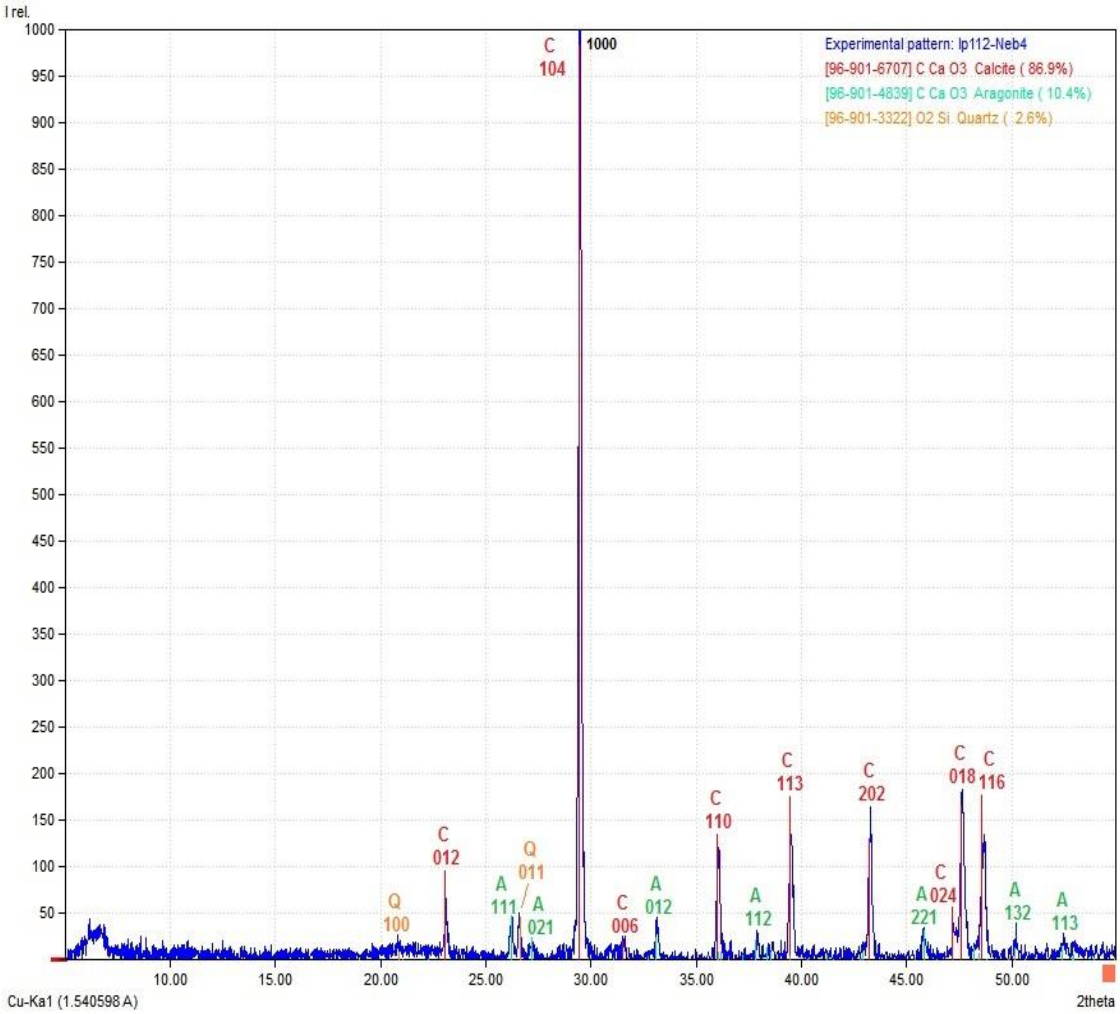
**Sample:** 112-Neb4

**Method:** Bulk Crush

**Height in Section:** 370 m

**Mineralogy:** Calcite, aragonite, barite



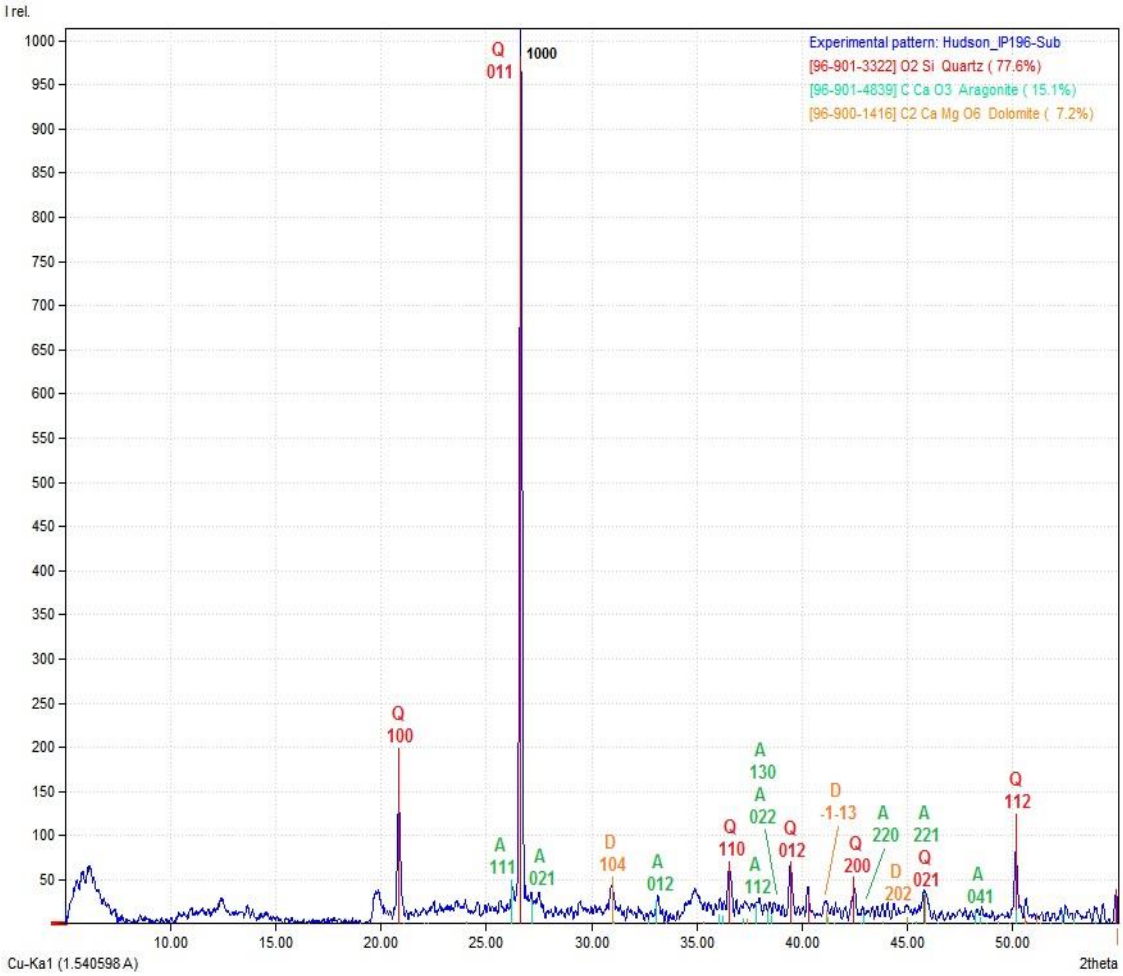



**Sample:** 196-Sub

**Method:** Bulk Crush

**Height in Section:** 179 m

**Mineralogy:** Quartz, aragonite, dolomite

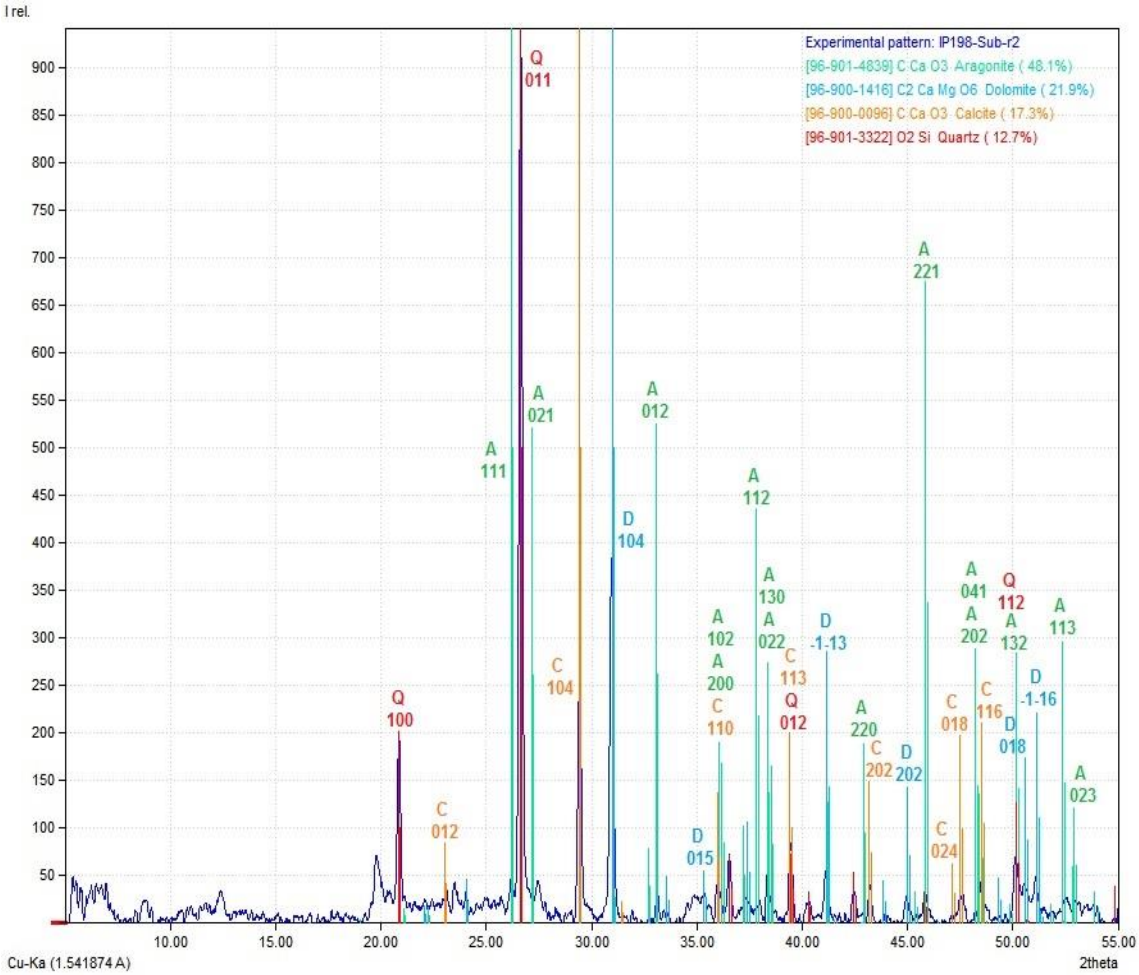



**Sample:** 198-Sub

**Method:** Bulk Crush

**Height in Section:** 127 m

**Mineralogy:** Aragonite, dolomite, calcite, and quartz

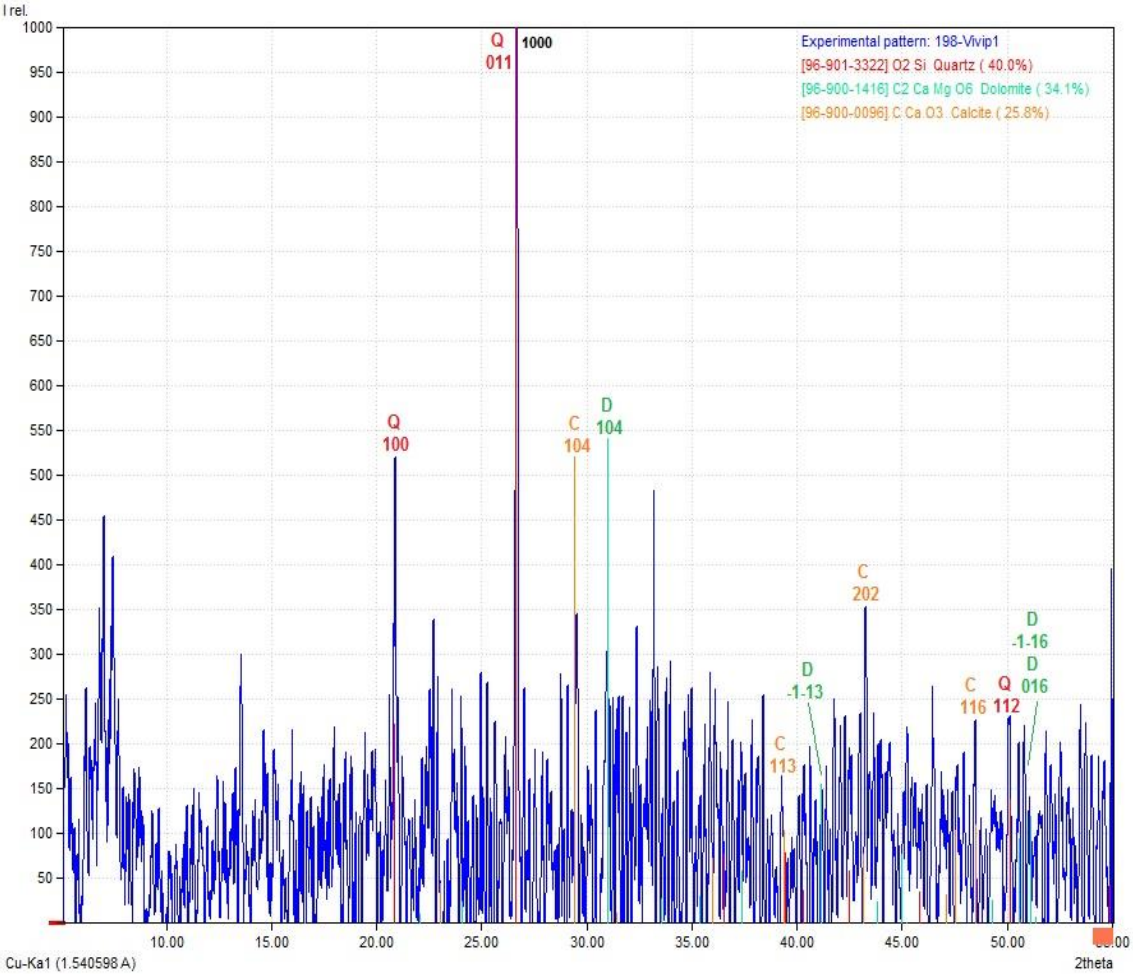



**Sample:** 198-Vivip1

**Method:** Shell Separation

**Height in Section:** 127 m

**Mineralogy:** Quartz, dolomite, and calcite

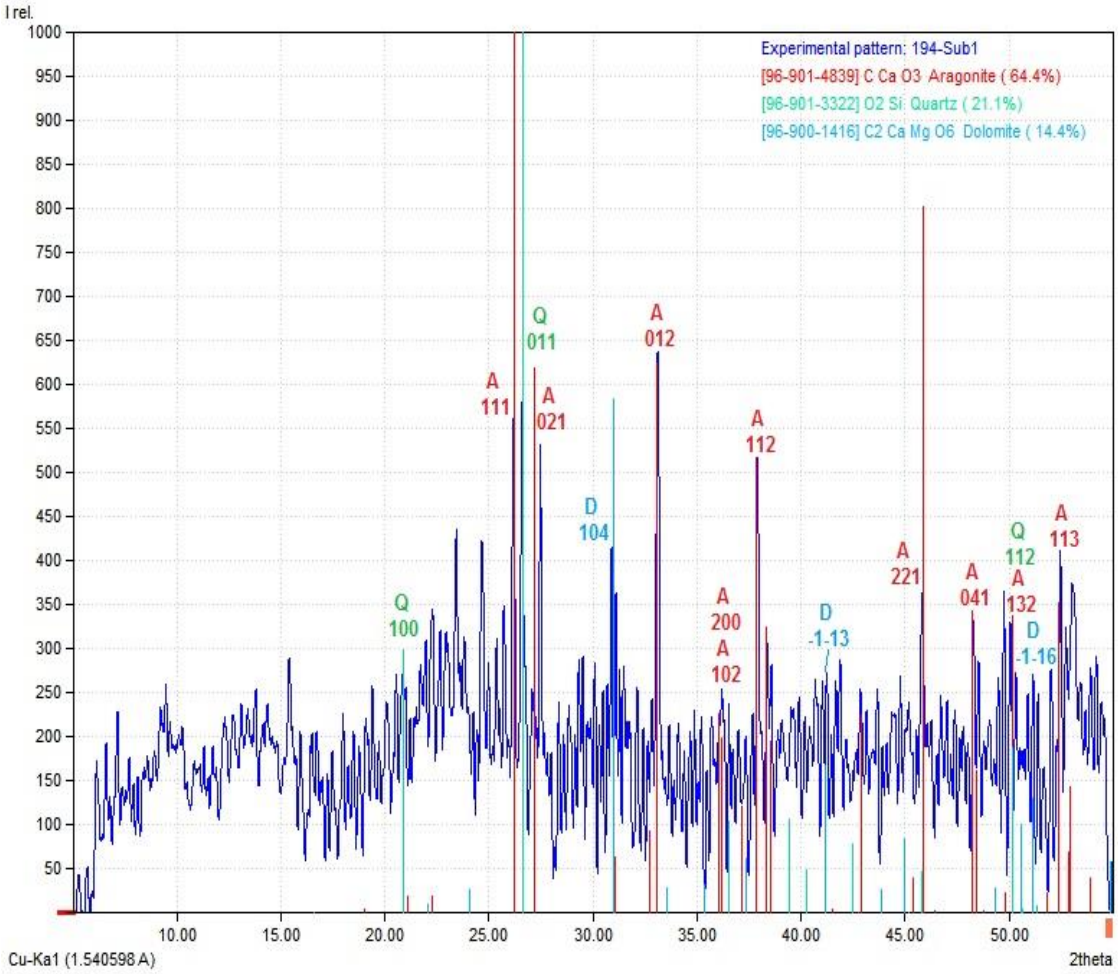



**Sample:** 194-Sub1

**Method:** Shell Separation

**Height in Section:** 182 m

**Mineralogy:** Aragonite, quartz, and dolomite

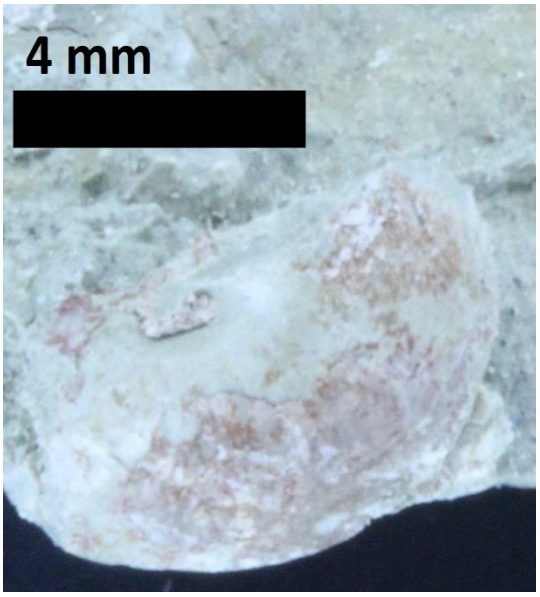



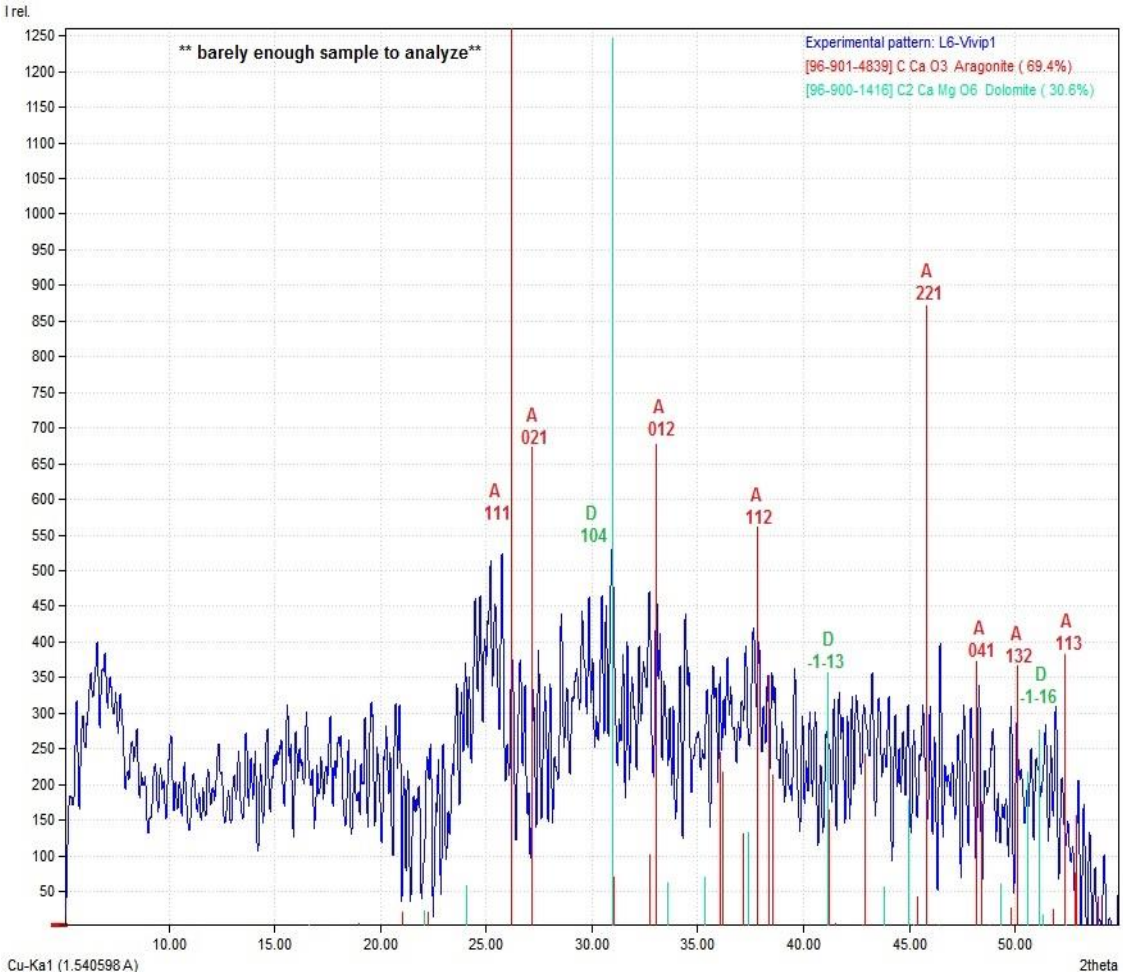
**Sample:** L6-Vivip1

**Method:** Shell Separation

**Height in Section:** 212 m

**Mineralogy:** Aragonite and dolomite



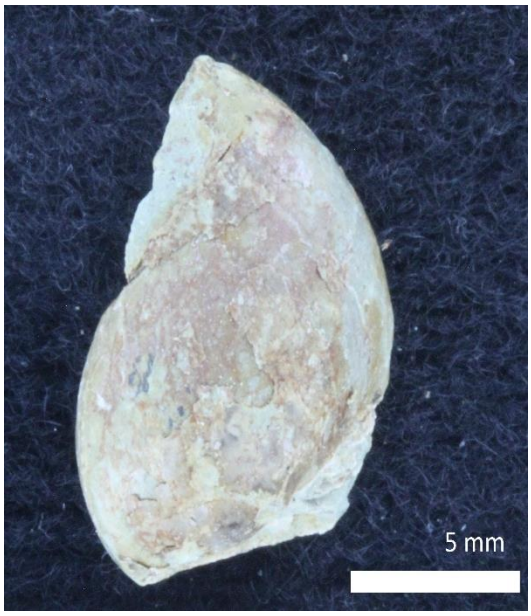



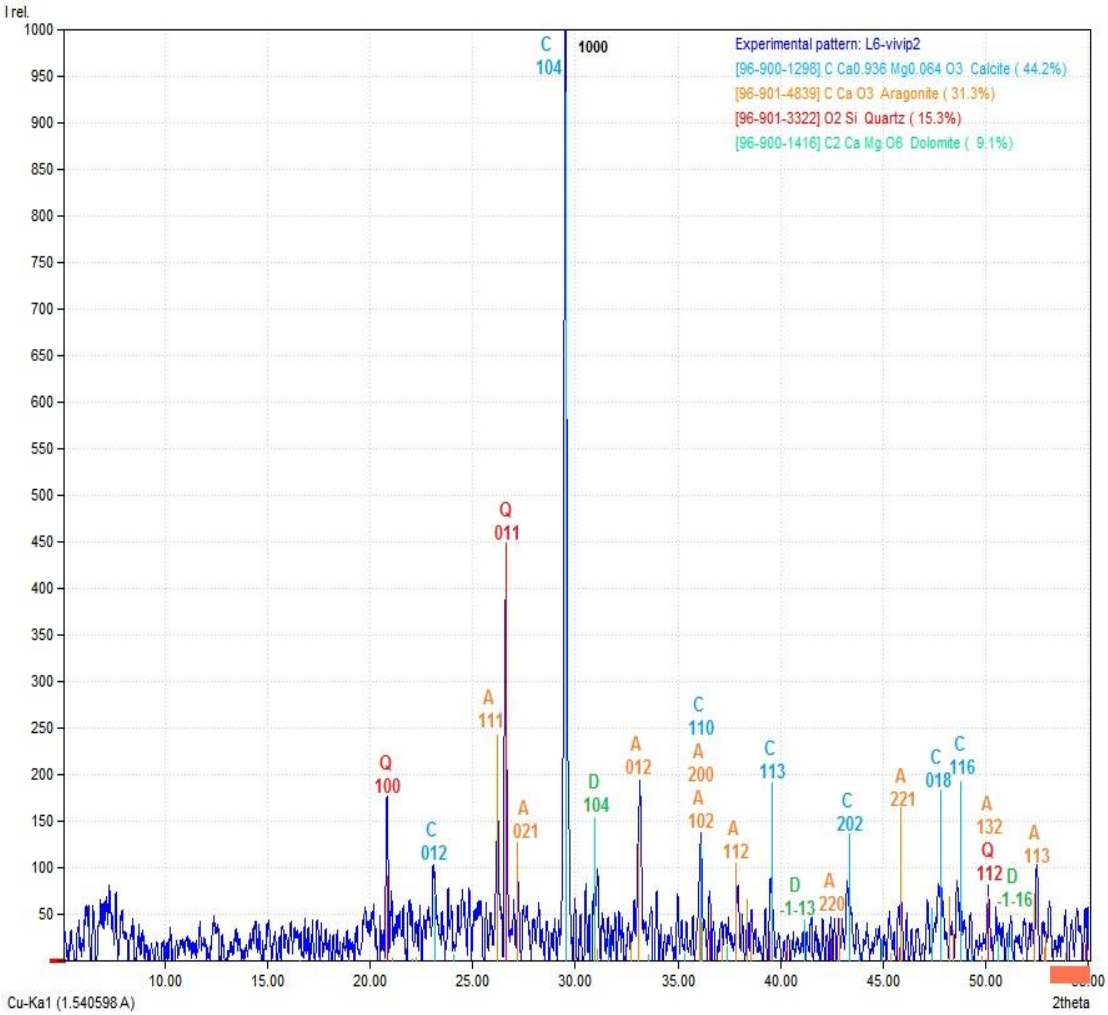
**Sample:** L6-Vivip2

**Method:** Shell Separation

**Height in Section:** 212 m

**Mineralogy:** Calcite, aragonite, quartz, and dolomite



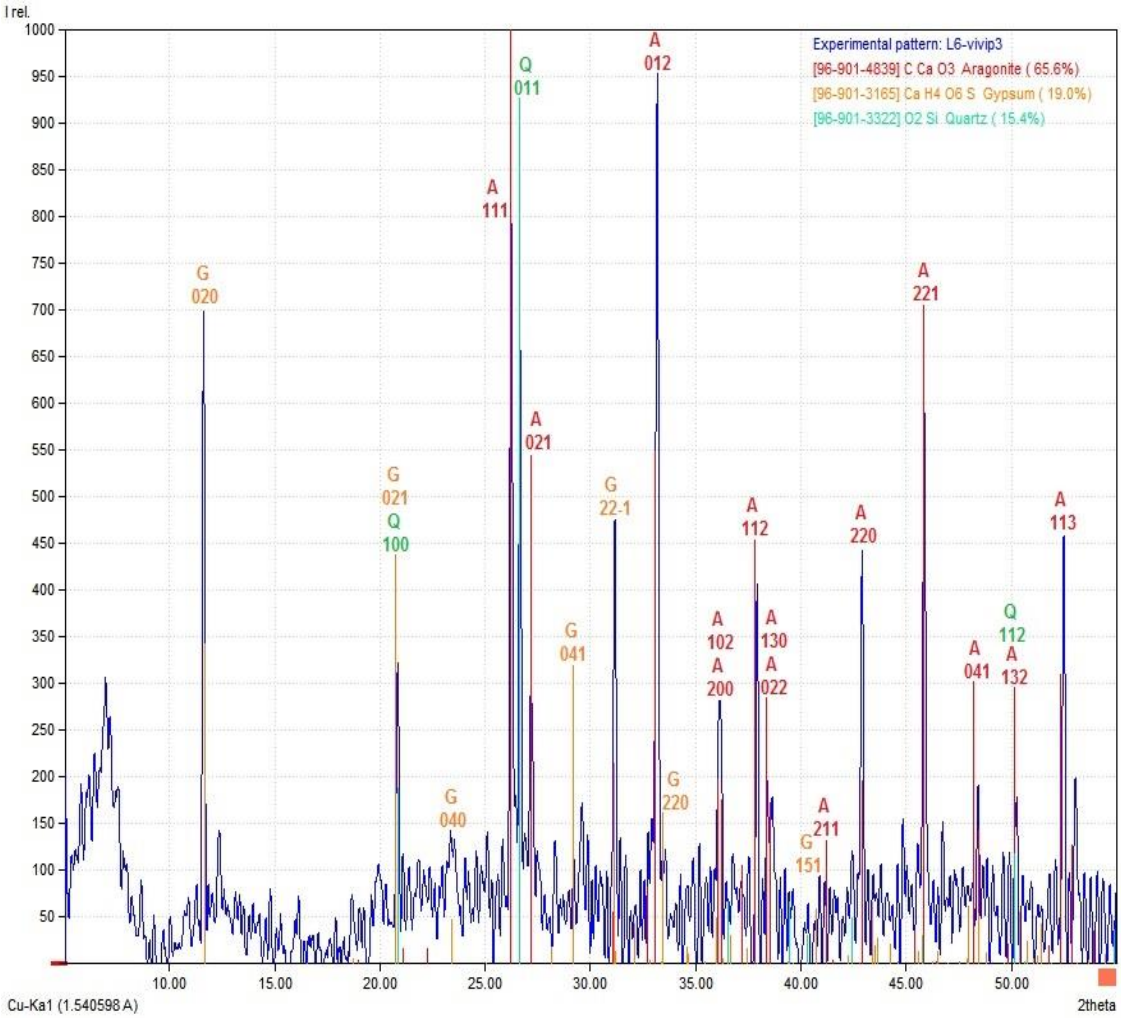



**Sample:** L6-Vivip3

**Method:** Shell Separation

**Height in Section:** 212 m

**Mineralogy:** Aragonite, gypsum, and quartz

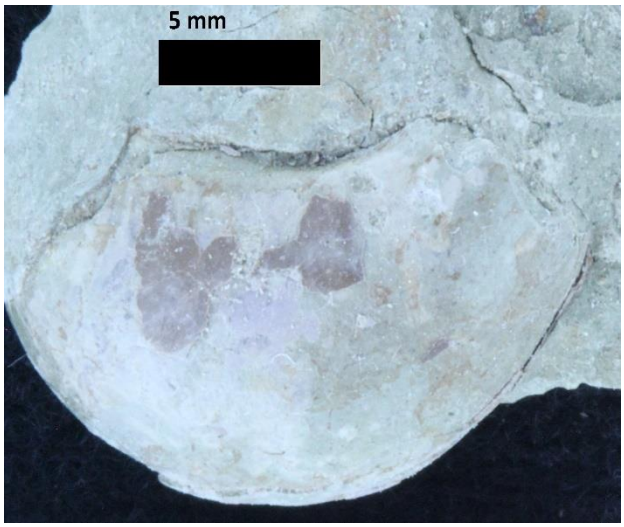



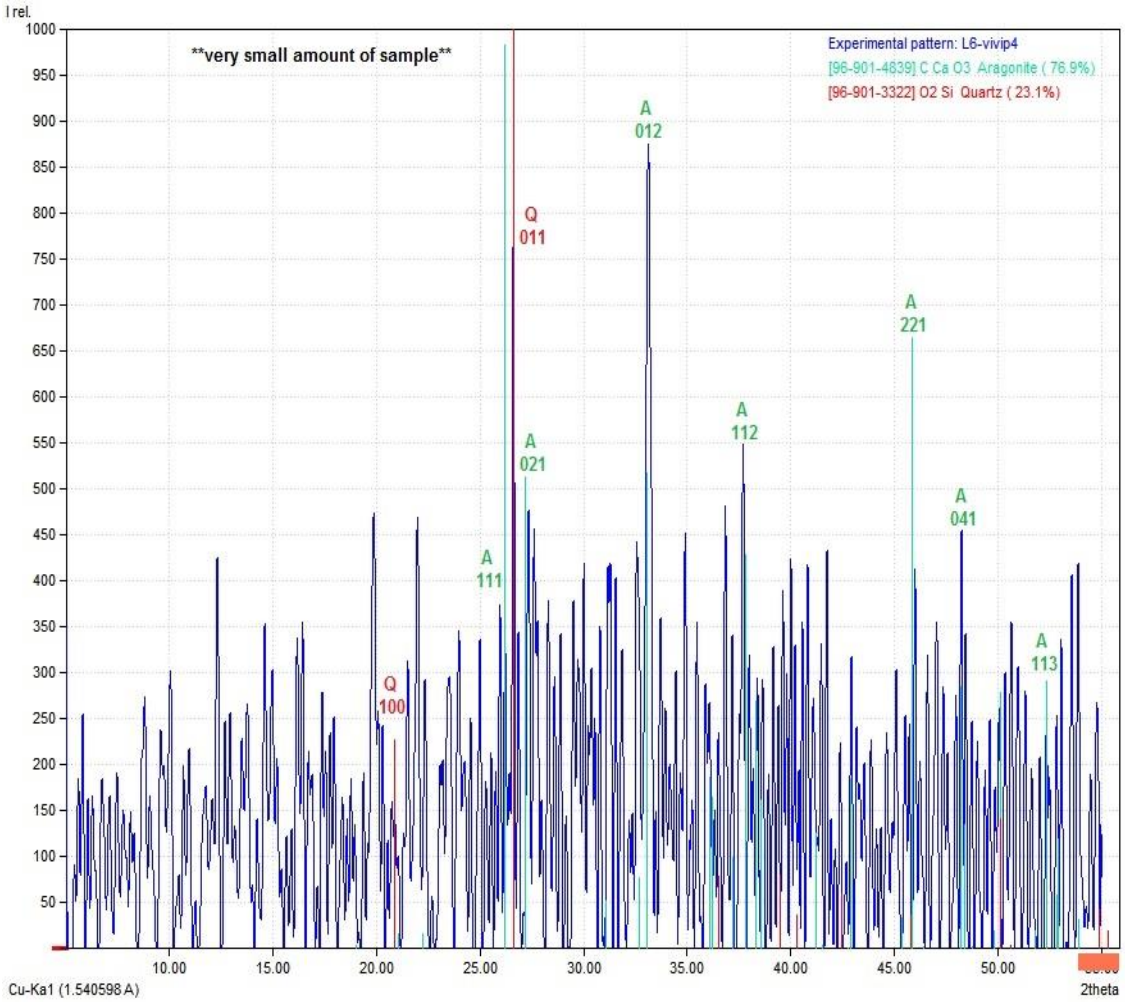
**Sample:** L6-Vivip4

**Method:** Shell Separation

**Height in Section:** 212 m

**Mineralogy:** Aragonite, quartz



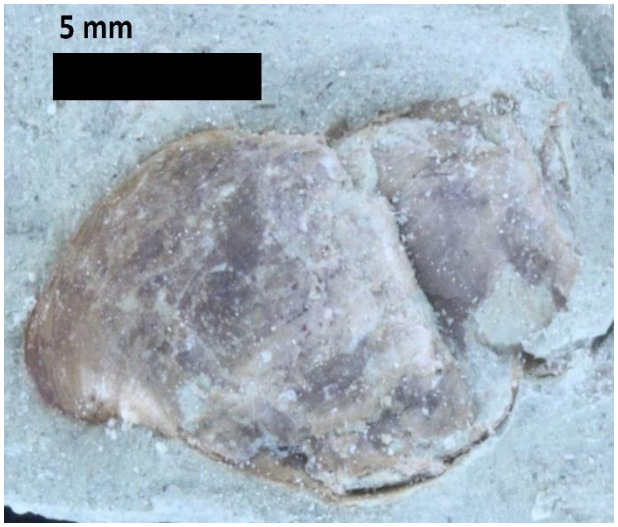



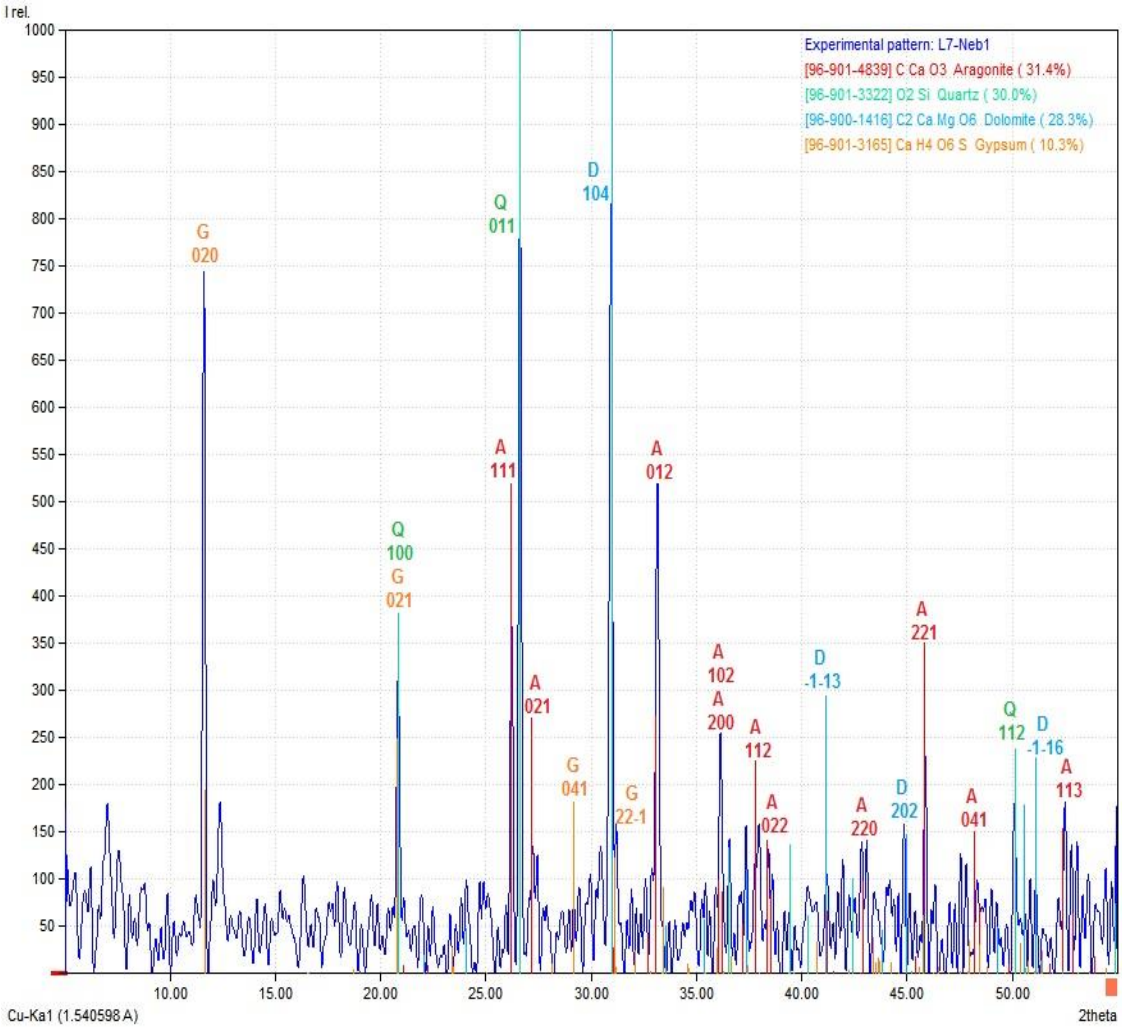
**Sample:** L7-Neb1

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, quartz, dolomite, and gypsum



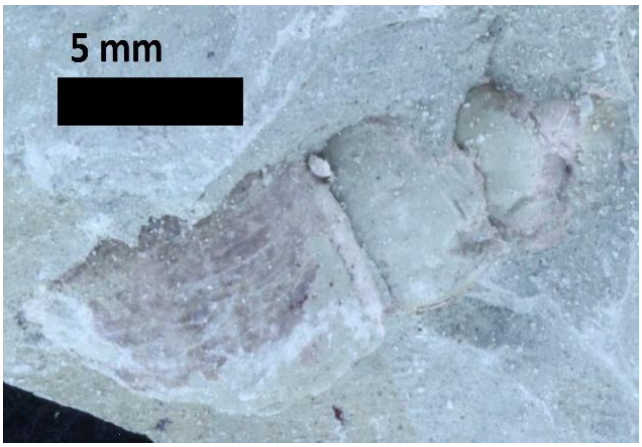



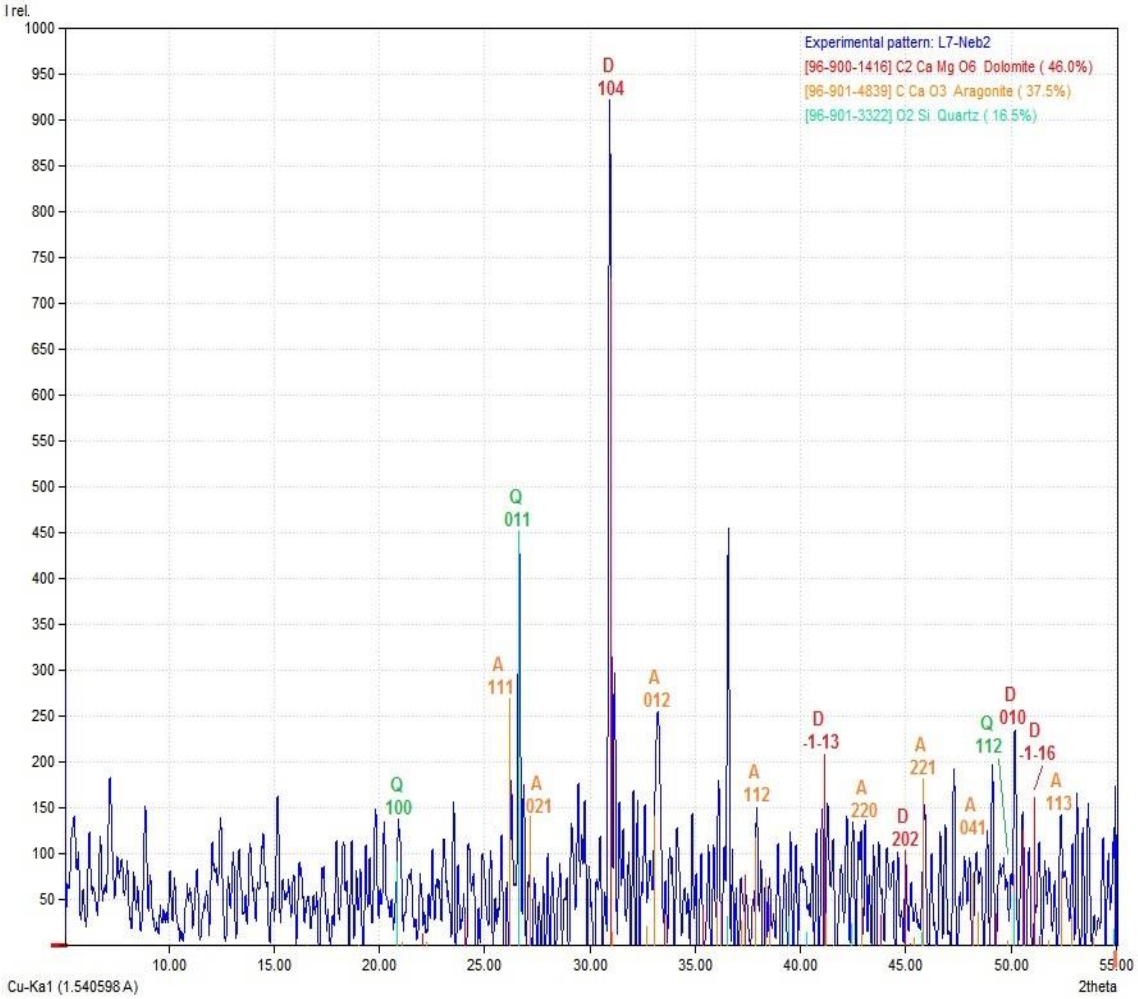
**Sample:** L7-Neb2

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Dolomite, aragonite, and quartz



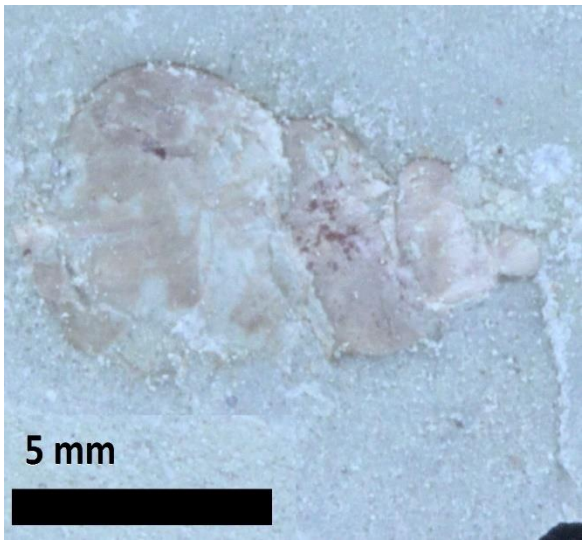



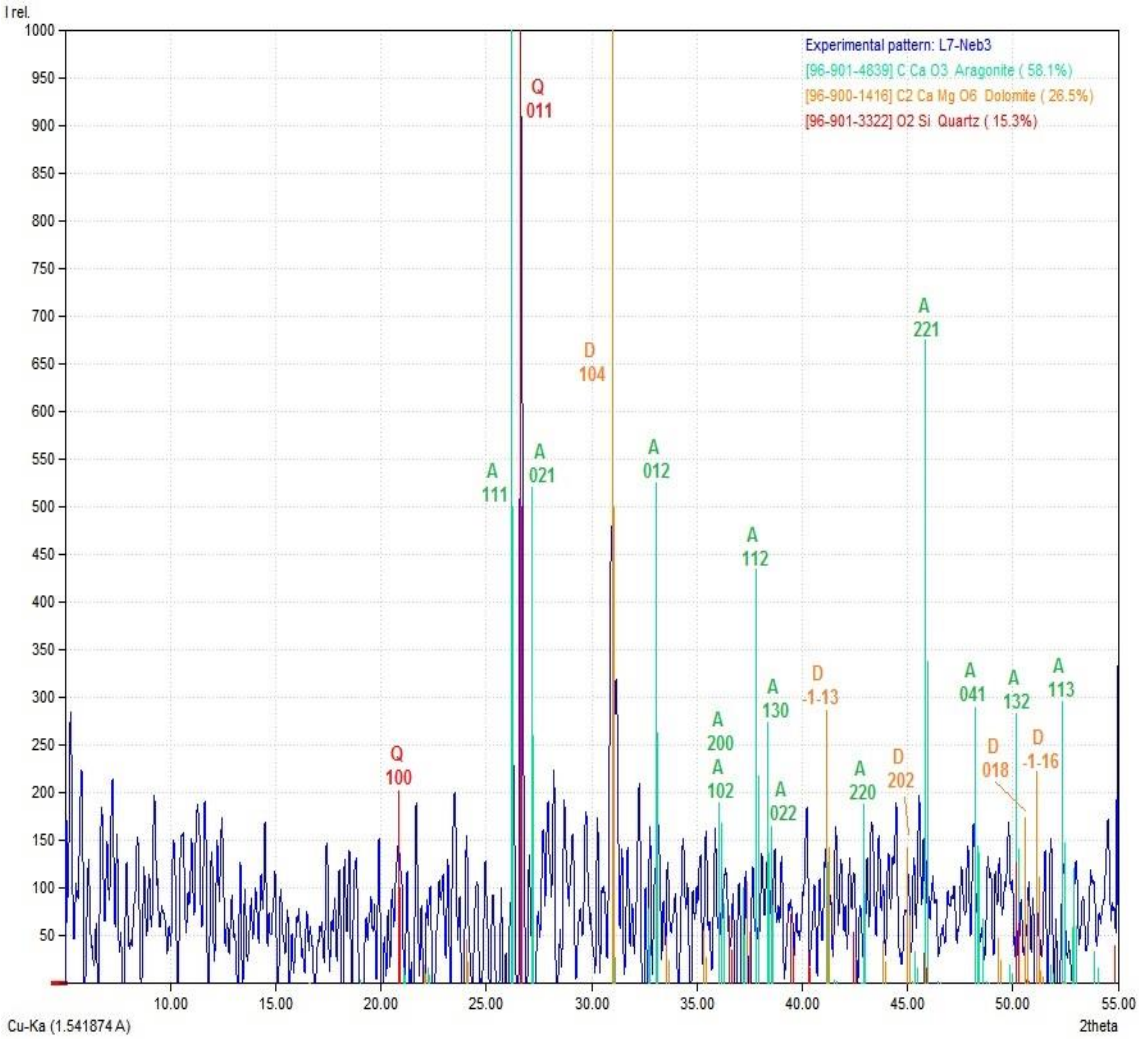
**Sample:** L7-Neb3

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, dolomite, and quartz



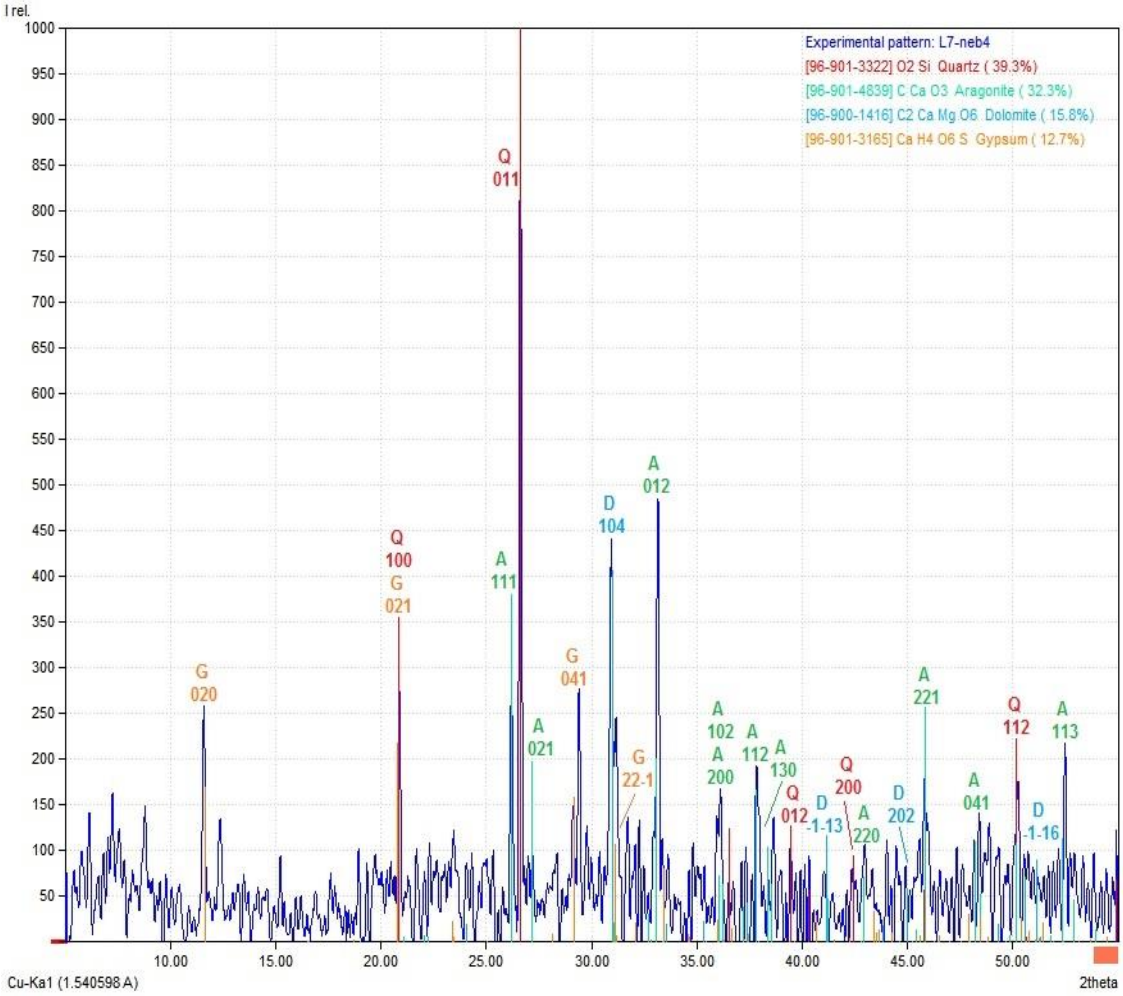



**Sample:** L7-Neb4

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Quartz, aragonite, dolomite, and gypsum

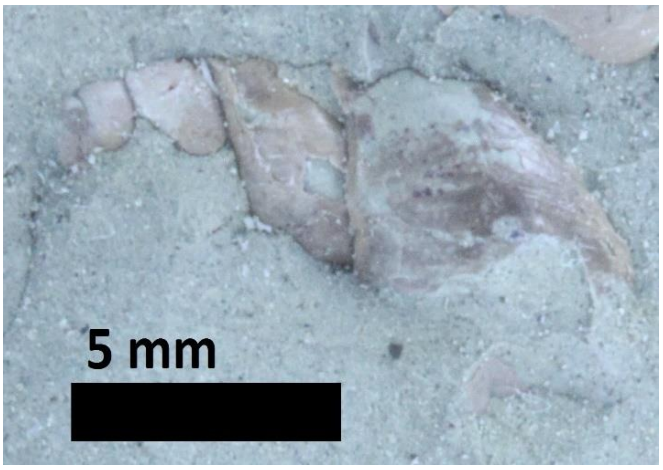



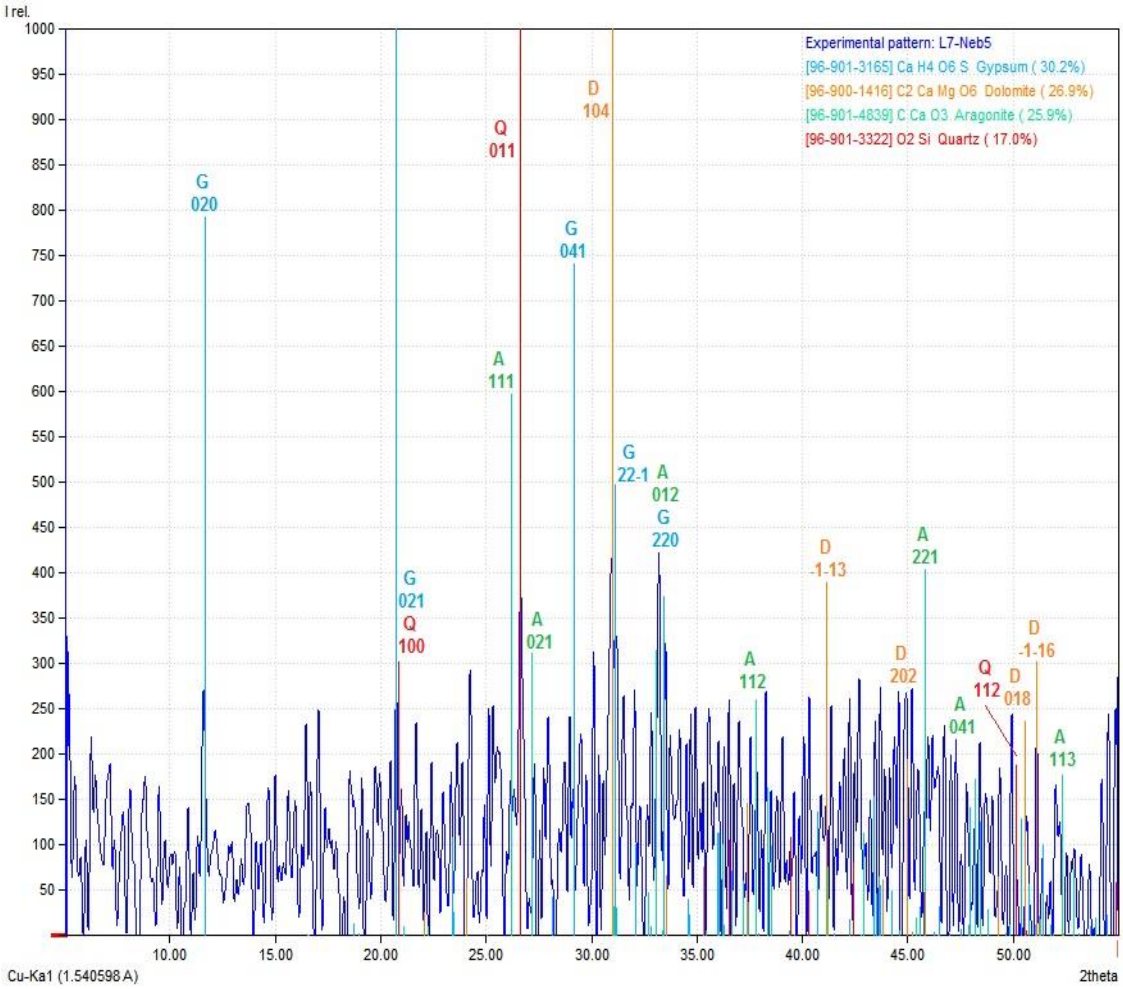
**Sample:** L7-Neb5

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Gypsum, dolomite, aragonite, quartz



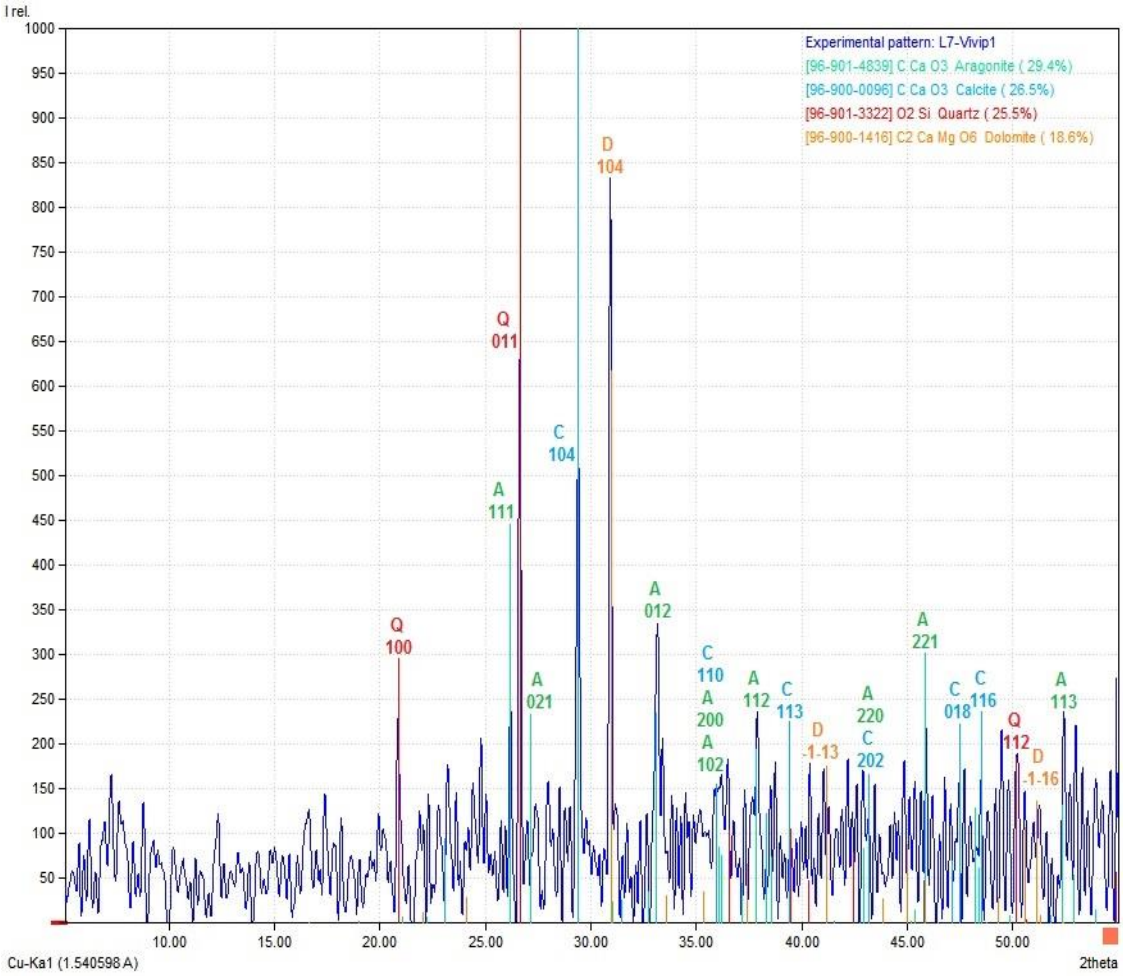



**Sample:** L7-Vivip1

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, calcite, quartz, and dolomite

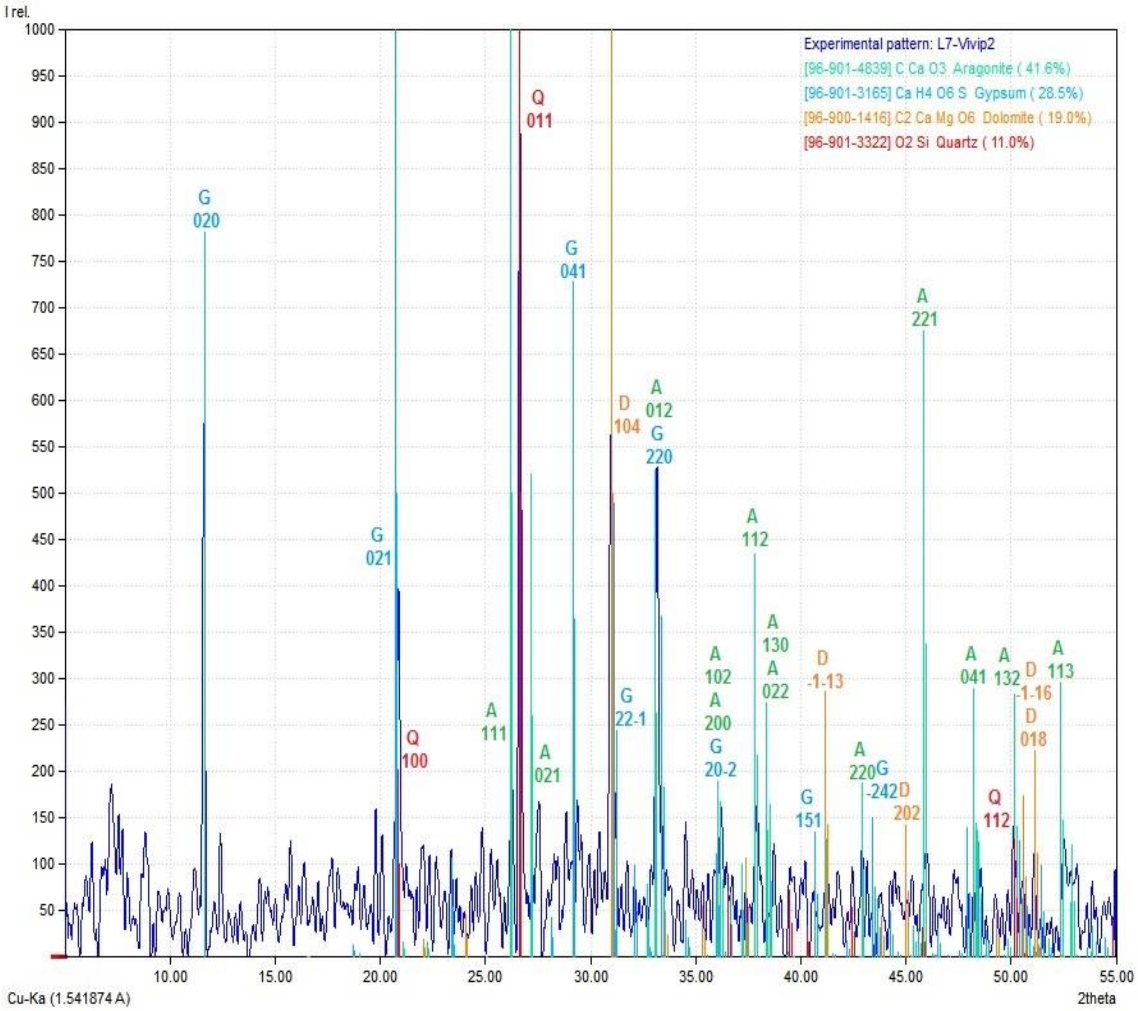



**Sample:** L7-Vivip2

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, gypsum, dolomite, quartz

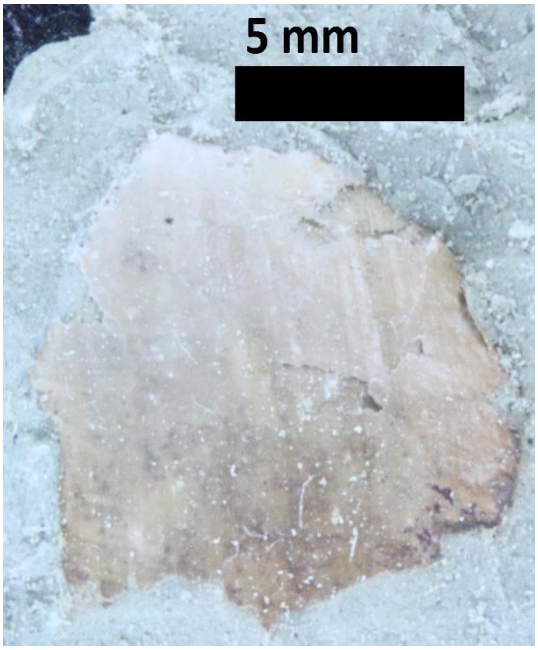



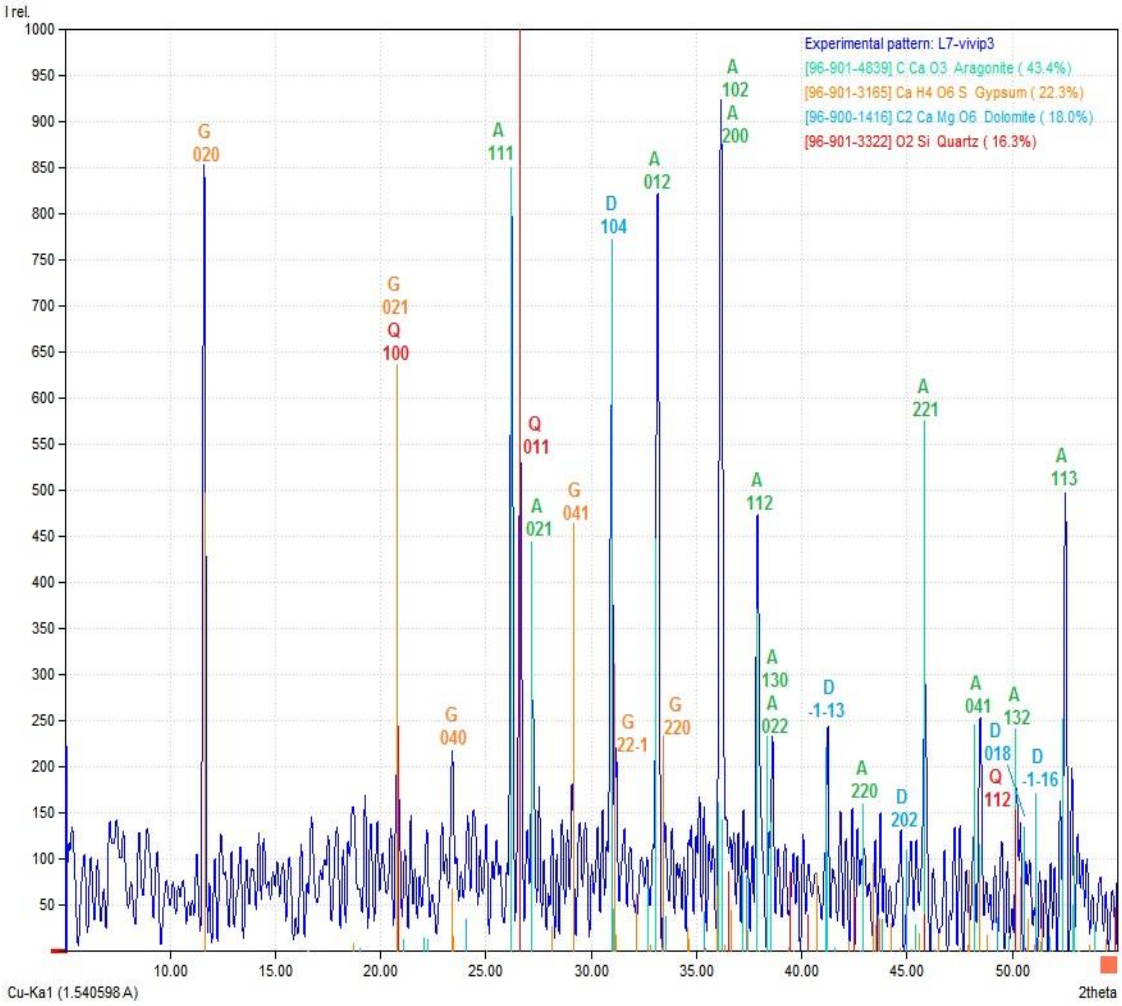
**Sample:** L7-Vivip3

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, gypsum, dolomite, and quartz



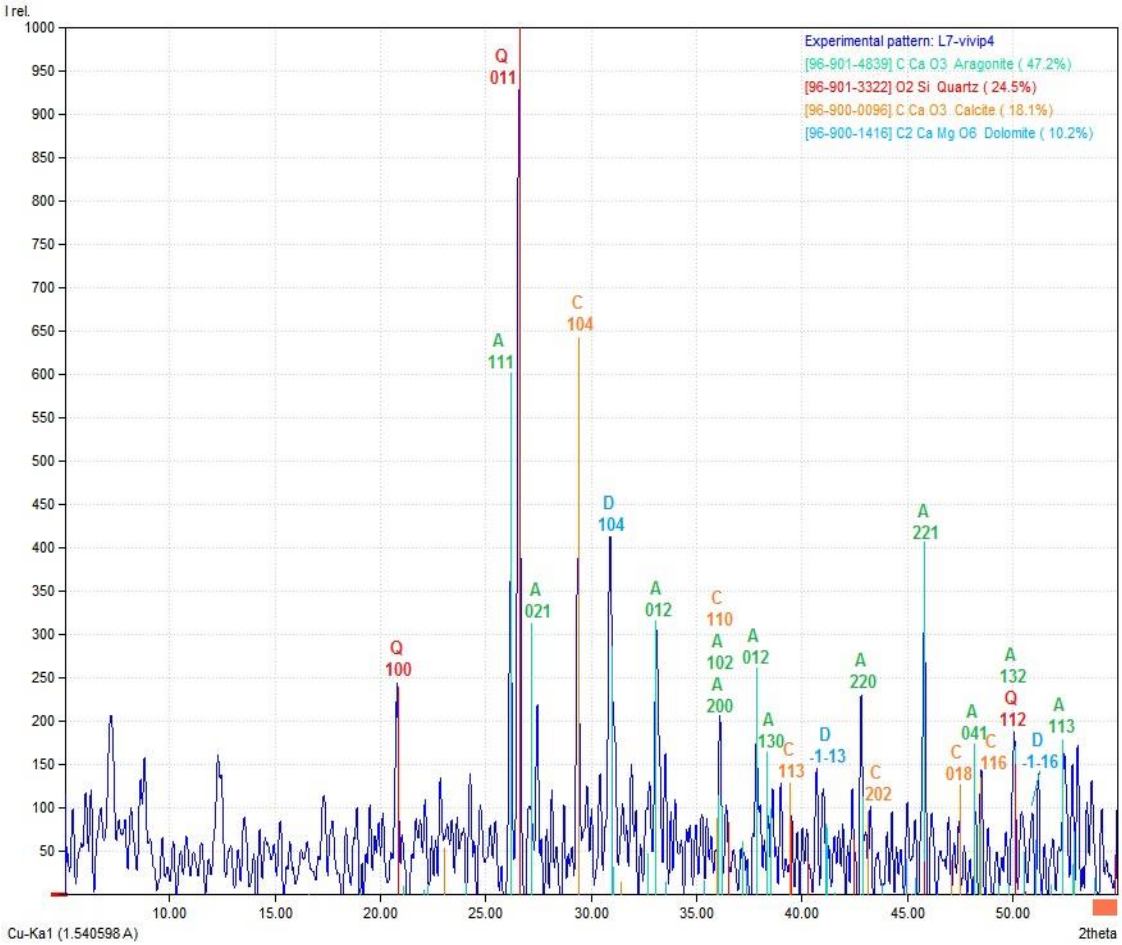



**Sample:** L7-Vivip4

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, quartz, calcite, and dolomite

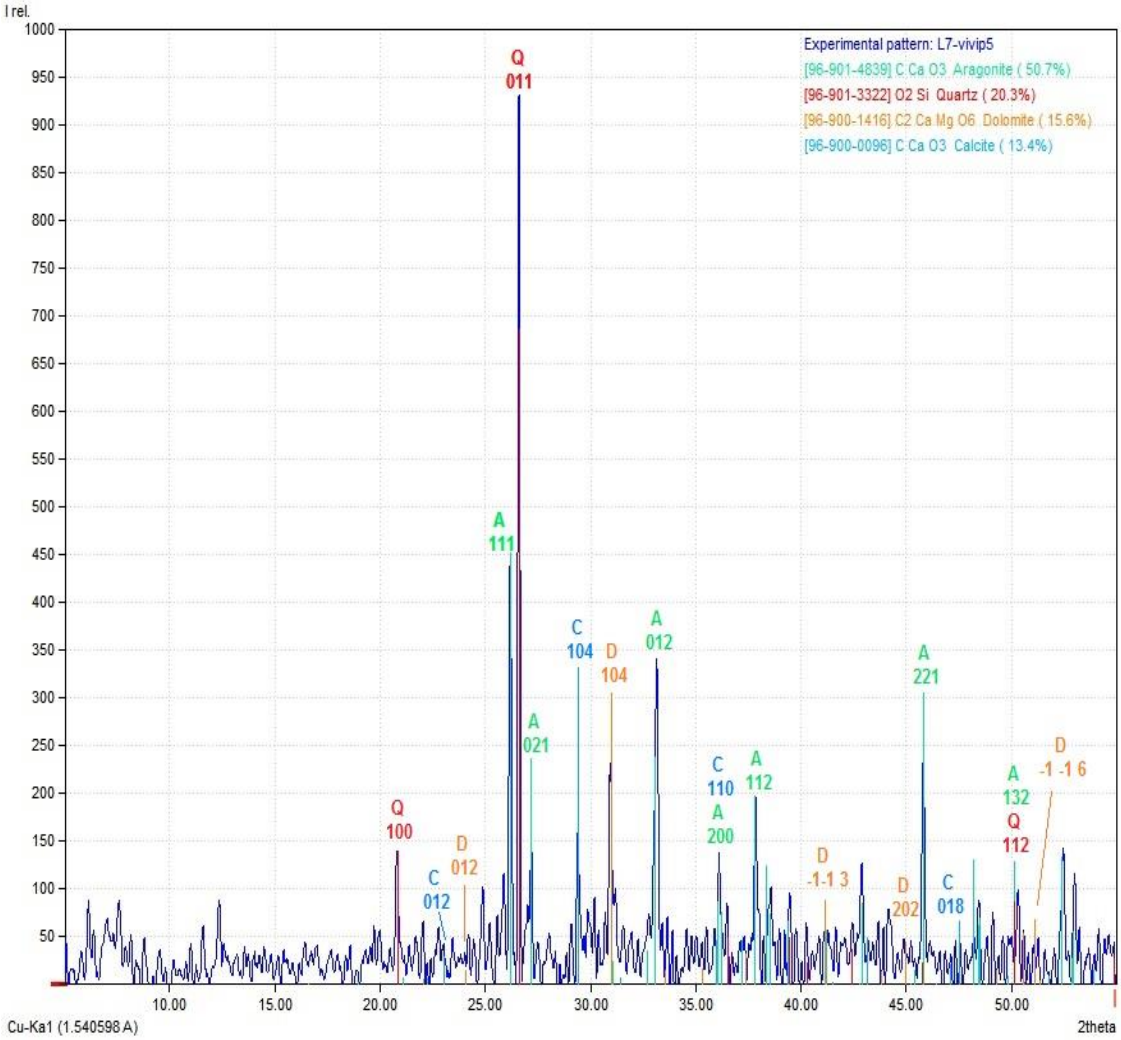



**Sample:** L7-Vivip5

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, quartz, dolomite, and calcite

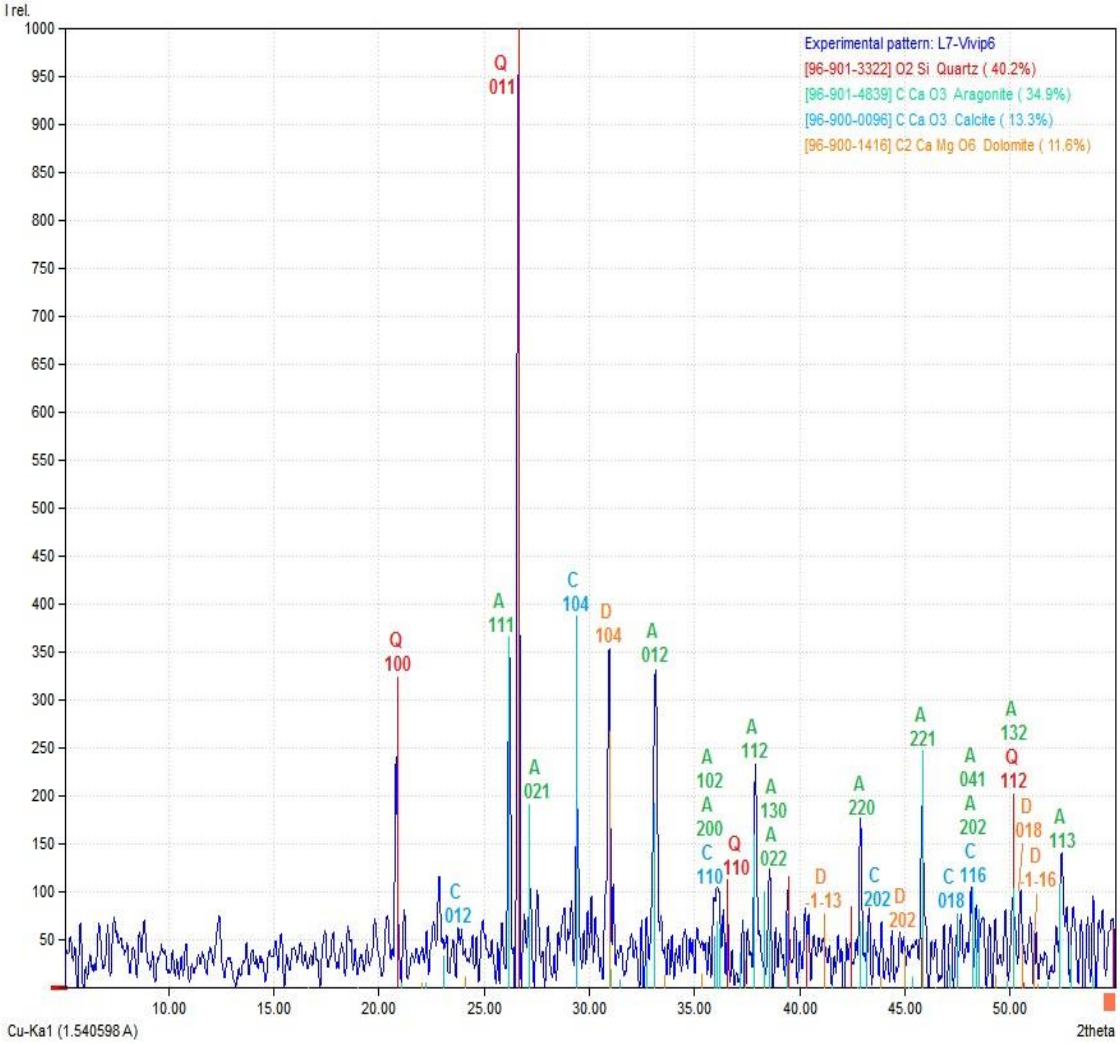



**Sample:** L7-Vivip6

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Quartz, aragonite, calcite, and dolomite

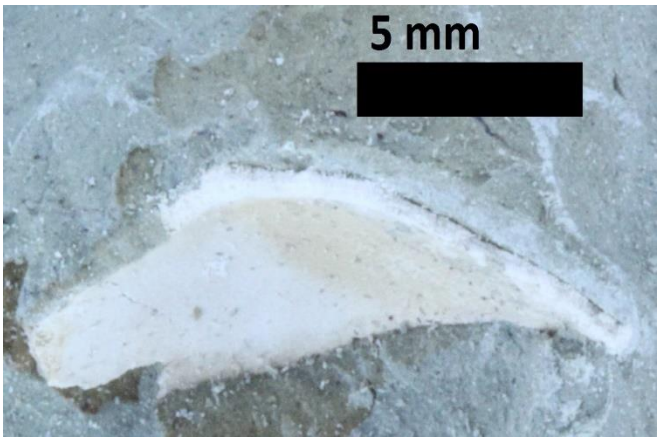



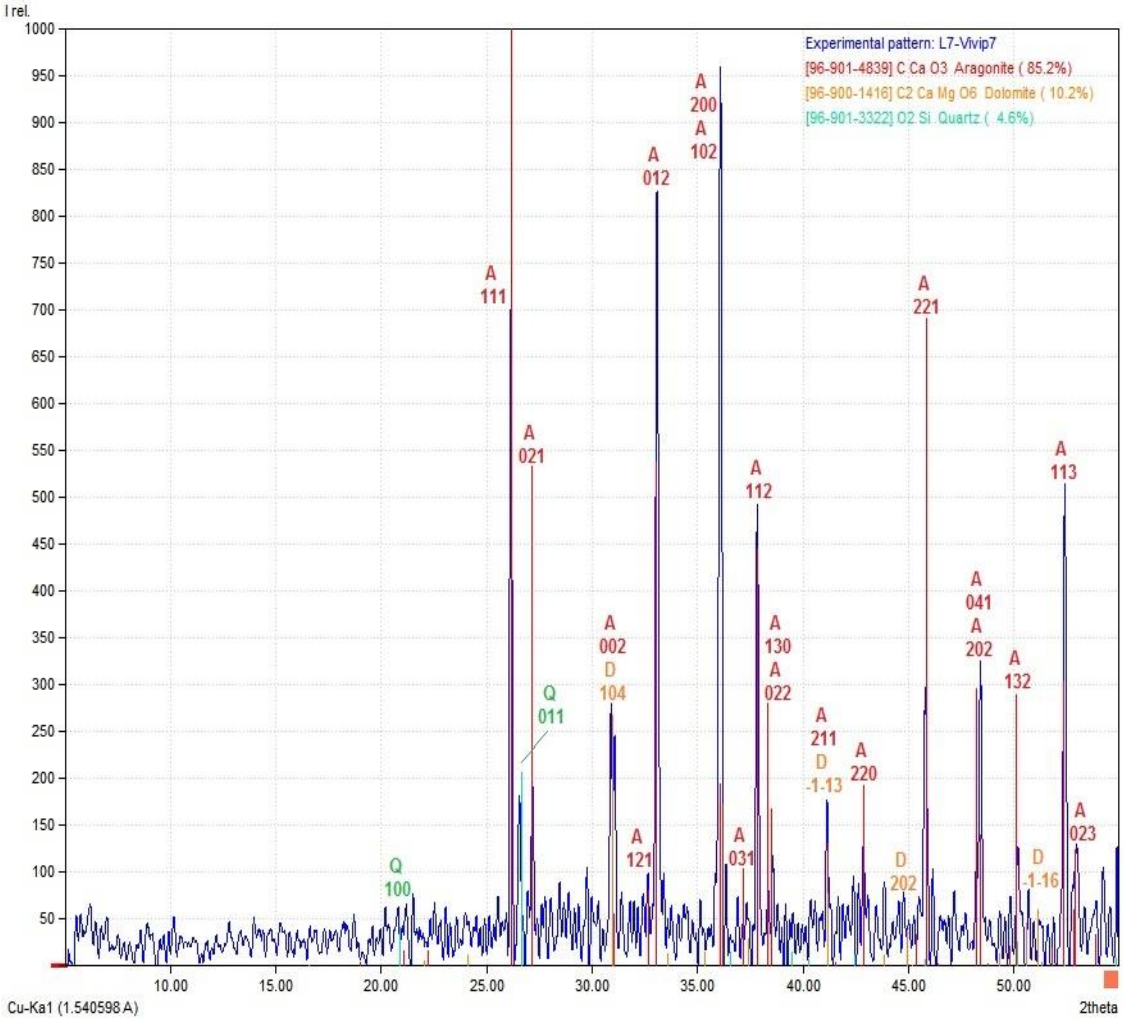
**Sample:** L7-Vivip7

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, dolomite, and quartz



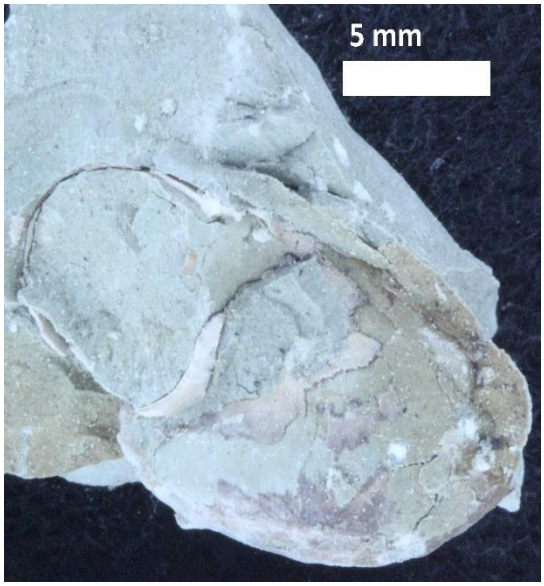



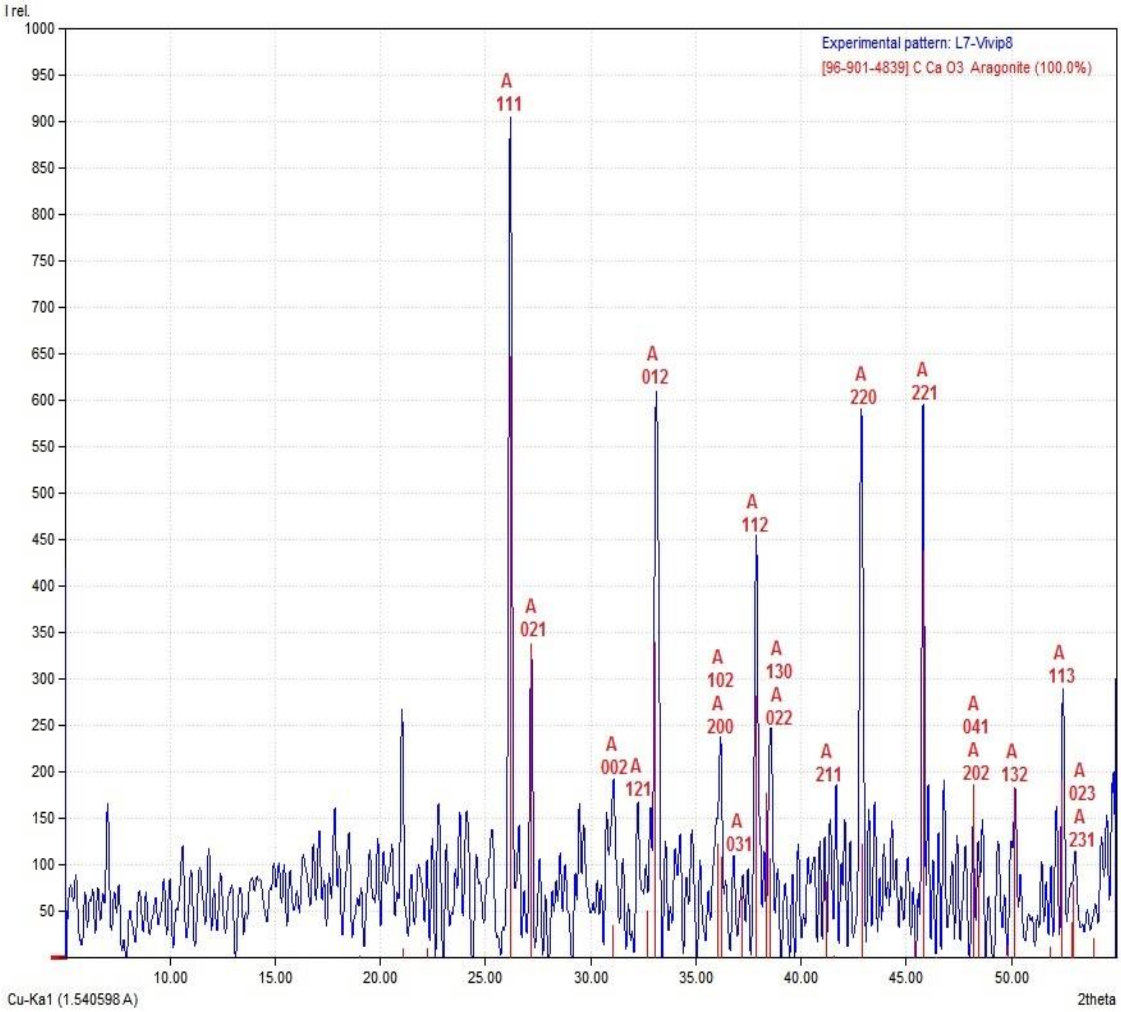
**Sample:** L7-Vivip8

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite



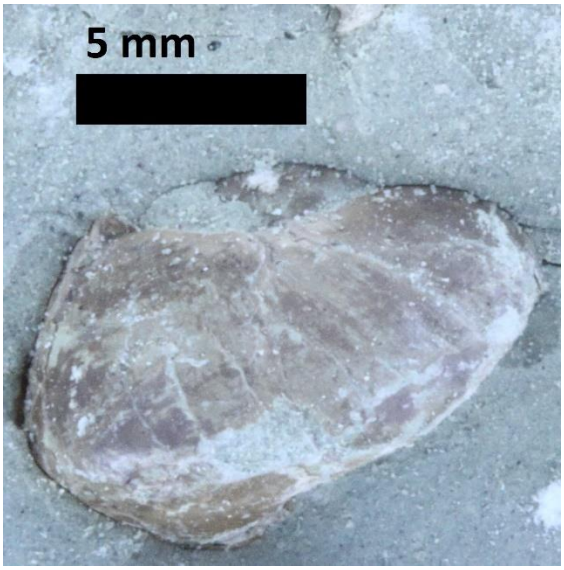



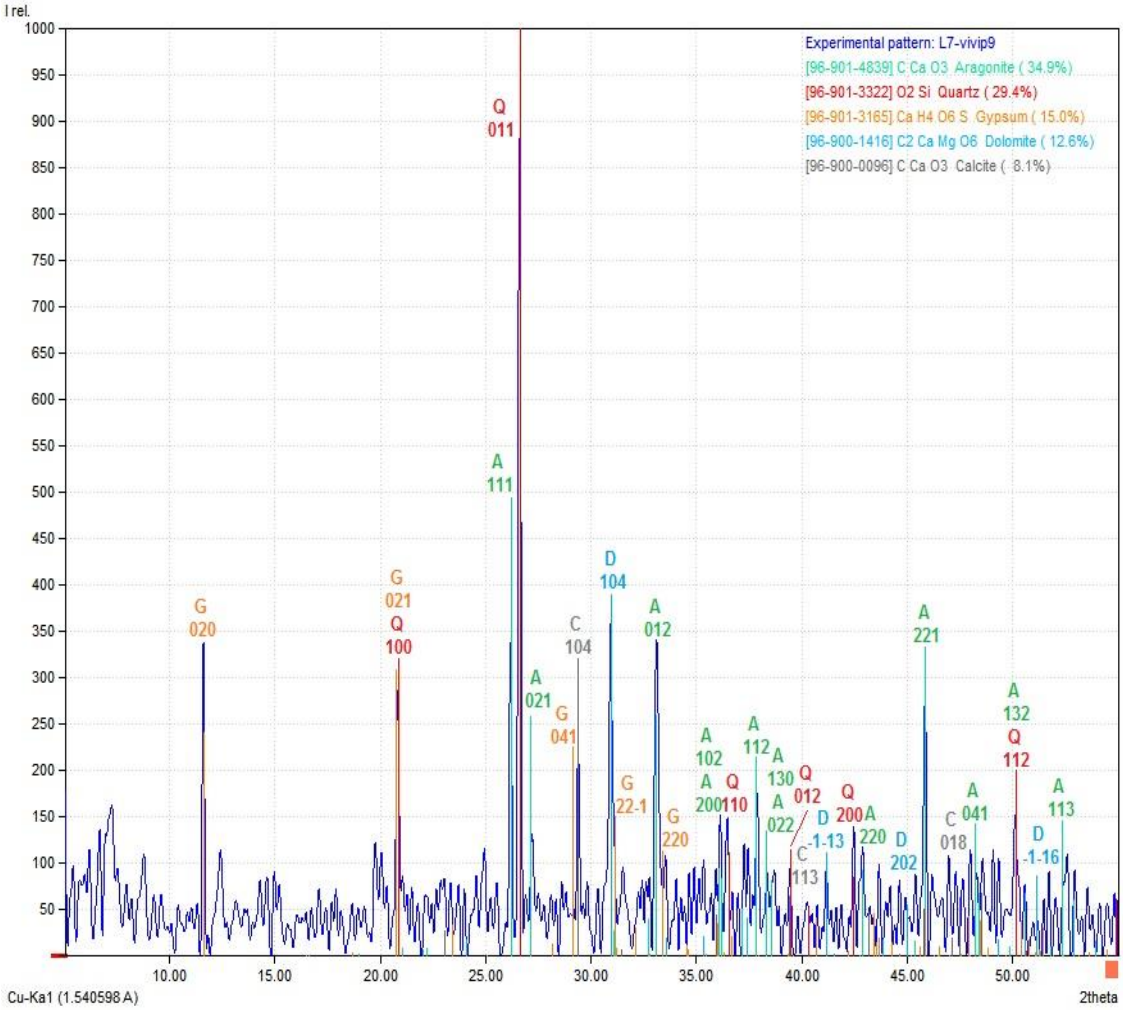
**Sample:** L7-Vivip9

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, quartz, gypsum, dolomite, and calcite



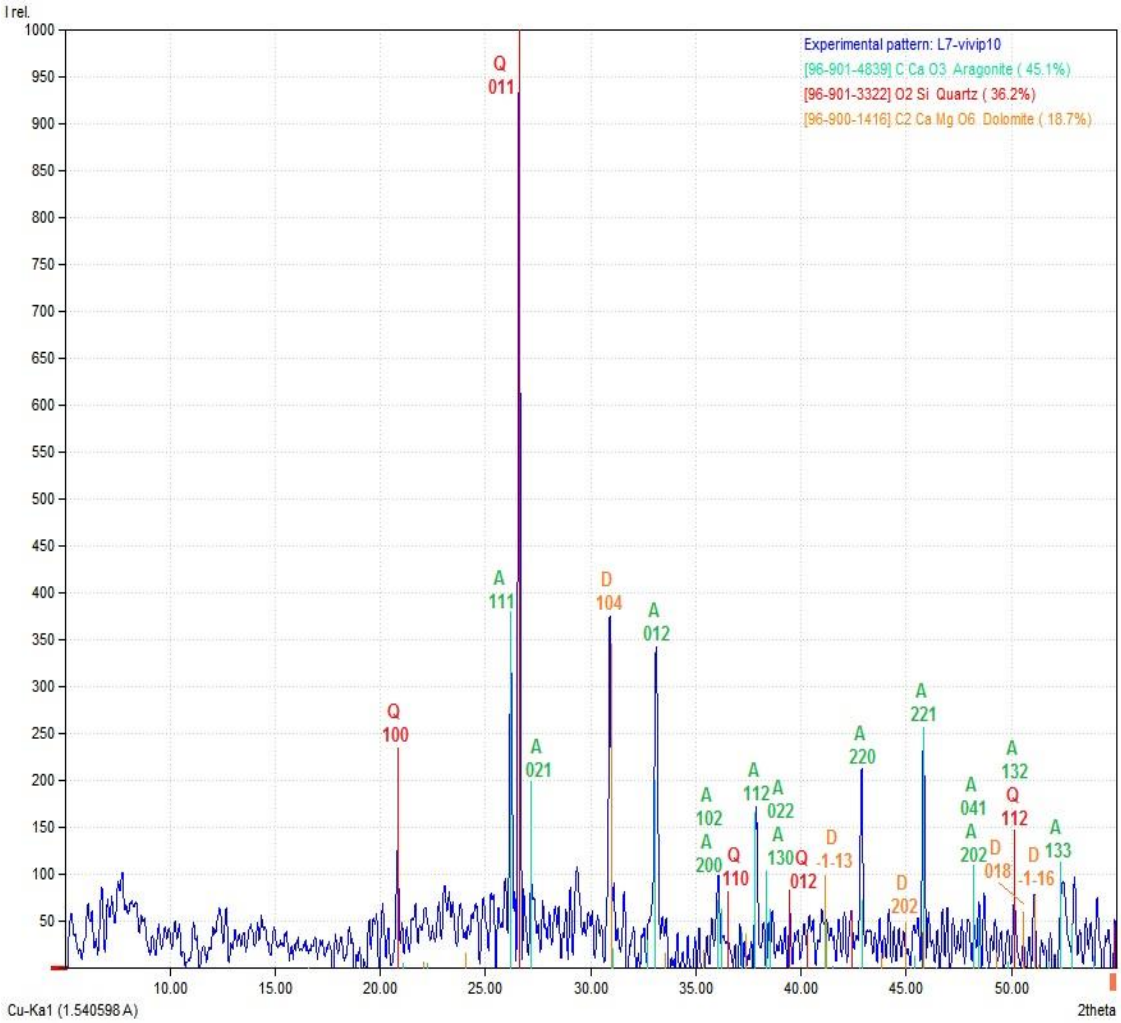



**Sample:** L7-Vivip10

**Method:** Shell Separation

**Height in Section:** 256 m

**Mineralogy:** Aragonite, quartz, and dolomite

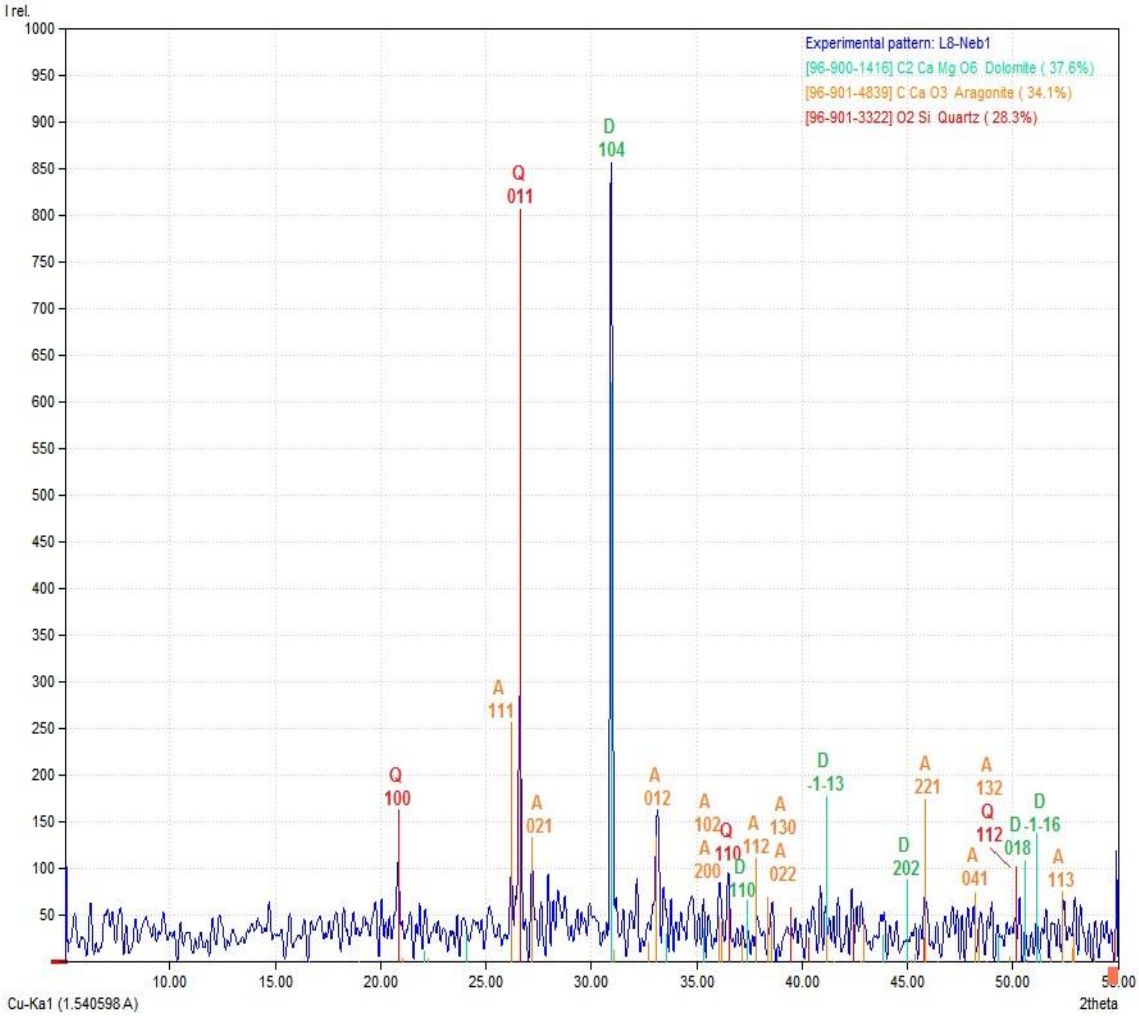



**Sample:** L8-Neb1

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Dolomite, aragonite, quartz

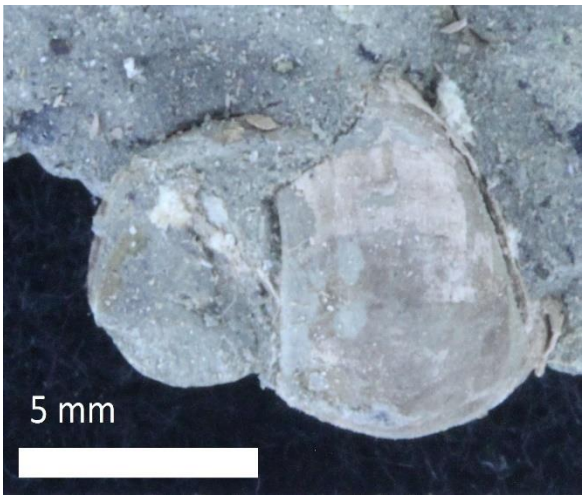



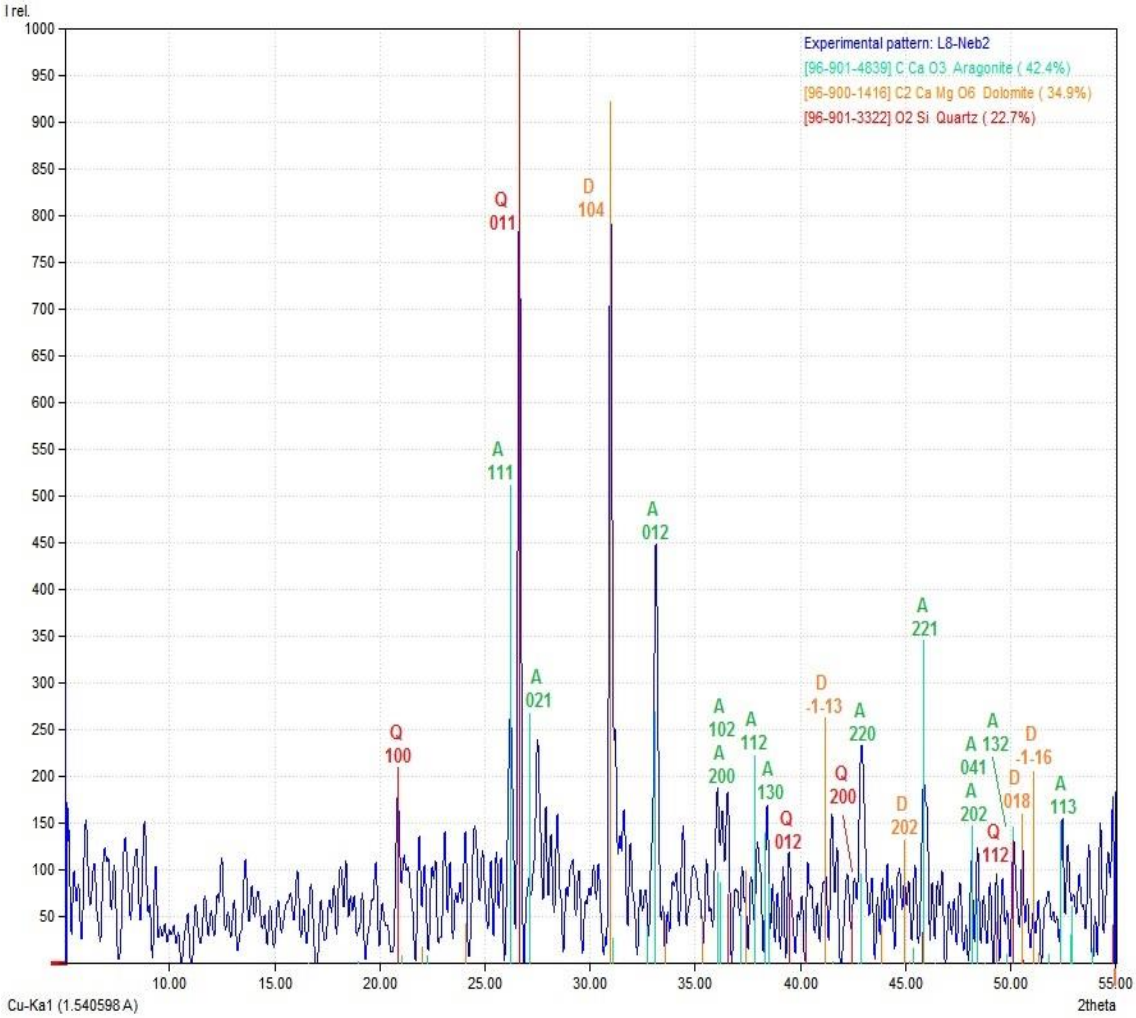
**Sample:** L8-Neb2

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite, dolomite, quartz



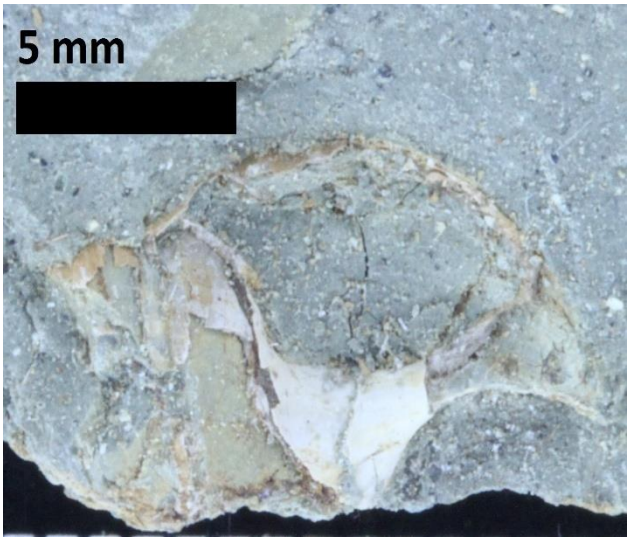



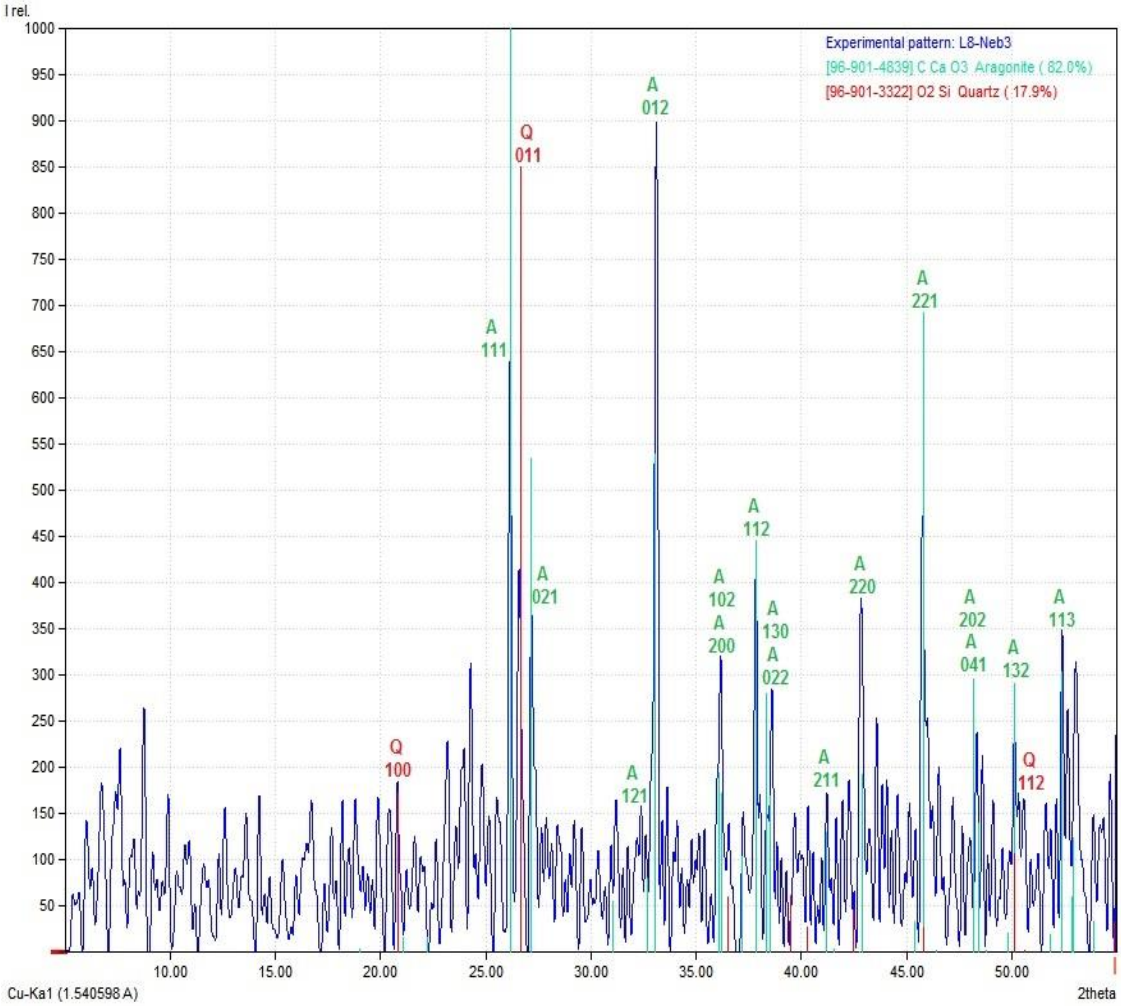
**Sample:** L8-Neb3

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite and quartz



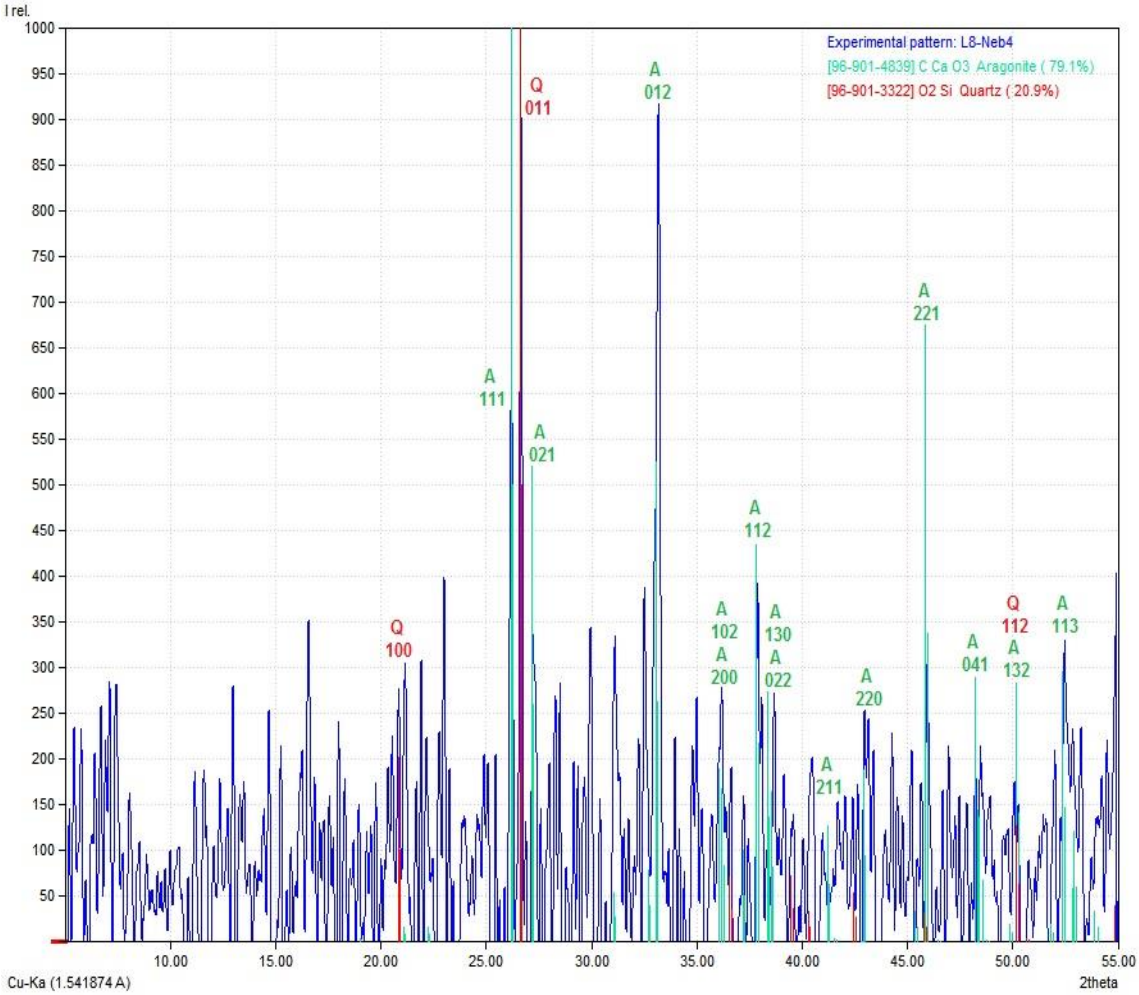



**Sample:** L8-Neb4

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite and quartz

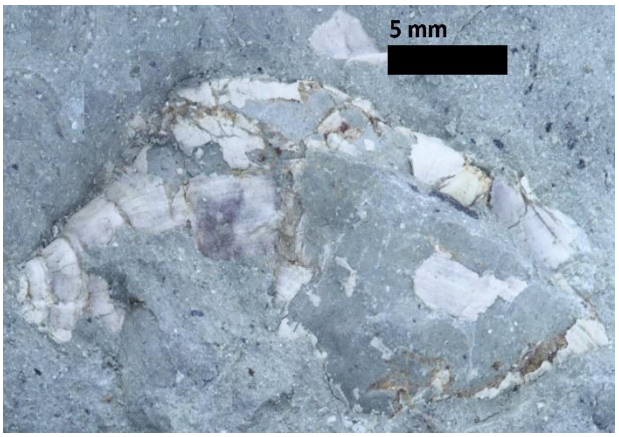



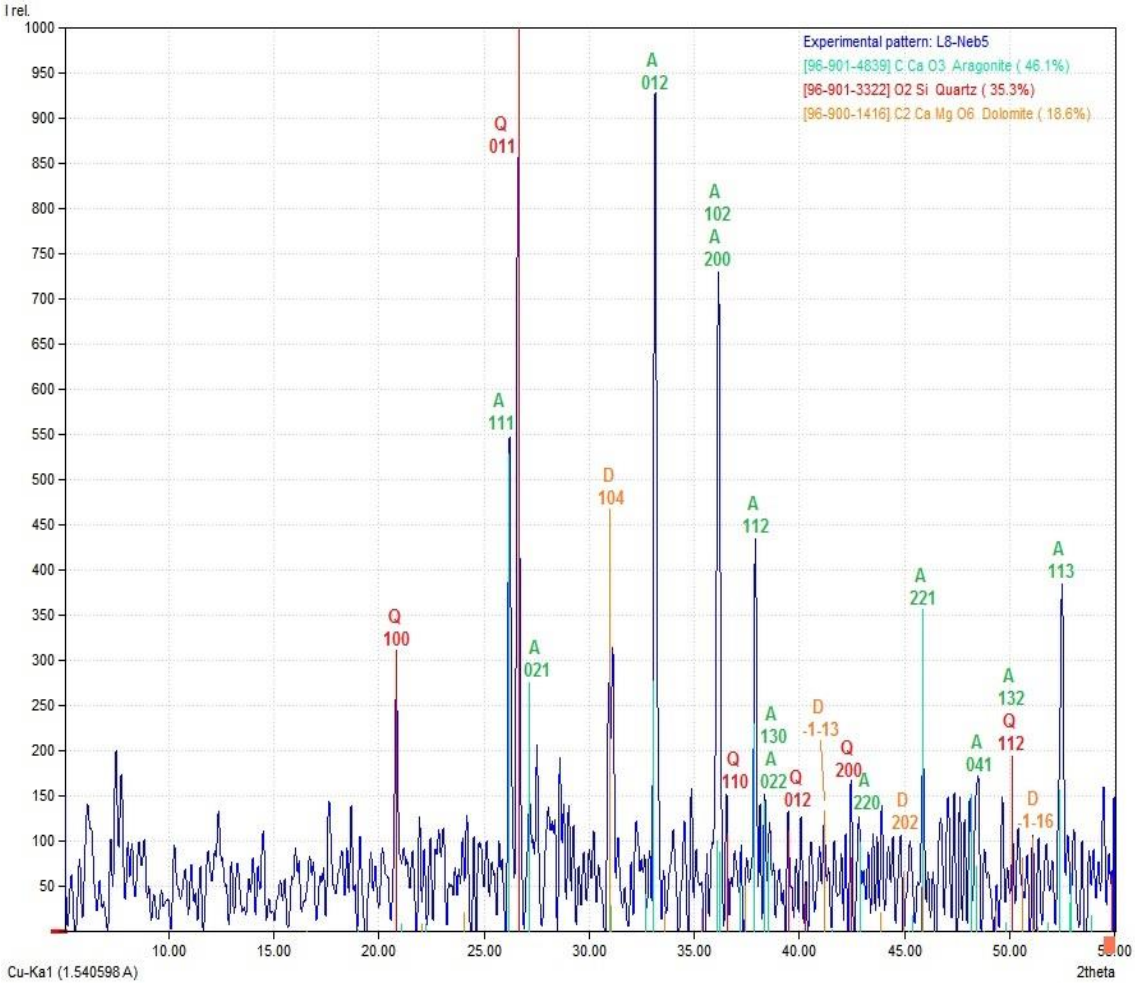
**Sample:** L8-Neb5

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite, quartz, and dolomite



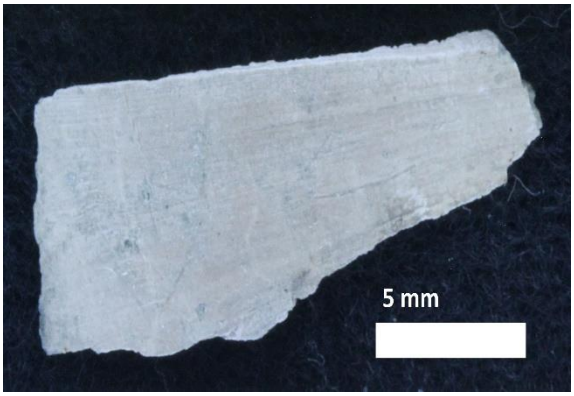



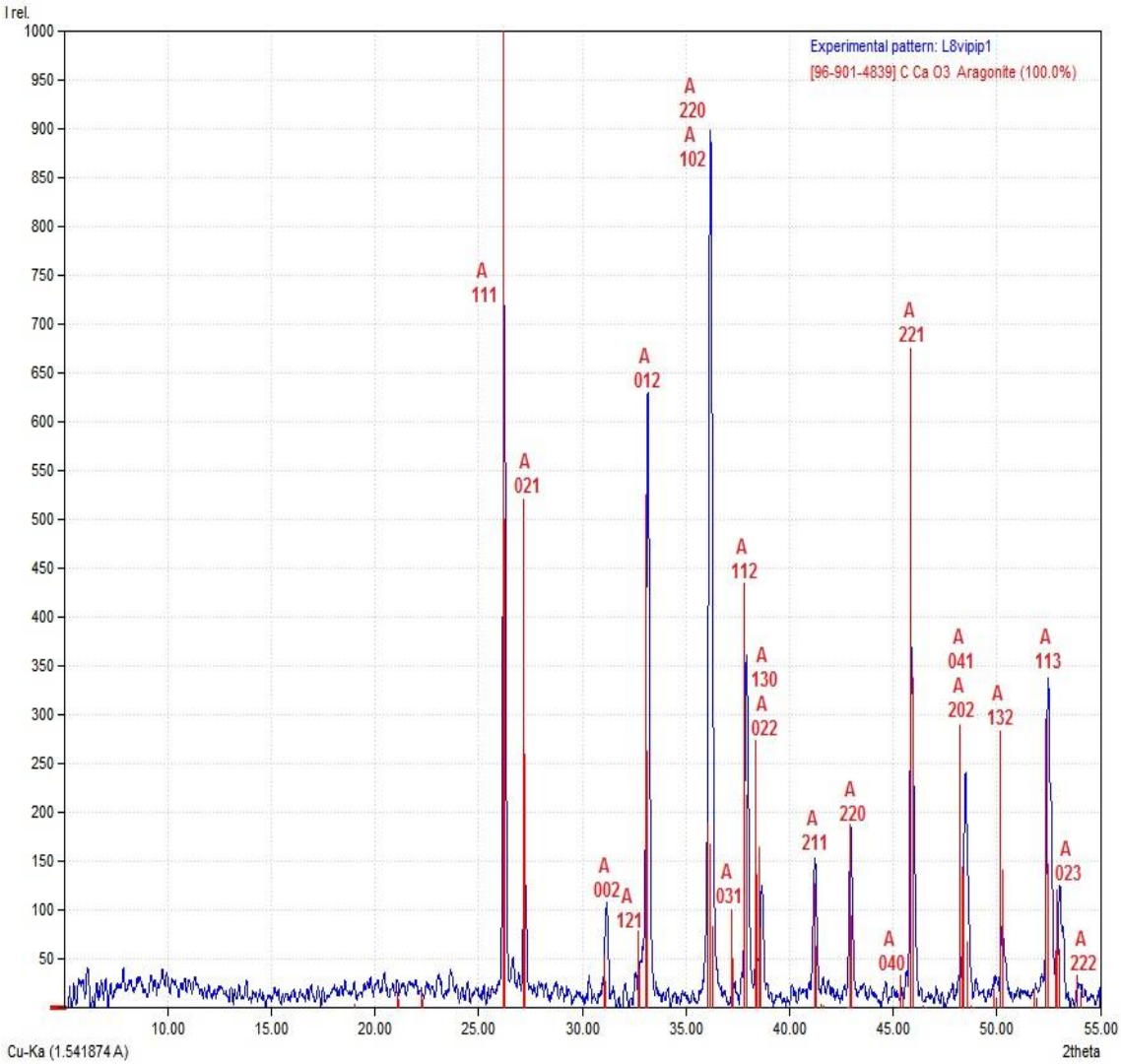
**Sample:** L8-Vivip1

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite



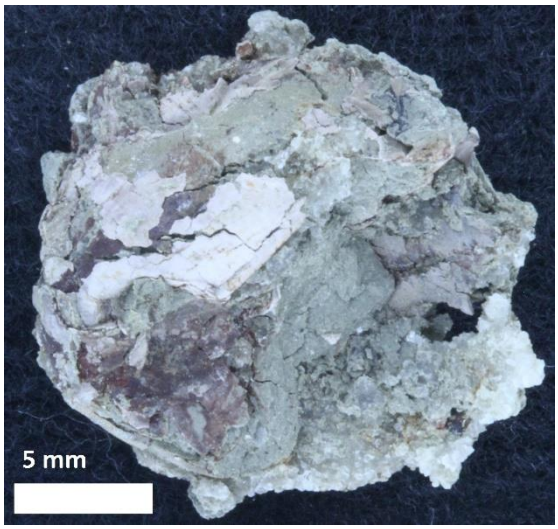



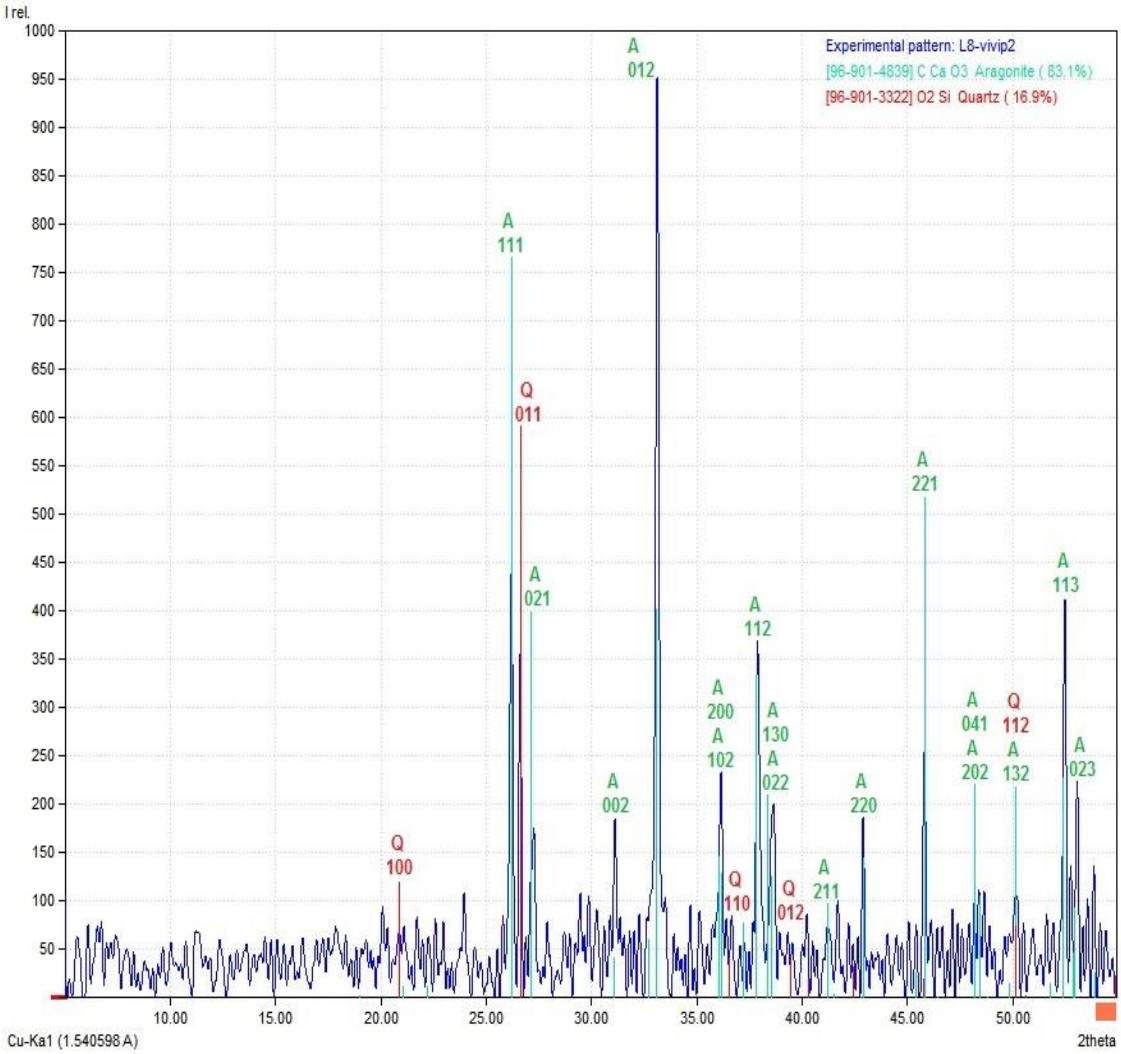
**Sample:** L8-Vivip2

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite and quartz



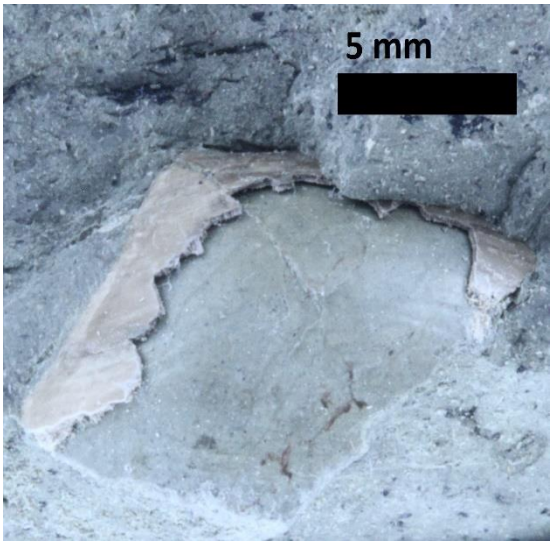



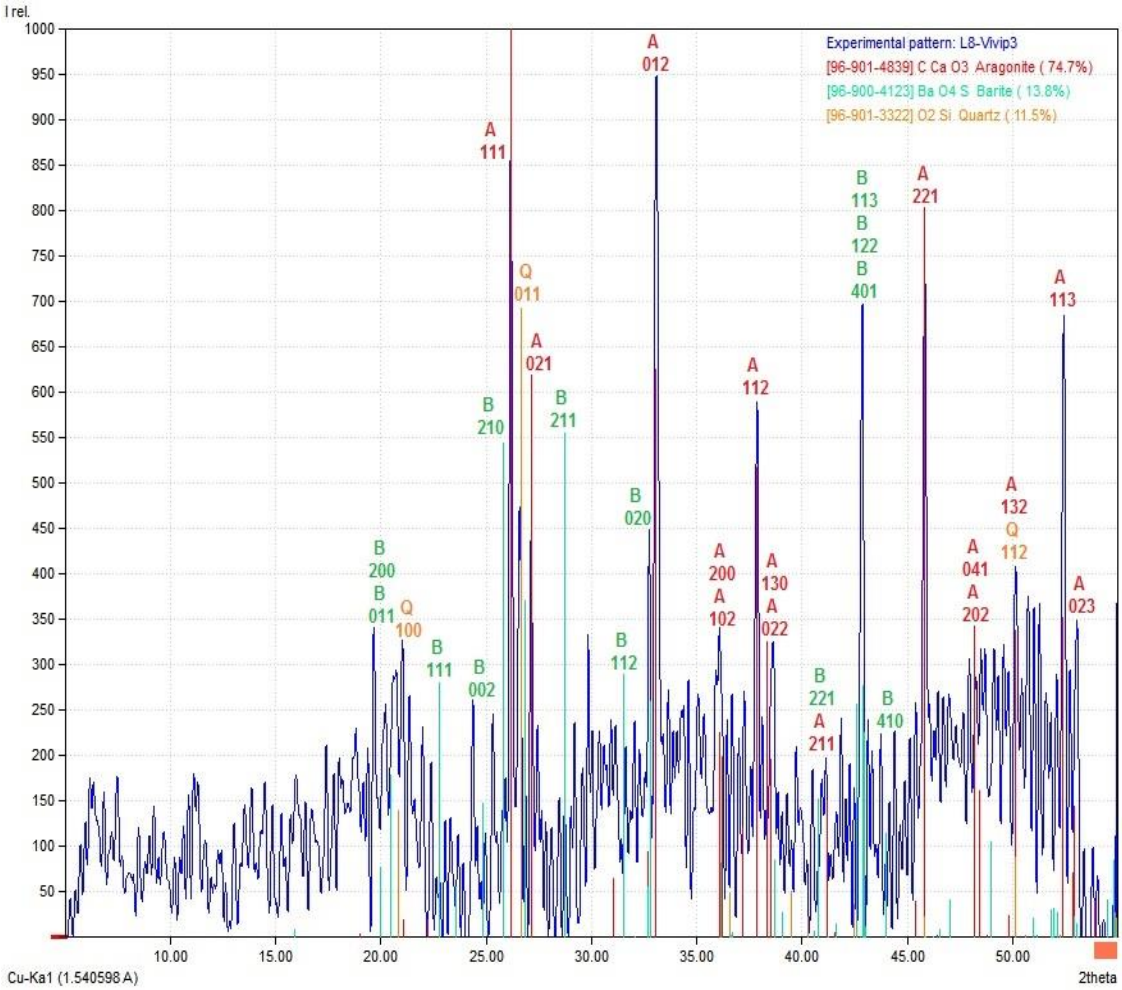
**Sample:** L8-Vivip3

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite, barite, and quartz

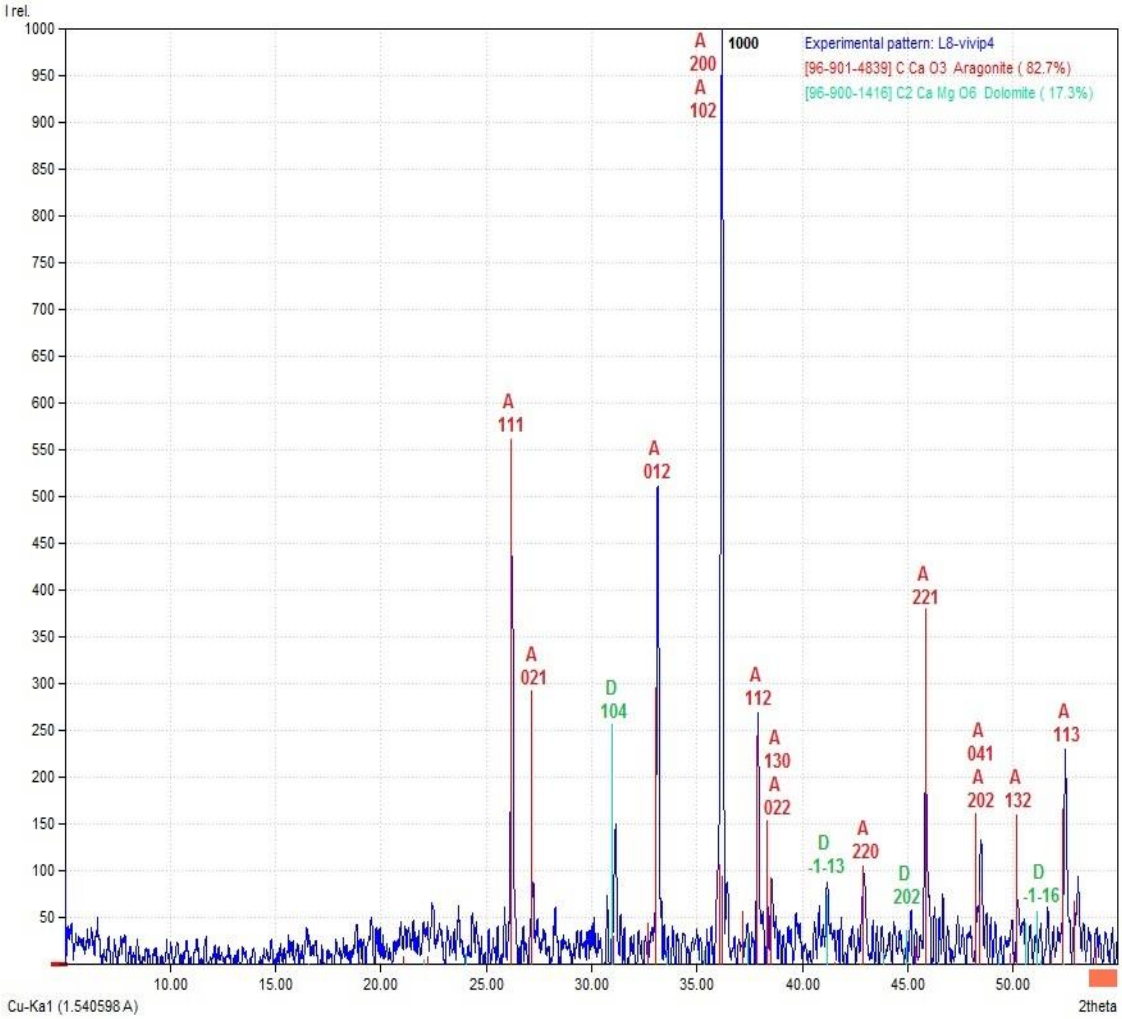


**Sample:** L8-Vivip4

**Method:** Shell Separation

**Height in Section:** 293 m
**Mineralogy:** Aragonite and dolomite

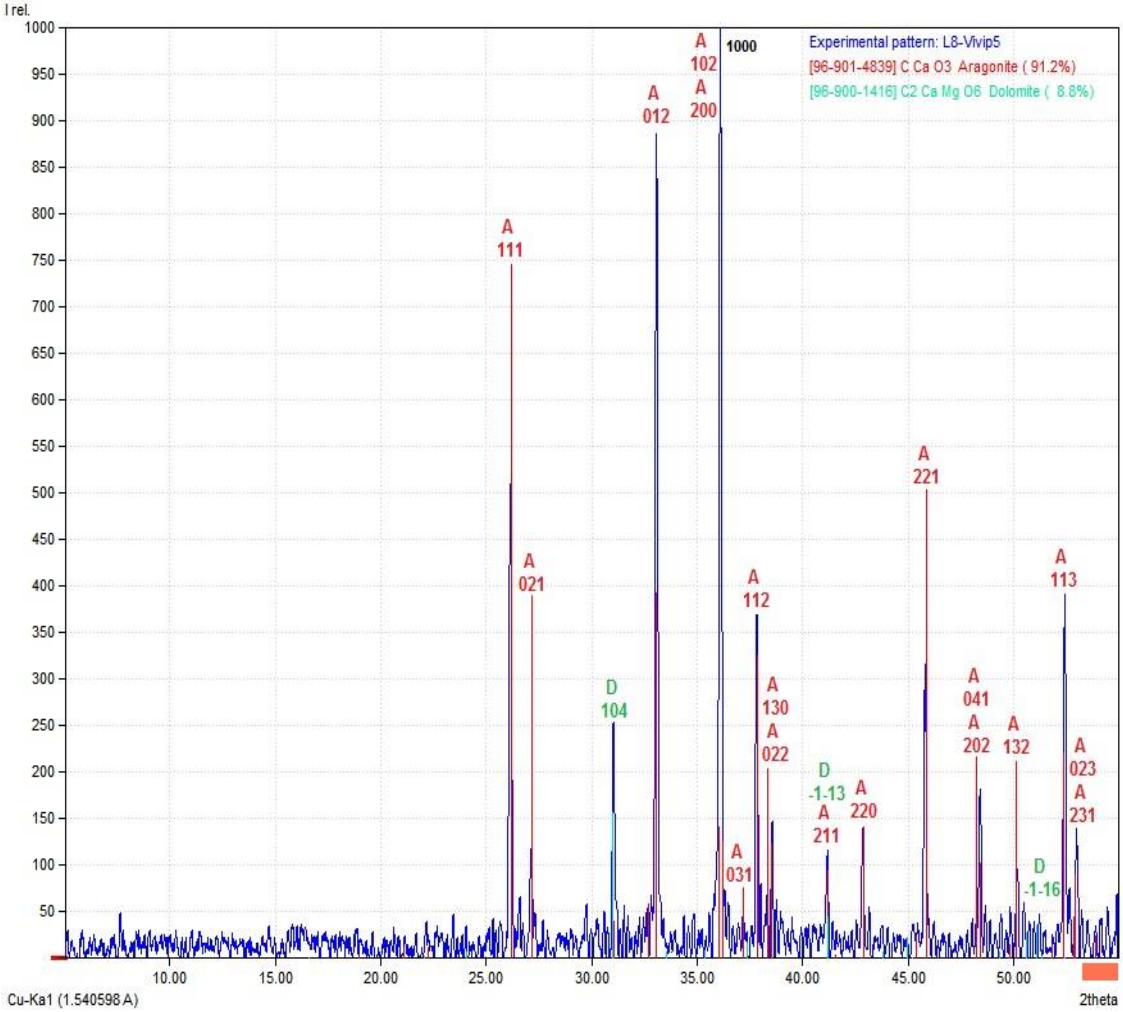



**Sample:** L8-Vivip5

**Method:** Shell Separation

**Height in Section:** 293 m

**Mineralogy:** Aragonite and dolomite

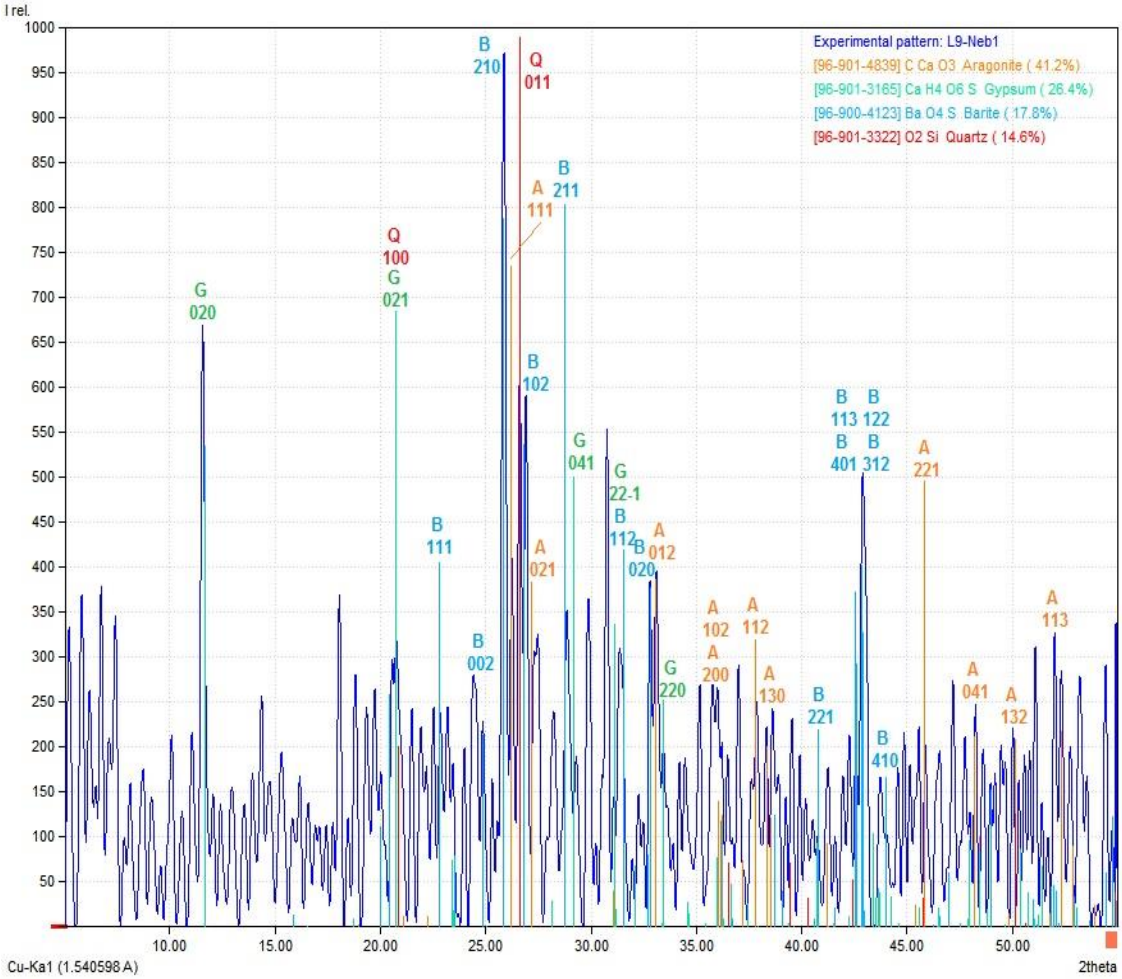



**Sample:** L9-Neb1

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, gypsum, barite and quartz

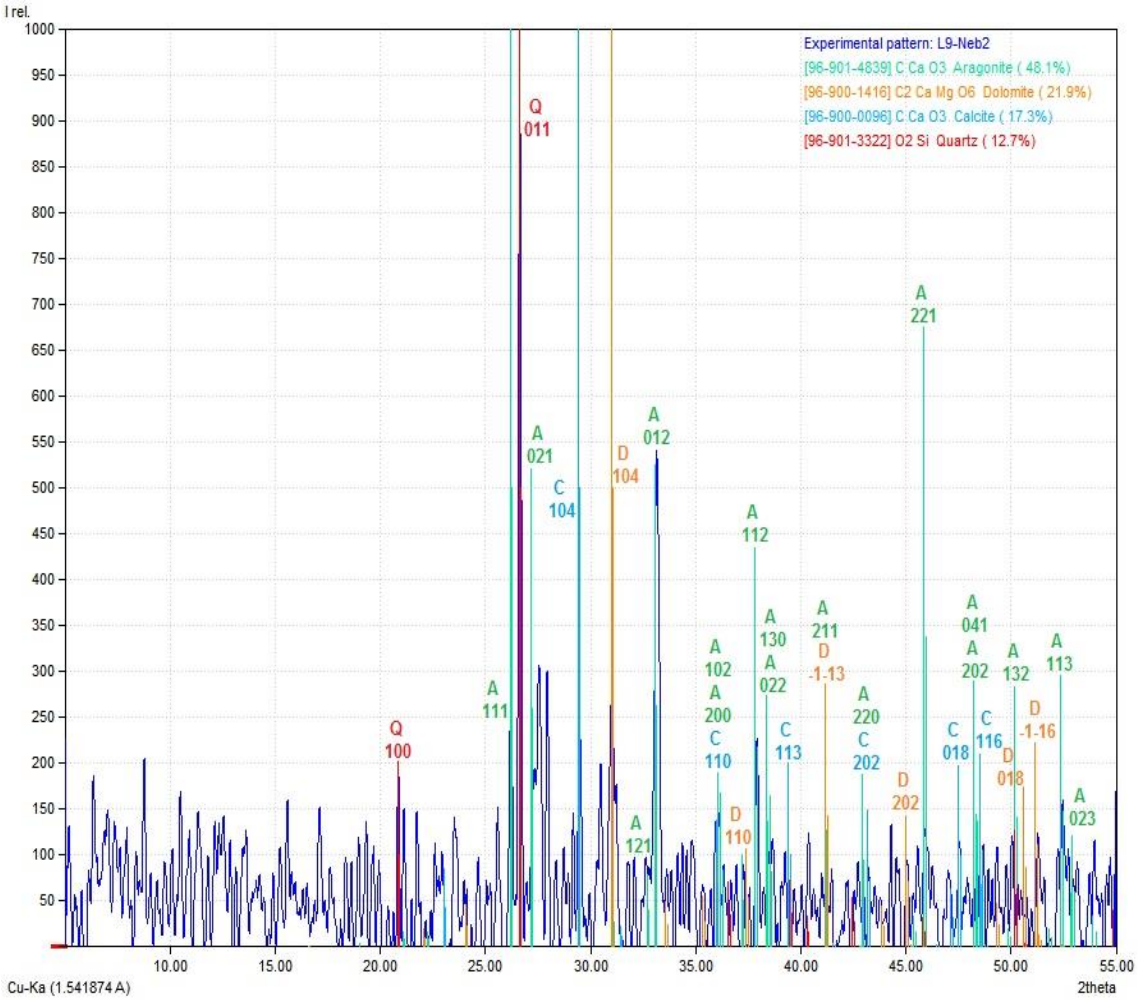



**Sample:** L9-Neb2

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, dolomite, calcite and quartz

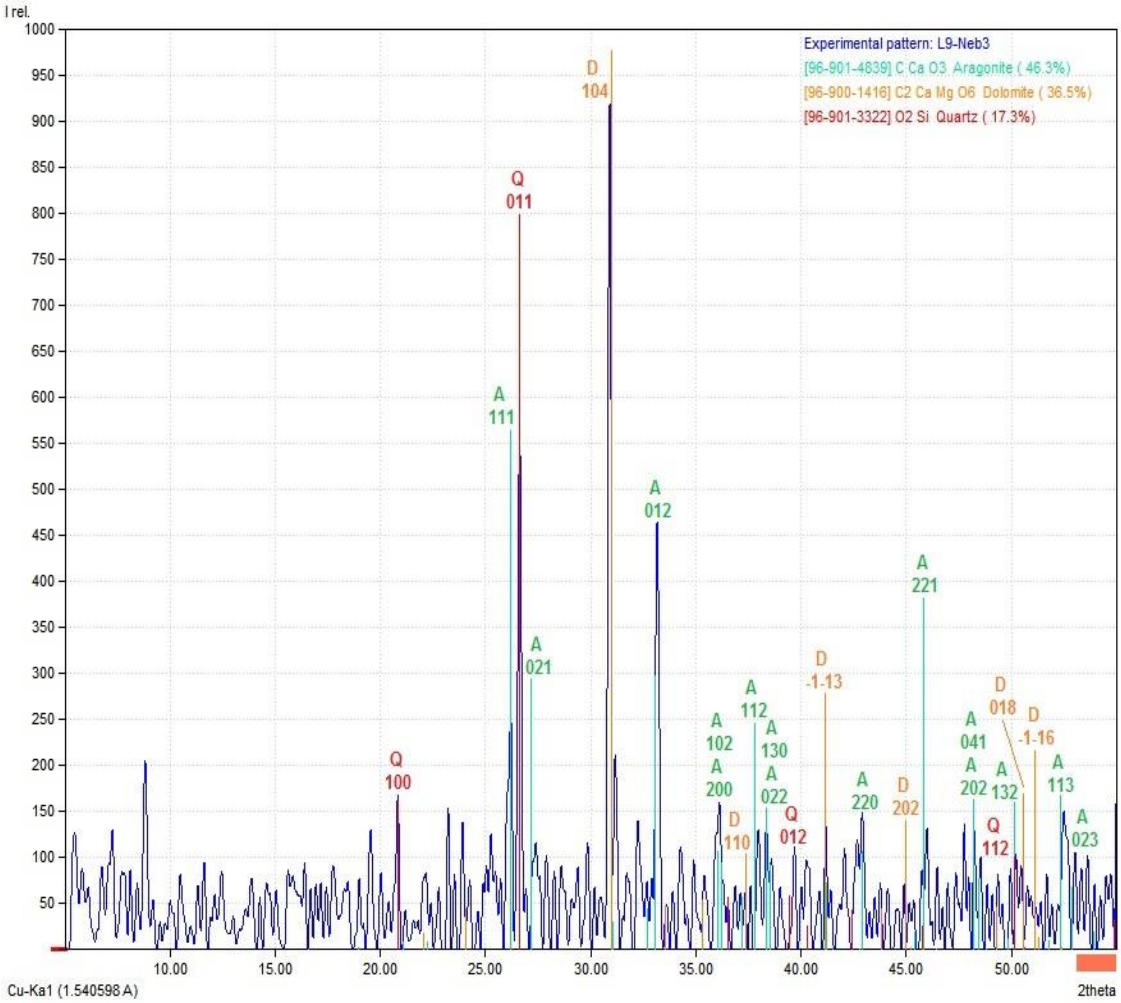



**Sample:** L9-Neb3

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, dolomite, and quartz

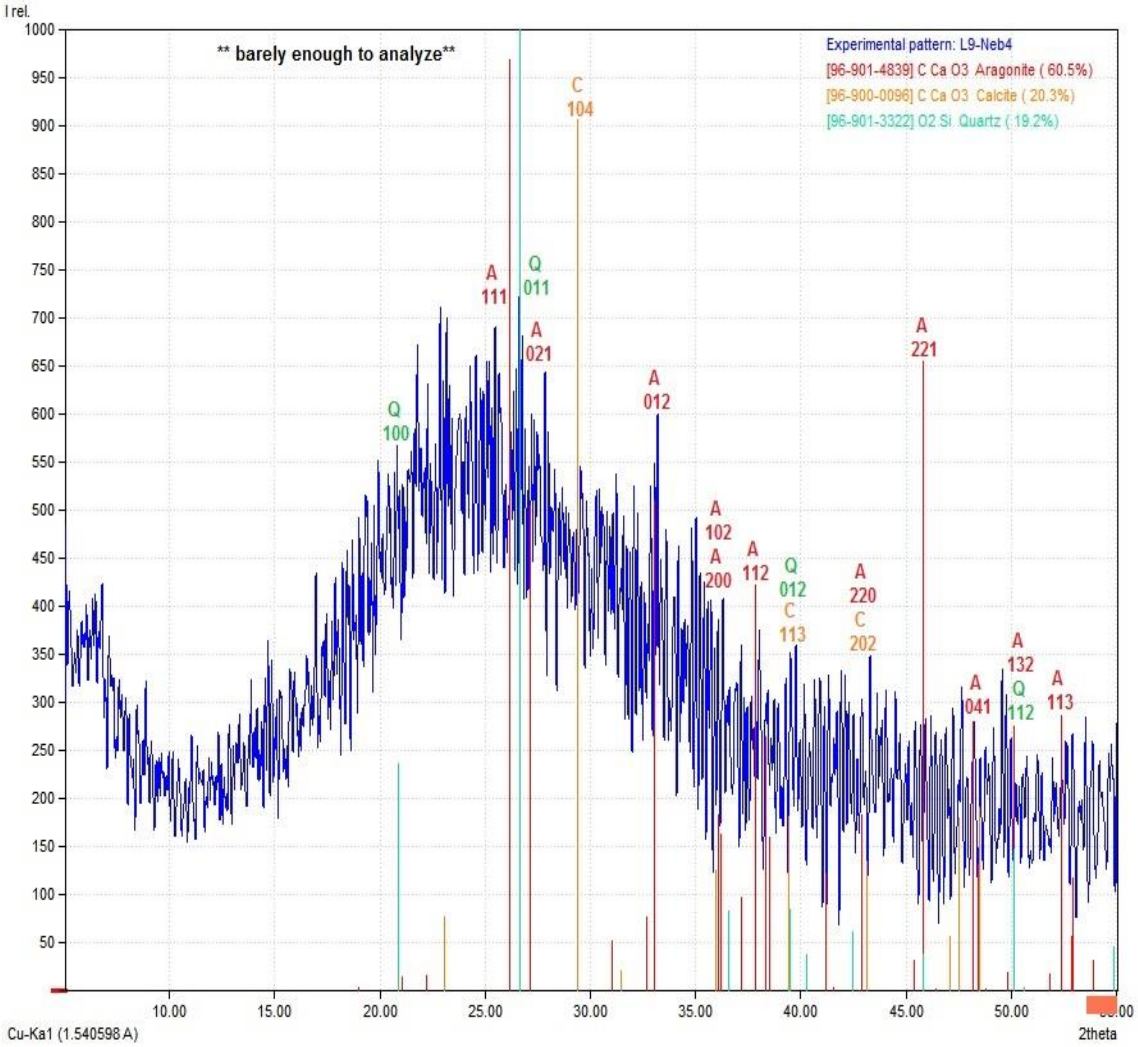



**Sample:** L9-Neb4

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, calcite, and quartz

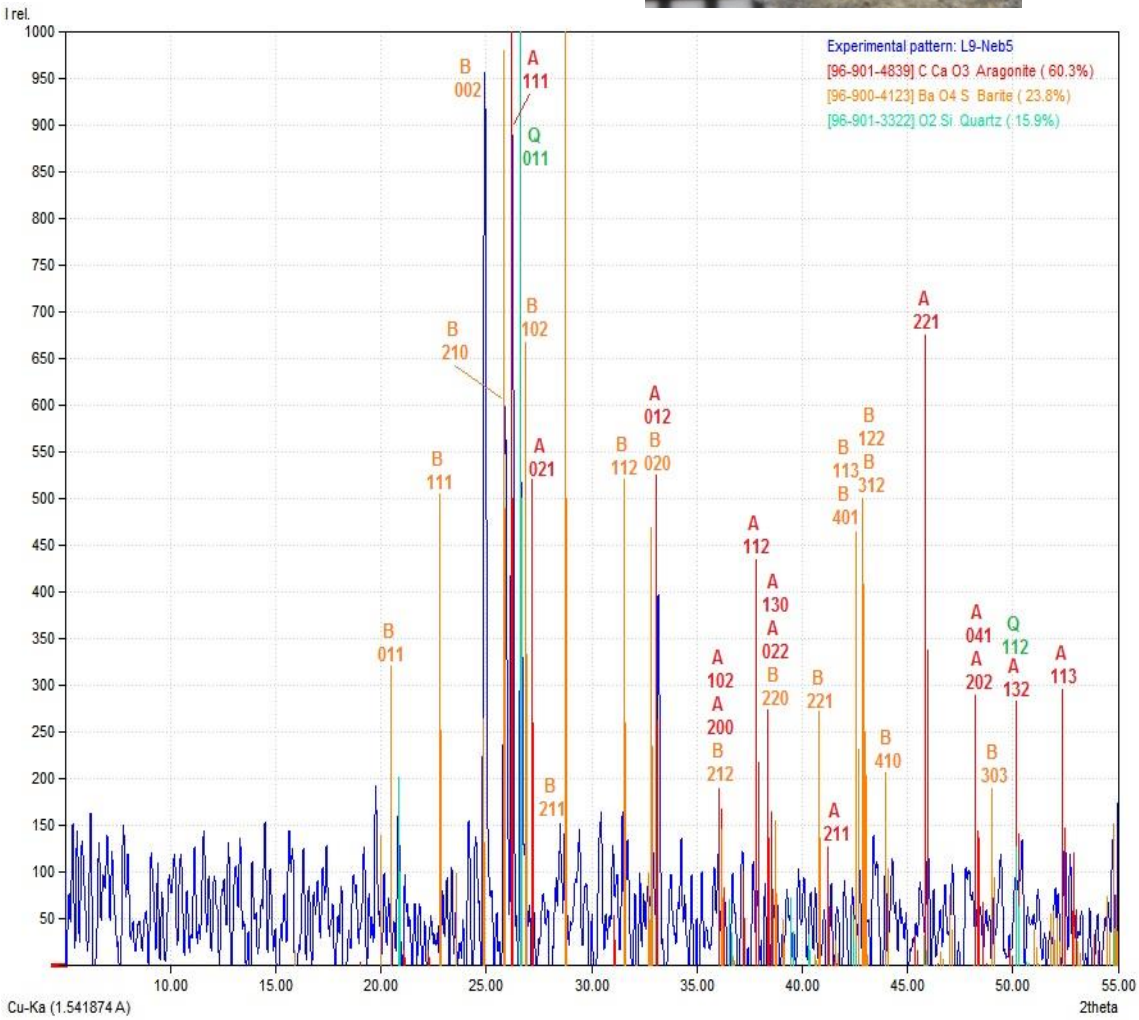



**Sample:** L9-Neb5

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, barite, and quartz

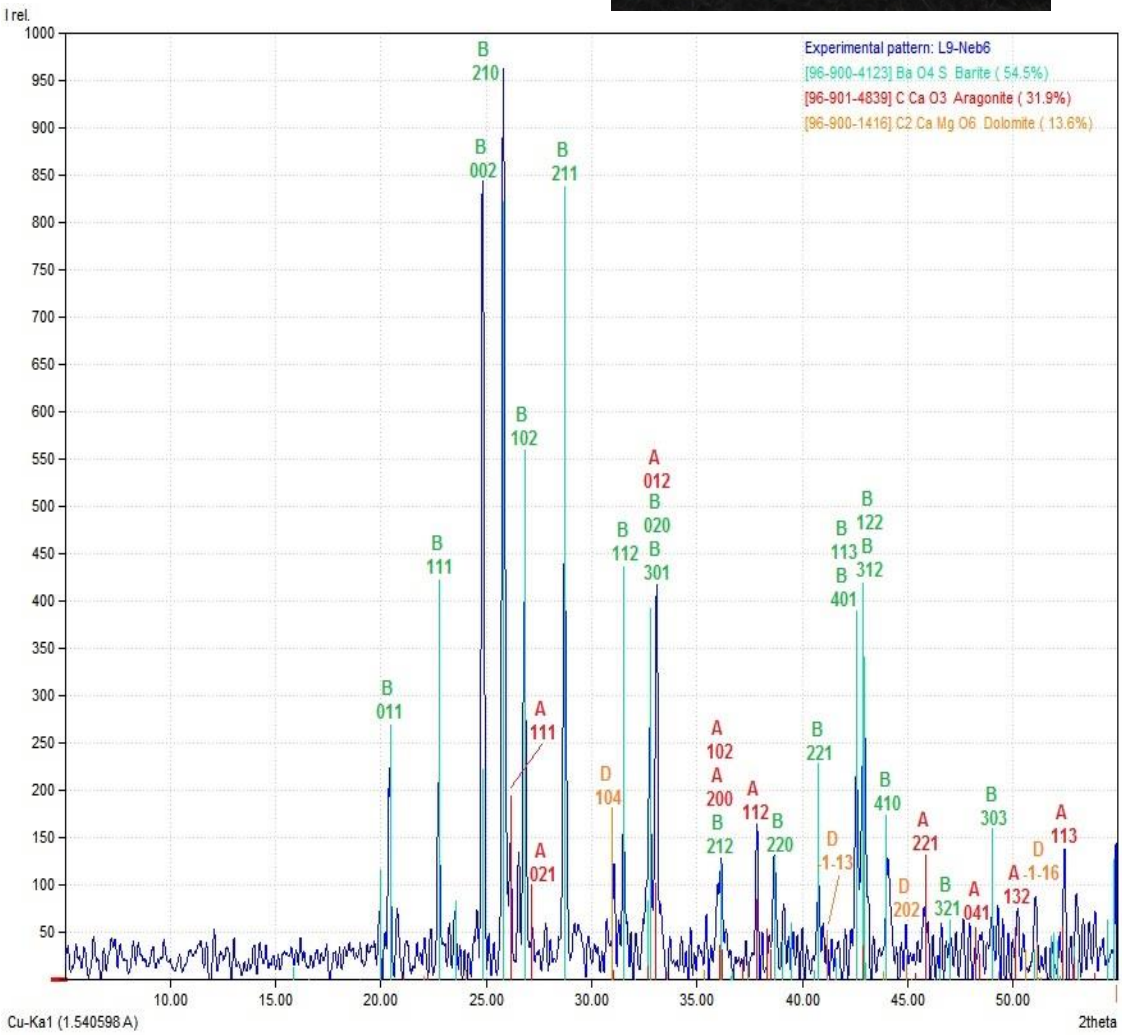



**Sample:** L9-Neb6

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Barite, aragonite, and dolomite

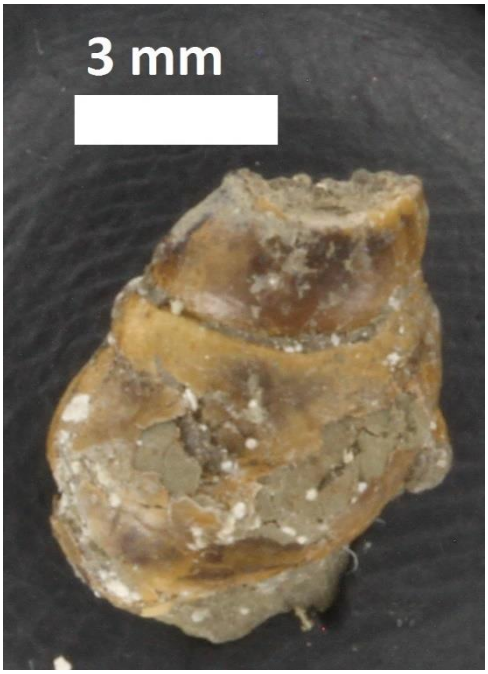



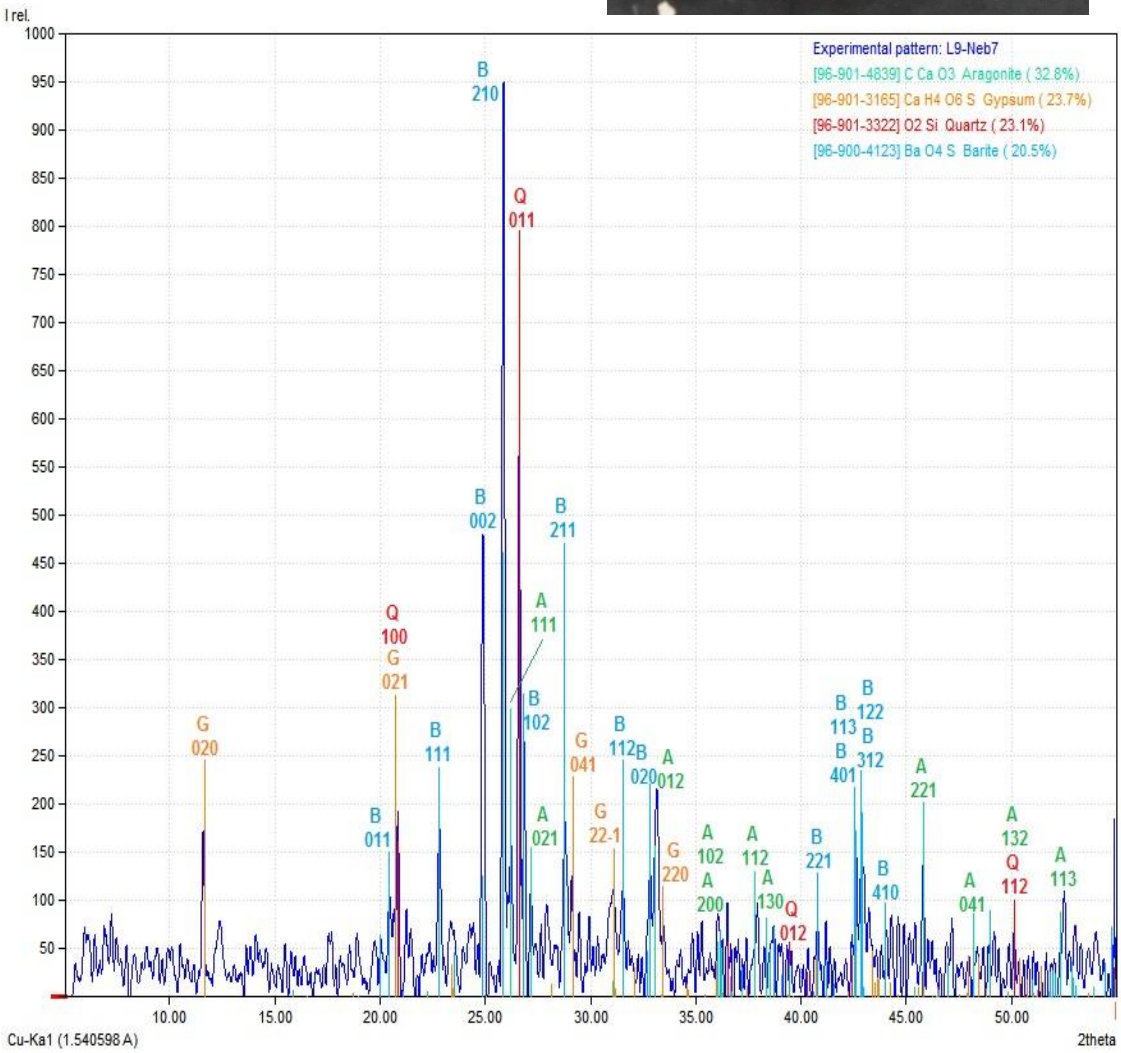
**Sample:** L9-Neb7

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, gypsum, quartz, and barite



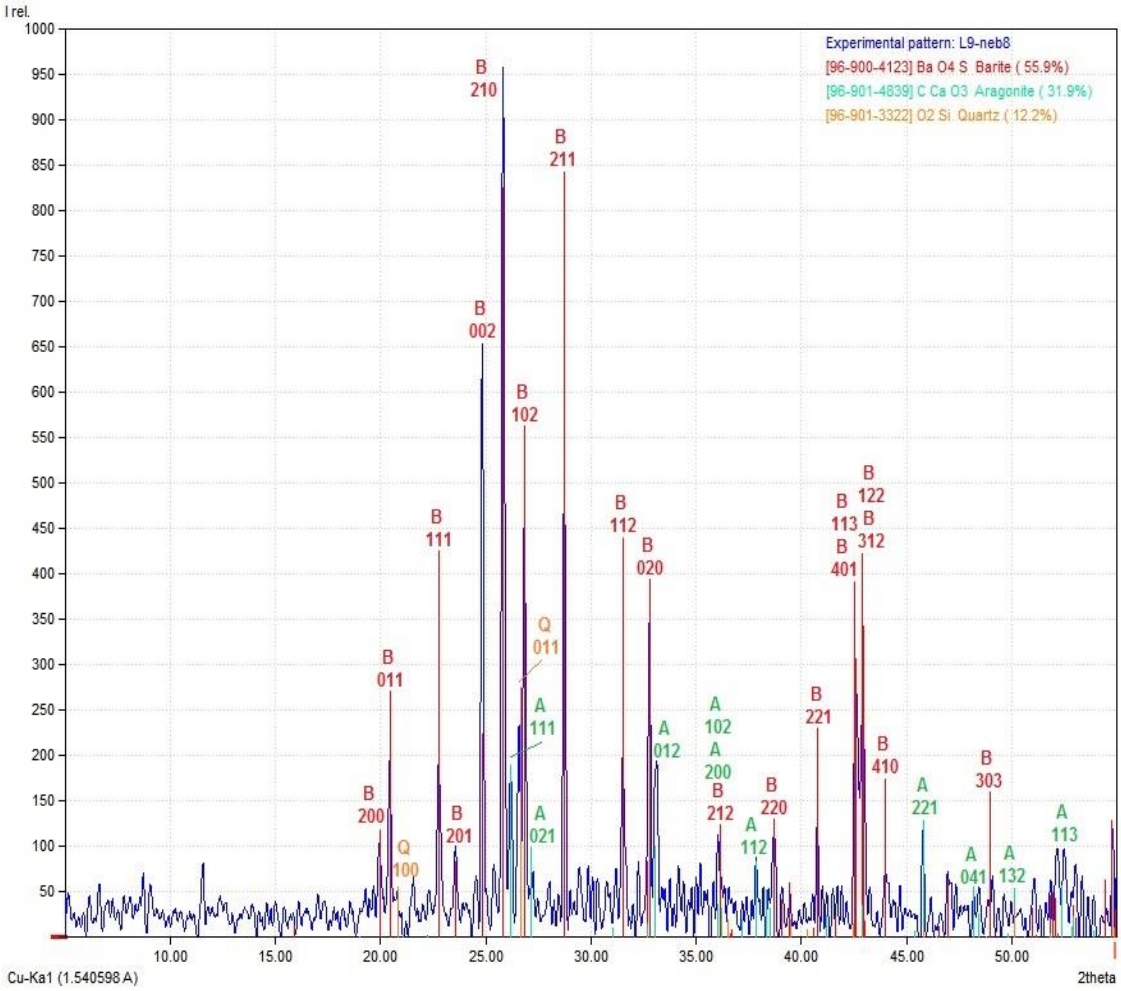



**Sample:** L9-Neb8

**Method:** Shell Separation

**Height in Section:** 315 m

**Mineralogy:** Barite, aragonite, and quartz

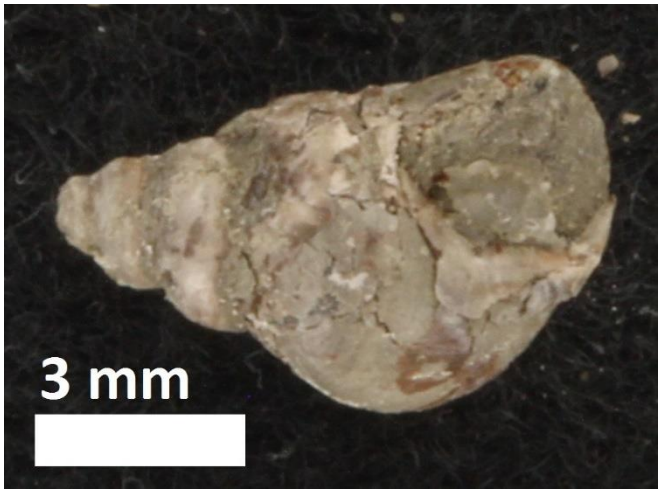



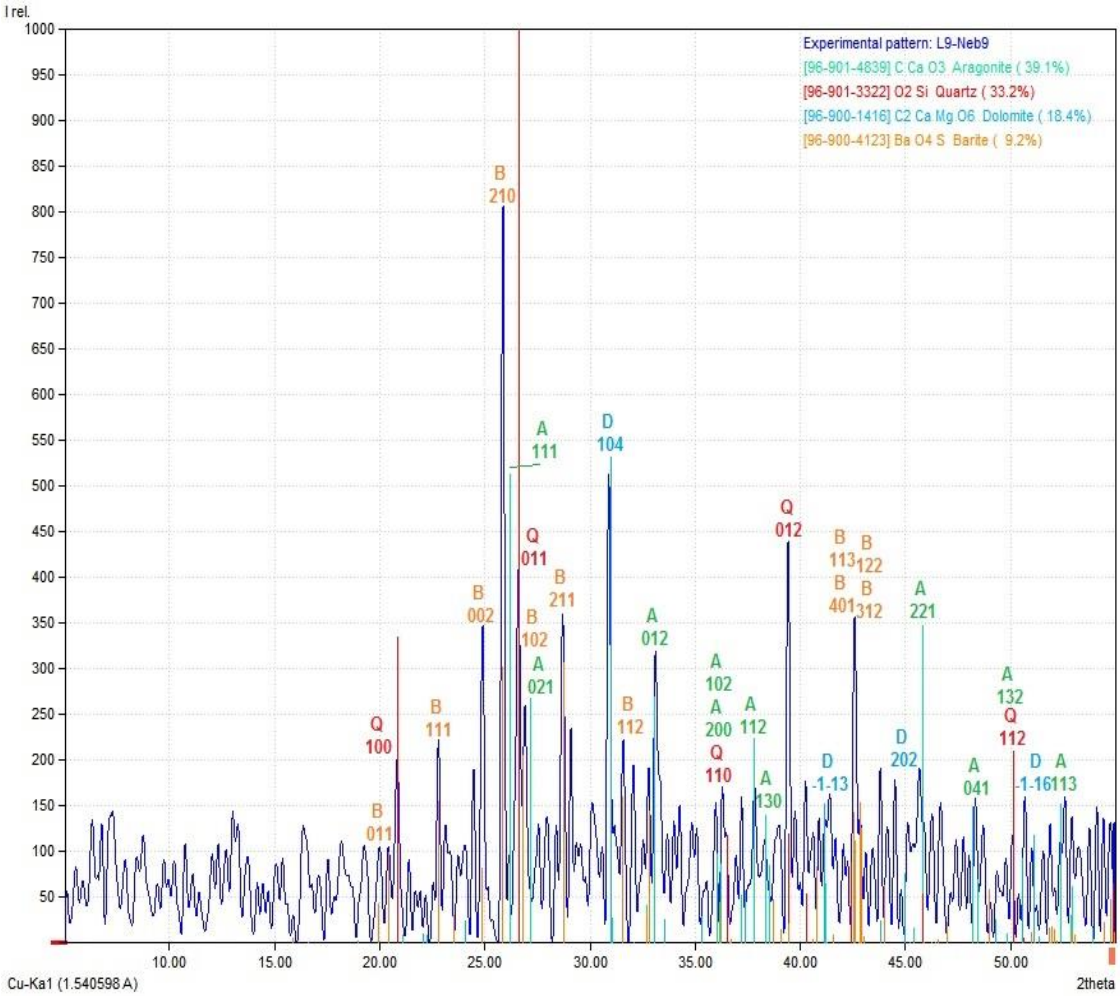
**Sample:** L9-Neb9

**Method:** Shell separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, quartz, dolomite, and barite



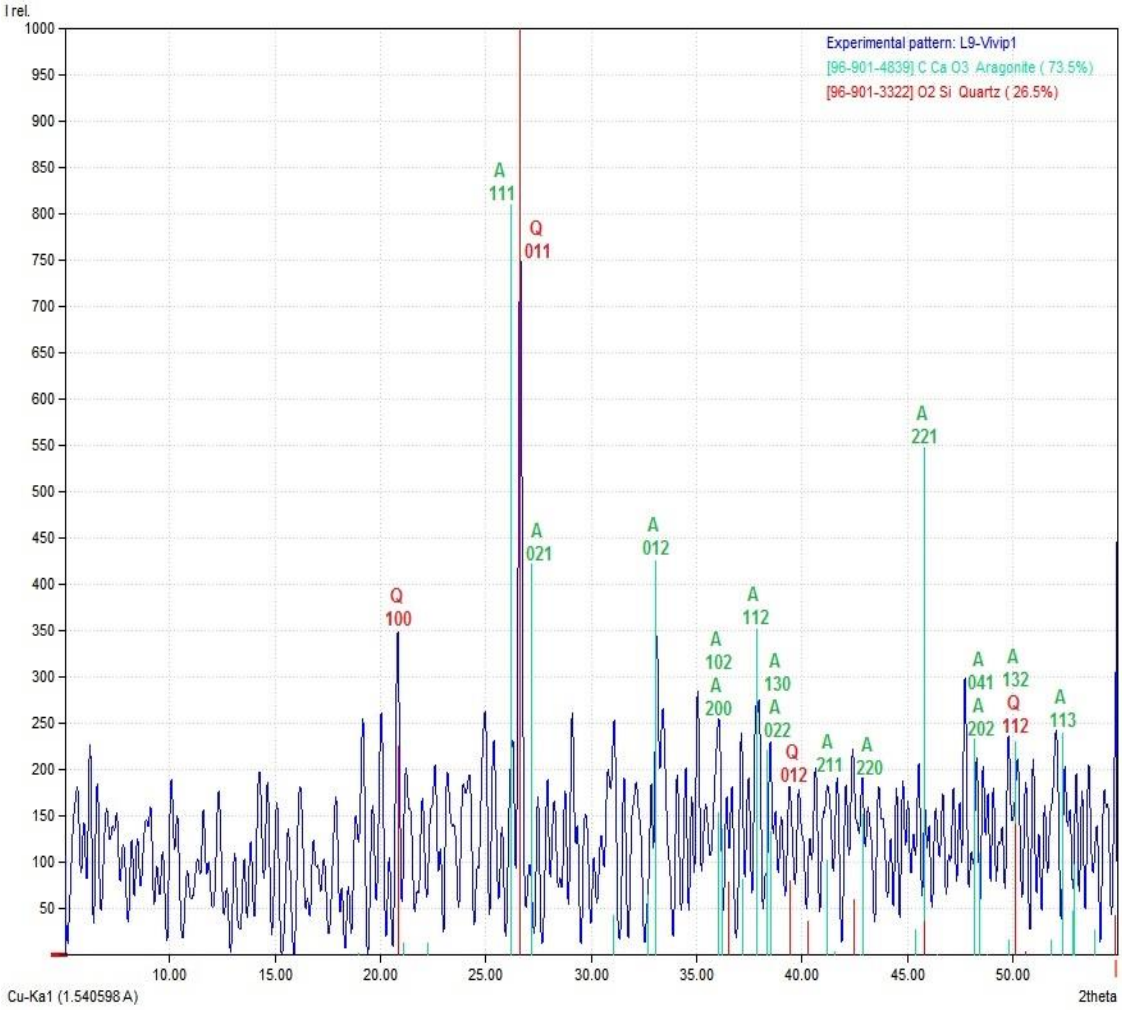



**Sample:** L9-Vivip1

**Method:** Shell separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite and quartz

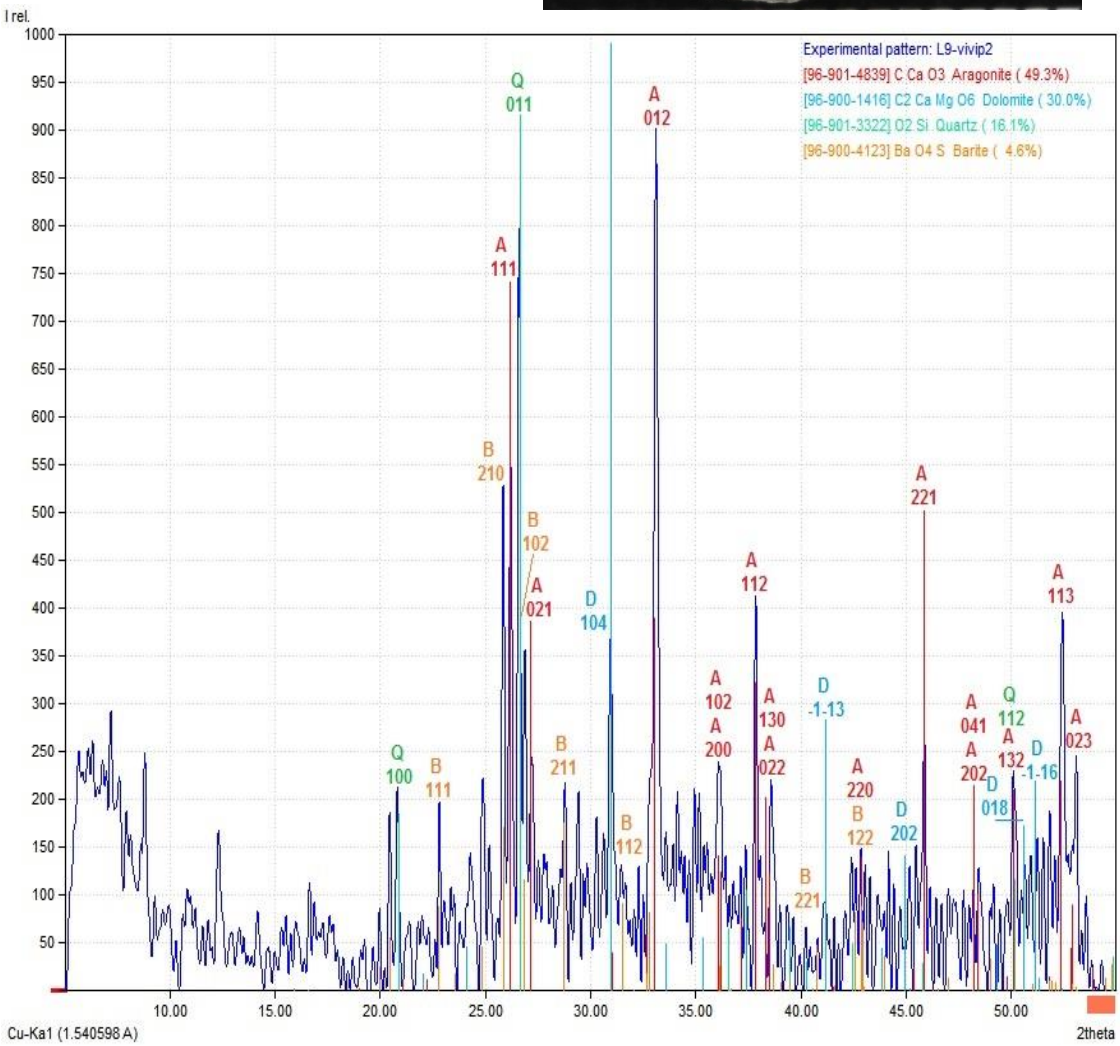



**Sample:** L9-Vivip2

**Method:** Shell separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, dolomite, quartz, and barite

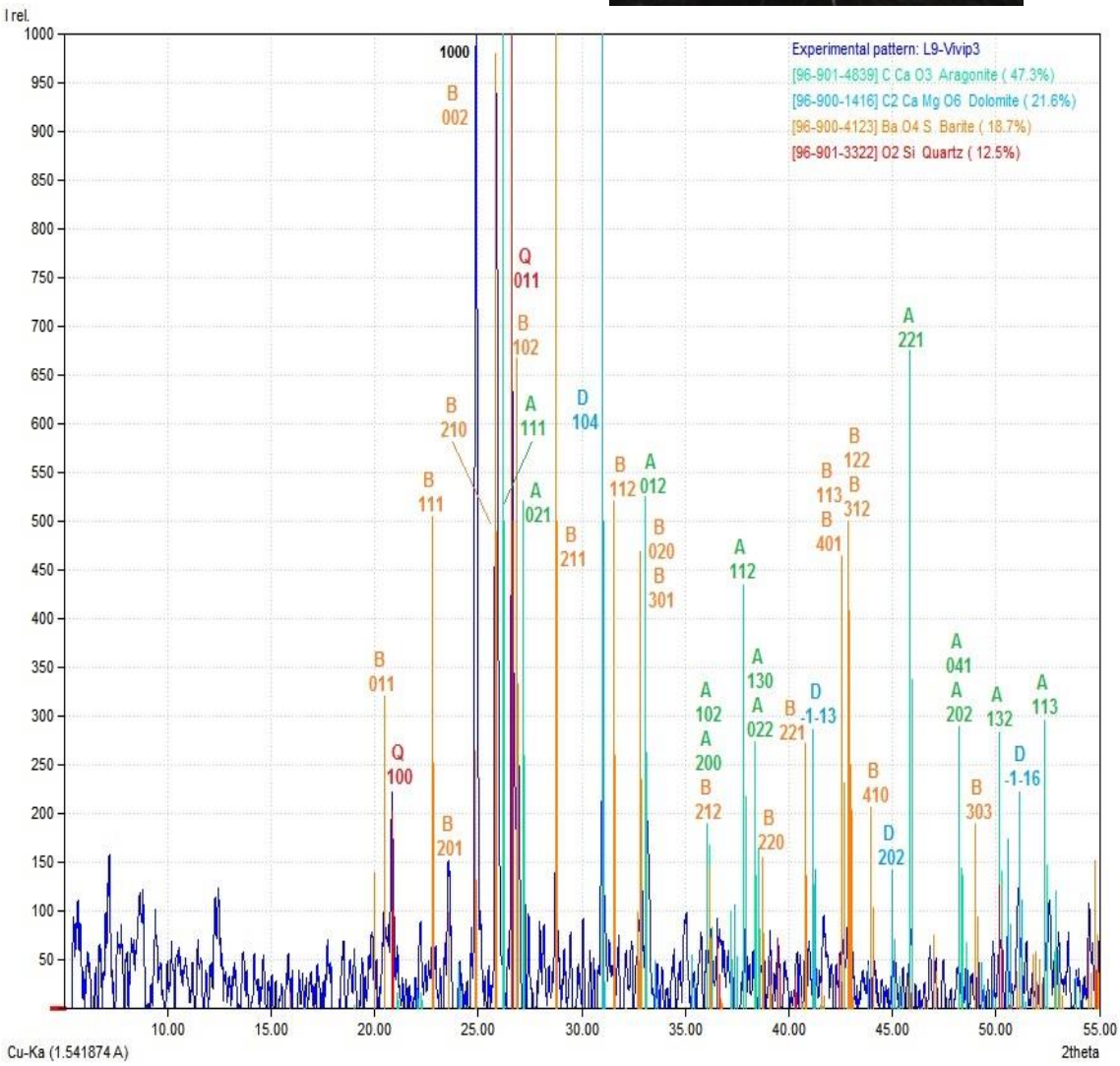



**Sample:** L9-Vivip3

**Method:** Shell separation

**Height in Section:** 315 m

**Mineralogy:** Aragonite, dolomite, barite, and quartz

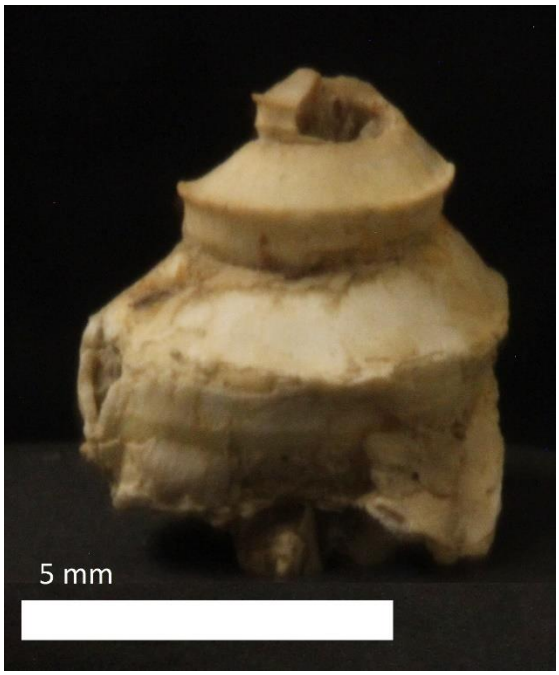



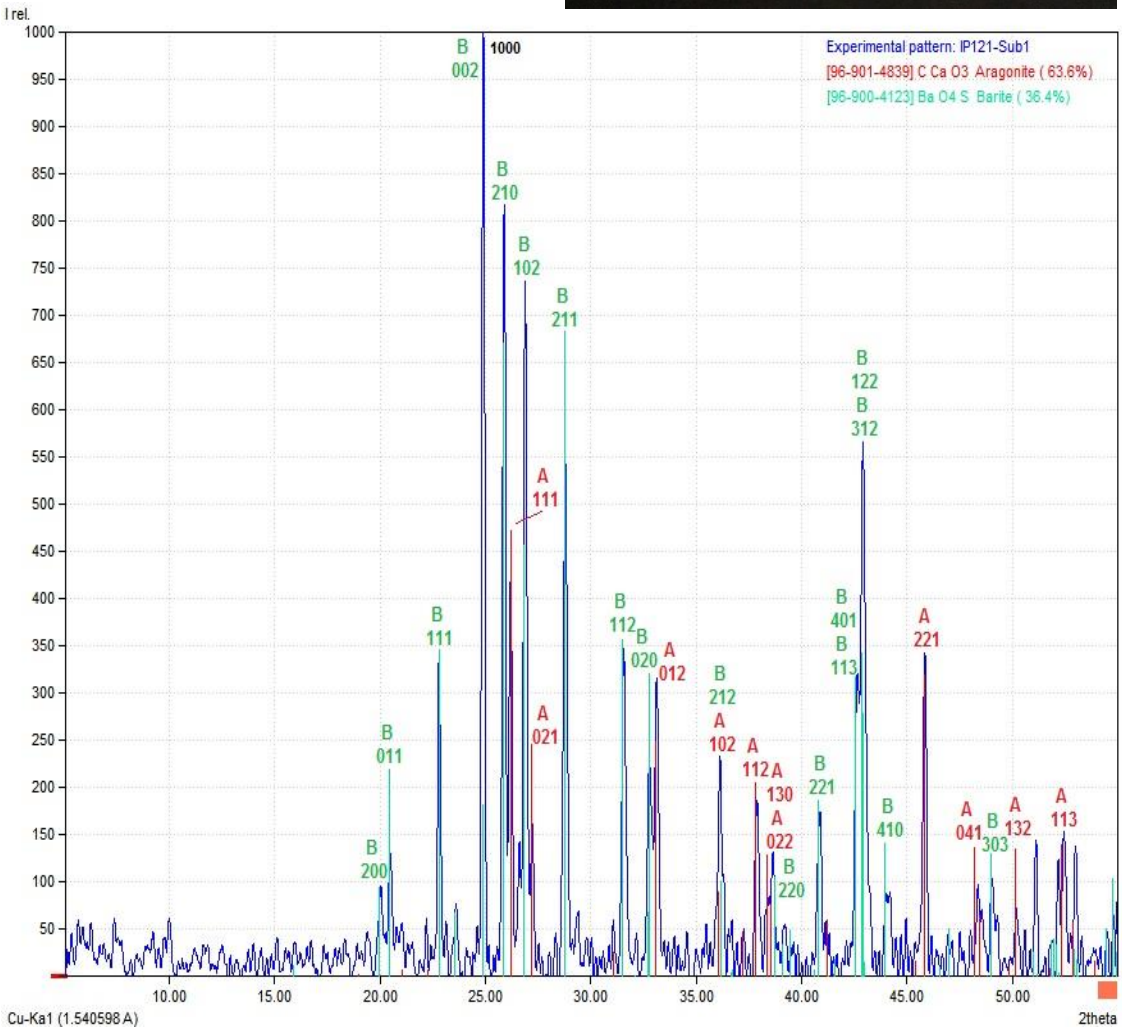
**Sample:** 121-Sub1

**Method:** Shell separation

**Height in Section:** 325 m

**Mineralogy:** Aragonite and barite



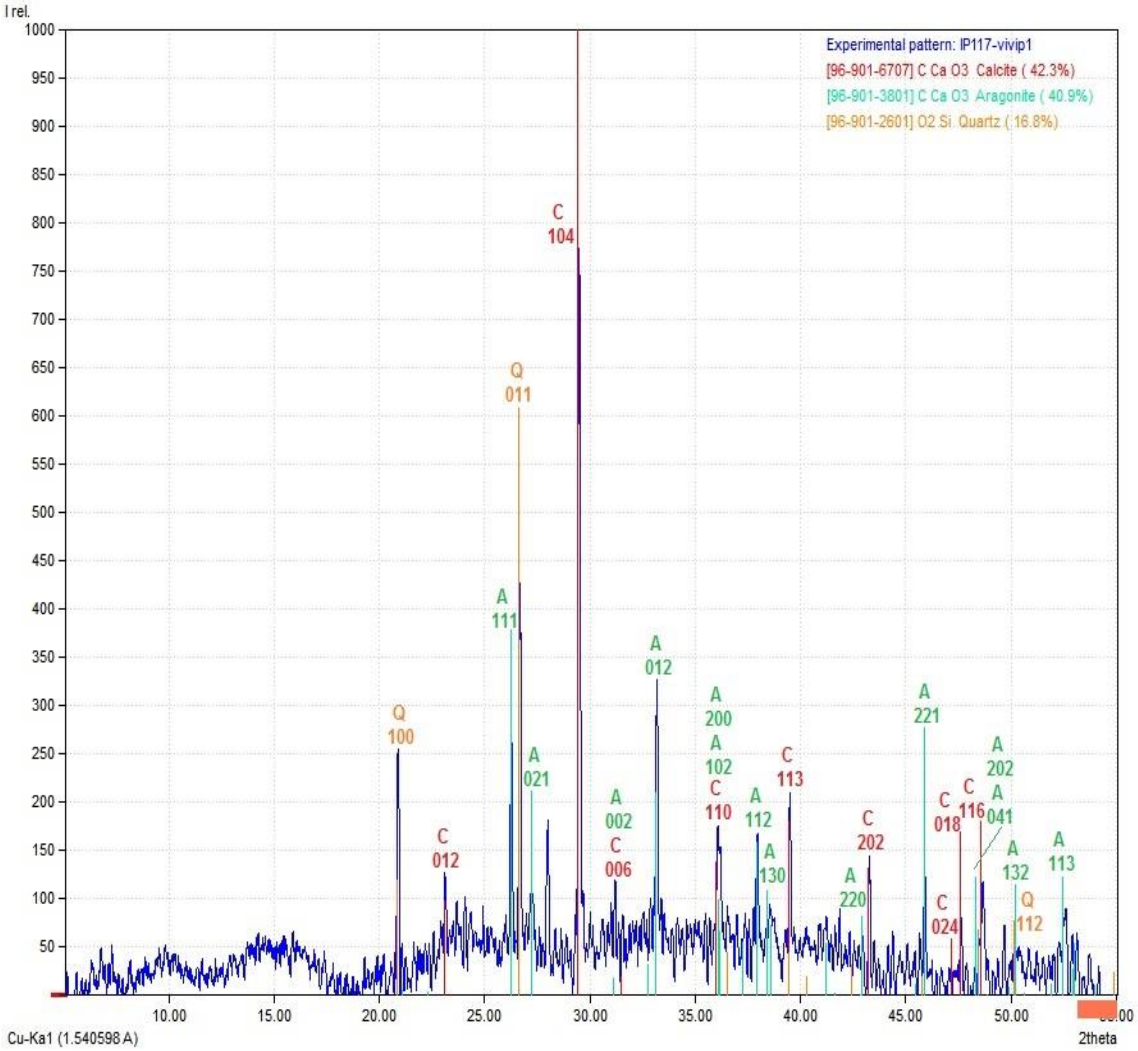



**Sample:** 117-Vivip1

**Method:** Shell separation

**Height in Section:** 343 m

**Mineralogy:** Calcite, aragonite, quartz

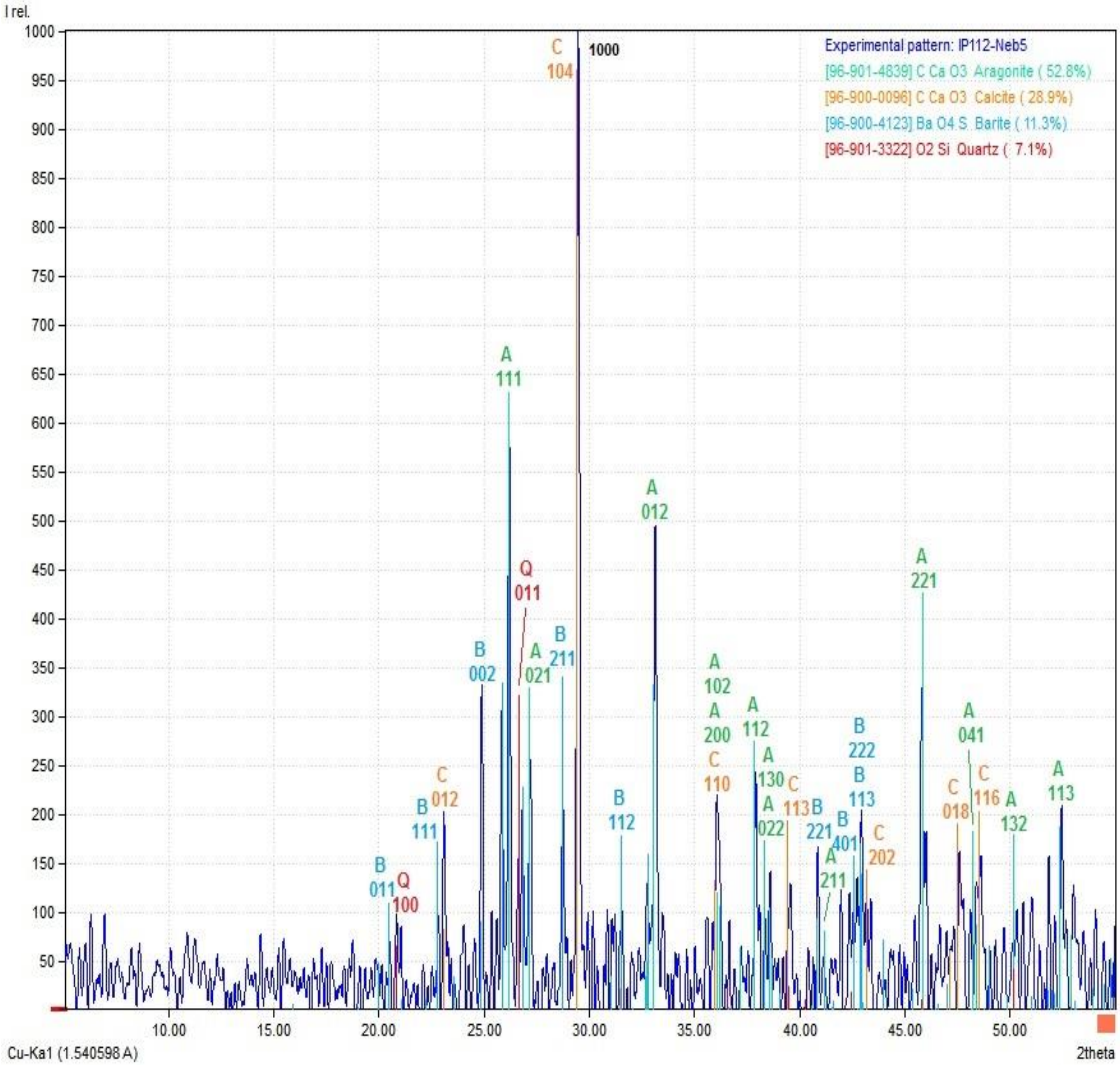



**Sample:** 112-Neb5

**Method:** Shell separation

**Height in Section:** 370 m

**Mineralogy:** Aragonite, calcite, barite, and quartz

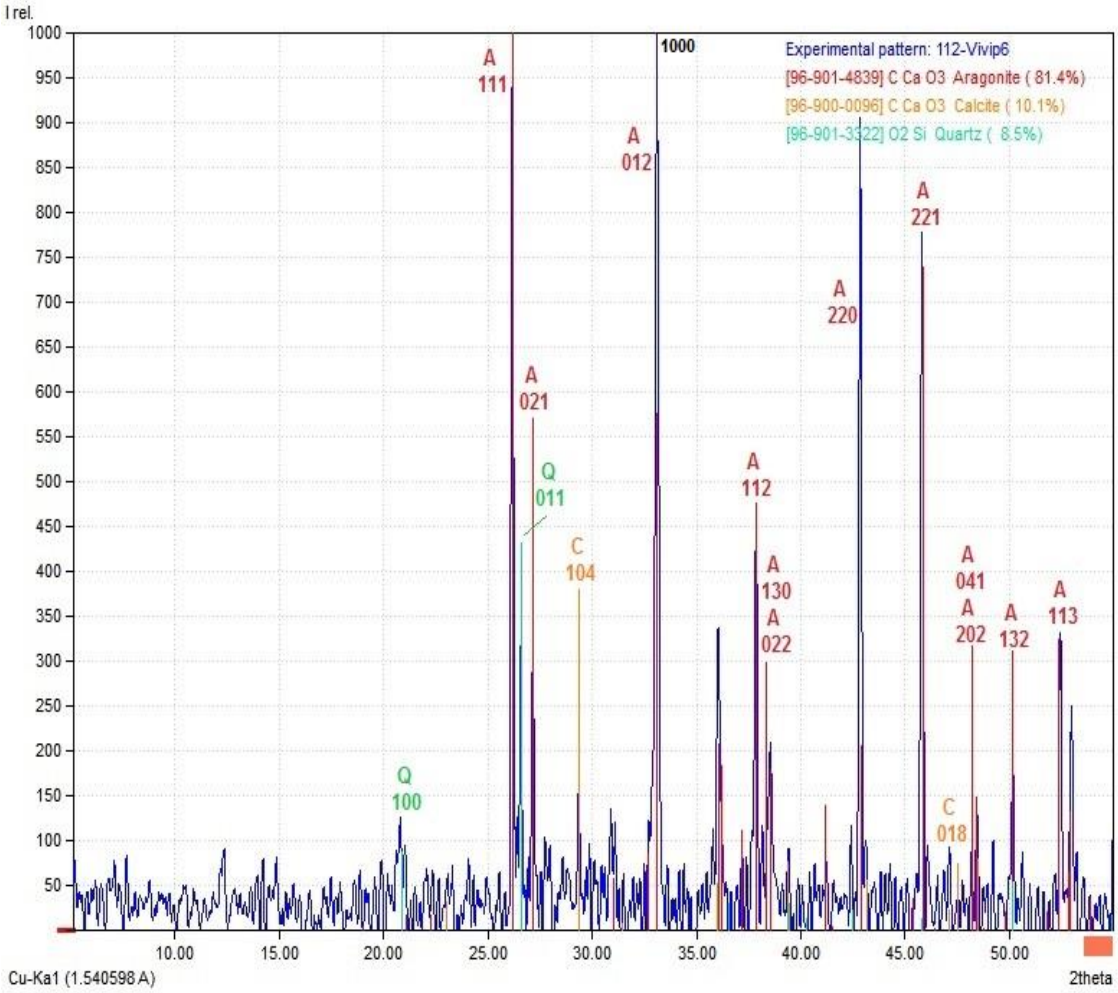



**Sample:** 112-Vivip6

**Method:** Shell separation

**Height in Section:** 370 m

**Mineralogy:** Aragonite, calcite, quartz

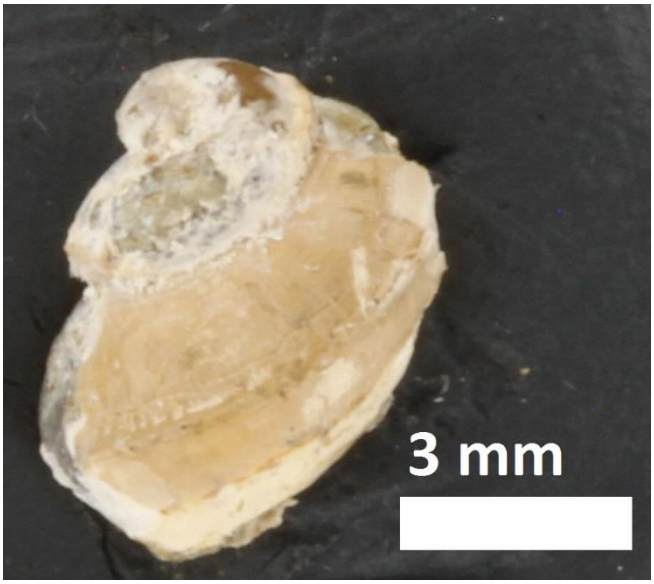



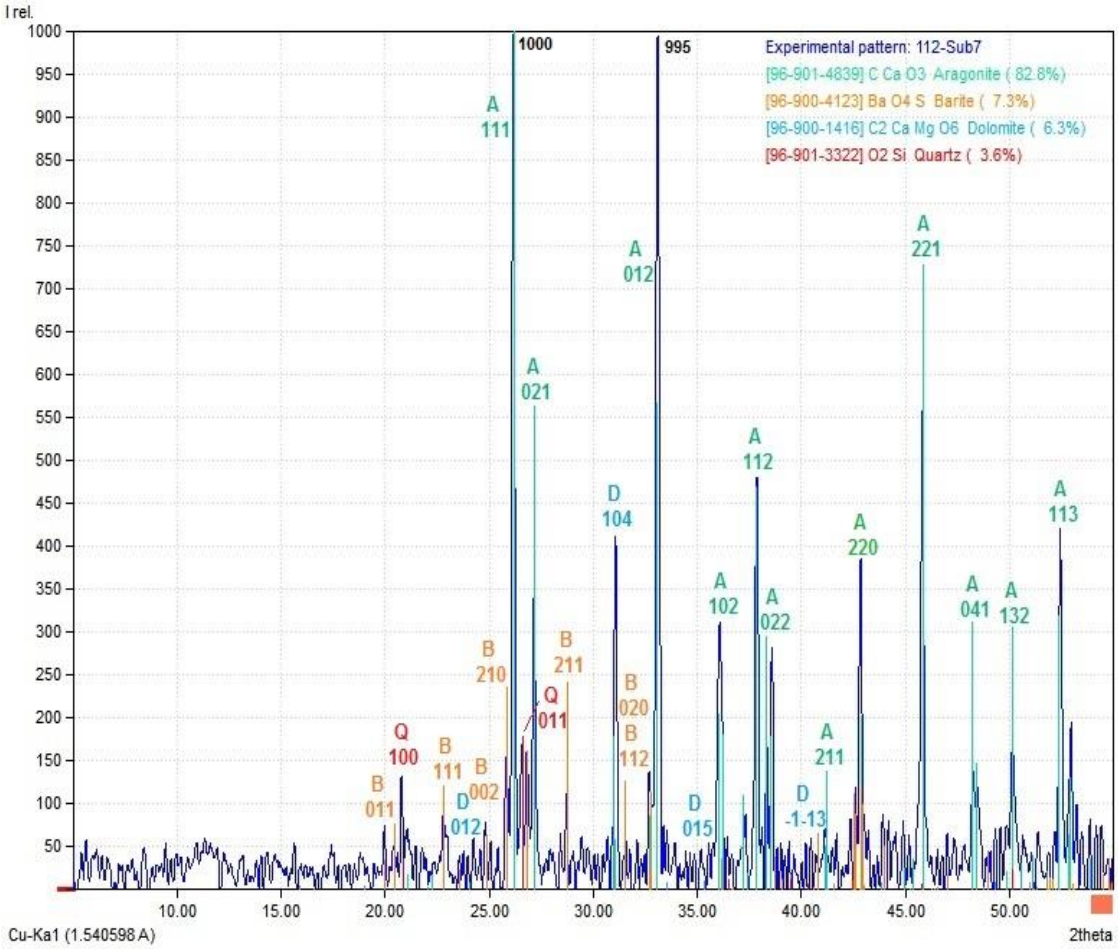
**Sample:** 112-Sub7

**Method:** Shell separation

**Height in Section:** 370 m

**Mineralogy:** Aragonite, barite, dolomite, quartz



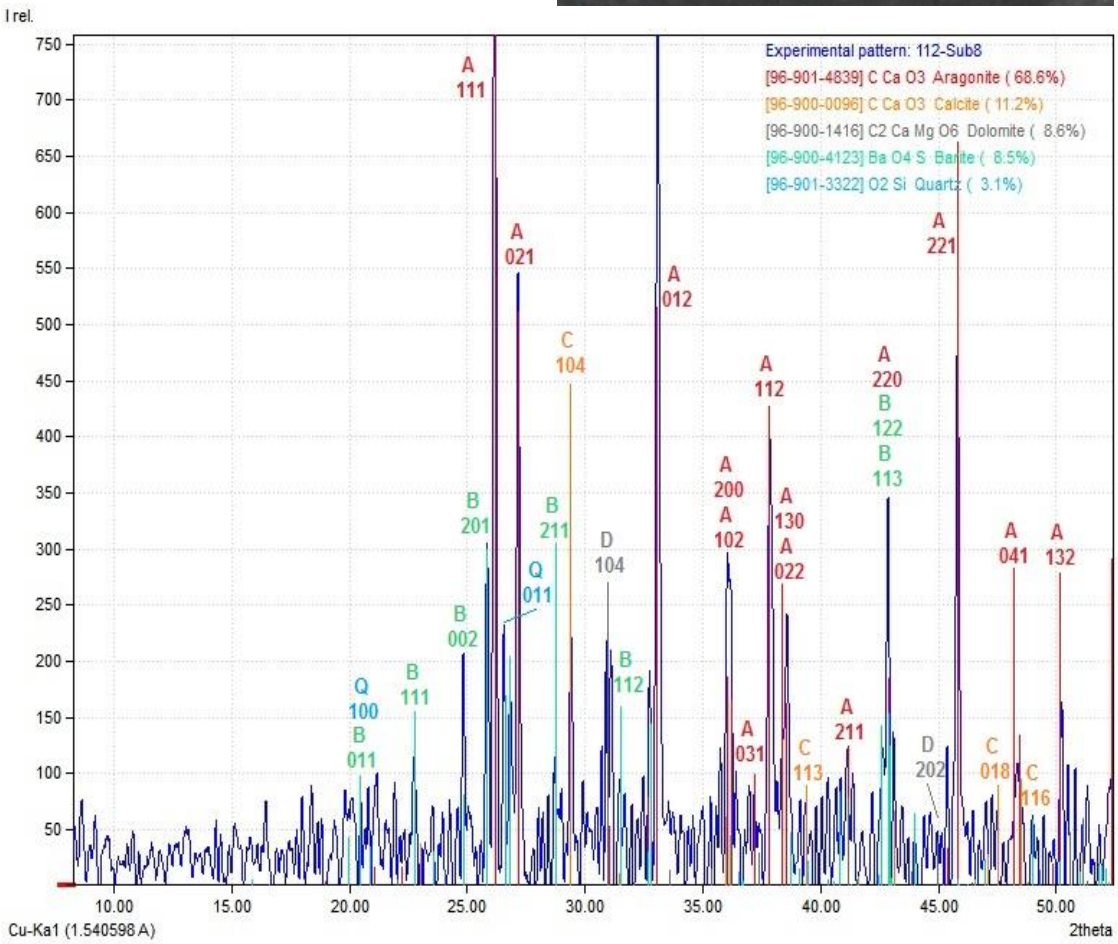



**Sample:** 112-Sub8

**Method:** Shell separation

**Height in Section:** 370 m

**Mineralogy:** Aragonite, calcite, dolomite, barite, and quartz

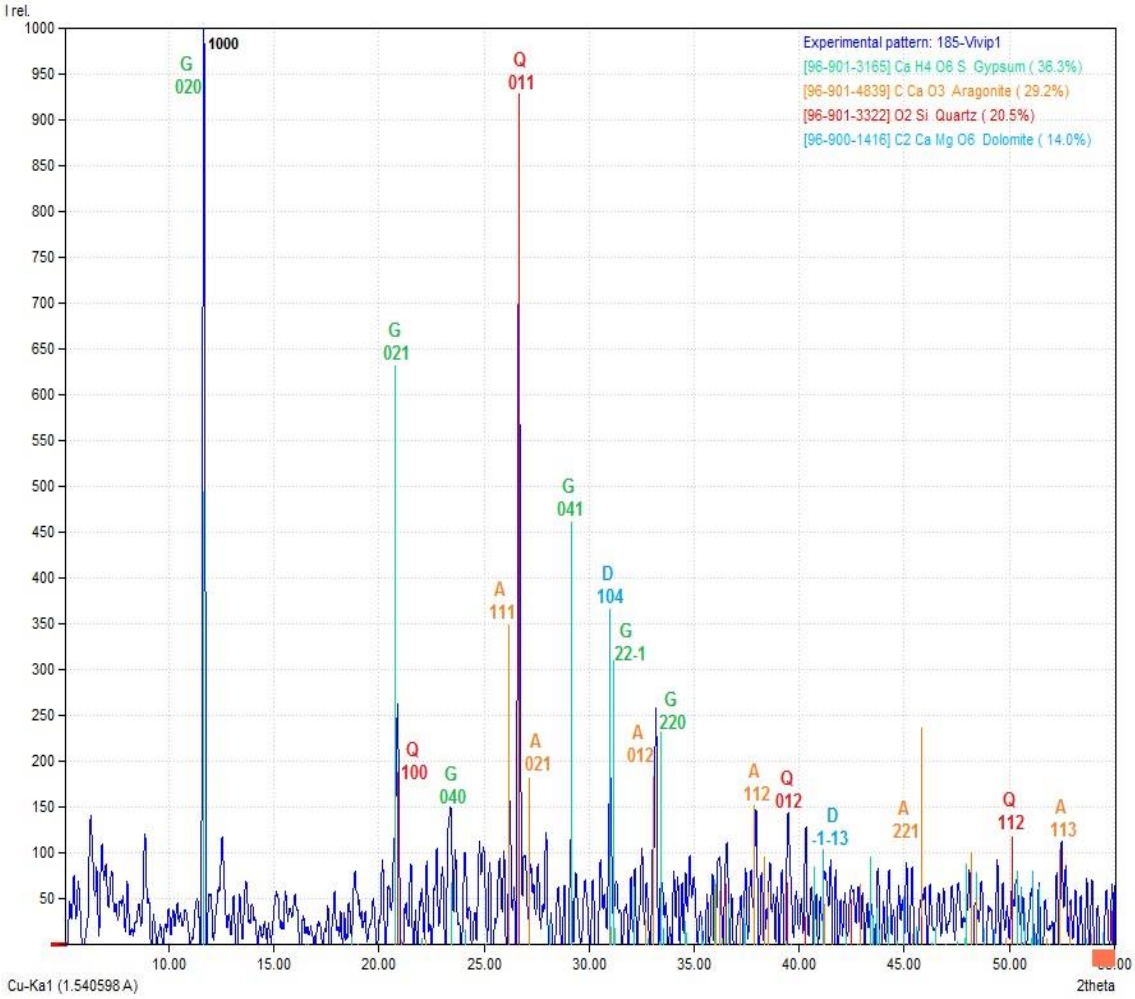



**Sample:** 185-Vivip1

**Method:** Shell separation

**Height in Section:** 532 m

**Mineralogy:** Gypsum, aragonite, quartz, dolomite

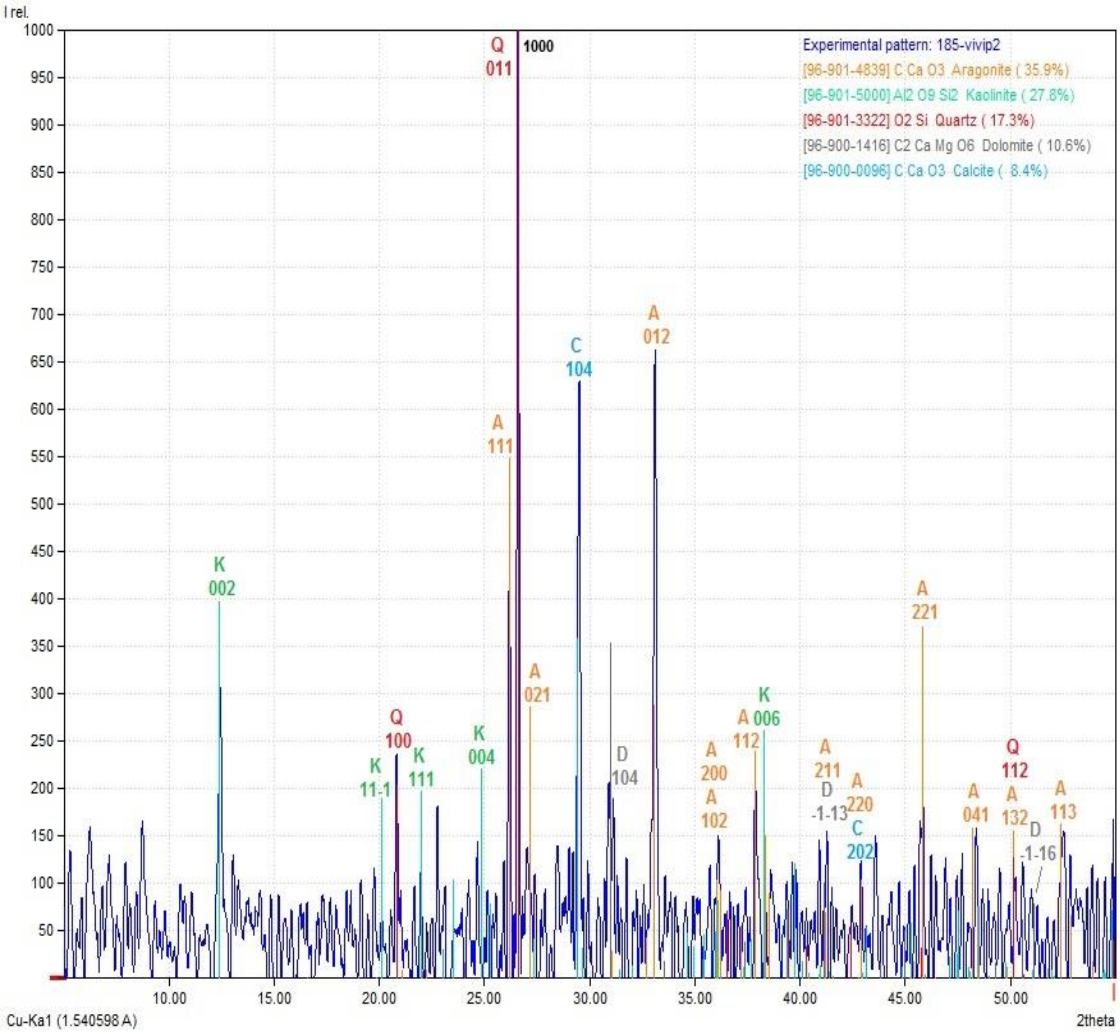



**Sample:** 185-Vivip2

**Method:** Shell separation

**Height in Section:** 532 m

**Mineralogy:** Aragonite, kaolinite, quartz, dolomite, calcite

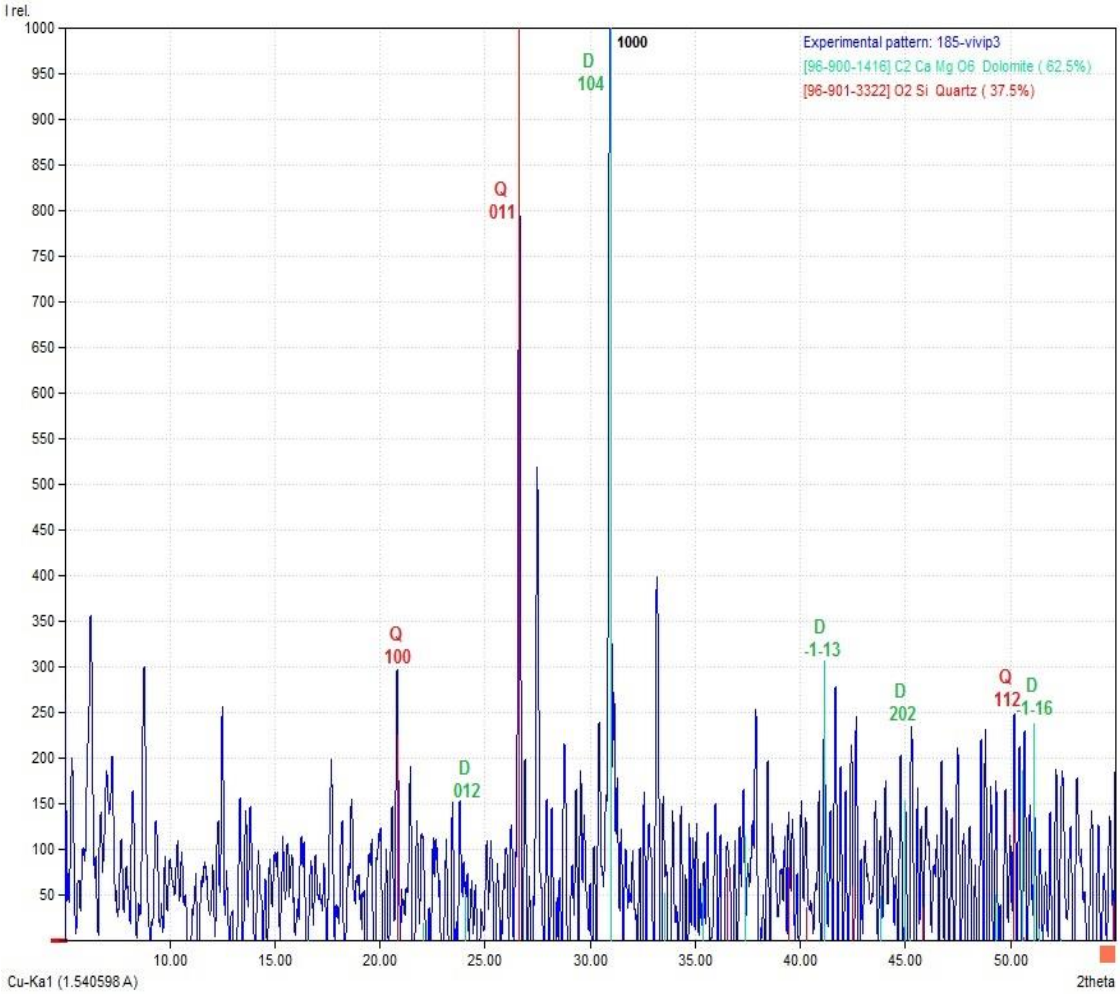



**Sample:** 185-Vivip3

**Method:** Shell separation

**Height in Section:** 532 m

**Mineralogy:** Dolomite and quartz

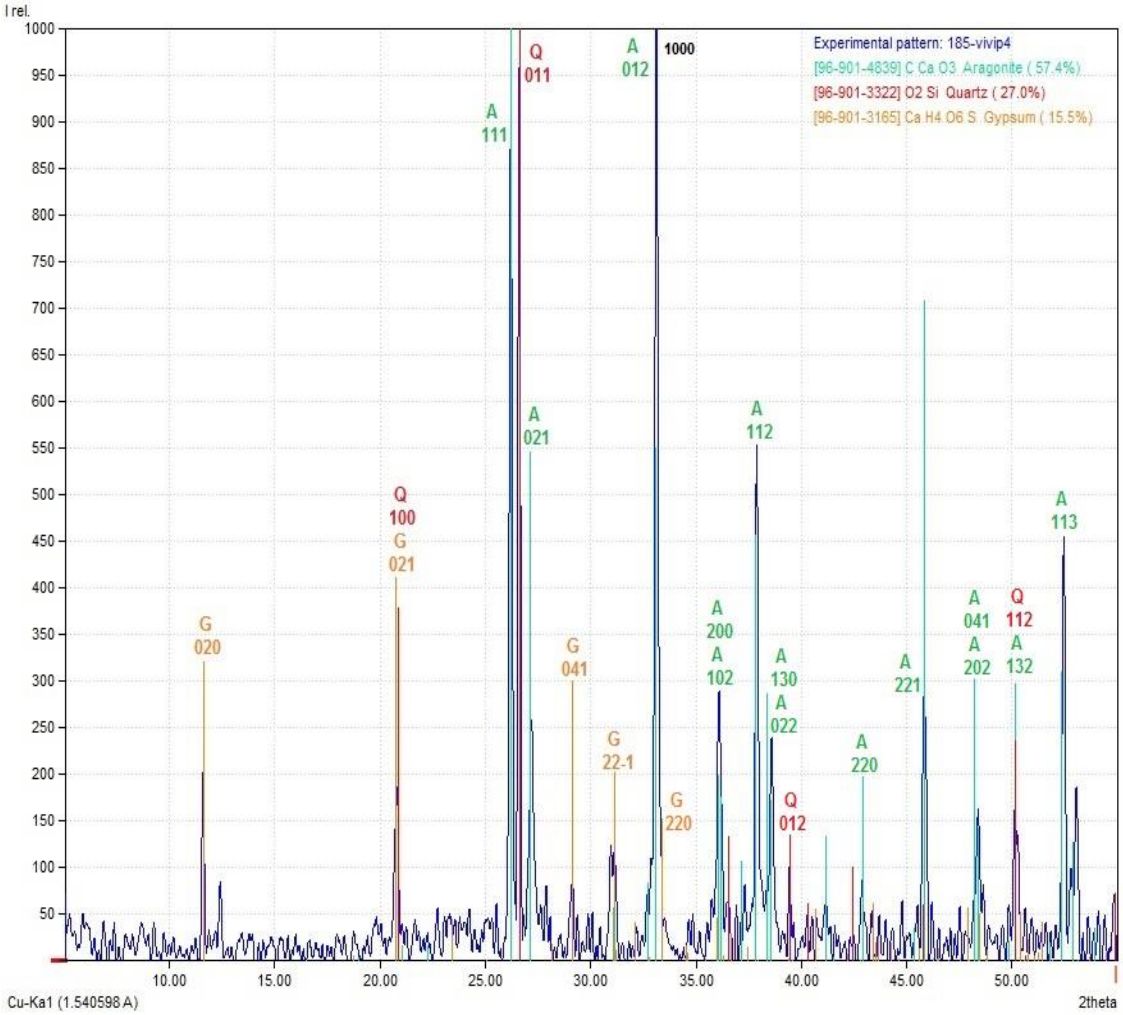



**Sample:** 185-Vivip4

**Method:** Shell separation

**Height in Section:** 532 m

**Mineralogy:** Aragonite, quartz, gypsum

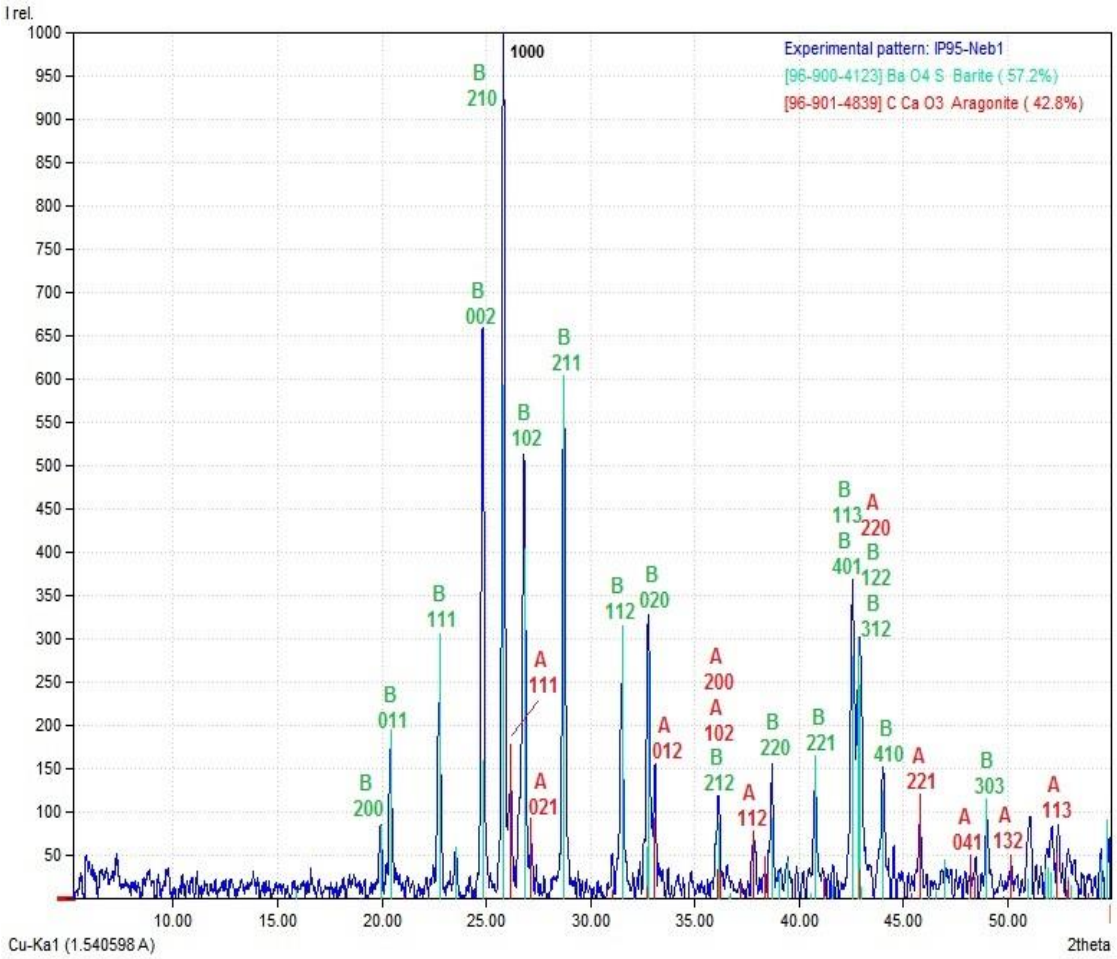



**Sample:** 95-Neb1

**Method:** Shell separation

**Height in Section:** 590 m

**Mineralogy:** Barite, aragonite

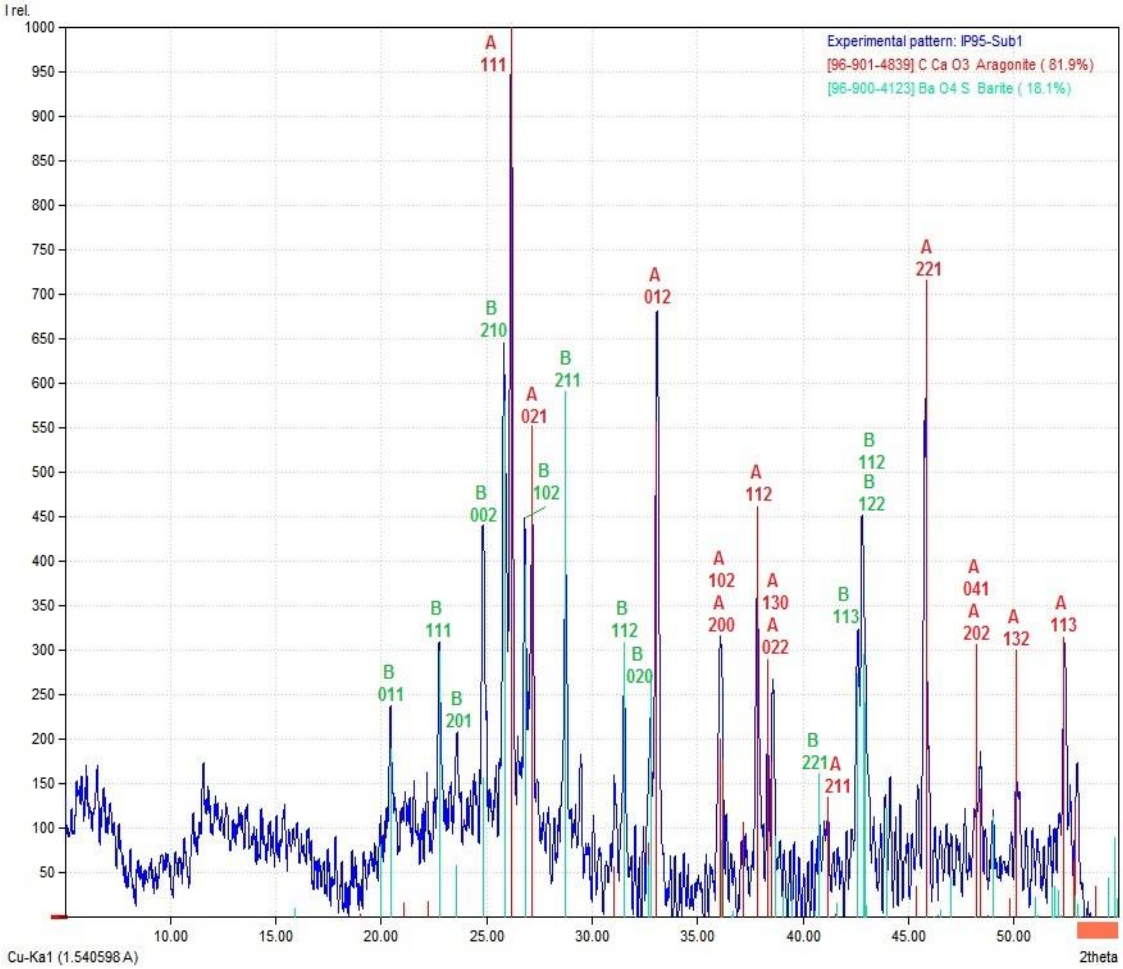



**Sample:** 95-Sub1

**Method:** Shell separation

**Height in Section:** 590 m

**Mineralogy:** Aragonite, barite

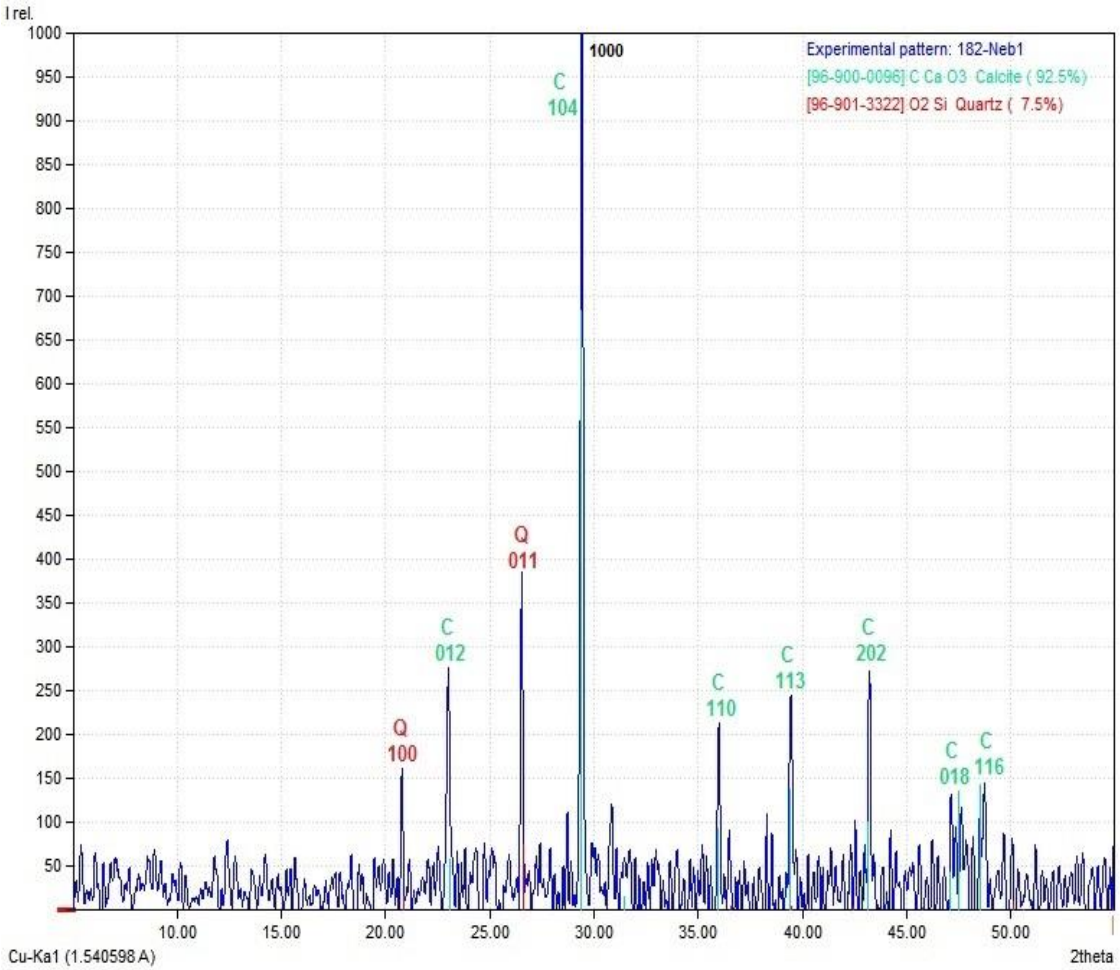



**Sample:** 182-Neb1

**Method:** Shell separation

**Height in Section:** 622 m

**Mineralogy:** Calcite and quartz

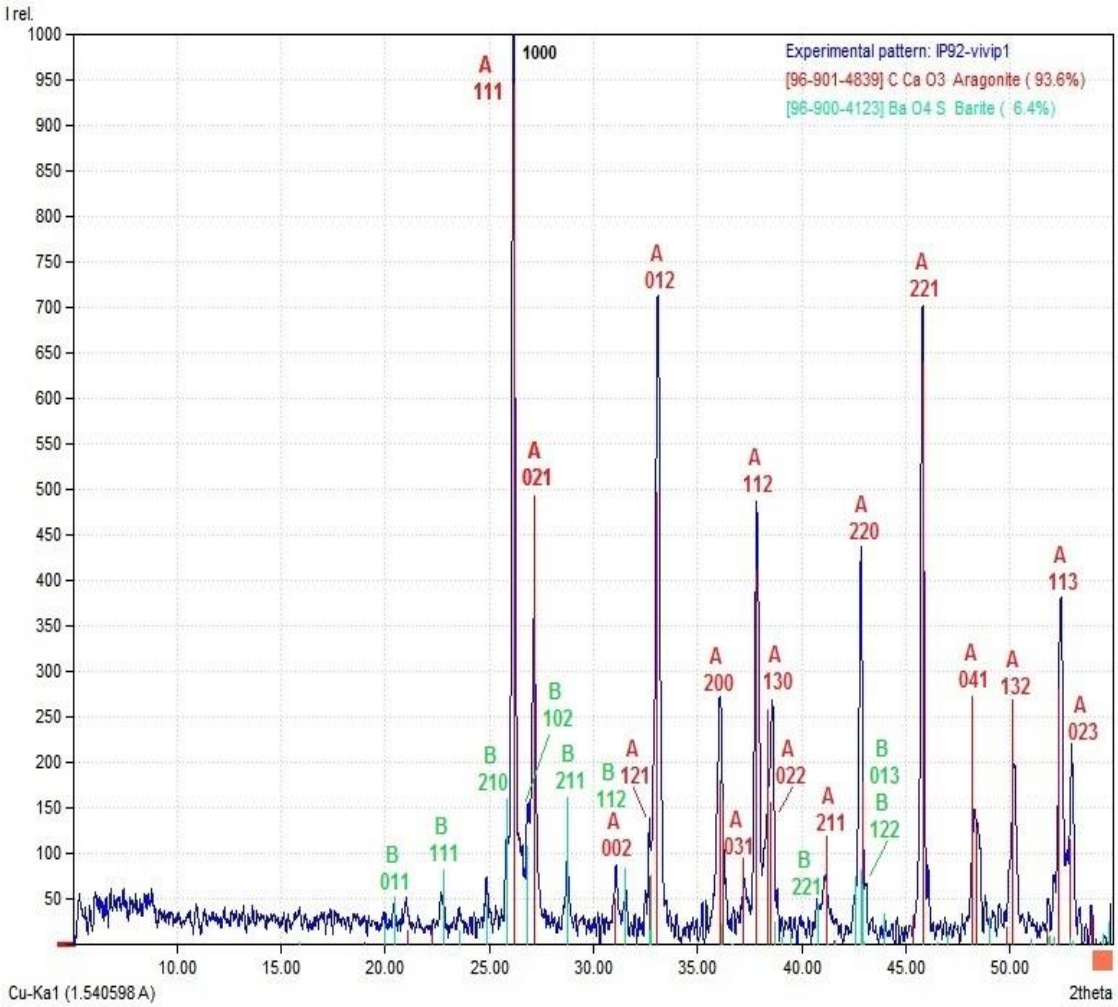



**Sample:** 92-Vivip1

**Method:** Shell separation

**Height in Section:** 668 m

**Mineralogy:** Aragonite and barite

**Appendix IV:** X-ray Diffraction Spectra Processing and Data

| | | | | |
|---|---|---|---|---|
| Type of Instrument | Bruker D8 | | | |
| Location of Lab | ISU Room PSB 350 (LEG) | | | |
| Analyst | Amy Hudson | | | |
| Sample Types | Calcium Crabonate Gastropod Shell ± matrix | | | |
| Purpose | $CaCO_3$ identification | | | |
| Operating Parameters | Target | DS | RS | Scan Rate (°2Θ/min) |
| | Cu-Kα | 1° | 1° | 1°/min |
| | 1.5405 Å | | | |
| | | | | |
| | Scan Range | Filter | Detector | Ionochromator |
| | 5-55° | Ni | Scintillator | None |

There are two main sources of error associated with mineral identification and quantification using x-ray diffraction spectra. Small quantities of sample material can cause errors with mounting samples. If the sample coating is insufficient to cover enough slide area, the x-ray beam will not be able get enough return signal to differentiate the individual minerals fully, resulting in increased background counts and false peaks, and even slight shifts of the entire spectra a few 100ths of a degree. Similarly, insufficient grinding of samples, particularly those samples that include a large amount of matrix material, can cause errors in peak intensity (Bish and Reynolds, 1989).

Another possible complication stems from the biologic nature of the shell samples. Unlike the inorganic mineral references, the shell material is a biogenic carbonate, which is comprised of mineral and organic components (Weiner and Dove, Θ003), the outer most layer is organic, while the inner 2-3 layers are composed of calcium carbonate (Shanahan et al., 2005). This organic layer, in addition to the fact that biogenic minerals display slightly different external morphologies (Weiner and Dove,

2003) may be responsible for slight changes in peak position or intensity, without changing the overall mineral signature.

If any of these errors are present in a sample, the quantification of the different mineral phases can be compromised. To detect these possible errors, when present in the sample, quartz was used as an internal reference to check for proper peak position and height ratios in the shell samples. Checking against quartz allowed for adjustment of the spectra, so that samples with peak positions that were off by a 0.01 to 0.06 degrees could be more accurately identified and quantified.

Additional steps taken to ensure as accurate a quantification as possible include the subtraction of background using linear interpolation, smoothing of the spectra to remove extra noise or small false peaks in the signals, and normalizing peak ratios so that the tallest peak did not exceed 1000 counts. Manual removal of some background was necessary, and a manual selection of matching mineral phases was done for every sample. For this reason, some samples have matching peaks even though not all of the smaller (less than 50% peaks) are able to be distinguished from the background.

The Match! 3 Software relies on the relative ratio of peak heights for each mineral identified in the samples, to calculate an estimate of how much each mineral contributes to the total composition of the sample. To estimate the percentages of only carbonate minerals, each carbonate mineral is isolated from the non-carbonates and normalized, so that the percentage of aragonite versus alteration phases can be estimated. This allows samples to be grouped based on how much of the original signal is likely to be preserved without the input of matrix minerals.

Despite the sources of error encountered while testing the mineralogical composition of the gastropods, the mineralogical assessments recorded reasonable proportions of minerals and were able to accurately identify the necessary peaks. Even the poorest quality data allowed proper identification of the minerals in the shell. Therefore, the mineralogical composition of the gastropods is considered accurate and quantitative calculations, although only estimates, are considered close to the true mineral percentages.

All original XrD data files for the individual gastropod shell samples are included in Microsoft Excel file format accompanying this manuscript. Original files for all stable isotope data, and a separate file with calculated oxygen values are also included in Microsoft Excel file format accompanying this manuscript.

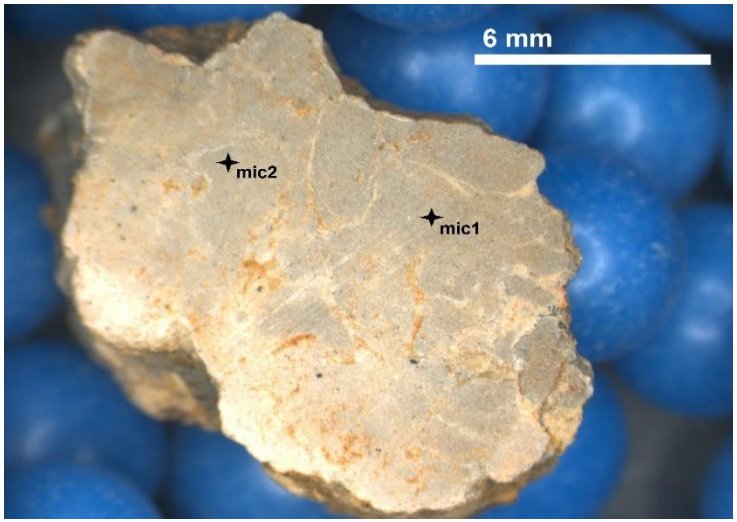
**Appendix V:** Pedogenic Soil Carbonate Sample Index

| Sample ID | Mineralogy | Height in Section (m) | Depositional Environment | $\delta^{13}C$ ‰ (VPDB) | $\delta^{18}O$ ‰ (VPDB) | $\delta^{18}O$ ‰ (VSMOW) | $\delta^{18}O$ ‰ of water (VSMOW) | Unit |
|---|---|---|---|---|---|---|---|---|
| L1CN1MIC1 | micrite | 42 | soil/pond | -9.5 | -7.4 | 23.3 | -5.5 | Lower |
| L1CN1MIC2 | micrite | 42 | soil/pond | -9.6 | -7.3 | 23.4 | -5.4 | Lower |
| L1CN2MIC1 | micrite | 42 | soil/pond | -9.0 | -7.0 | 23.7 | -5.1 | Lower |
| L1CN2MIC2 | micrite | 42 | soil/pond | -9.1 | -7.3 | 23.4 | -5.4 | Lower |
| L1CN2SPAR1 | spar | 42 | soil/pond | -10.9 | -8.5 | X | X | Lower |
| L1CN3MIC1 | micrite | 42 | soil/pond | -9.2 | -7.4 | 23.2 | -5.5 | Lower |
| L1CN3MIC2 | micrite | 42 | soil/pond | -9.3 | -7.2 | 23.5 | -5.3 | Lower |
| L1CN3SPAR1 | spar | 42 | soil/pond | -10.1 | -7.5 | X | X | Lower |
| L2CN1MIC1 | micrite | 74 | soil/pond | -9.3 | -7.7 | 23.0 | -5.8 | Lower |
| L2CN1MIC2 | micrite | 74 | soil/pond | -9.3 | -7.4 | 23.3 | -5.5 | Lower |
| L2CN1MIC3 | micrite | 74 | soil/pond | -9.6 | -7.4 | 23.3 | -5.5 | Lower |
| L2CN1SPAR1 | spar | 74 | soil/pond | -8.2 | -11.5 | X | X | Lower |
| L2CN2MIC1 | micrite | 74 | soil/pond | -9.4 | -8.8 | 21.8 | -6.9 | Lower |
| L2CN2MIC2 | micrite | 74 | soil/pond | -8.7 | -10.5 | 20.1 | -8.6 | Lower |
| L2CN2SPAR1 | spar | 74 | soil/pond | -6.5 | -15.2 | X | X | Lower |
| L3CN2MIC1 | micrite | 81 | soil/pond | -8.9 | -7.7 | 22.9 | -5.8 | Lower |
| L3CN3MIC1 | micrite | 81 | soil/pond | -8.4 | -8.0 | 22.7 | -6.1 | Lower |
| L3CN3MIC2 | micrite | 81 | soil/pond | -6.9 | -7.9 | 22.8 | -6.0 | Lower |
| L3CN3MIC3 | micrite | 81 | soil/pond | -7.5 | -8.5 | 22.1 | -6.6 | Lower |
| L5CN1MIC1 | micrite | 162 | soil/pond | -9.8 | -7.9 | 22.7 | -6.0 | Middle |
| L5CN2MIC1 | micrite | 162 | soil/pond | -9.3 | -4.8 | 25.9 | -2.9 | Middle |
| L5CN2MIC2 | micrite | 162 | soil/pond | -9.1 | -7.7 | 23.0 | -5.8 | Middle |
| L6CN1MIC1 | micrite | 212 | soil/pond | -9.1 | -8.2 | 22.4 | -6.3 | Middle |

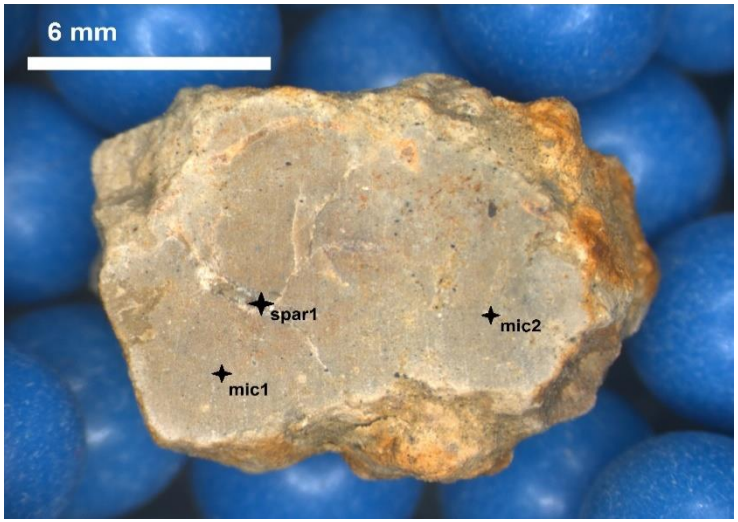
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| L6CN1MIC2 | micrite | 212 | soil/pond | -9.1 | -8.1 | 22.6 | -6.2 | Middle |
| L6CN2MIC1 | micrite | 212 | soil/pond | -9.3 | -7.5 | 23.1 | -5.6 | Middle |
| L6CN2MIC2 | micrite | 212 | soil/pond | -9.5 | -7.6 | 23.1 | -5.7 | Middle |
| L6CN3MIC1 | micrite | 212 | soil/pond | -9.0 | -7.7 | 22.9 | -5.8 | Middle |
| L6CN3MIC2 | micrite | 212 | soil/pond | -9.1 | -7.8 | 22.8 | -5.9 | Middle |
| L9CN1MIC1 | micrite | 315 | soil/pond | -8.6 | -7.1 | 23.6 | -5.2 | Middle |
| L9CN1MIC2 | micrite | 315 | soil/pond | -8.4 | -6.2 | 24.5 | -4.3 | Middle |
| L9CN1SPAR1 | spar | 315 | soil/pond | -8.9 | 13.7 | X | X | Middle |
| L9CN2MIC1 | micrite | 315 | soil/pond | -9.1 | -6.1 | 24.6 | -4.2 | Middle |
| L9CN2MIC2 | micrite | 315 | soil/pond | -9.3 | -6.5 | 24.2 | -4.6 | Middle |
| L9CN2MIC3 | micrite | 315 | soil/pond | -9.6 | -8.3 | 22.4 | -6.4 | Middle |
| L9CN2SPAR1 | spar | 315 | soil/pond | -3.6 | 64.8 | X | X | Middle |
| L9CN3MIC1 | micrite | 315 | soil/pond | -8.8 | -7.6 | 23.0 | -5.7 | Middle |
| L9CN3MIC2 | micrite | 315 | soil/pond | -8.8 | -7.9 | 22.8 | -6.0 | Middle |

** Spar samples are not included in any of the stable isotopic interpretation, but are included to demonstrate that the micrite from the samples record different stable isotopic values, particularly the oxygen. X= value not determined. **

**Appendix VI:** Sample locations on pedogenic soil carbonates

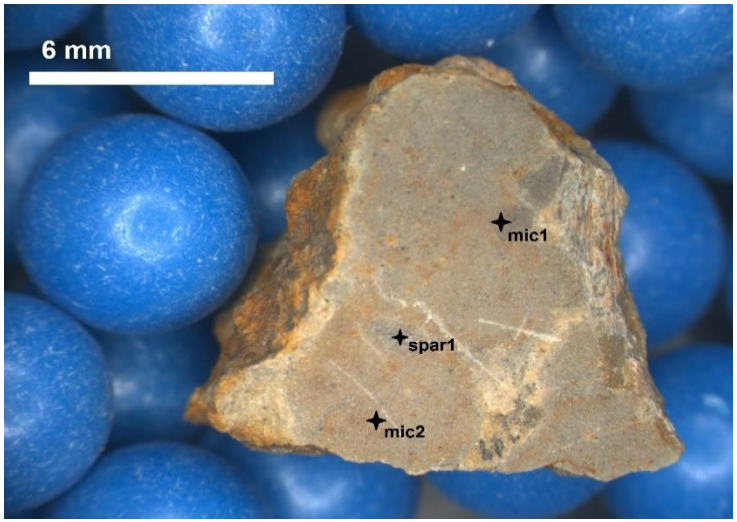



L1-CN1 (top)

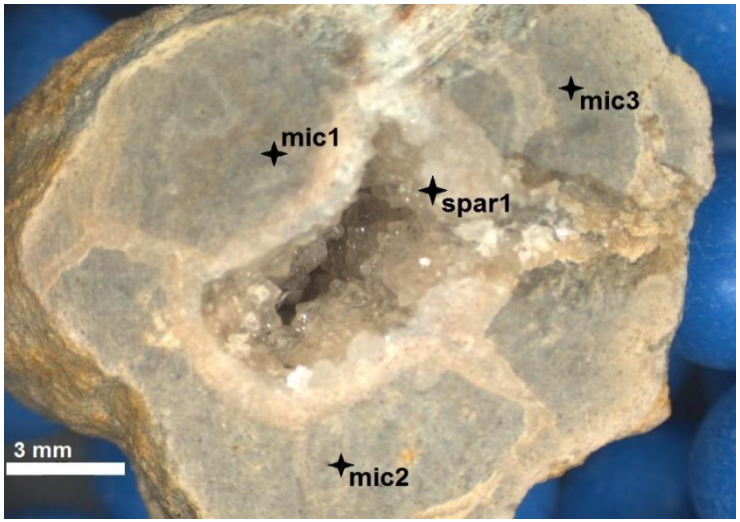


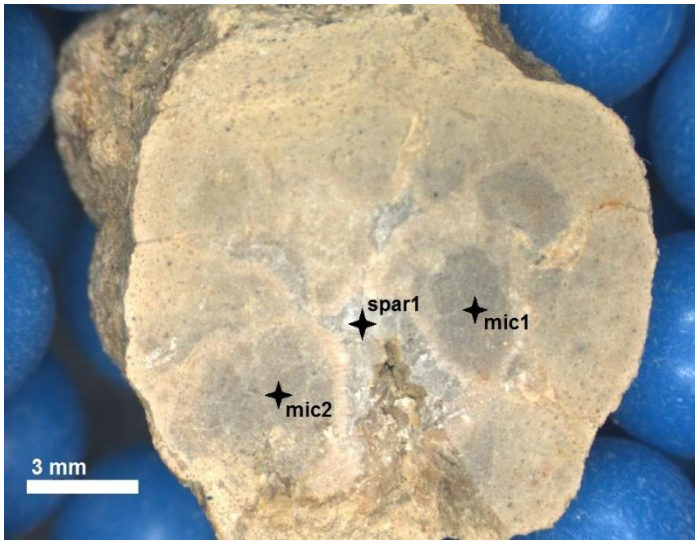

L1-CN2 (top)

L1-CN3

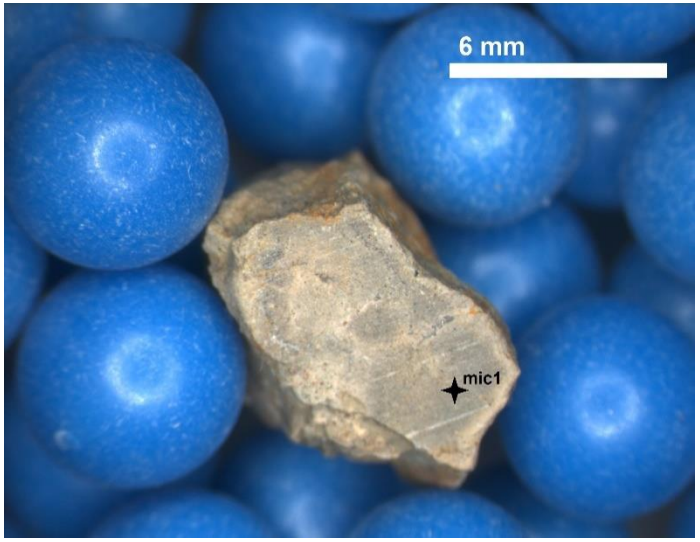



L2-CN1



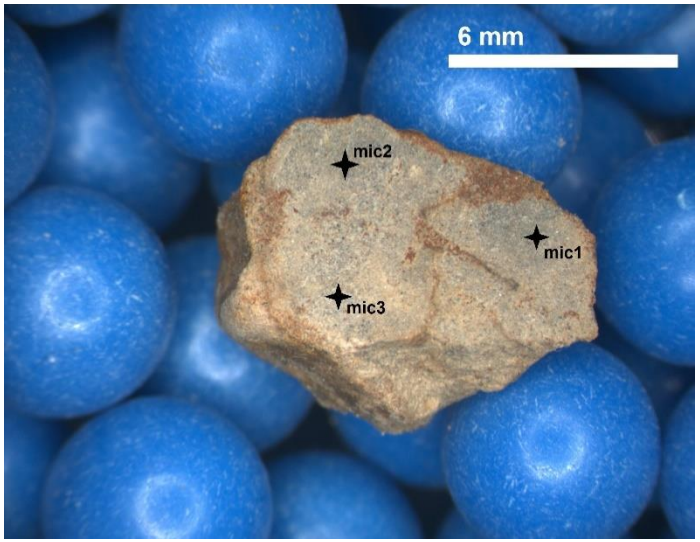



L2-CN2 (top)

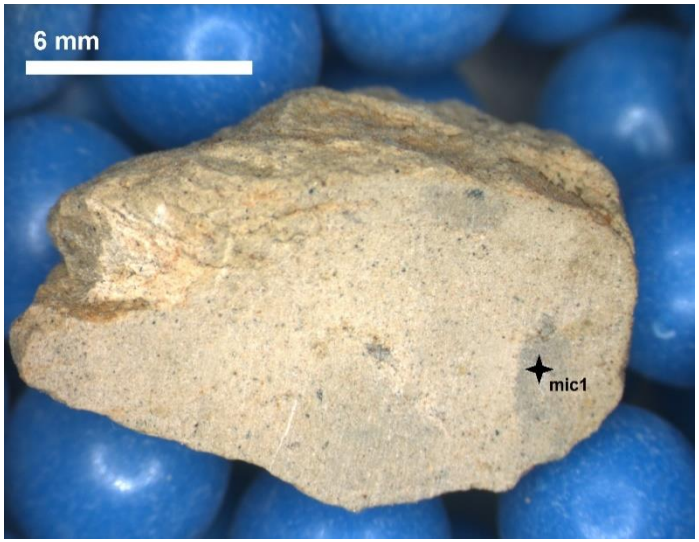


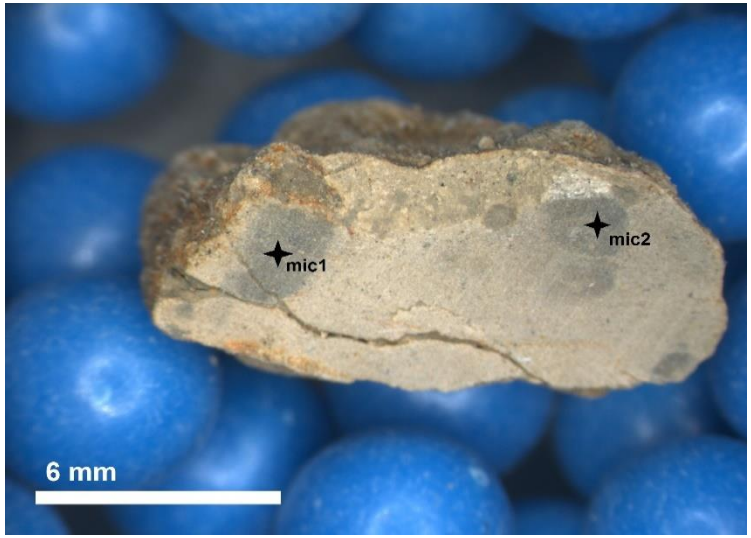

L3-CN2 (top)

L3-CN3

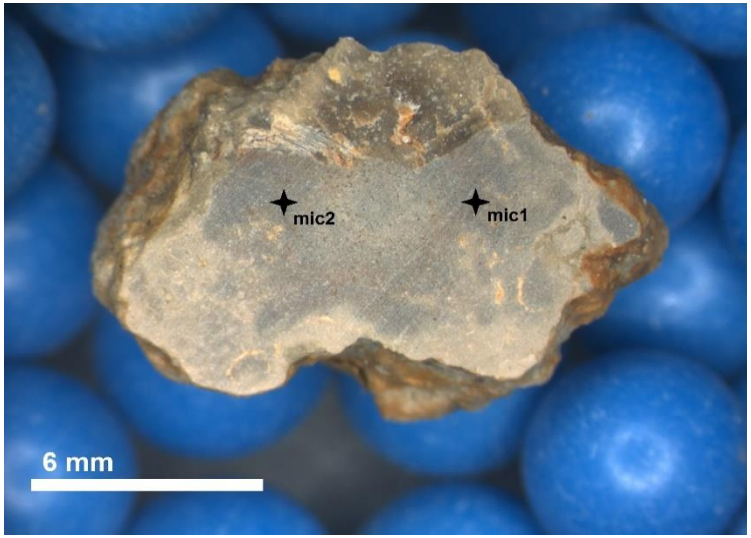



L5-CN1



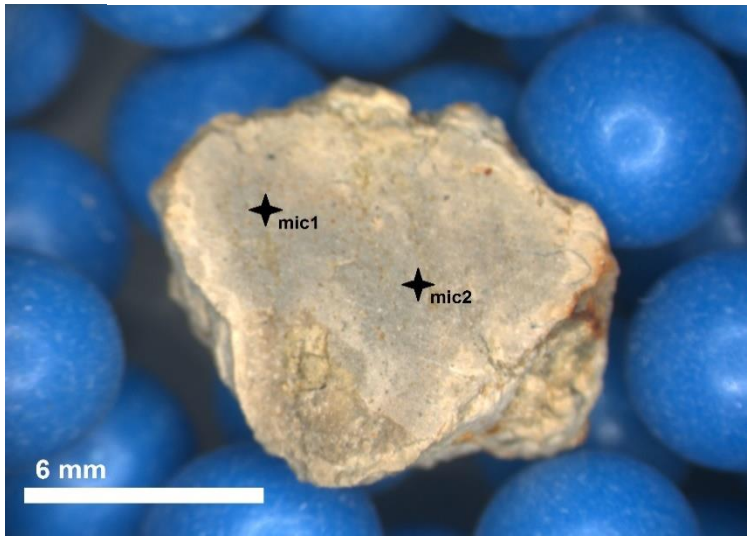



L5-CN2 (top)

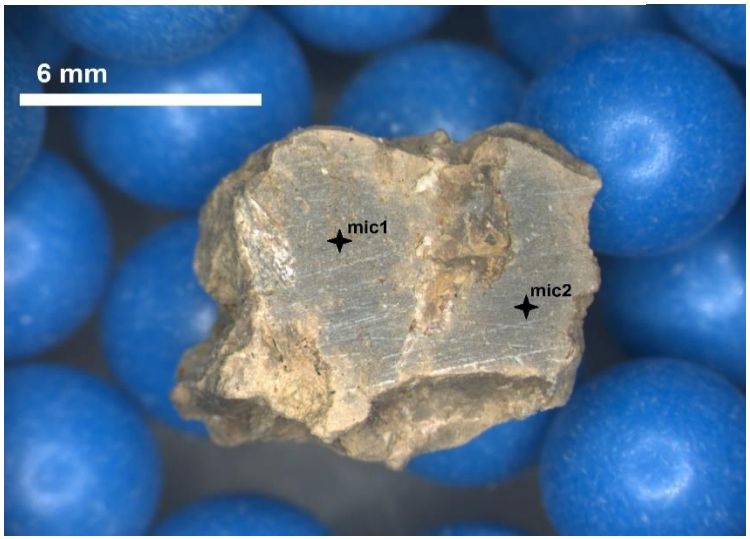


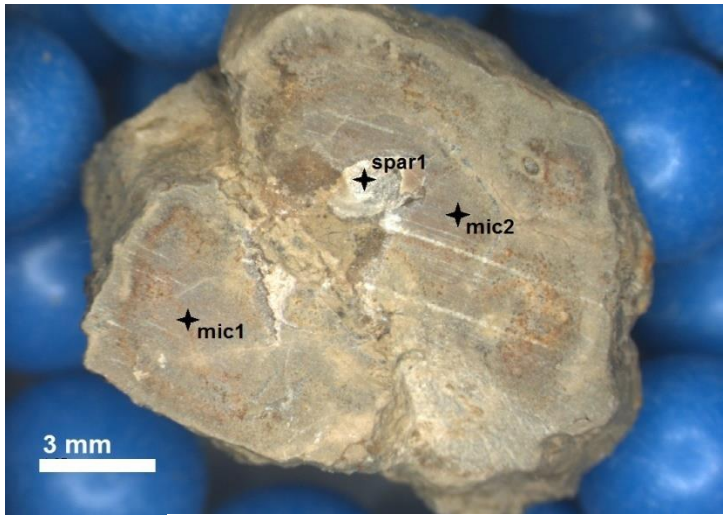

L6-CN1 (top)

L6-CN2

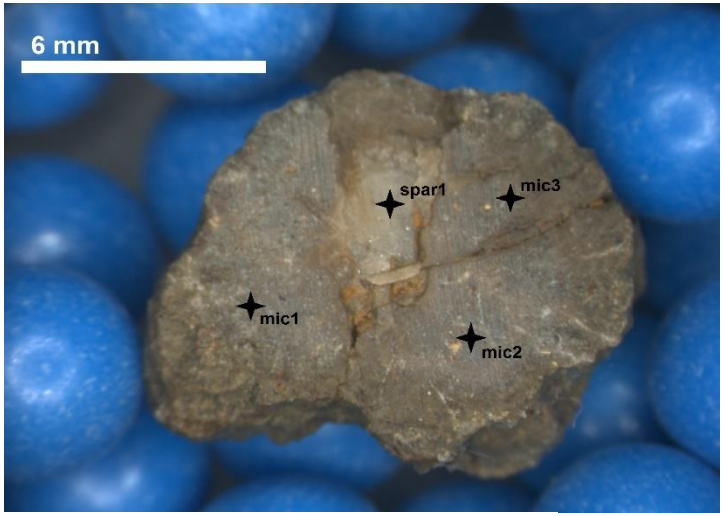



L6-CN3






L9-CN1 (top)




L9-CN2 (top)

L9-CN3