

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**LATE QUATERNARY PALEOCLIMATE AND PALEOENVIRONMENT
CHANGES IN URMIA LAKE, NW IRAN**



Ph.D. THESIS

Gülgün ERTUNÇ

Department of Solid Earth Sciences

Geodynamics Programme

MARCH 2025

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MARCH 2025

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**URMİYE GÖLÜ, KB İRAN GEÇ KUVATERNER PALEOİKLİM VE
PALEOORTAM DEĞİŞİMLERİ**

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To my father,



FOREWORD

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January 2025

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ABBREVIATIONS

μ-XRF	: Micro-X-Ray Fluorescence
AMS	: Accelerator Mass Spectrometry
AP	: Arboreal Pollen
BAP	: Scientific Research Projects Coordination Unit
cal ka BP	: Calibrated thousand years before present
cm	: Centimeter
cps	: Count per second
DO	: Dansgaard–Oeschger
EMCOL	: Eastern Mediterranean Centre for Oceanography and Limnology
HCO	: Holocene Climatic Optimum
HE	: Heinrich Events
ITRAX-XRF	: X-ray fluorescence core scanner
ITU	: Istanbul Technical University
IWPRD	: Iran Water and Power Resources Development Company
LGM	: Last Glacial Maximum
LIA	: Little Ice Age
m	: Meter
MAM	: Marmara Research Center
MCG	: Modern Coated Grain
mg	: Milligram
MIS	: Marine Isotope Stage
MSCL	: Multi Sensor Core Logger
MWP	: Medieval Warm Period
NAP	: Non Arboreal Pollen
NGRIP	: North Greenland Ice Core Project
NW	: Northwest
RIES-GSI	: Research Institute for Earth Sciences, Geological Survey of Iran
SEM	: Scanning Electron Microscope
TIC	: Total Inorganic Carbon
TOC	: Total Organic Carbon

TÜBİTAK	: The Scientific and Technical Research Council of Turkey
U	: Unit
wt	: Weight
XRD	: X-Ray Diffraction
YD	: Younger Dryas
B-A	: Bølling-Allerød
GD	: Genç Dryas



SYMBOLS

$\sim$	: Approximately
$>$	: Greater than
μm	: Micrometer
^{14}C	: Carbon-14 isotope
Ca	: Calcium
CaCO_3	: Calcium carbonate
$\delta^{18}\text{O}$	: Ratio of stable isotopes oxygen-18
$\delta^{13}\text{C}$	: Ratio of stable isotopes carbon-13
Fe	: Iron
HCl	: Hydrochloric acid
K	: Potassium
mm/yr	: Millimeter per year
Mn	: Manganese
Sr	: Strontium
Ti	: Titanium



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LATE QUATERNARY PALEOCLIMATE AND PALEOENVIRONMENT CHANGES IN URMIA LAKE, NW IRAN

SUMMARY

The Urmia Hypersaline Lake in NW Iran offers an exceptional opportunity to investigate the intricate relationships between climate, the environment, lake level change, and the development of characteristic sedimentary structures within sedimentary archives. Urmia Lake is the largest hypersaline lake in the Middle East and ranks among the largest saline lakes globally. Over the two decades (between 1996 and 2017), the lake has experienced significant desiccation, threatening its ecosystem, including the brine shrimp *Artemia urmiana*. The lake offers unique sedimentary environments fostering coated grain formation and serving as a vital indicator of paleoenvironmental conditions. Paleoenvironmental research on the Late Pleistocene in Iran, especially in Urmia Lake, remains limited, with existing studies primarily focusing on reconstructions based on palynology, stable isotopes, and limnological characteristics. While these approaches have provided valuable insights, they often lack the high-resolution and long-term perspective to fully understand the connections between lake-level changes and sedimentary processes.

This study addresses this gap by utilizing a detailed, high-resolution analysis of a 25-meter-long sediment core retrieved from the northern part of the lake. ITU Eastern Mediterranean Centre for Oceanography and Limnology (EMCOL) Laboratories was the primary facility for conducting experiments and measurements. Through a multiproxy approach, this research sheds light on the environmental history, sedimentary processes, and climate variability in Urmia Lake over the last ~50 cal ka BP. The research further includes an in-depth characterization of coated grains, assessing their significance through morphology, internal structures, mineralogy, and geochemistry.

Visual lithological observations and physical property measurements (including gamma density and magnetic susceptibility) of the sediments document high lithofacies variations throughout the core. The sedimentary sequence consists of biogenic mud (micrite) and sand (primarily fecal pellets of *Artemia urmiana* with occasional shell fragments), terrigenous components (quartz, feldspar, pyroxene, volcanic lithics, volcanic glass, and clay), coated grains, diagenetic sulfate minerals (mainly gypsum), and evaporite minerals (salt crust). A surface salt crust, up to 3 meters thick, reflects the lake's recent desiccation event. High-resolution μ -XRF, and total organic carbon (TOC) total inorganic carbon (TIC) analyses complement these findings. Mineralogical analysis of both handpicked coated grain samples and bulk sediment samples was performed at the ITU Geological Engineering Department X-Ray Laboratory. Additionally, high-resolution pollen studies provided further insights into the reconstructing paleovegetation and paleoclimate changes.

Coated grains were analyzed using binocular microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD) to examine their morphology, internal structures, mineralogical composition, and geochemical properties. Coated grains in Urmia Lake exhibit concentric laminations, primarily calcite and aragonite, revealing alternating light carbonate-rich and dark organic-rich laminations. These reflect seasonal and long-term variations in water chemistry and biogenic production. Dry season algal blooms contribute to lamination, showcasing the interplay between seasonal climate fluctuations and the consequent lake water enrichment in calcium and bicarbonate ions.

The timing of climatic variability in the lake was determined using an age-depth model based on radiocarbon dating of *Artemia urmiana* fecal pellet concentrates, supplemented with radiocarbon ages of fecal pellets and bulk sediments from the same sediment core. The radiocarbon measurements were conducted at the Poznan Radiocarbon Laboratory in Poland and the TÜBİTAK Marmara Research Center (MAM) in Turkey. In addition to radiocarbon dating, the construction of precise age-depth models for the sediment core has been significantly enhanced by integrating high-resolution geochemical proxies. Comparisons of micro-X-ray fluorescence (μ -XRF) derived Ca/Ti ratios from sediment cores with well-dated $\delta^{18}\text{O}$ records from Lake Van and the North Greenland Ice Core Project (NGRIP) have been particularly valuable, alongside TOC correlations between Lakes Van and Urmia, provided robust chronological markers. This integrated approach enabled the reconstruction of the lake's paleoclimate evolution with a robust chronology spanning the last ~50 cal ka BP, accounting for a calculated reservoir age of approximately 2 cal ka BP.

Three distinct stages of lake-level fluctuations were identified: (1) a lowering stage dominated by coated grains (MIS 3), (2) a low lake level with abundant terrigenous fragments and broken coated grains (late MIS 3- early MIS 2), and (3) a high lake level characterized by layers rich in *Artemia urmiana* fecal pellets (MIS 1). The modern low lake level is represented by a salt crust. Geochemical proxies reveal dynamic environmental conditions, with variations in the Ca-Ti ratio reflecting carbonate production during warm, dry periods and increases in K, Fe, and Ti indicating enhanced terrigenous input during wetter phases. The brine shrimp *Artemia urmiana*'s role in coated grain formation involves absorbing calcium, carbonate, and bicarbonate ions and inhibiting coated grain formation during high lake levels while providing nuclei during lake lowering. An in-depth investigation of coated grains provides a chemical and biological formation framework, highlighting three main episodes in the lake's history.

During MIS 3 (50–29 cal ka BP), episodic climatic oscillations marked by alternating stadials and interstadials are recorded in Urmia Lake's sediments. Lower lake levels under cooler and drier conditions are evidenced by reduced biological activity and proxies for physical weathering. Coated grains formed in shallow, wave-dominated settings with high ionic supersaturation, while brief wet phases are inferred from elevated Ca/Ti and Sr/Ca ratios. Comparisons with Lake Van indicate synchronous transgressive events driven by regional climatic changes.

MIS 2 (29–12 cal ka BP), including the Last Glacial Maximum (LGM), represents a period of extreme aridity and cold temperatures. Persistent low lake levels, hypersaline conditions, and sulfate crystal deposition reflect reduced precipitation and increased

evaporation. Sparse vegetation led to intensified erosion, as shown by high detrital inputs. Sediment transitions from gray to brown indicate lake desiccation and lake bottom exposure, with gypsum deposits marking heightened salinity. Regional comparisons reveal similar conditions in Lake Van and Zeribar, though Lake Van experienced earlier moisture recovery post-LGM.

MIS 1 (12 cal ka BP–Recent) encompasses the Holocene and Anthropocene, marking a transition to warmer and wetter conditions during the early Holocene. Increased lake levels, higher fecal pellet abundance, and TOC content indicate productive ecosystems during the Holocene Climatic Optimum (HCO). The Younger Dryas (YD) appears as a brief regression phase, while the late Holocene saw declining precipitation and lake shrinkage due to climatic events like the Medieval Warm Period (MWP) and Little Ice Age (LIA). In the Anthropocene, human activities such as dam construction and agriculture have caused rapid desiccation, transforming the lake into a chemical playa environment. Regional comparisons, including with Lake Van, the Dead Sea, and other Middle Eastern systems, highlight synchronous responses to climatic drivers such as the Younger Dryas and Holocene Climatic Optimum.

The sedimentary and geochemical records of Urmia Lake reveal a complex interplay of biological activity, seasonal variability, and climate-driven lake level fluctuations, providing a benchmark for understanding the response of hypersaline ecosystems to long-term environmental change.



URMİYE GÖLÜ, KB İRAN GEÇ KUVATERNER PALEOİKLİM VE PALEOORTAM DEĞİŞİMLERİ

ÖZET

Kuzeybatı İran'da bulunan Urmıye Hipersalin Gölü, iklim, çevre, göl seviyesi değişimleri ve sedimanter arşivlerdeki karakteristik sedimanter yapılar arasındaki karmaşık ilişkileri araştırmak için benzersiz bir fırsat sunmaktadır. Urmıye Gölü, Orta Doğu'nun en büyük hipersalin gölü ve dünyanın en büyük tuzlu göllerinden biridir. Son on yıllarda (1996-2017) gölde meydana gelen ciddi kuruma, gölün eşsiz ekosistemini, özellikle *Artemia urmiana* tuzlu su karidesi türünü tehdit etmektedir. Göl, giysili zarflı tanelerin oluşumunu teşvik eden benzersiz sedimanter ortamlar sunmakta ve paleoekolojik koşulların önemli bir göstergesi olarak hizmet etmektedir. İran'da, özellikle Urmıye Gölü'nde Geç Pleyistosen dönemine ilişkin paleoekolojik araştırmalar sınırlıdır. Mevcut çalışmalar genellikle palinoloji, sabit izotoplar ve limnolojik özelliklere dayalı rekonstrüksiyonlara odaklanmıştır. Bu yaklaşımlar değerli bilgiler sağlamış olsa da, göl seviyesi değişimleri ve sedimanter süreçler arasındaki bağlantıları tam anlamıyla anlamak için gereken yüksek çözünürlük ve uzun dönem perspektifini genellikle sunamamaktadır. Bu çalışma, gölün kuzey kısmından alınan 25 metre uzunluğundaki bir sediman karotu üzerinde yapılan detaylı, yüksek hassasiyetli çoklu proxy analizleriyle bu boşluğu doldurmayı amaçlamaktadır. Analiz ve ölçümlerin büyük bir kısmı Doğu Akdeniz Oşinografi ve Limnoloji (EMCOL) Araştırma Merkezi'nde gerçekleştirilmiştir. Çoklu proxy yöntemlerin kullanıldığı bu araştırma, gölün çevresel geçmişine, sedimanter süreçlerine ve iklim değişkenliğine tepkilerine dair önemli bulgular sunmaktadır ve son ~50.000 yılın (cal BP) kayıtlarını ortaya koymaktadır. Araştırma ayrıca, giysili zarflı tanelerinin morfoloji, iç yapılar, mineralojik bileşim ve jeokimyasal özellikler yoluyla ayrıntılı bir şekilde karakterize edilmesini de içermektedir.

Litolojik gözlemler ve fiziksel özellik ölçümleri (gamma yoğunluğu ve manyetik duyarlılık) sedimanter karotun genelinde yüksek litofasiyes değişimlerini belgelemektedir. Sedimanter istif; biyojenik çamur (mikrit) ve kum (çoğunlukla *Artemia urmiana*'nın fekal pelletleri ve nadiren fosil kavrı kırıntıları), kırıntılı mineral parçaları (kuvars, feldspat, piroksen, volkanik litikler, volkanik cam ve kil), giysili zarflı taneler, diyajenetik sülfat mineralleri (genellikle jips) ve evaporit mineralleri (tuz kabuğu) içermektedir. 3 metre kadar kalınlığa ulaşan yüzey tuz kabuğu, gölün yakın tarihli kuraklık olayını yansıtmaktadır. Yüksek çözünürlüklü μ -XRF ve toplam organik karbon (TOC) ve toplam inorganik karbon (TIC) analizleri bu bulguları desteklemektedir. Tek tek ayrıştırılmış giysili zarflı tanelerden oluşan örneklerin ve toplam sedimandan oluşan örneklerin mineralojik analizi İTÜ Jeoloji Mühendisliği Bölümü X-Işını Laboratuvarı'nda gerçekleştirilmiştir. Ayrıca, yüksek çözünürlüklü polen çalışmaları paleovejetasyon ve paleoiklimsel değişimlerin yeniden yapılandırılmasına dair daha fazla bilgi sağlamıştır.

Giysili zarflı taneler, morfoloji, iç yapılar, mineralojik bileşim ve jeokimyasal özellikleri incelemek için binoküler mikroskop, taramalı elektron mikroskobu (SEM), enerji dağılımlı spektroskopi (EDS) ve X-ışını difraksiyonu (XRD) kullanılarak analiz edilmiştir. Urmıye Gölü'ndeki giysili zarflı taneler, çoğunlukla kalsit ve aragonitten oluşan konsantrik laminasyonlar göstermektedir. Bu laminasyonlar, mevsimsel ve uzun vadeli su kimyası değişikliklerini ve biyojenik üretimi yansıtmaktadır. Kurak

mevsimde meydana gelen alg patlamaları, laminasyon oluşumuna katkıda bulunarak mevsimsel iklim dalgalanmalarının ve göl suyundaki kalsiyum ve bikarbonat iyonlarının zenginleşmesinin etkileşimini ortaya koymaktadır.

Göldeki iklim değişkenliğinin zamanlaması, *Artemia urmiana* fekal pelletlerinden elde edilen radyokarbon tarihlemesine dayanan bir yaş-derinlik modeli ile belirlenmiştir. Bu tarihlendirme, aynı sediman karotundan alınan fekal pelletler ve toplam sedimandan yapılan radyokarbon yaşlarıyla desteklenmiştir. Radyokarbon ölçümleri, Polonya'daki Poznan Radyokarbon Laboratuvarı ve Türkiye'deki TÜBİTAK Marmara Araştırma Merkezi'nde (MAM) gerçekleştirilmiştir. Radyokarbon tarihlemenin yanı sıra, sediman karotu için kesin yaş-derinlik modellerinin oluşturulması, yüksek çözünürlüklü jeokimyasal proxylerin entegrasyonu ile önemli ölçüde geliştirilmiştir. μ -XRF'den türetilen Ca/Ti oranlarının, Van Gölü'nden elde edilen iyi tarihlenmiş $\delta^{18}\text{O}$ kayıtları ve NGRIP kayıtları ile karşılaştırılması özellikle değerli olmuştur. Ayrıca, Van ve Urmiye Gölleri arasındaki TOC (toplam organik karbon) karşılaştırmaları da sağlam kronolojik göstergeler sağlamıştır. Bu bütünlük yaklaşımıyla, yaklaşık 2 cal ka BP olarak hesaplanan rezervuar yaşını dikkate alarak, gölün paleoklimatik evrimini son ~50 cal ka BP boyunca yeniden yapılandırmayı mümkün kılmıştır. Üç belirgin göl seviyesi dalgalanma aşaması tanımlanmıştır: (1) Giysili zarflı tanelerin baskın olduğu bir alçalma evresi (MIS 3), (2) Bol miktarda terrijen parçalar ve kırılmış giysili zarflı taneler içeren düşük göl seviyesi (geç MIS 3 - erken MIS 2), (3) *Artemia urmiana* fekal pelletleri açısından zengin katmanlarla karakterize edilen yüksek göl seviyesi (MIS 1). Modern düşük göl seviyesi, bir tuz kabuğu ile temsil edilmektedir. Jeokimyasal göstergeler, sıcak ve kurak dönemlerde karbonat üretimini yansıtan Ca/Ti oranındaki değişimlerle, daha nemli evrelerde artan terrijen girdiğini gösteren K, Fe ve Ti artışlarıyla dinamik çevresel koşulları ortaya koymaktadır. *Artemia urmiana*, kalsiyum, karbonat ve bikarbonat iyonlarını absorbe ederek yüksek göl seviyelerinde giysili zarflı tane oluşumunu engellerken, göl seviyesinin düştüğü dönemlerde çekirdek sağlayarak giysili zarflı tanesi oluşumunda kritik bir rol oynamaktadır. Giysili zarflı tanelerinin detaylı incelenmesi, göl tarihindeki üç ana dönemi vurgulayarak kimyasal ve biyolojik oluşum süreçlerine ışık tutmaktadır.

MIS 3 (50–29 kyr BP): Bu dönemde, küresel ölçekte yaşanan dönemsel iklim dalgalanmaları, Urmiye Gölü'nün sedimanter kayıtlarında ardışık stadial (soğuk) ve interstadial (ılık) dönemler olarak yansımaktadır. Göl seviyesindeki düşüşler, azalan biyolojik aktivite ve fiziksel aşınım göstergeleri ile ilişkilendirilmiştir. Giysili zarflı taneler, yüksek iyonik aşırı uygunluk koşulları altında sığ ve dalga etkisindeki ortamlarda oluşmuştur. Artan Ca/Ti ve Sr/Ca oranları gibi kimyasal göstergeler kısa süreli nemli fazlara işaret etmektedir. Van Gölü ile yapılan karşılaştırmalar, bölgesel iklim değişimlerinin etkisiyle senkronize transgresif olayları işaret etmektedir.

MIS 2 (29–12 kyr BP): Son Buzul Maksimumu'nu (LGM) kapsayan bu dönem, aşırı kuraklık ve düşük sıcaklıklarla tanımlanır. Urmiye Gölü'nde, bu döneme düşük göl seviyeleri, hipersalin koşullar ve sülfat kristallerinin çökmesi damga vurmuştur. Sedimanter geçişlerdeki griden kahverengiye renk değişimleri, gölün kurumasını ve göl tabanının kısmen açığa çıkmasını göstermektedir. Bölgesel karşılaştırmalar, Van ve Zeribar göllerinin benzer koşulları paylaştığını ortaya koyarken, Van Gölü'nün LGM sonrası daha erken ve istikrarlı bir nem geri kazanımı yaşadığı gözlemlenmiştir.

MIS 1 (12 kyr BP–Günümüz): Holosen ve Antroposen’i kapsayan bu dönem, daha sıcak ve nemli koşullara geçişi temsil etmektedir. Holosen İklim Optimumu sırasında artan göl seviyeleri, fekal pelletlerin bolluğu ve yüksek TOC içerikleri, üretken ekosistemlerin varlığına işaret etmektedir. Genç Dryas (~12.9–11.7 cal ka BP) göl seviyesindeki bir gerileme dönemi olarak kaydedilmiştir. Antroposen döneminde ise, baraj inşaatları, tarım ve yer altı suyu kullanımı gibi insan faaliyetleri gölün hızlı bir şekilde küçülmesine yol açarak kimyasal bir playa ortamına dönüşmesine neden olmuştur.

Urmiye Gölü’nün sedimanter ve jeokimyasal kayıtları, biyolojik aktivite, mevsimsel değişkenlik ve iklim kaynaklı göl seviyesi dalgalanmalarının karmaşık etkileşimini ortaya koyarak, hipersalin ekosistemlerin uzun vadeli çevresel değişimlere tepkilerini anlamak için önemli bir referans oluşturmaktadır.





1. INTRODUCTION

Urmia Lake, located in northwestern Iran, is the largest hypersaline lake in the Middle East and one of the largest saline lakes in the world. It has a long history of environmental and climatic changes that have affected its hydrological and geochemical characteristics. Paleoclimate reconstruction of Urmia Lake can provide valuable insights into the region's past climate and help us understand the mechanisms driving the lake's dynamics. Paleoenvironmental research on the Late Pleistocene period in Iran, particularly in Urmia Lake, is limited. Previous studies have mainly focused on reconstructing paleoenvironmental changes using palynology, stable isotopes, and limnological characteristics, especially in lake systems. The first studies related to Urmia Lake were conducted in 1977 by the ETH Zurich Institute of Earth Sciences using high-resolution shallow seismic surveys to examine the lake's basin topography and sedimentation (Kelts and Shahrabi, 1986). In their studies, Kelts and Shahrabi (1986) examined the Holocene sedimentological features of the lake, showing similarities in sediment and chemical characteristics with the Great Salt Lake in the United States. They identified several terrace levels around the lake corresponding to the Pleistocene and found that the lake level had changed several times.

Although the lake has many small and large islands, the Islam Peninsula in the middle turns into an island when the lake level rises. Historical records and satellite imagery analysis indicate that the lake level significantly dropped during the Little Ice Age (Kelts and Shahrabi, 1986; Sharifi, 2002). Due to a lack of seismic and technical studies, the formation, chemical properties, and geological features of the lake were not fully explained in previous studies (Shahrabi, 1994). Later, in 2002, during the construction of the Shahid-Kalantary highway in the middle of the lake, four deep sediment cores were taken, the longest being 110 m, to investigate its geotechnical properties (Iranian Marine Industrial Company, 2003). These sediment cores were used to study the sedimentological properties and origin of sediments along the highway (Amini et al., 2010), to reconstruct climate records based on pollen records

(Djamali et al., 2008a, 2008b, 2010), and to examine the oxygen isotopes of aragonite-rich shrimp fecal pellets supported by radiocarbon dating (Stevens et al., 2012). These studies indicate that Urmia Lake began to form in the Pleistocene and that the initially freshwater lake water eventually became saline, with active faults in the surrounding area having played a role in its formation. Urmia Lake experienced significant level changes in the Pleistocene, and since 1996, the lake level has decreased, exposing large salt clay flats from the ancient lakebed. These exposed surfaces provide an opportunity for drilling studies related to the lake. In subsequent years, drilling studies have continued on the exposed lakebed surfaces on the east and west coasts of the lake's northern part (Haghipour et al., 2016). In 2017, 16 sediment cores were taken, each up to 25 m long, from the lake to examine the feasibility of transferring water to Urmia Lake from other basins (Iranian Water and Power Resources Development Company, 2018). The decrease in lake level and increased salinity due to evaporative processes lead to the precipitation of evaporite minerals in the lake bed. To better understand the temporal and spatial changes in the thickness of salt deposits over the last 40 years (1977-2017), as well as the parameters that control salt accumulation and dissolution rates, a total of 90 sediment cores were collected from shallow, intermediate, and deep-water locations within and around the lake and some analyzed (Mohammadi et al., 2021).

Additionally, climate conditions and the environmental evolution of Urmia Lake over the past 30 cal ka BP were investigated using a composite record from seven cores on the southwestern shores of the lake. Two major drought events were identified, indicating multiple episodes of low water levels since the Last Glacial Maximum (LGM) (Tudryn et al., 2021). Recently, Kong et al. (2022) analyzed a 12.5 m core taken from the western edge of the lake to infer paleoclimate and paleoenvironmental conditions, particularly by examining relative lake water levels over the past 30 cal ka BP. They combined previous data with ^{14}C AMS chronology and grain size data with major mineral distribution, albeit at a lower temporal resolution than XRF-CS data, to assess hydrological changes and associated sedimentary processes in the Lake Urmia basin, including weathering, depositional fluxes, carbonate crystallization in lake water, and early diagenesis in anoxic bottom sediments (Kong et al., 2023). Furthermore, Sarı et al. (2024) utilized the same 25 m long sediment core that we employed in this study, examining the abundance and compositional characteristics of

Artemia urmiana fecal pellets to elucidate the Late Quaternary depositional history and paleoclimate variations. Finally, a high-resolution, multi-proxy reconstruction of climate and hydrological variability from the lake's sediments has identified several episodes of wet and dry conditions over the past 11.3 cal ka BP, as well as an atmospheric teleconnection between the climate of the interior of West Asia and the North Atlantic region, through a combination of geochemical proxies and pollen reconstruction (Sharifi et al., 2023).

The hypersaline Urmia Lake in NW Iran offers an exceptional opportunity to investigate the intricate relationships between climate, the environment, lake level change, and the development of characteristic sedimentary structures within sedimentary archives. These types of over-saturated aquatic systems are characterized by elevated ion concentrations and shallow water depths, creating a distinct setting for the formation of coated grains. Coated grains are sedimentary particles with a nucleus of variable origin and composition surrounded by concentric laminae of calcium carbonate, though they may also contain other evaporitic minerals such as halite and gypsum (e.g., Peryt, 1983; Tucker and Wright, 1990; Adams and MacKenzie, 1998; Flügel, 2010). Numerous studies have reported the occurrence of lacustrine-coated grains in a diverse array of hypersaline lakes across the globe, including notable examples such as the Great Salt Lake (e.g., Eardley, 1938; Kahle, 1974; Sandberg, 1975; Halley, 1977; Pedone and Norgauer, 2002), the Dead Sea (e.g., Garber and Friedman, 1983), Pyramid Lake in Nevada (Popp and Wilkinson, 1983), Lake Geneva (Davaud and Girardclos, 2001), and Urmia Lake (Kelts and Sharabi, 1986; Mohammadi, 2005; Amini et al., 2010; Stevens et al., 2012; Sharifi et al., 2018; Mohammadi et al., 2019; 2021; Tudyrn et al., 2021; Sharifi et al., 2023; Sarı et al., 2024; Mohammadi, 2024). The abundance, size, color, mineralogy, and microfabrics of coated grains are valuable indicators that reflect the physical and chemical conditions of depositional environments, serving as indicators of paleoenvironmental conditions, including water depth, water salinity, and water energy (Flügel, 2010). The prevalence of coated grains in the stratigraphic record, especially in shallow-water carbonate environments, makes them significant paleoenvironmental indicators for investigating past hydro-chemical conditions due to their specific growth requirements (Howes et al., 2021). Applying coated grains as paleoenvironmental proxies in lakes

offers an understanding of the environmental dynamics of lacustrine systems and their responses to past climatic and water level fluctuations.

Urmia Lake has a well-documented history of substantial fluctuations in its water level throughout the Quaternary (e.g., Lak et al., 2011; 2012; Mohammadi et al., 2021; Sharifi et al., 2023; Sarı et al., 2024). The 25-m sediment core (UL2; Figure 2.1) extracted from the northwestern part of Urmia Lake revealed a predominant assemblage of fine to medium sand-sized coated grains with distinct internal structures and morphological features and apparent outer coatings of various colors and shapes. The core has already been dated by Sarı et al. (2024), establishing an age extending back to ~50 cal ka BP. Prior investigations (Kelts and Sharabi, 1986; Amini et al., 2010; Stevens et al., 2012; Lankarani et al., 2017; Sharifi et al., 2018; Mohammadi et al., 2019, 2021; Tudyryn et al., 2021; Sarı et al., 2024) have reported the existence of coated grains that resemble coated grains in the sedimentary deposits of Urmia Lake, yet a lack of comprehensive research on the formation, distribution, internal structure and morphological features, and depositional physico-chemical conditions makes interpretations difficult. Thus, Urmia Lake presents a prime example of the potential for hypersaline lakes to yield crucial insights into past climate and environmental changes through the analysis of coated grain deposits.

This study investigates a 25 m-long sediment core obtained from the northern part of Urmia Lake, covering the Late Quaternary period. Multi-proxy methods, including physical and geochemical analyses, were used to identify past climate changes affecting sedimentation processes. The study also aimed to compare regional climate variations with global climate changes and examine the changes in lake levels. The multi-proxy approach allows for the identification of paleoenvironmental and paleolimnological modifications with respect to paleoclimate and lake-level variations. The timing of the variable paleoclimate conditions in the lake was determined using a depth-age model based on radiocarbon dating. Sedimentological analyses, including lithological observations and physical properties, were used to identify variations in lithofacies along the core. The main lithological units were determined based on the lithological description of the core, microscopic examination of smear slides, and physical properties. The sedimentary sequence mainly consists of clay and silt, including *Artemia urmiana* fecal pellets, coated grains, and evaporites. These findings were combined with high-resolution μ -XRF and total organic carbon

(TOC) analyses to reveal paleoenvironmental variations around the lake. The lake's unique physicochemical properties and hypersaline nature have attracted scientific interest, and it has been a critical study site for understanding the climate in extreme environments. We further aim to investigate the dynamic fluctuations of water levels in Urmia Lake and their consequent impact on sedimentary deposits, comprehensively characterize various coated grains and assess their paleoenvironmental significance and relationship with past lake level fluctuations. To achieve this, we investigated the morphology, internal structures, mineralogy, and geochemistry of coated grains and their abundances and types of variation throughout the studied core. These characteristics, linked to the lake level fluctuations, contribute to a comprehensive understanding of the critical factors that control the formation and types of coated grains in Urmia Lake throughout its historical evolution. This also helps to improve understanding of coated grain formation in other hypersaline lakes.

1.1 Purpose of Thesis

This study uses a multi-proxy approach to investigate the Late Quaternary paleoclimate and paleoenvironmental evolution of Urmia Lake, a hypersaline lake in northwestern Iran. Multi-proxy analyses, such as μ -XRF, Multi-sensor core logger (MSCL), Total Organic Carbon (TOC), palynological analysis, and SEM measurements from the core sections, allowed us to investigate the paleoclimatic and paleoenvironmental history of Urmia Lake. The primary focus is reconstructing past lake-level fluctuations, depositional processes, and hydrochemical changes while comparing these findings to global examples.

This research aims to elucidate the interactions between climatic drivers, sedimentary processes, and lake hydrology, shedding light on Urmia Lake's response to regional and global climate variability.

To achieve this, a 25-meter-long sediment core (UL2) from the northern basin of Urmia Lake was analyzed using high-resolution sedimentological, geochemical, and biological proxies.

The specific objectives of this thesis are as follows:

1. Reconstructing the paleoclimate and paleoenvironment conditions of Urmia Lake through multiproxy analyses, including sedimentary facies, elemental geochemistry, and biogenic components.
2. Characterizing the morphology, internal structures, and mineralogy of coated grains and assessing their relationship with biogenic components, such as *Artemia urmiana* fecal pellets, will help us understand their combined influence on the sedimentary structure, water chemistry, and broader paleoenvironmental conditions.
3. Comparing the paleoclimate and paleoenvironmental evolution of Urmia Lake with other lake systems, such as Lake Van and the Great Salt Lake, to identify similarities and differences in their responses to climatic and hydrological forcing during the Late Quaternary.

This thesis integrates multi-proxy analyses to advance our understanding of the paleoenvironmental dynamics of Urmia Lake and provide insights into the broader mechanisms governing hypersaline lake systems in semi-arid regions. The comparative approach also places the findings within a global context, offering valuable perspectives on how similar systems have responded to natural and anthropogenic climate variability over time.

1.2 Thesis Structure

This thesis is divided into six chapters. The introduction outlines the study's significance, research objectives, and key questions, highlighting Urmia Lake's importance as a paleoclimate archive within a global context.

The second chapter focuses on the study area and describes Urmia Lake's geographical, geological, and climatic characteristics and the anthropogenic impacts it has experienced.

The third chapter explains the methodologies employed, including μ -XRF geochemical profiling, physical properties, palynological analysis, SEM analysis and radiocarbon dating.

Results are presented in the fourth chapter, detailing sedimentation patterns, lake level fluctuations, and key climatic events, such as the Younger Dryas and Heinrich events (HE), alongside regional and global comparisons.

The discussion synthesizes these findings, examining the interplay of climatic variability and addressing gaps in the literature. Finally, the conclusions and recommendations chapter summarizes the main findings and proposes directions for future research, particularly in improving high-resolution records.

Through this comprehensive approach, the study aims to contribute to broader discussions on paleoclimate reconstruction, sedimentary processes, and the environmental evolution of arid and semi-arid regions.





2. STUDY AREA

Urmia Lake is a shallow hypersaline lake located in NW Iran, covering an area of 5200 km² within an internationally protected region. It was formed by the activity of the Zarine-Rud and Tabriz strike-slip faults (e.g., Berberian and King, 1981; Sembroni et al., 2024) in the eastern segment of the Turkish-Iranian Plateau. The lake water supply is maintained by 28 perennial and ephemeral rivers, snow and rainfall, and underground water springs. The main perennial rivers that contribute to Urmia Lake are Jighati-chay, Tatao-chay, Sablagh-chay, Gadar-chay, Baranduz-chay, Sheher-chay, Qoduq Boghan-chay, Nazli-chay, Zola-chay, and Aji-chay rivers (Mohammadi et al., 2021). The salinity of the lake water fluctuates between 120 g/l and 380 g/l depending on the season, location, and water depth (e.g., Alipour, 2006; Karbasi et al., 2010; Lak et al., 2022; Mohammadi et al., 2023).

The lake is naturally divided into a deep northern basin and a shallow southern basin, and a manmade stone causeway further isolates these two basins, significantly affecting the lake's hydrodynamics and water salinity. Such a construction impacted water circulation patterns between the two lake parts, leading to temporal variability in the physicochemical properties of the water on either side of the causeway (e.g., Lak et al., 2022; Mohammadi et al., 2023). The limited inflow into the northern part due to a narrow water passage under the causeway created an intensified salinity gradient in the lake (e.g., Karbasi et al., 2010; Mohammadi et al., 2023). The lake water composition is characterized by a significant presence of major cations, namely Na⁺, Mg²⁺, Ca²⁺, K⁺, and Li⁺, and major anions, including Cl⁻, SO₄²⁻, CO₃²⁻, and HCO₃⁻ (e.g., Alipour 2006; Karbasi et al., 2010; Darvishi Khatouni et al., 2015; Lak et al., 2022).

2.1 Geological Settings

The geology of the lake catchment is highly diverse and encompasses a wide range of rocks dating back from the Precambrian to the Quaternary (Figure 2.1). Precambrian and Paleozoic terrigenous rocks are exposed in the north, northeast, and east of the

lake (e.g., Moazzen et al., 2023). Metamorphic rocks surround the basin in the southwest and west. Paleozoic and Mesozoic plutonic rocks are exposed in the north, northwest, and northeast of the lake (e.g., Lechmann et al., 2018; Delavari et al., 2019; Mohammadi et al., 2020). While Mesozoic carbonate and terrigenous rocks are exposed in the basin's north, south, and southeast (e.g., Mohammadi et al., 2022), Lower Miocene limestones are present along the northwest and most lake islands. The Eocene-Miocene marl and terrigenous rocks crop out in the different parts of the catchment. Quaternary alluvial sediments are widely spread throughout the basin (Figure 2.1; Shahrabi et al., 1985; Eftekhari-Nezhad et al., 1989). In addition, the volcanic activities of Sahand (3707 m) and Savalan (4814 m) volcanoes have contributed to the region's diverse landforms (e.g., Kelts and Shahrabi, 1986).

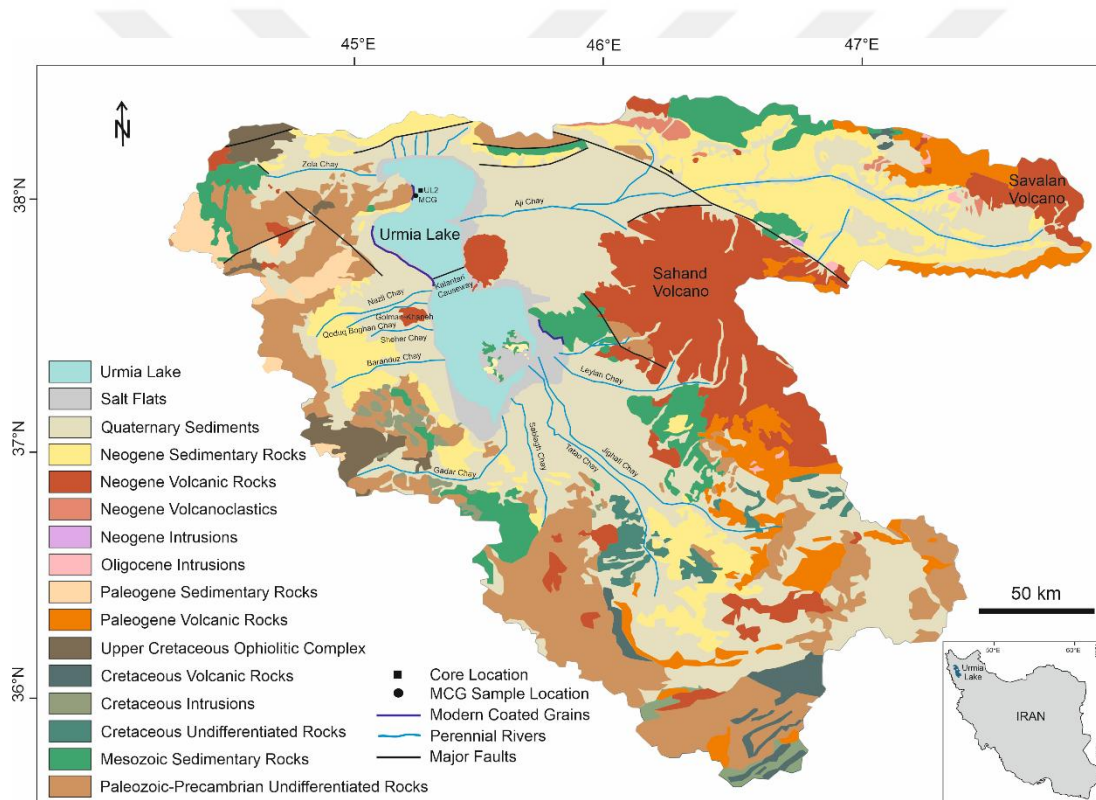


Figure 2.1: Simplified geological map of the Urmia Lake catchment and coring site. The map was modified after Sharifi et al. (2018) and Lak et al. (2022).

2.2 Climate and Vegetation

The climate of the Urmia Lake Basin is predominantly influenced by the surrounding mountains. It exhibits semi-arid continental characteristics characterized by cold and wet winters and warm and dry summers. The mean annual precipitation in the region is estimated to be around 350 mm, while the mean annual temperature is 11.2 °C. The

climate is known for its extreme weather patterns, with winter temperatures reaching as low as -20°C and summer temperatures reaching as high as 40°C (Bottema, 1986; Djamali et al., 2008). The Urmia Lake Basin is in the Irano-Turanian phytogeographical region, renowned for its rich and diverse flora. The vegetation in the region is dominated by steppe-like vegetation, with *Artemisia fragrans* and *Amaranthaceae* being the primary species. At higher elevations, this vegetation gives way to mountain steppes, with various species of *Quercus* and *Juniperus* trees found in the northern Zagros Mountains in the western part of the lake basin. The valley and mountainous regions are primarily occupied by small trees of the *Rosaceae* family. The vegetation surrounding the lake is predominantly halophytic and halotolerant, with the distribution of vegetation being influenced mainly by climatic conditions, topography, soil structure, and anthropogenic factors (Djamali et al., 2008).



3. MATERIALS AND METHODS

3.1 Core Recovery

This study is based on a 25 m-long sediment core collected from the northwestern region of Urmia Lake (UL2; Figure 2.1). The core's uppermost sediments (~3 m) consist of salt crust from recent extreme drying events. The coring was conducted using Shelby drilling equipment in 2017 by the Iran Water and Power Resources Development Company (IWPRD). The core segments (36 sections), 60 cm long each, were split longitudinally, photographed, described, and sub-sampled for further analysis (palynological, TOC- TIC, XRD, SEM, smear slide, and radiocarbon) in the sedimentology/geochemistry laboratory of ITÜ EMCOL (Eastern Mediterranean Centre of Oceanography and Limnology). The sediment samples were characterized by their lithology, physical properties, and geochemical features, including MSCL, μ -XRF, and TOC measurements. Sedimentary components were identified based on color, lithology, sedimentological characteristics, and examination of smear slides (110 samples). The chronology was established based on AMS ^{14}C dates obtained from fecal pellets of *Artemia urmiana* concentrates. The sediment cores were then stored at 4°C in the ITU EMCOL Core Repository, following the non-destructive physical, geochemical analyses and sub-sampling conduction. The distinctive dark gray modern beach sand, composed mainly of coated grains, was also sampled in 2023 for further examination in addition to core sections.

3.2 Physical Properties, Geochemistry, and Lithology

Physical properties of the sediment core, including gamma density and magnetic susceptibility measurements at a 1 cm resolution, were carried out on split cores using a Geotek Multi-Sensor Core Logger (MSCL) at the ITU-EMCOL Core Analysis Laboratory. Geochemical analyses, including high-resolution μ -XRF, total organic carbon (TOC), and total inorganic carbon (TIC) analyses, were conducted in the ITU-EMCOL Core Analysis Laboratory. To determine the element concentrations of K, Fe, Ti, Mn, Ca, and Sr, an ITRAX X-Ray Fluorescence (XRF) core scanner (COX

Analytical Systems) was utilized, which enabled the measurement of element ratios such as Fe/Mn, Ca/Ti, and Sr/Ca. The measurements were performed at a spatial resolution of 0.5 mm using a Mo X-ray tube under 30 kV voltage, 50 mA current, and 10 s exposure time and recorded as counts per second (cps). Total Organic Carbon (TOC) and total inorganic carbon (TIC) were measured using a Shimadzu TOC/TIC Analyzer. The samples were subjected to freeze-drying at -60°C for 48 hours to achieve a uniform particle size and ground using an agate mortar. Each sample was then precisely weighed (19-21 mg) and placed inside sterilized ceramic cups before undergoing analysis. The samples' total carbon (TC) content was determined by burning at 900°C, while TIC was measured by treating the samples with 85% phosphoric acid and heating them to 200°C. The total organic carbon (TOC) value in the samples was determined by subtracting TIC from TC.

3.3 XRD Mineralogical Analysis

Mineralogical analysis of 12 powdered bulk sediment samples was done using the Bruker™ D8 Advance X-ray diffraction (XRD) instrument at the ITU Geological Engineering Department X-Ray Laboratory. The samples were taken from levels representative of each sedimentary facies observed along the core and from levels where additional data is needed.

XRD mineralogical analyses were conducted on 12 levels from sediment core UL2, utilizing sediment samples. To contribute to the previous geochemical analyses, sampling was performed from levels where the observed sedimentary components were dominantly present throughout the core (5.05 m fecal pellets, 7.85 m gypsum, 11.95 m terrigenous minerals, 24.45 m coated grains) to represent each sedimentary component. Furthermore, analyses were conducted for levels (3.53 m, 6.85 m, 6.25 m, 8.35 m, 11.95 m, 18.25 m, 18.55 m, 19.35 m, 23.85 m) where additional data were required based on previous analyses and observations (μ -XRF and Smear Slide).

Additionally, hand-picked coated grain samples powdered using a mortar and pestle from 10 representative stratigraphic layers (Table B1) were selected for XRD analysis, conducted using the Bruker™ D8 Advance XRD instrument at the ITU Geological Engineering Department X-Ray Laboratory to investigate further and double-check the mineralogical compositions of the coated grains.

3.4 Palynological Analysis

High-resolution palynological analyses were performed on sediment samples extracted from the core. Fossil pollen and spore analysis consists of two stages: sampling and preparation of pollen sections and identifying and counting pollen and spore grains. A total of 163 sediment samples were prepared using standard pollen preparation methods (Cour, 1974), which involved using 35% HCl acid to eliminate carbonate content and 47% HF acid to eliminate silica content. The palynomorphs were separated from the remaining sediment sample using a ZnCl_2 (density >2.0) solution. The remaining sample was then passed through 200 μm and 10 μm mesh sieves, and the resulting material was used to prepare microscopic slides for pollen identification. Pollen identifications were analyzed using a Leica transmitted light microscope with different objectives (x40 and x100) and immersion oil at the ITU Eurasia Institute of Earth Sciences. Subsequently, the pollen data underwent a transformation into an AP (Arboreal Plants) - NAP (Non-Arboreal Plants) curve utilizing Tilia 2.0.41 software (Grimm et al., 2015).

3.5 Age-Depth Modelling and Chronological Analysis

3.5.1 Accelerated mass spectroscopy (AMS) radiocarbon analysis

The sediment core's chronology was established by applying Accelerator Mass Spectroscopy (AMS) radiocarbon dating. Nine fecal pellet samples (20 mg) were selected for dating along the sediment core (Table 4.3). The ^{14}C measurements have been performed at the Poznan Radiocarbon Laboratory in Poland and the TUBITAK Marmara Research Center (MAM) in Turkey. Radiocarbon ages were calibrated using Calib 8.2 software (Reimer et al., 2020). Sarı et al. (2024) previously dated core UL2 using the ^{14}C age from *Artemia urmiana* fecal pellets and bulk sediments. We used their five ages and combined them with our eight additional dates to construct an age-depth model. To avoid uncertainties, we excluded three radiocarbon dates below 7 meters in the age-depth model, where there are two unconformities at 6.07 meters and 4.90 meters. The non-Bayesian age-depth model was derived utilizing the "clam" script within R-studio (Blaauw, 2010).

A reservoir age of 2 cal ka BP was used for the calibration. All ages reported in this paper are reservoir corrected, calibrated to calendar years, and expressed as cal ka BP unless otherwise stated.

3.5.2 Age data derived from correlation of μ -XRF Ca/Ti ratios from Urmia Lake with NGRIP $\delta^{18}\text{O}$ records, Lake Van $\delta^{18}\text{O}$ records, and TOC correlations

The age-depth model for Urmia Lake was refined by integrating high-resolution geochemical data, particularly μ -XRF-derived calcium-to-titanium (Ca/Ti) ratios, with well-dated $\delta^{18}\text{O}$ records from the North Greenland Ice Core Project (NGRIP) and Lake Van. The Ca/Ti ratio, a reliable proxy for variations in carbonate precipitation and detrital input, reflects climatic oscillations such as arid and wet phases in the lake's history. These oscillations are closely aligned with global and regional climate events recorded in the $\delta^{18}\text{O}$ isotopic profiles of the NGRIP ice core and Lake Van sediments. TOC correlations further strengthened the chronological model. Organic carbon content variations in both lakes exhibit synchronous fluctuations, driven by regional productivity and organic matter preservation linked to climatic conditions. By integrating μ -XRF, isotopic, and TOC data, this approach provided a robust age-depth framework for Urmia Lake, covering the last ~50 cal ka BP. The calculated reservoir effect for Urmia Lake was estimated at approximately 2 cal ka BP.

3.6 Core Description, Binocular Microscope Observation, and Sample Preparation for Coated Grains

One hundred forty-four samples from coarse-grained (sand size) layers were collected along the sediment core, depending on the facies changes and coated grains availability. Although uniform sub-sampling is not always feasible, the approximate sampling resolution is 15.8 cm. The samples were washed and sieved using distilled water to remove finer sediments ($< 63\mu\text{m}$), and representative coated grains were hand-picked for further analysis. Coated grains were studied using binocular and scanning electron microscopes (SEM). The coated grains exhibited variations in color, size, shape, and frequency, which were examined and photographed using a binocular microscope at the ITU Eurasia Institute of Earth Sciences Microscopy Laboratory. In addition to the core sections, a sand sample was procured from a location proximate to the core site in 2023. The coarse grains ($> 63\mu\text{m}$) of the Modern Coated Grain

(MCG) from the lake beach (Figure 2.1) were used for thin section preparation for further examination.

3.7 SEM-EDS Imaging and Geochemical Analysis

Selected coated grains were embedded in epoxy resins and polished on one side to facilitate a comprehensive mineralogic and petrographic characterization. Before SEM examination, samples were subjected to an ultrasonic cleaning process using deionized water to eliminate contamination. Subsequently, the samples were carefully dried, mounted onto an aluminum stub, and coated with carbon and gold to enhance conductivity. The carbon-coated section was used for the grain-based examination, and the gold-coated section was applied for high magnification examination of the grain cortex using an SEM (Carl-Zeiss EVO 50 EP SEM) operating at 15 kV at Hacettepe University, Turkey. An Energy Dispersive Spectrometer (Bruker XFlash 3001 EDS) attached to the SEM was utilized to perform the elemental analysis and mapping of 280 representative coated grains from the selected samples. We emphasized the depth range between 25 m and 16 m, as this zone exhibited a higher dominance of coated grains. Through SEM observations, the selected grains' internal structures and surface morphology were imaged in detail, enabling a more comprehensive understanding of their characteristics. Coated grains were subjected to line scans and elemental mapping for qualitative analysis to identify large-scale geochemical differences. Spot analyses were conducted to determine detailed semi-quantitative geochemical data within the nucleus and the cortex. During the measurements of individual grains, we focused on different areas to obtain comprehensive information on the elemental composition.

3.8 Morphometric Analysis

Morphometric analysis was performed on 280 coated grains from different depths using PolyMorph-2D (Güler et al., 2021), an open-source geographic information system (GIS) plug-in built on OpenJUMP. The coated grains were assessed for axis ratios, ellipticity, circularity, compactness, dispersion, complexity, elongation, regularity, convexity, concavity, solidity, rectangularity, roundness, and sphericity (Table B.2). In this study, we focused on rectangularity and roundness parameters to compare coated grains from different depths.



4. RESULTS

4.1 Late Quaternary Paleoclimate and Paleoenvironment Reconstruction Using Multiproxy Approach in Urmia Lake (NW Iran)

The examination of sedimentary cores utilizing physical property measurements, total organic carbon analysis, and scanning X-ray fluorescence (μ -XRF) profiles have revealed the presence of five distinct sedimentary components across six stratigraphic units: U1 (25 m - 22.5 m), U2 (22.5 m - 15.8 m), U3 (15.8 m - 9.8 m), U4 (9.8 m - 6.8 m), U5 (6.8 m - 3.2 m), and U6 (3.2 m - 0 m). We comprehensively describe the observed changes in each proxy record along the sediment core to enhance our understanding of the sedimentary processes during their formation.

4.1.1 Sedimentary components and stratigraphic units

The sedimentological analysis, including visual observation of lithological characteristics and physical property measurements, documents significant lithofacies variations throughout the sediment core. The sedimentary sequence is composed of biogenic mud (micrite) and sand (mainly fecal pellets of brine shrimp *Artemia urmiana* and rarely shell fragments, terrigenous minerals (quartz, feldspar, pyroxene, volcanic lithics, volcanic glass, and clay), coated grains, diagenetic sulfate minerals (mostly gypsum), and evaporite minerals (salt crust).

The stratigraphic units are defined through a comprehensive sediment core analysis, which integrates visual core description, microscopic investigation of smear slides, and physical property measurements. Six major stratigraphic units, from the oldest to the most recent, are identified and designated as Units 1 through 6 (Figure 4.2-4.7).

Unit 1 predominantly consists of dark gray, sand-sized coated grains, except for a thin layer (20 cm) of grayish-brown, fecal pellet-dominant mud found between depths of 23 m and 22.8 m.

Unit 2 represents an alternation of fecal pellets and coated grains intercalated by occasional diagenetic gypsums. The lowermost 60 cm of the unit is composed of

brown silty clay with an abundance of diagenetic gypsum. From 22.1 m to 20 m, it continues with thick, medium sand-sized fecal pellets within a brown silty clay matrix. The overlying interval between 20 m and 18.8 m consists of alternating grayish-brown fecal pellets and coated grains, interrupted by occasional diagenetic gypsum from 18.8 m to 18.1 m. The upper boundary of the diagenetic gypsum dominant layer is marked by a color change from grayish-brown to greenish-grey. From 18.1 m up to 15.8 m, units consist of greenish-gray alternations of fecal pellets and coated grains at various thicknesses and are noticeably finer-grained towards the end.

Unit 3 (15.8 m - 9.8 m) is characterized by homogenous, partially laminated deposits, oxidized surfaces, and minor color variation. The massive dark to light grayish-brown clayey matrix includes terrigenous minerals (quartz, feldspar, pyroxene, volcanic lithics, volcanic glass, clay) and diagenetic gypsum. This unit begins with an 80 cm thick terrigenous minerals-dominated layer with occasional small fecal pellets and infrequent coated grains. Gypsums are found in the primary form at 14.6 m - 14.3 m depths. The overlying interval consists of alternating grayish-brown terrigenous minerals and fecal pellets at various thicknesses from 14.3 m to 11 m. Another diagenetic gypsum dominant level occurs in the upper part of the unit, including large and transparent secondary gypsum crystals located at 11 m - 10.7 m depths. Lastly, the unit ends with a thick terrigenous mineral-dominated layer.

Unit 4 comprises alternating intervals of laminated greenish-gray silty clay intercalated with fine sands and brown silty clay of varying thickness. The unit is characterized by the abundance of gypsum and relatively higher content of the fecal pellets. The lowermost part of the unit starts with an 80 cm thick pellet-rich layer. It progresses to an alternation of brown to olive-gray fecal pellets and gypsum layers between 9 m and 7.2 m. Brown silty clay tends to contain large and transparent secondary gypsum crystals. Between 7.2 m - 6.8 m, sediments are defined by the dominance of fecal pellets.

Unit 5 is distinguished by the abundance of fecal pellets and by an abrupt color change above 6.8 m from brown to greenish-gray silty clay without a distinct mineralogical change until 3.2 m. It consists by far the thickest fecal pellet-dominated layer of the entire sediment core. Fecal pellets are abundant in the lower part and become relatively scarce towards the top. They are present in a biogenic mud (micrite), particularly between 5 m and 3.2 m.

Unit 6 represents the 3.2 m thick salt crust in the upper part of the sediment core, which has accumulated over the last two decades. The lake surface sediments are mainly halite and are not used for the multiproxy analysis.

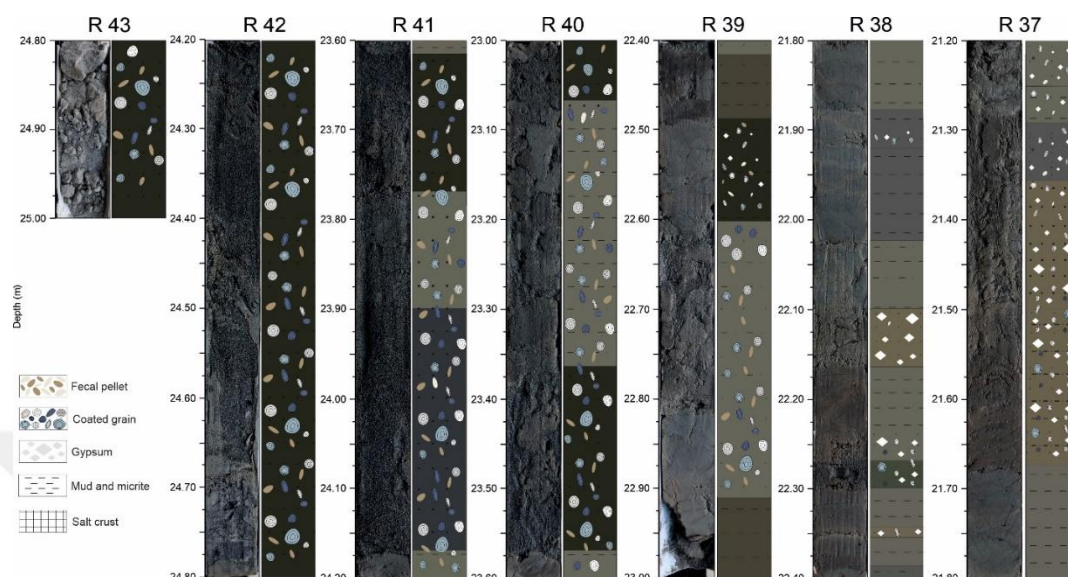


Figure 4.1: Detailed lithostratigraphy of the studied sediment core sections 43-37.

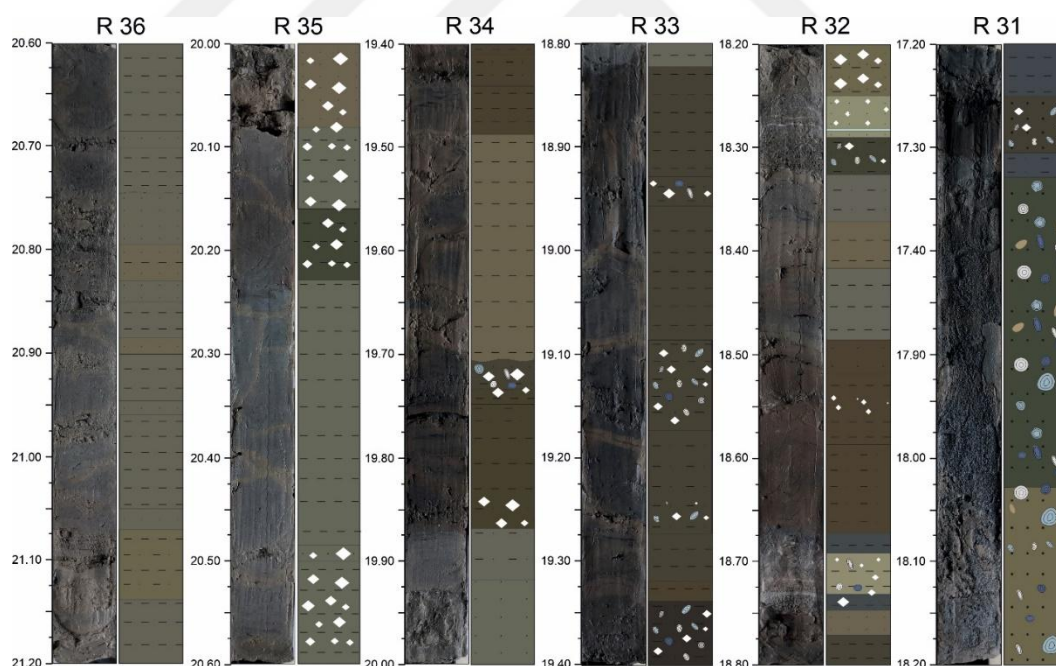


Figure 4.2: Detailed lithostratigraphy of the studied sediment core sections 36-31.

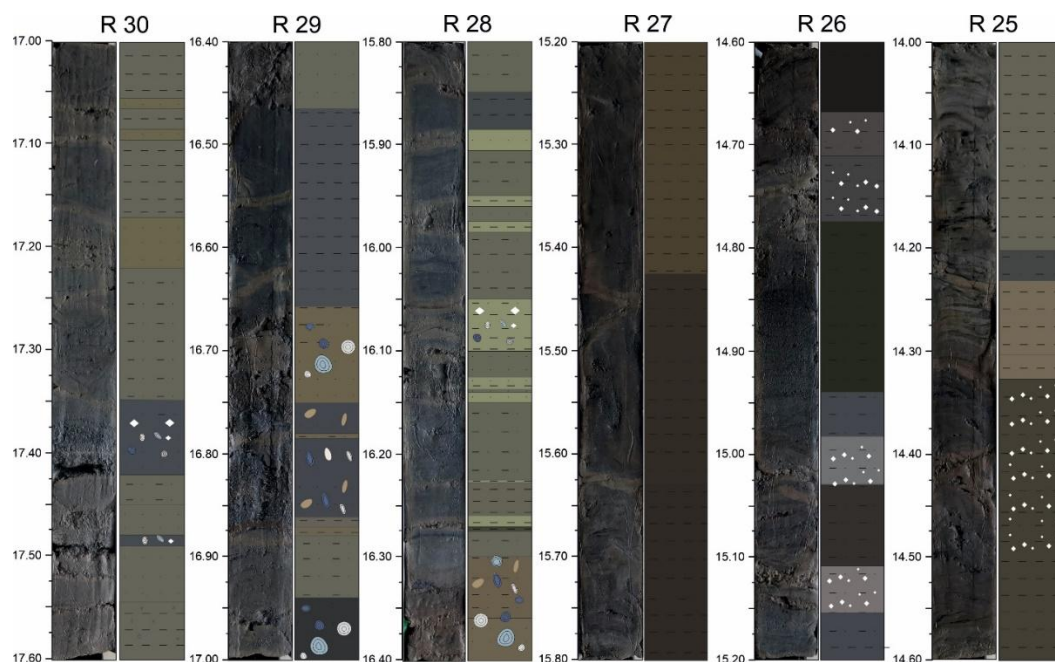


Figure 4.3: Detailed lithostratigraphy of the studied sediment core sections 30-25.

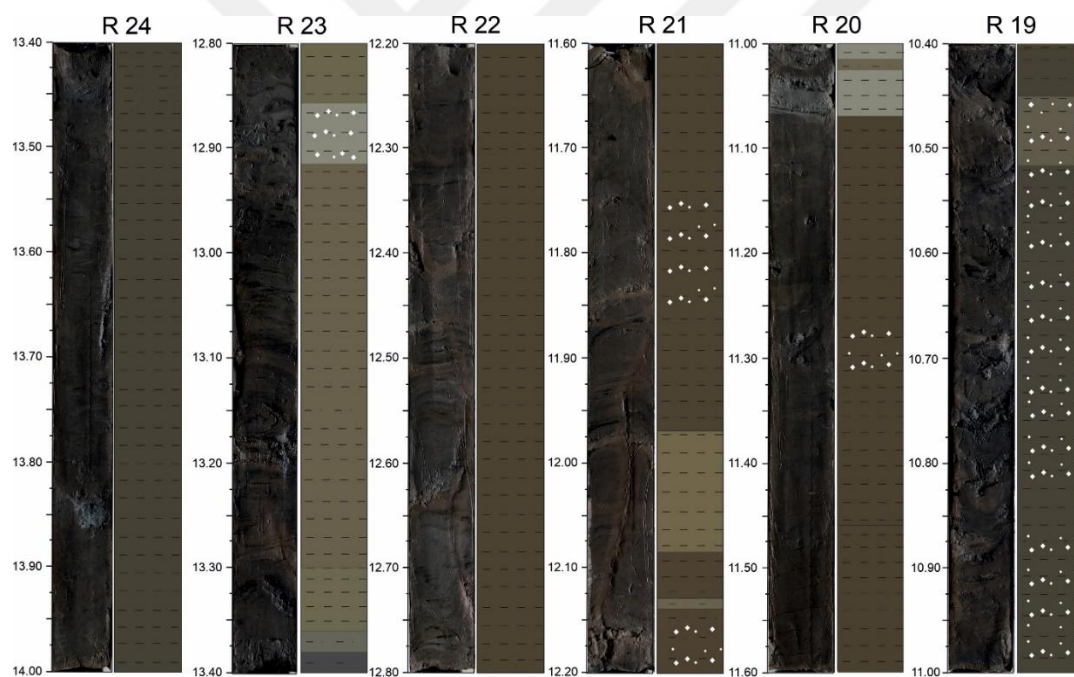


Figure 4.4: Detailed lithostratigraphy of the studied sediment core sections 24-19.

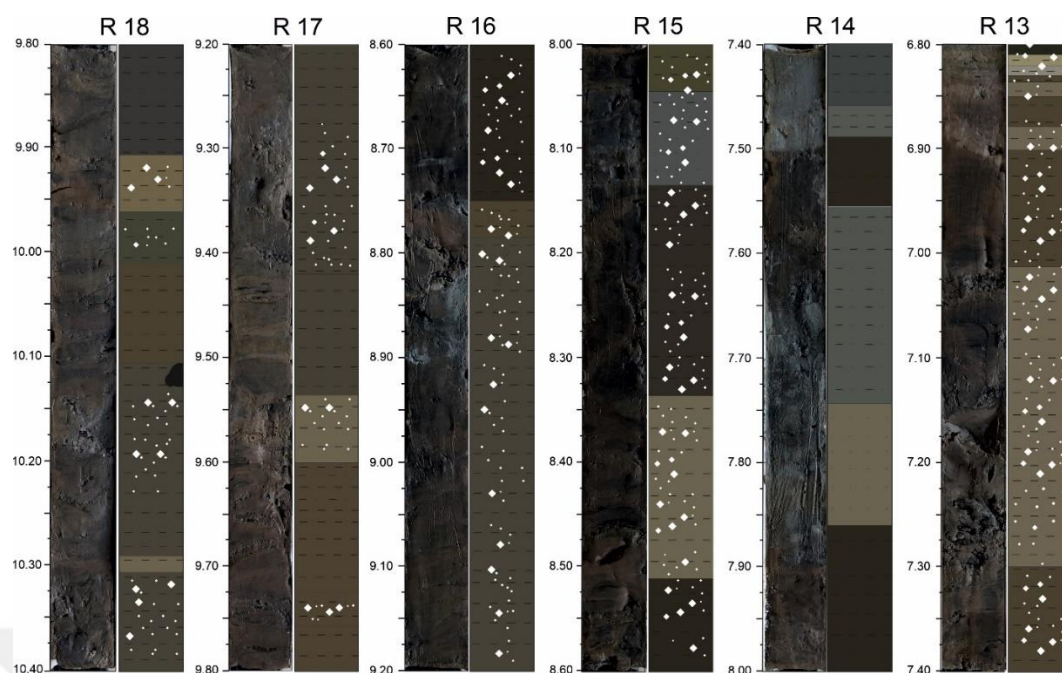


Figure 4.5: Detailed lithostratigraphy of the studied sediment core sections 18-13.

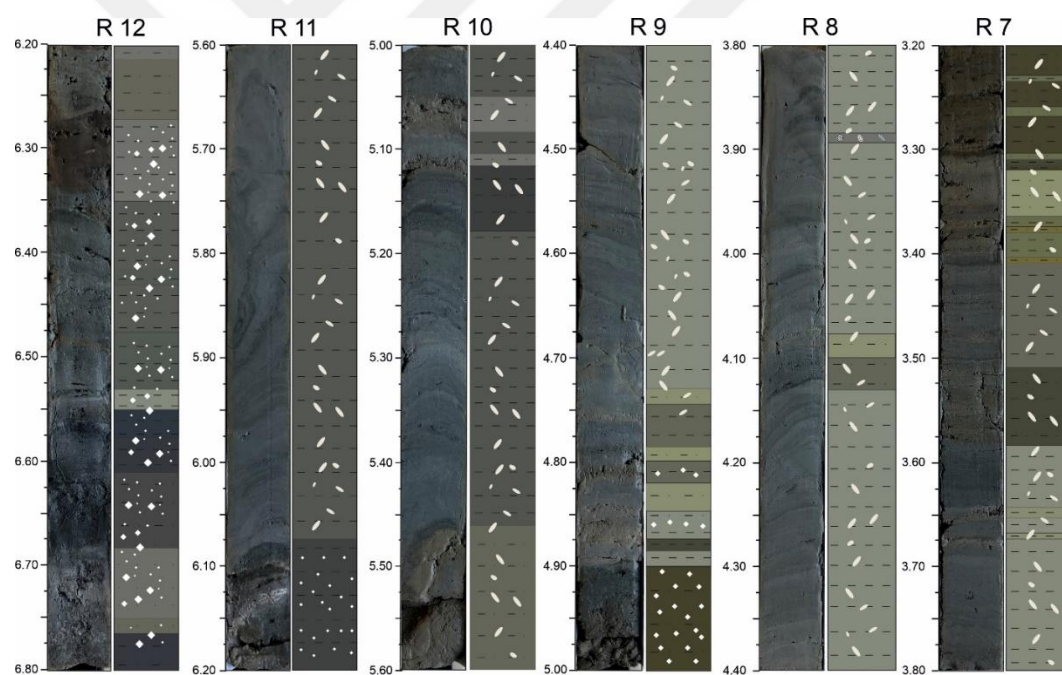


Figure 4.6: Detailed lithostratigraphy of the studied sediment core sections 12-7.

4.1.2 Chronology

Sari et al. (2024) previously dated core UL2 using the ^{14}C age from *Artemia urmiana* fecal pellets and bulk sediments. We used their five ages and combined them with our eight additional dates to construct an age-depth model. To avoid uncertainties, we excluded three radiocarbon dates below 7 meters in the age-depth model, where there are two unconformities at 6.07 meters and 4.90 meters. The age-depth model of Urmia Lake provides a chronology extending back to 50 cal ka BP, covering the upper parts of MIS 3 (Table 4.1). The dates present a mostly systematic sequence. The age-depth model was constructed using the Non-Bayesian approach, a widely accepted method in scientific research (Figure 4.7).

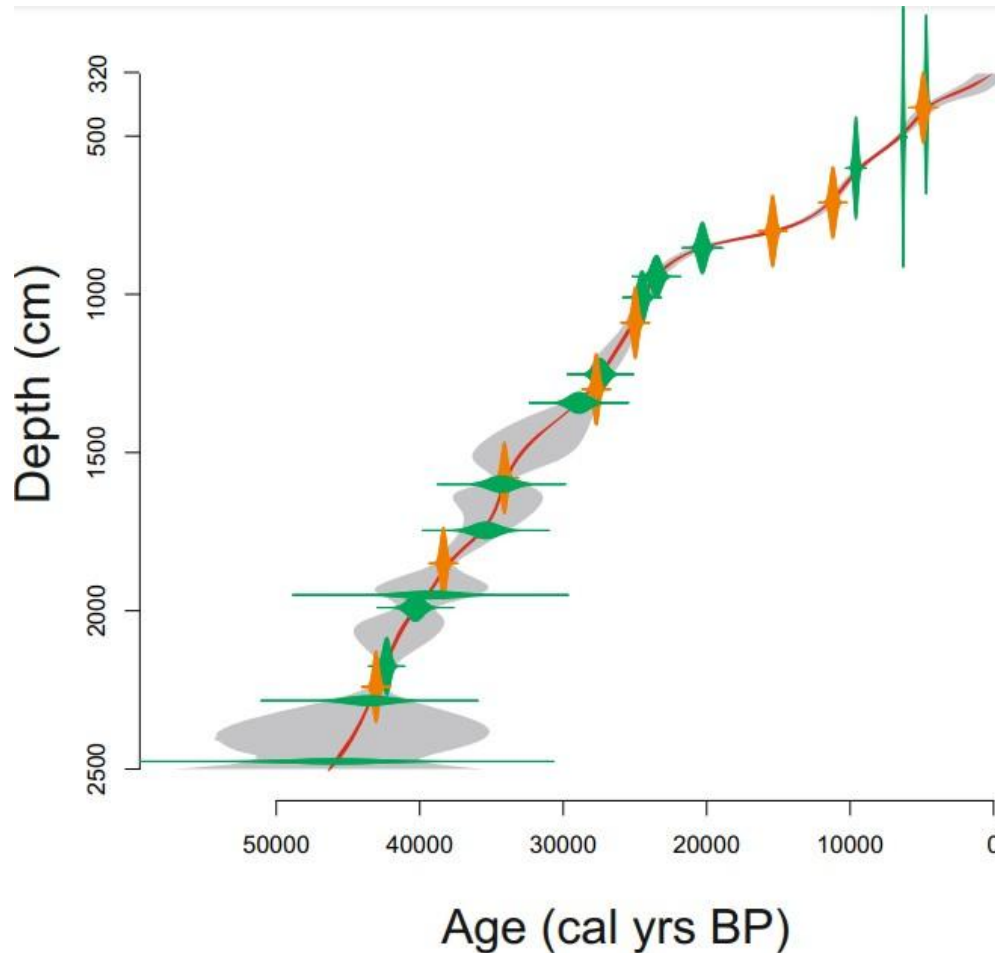


Figure 4.7: The age-depth model of the examined core UL2 was reconstructed based on AMS ^{14}C ages obtained from *Artemia urmiana* fecal pellets using inorganic carbon and bulk sediments (green) and derived from correlation of $\mu\text{-XRF Ca/Ti}$ Ratios from Urmia Lake with NGRIP $\delta^{18}\text{O}$ Records, Lake Van $\delta^{18}\text{O}$ Records, and TOC correlations (orange).

Table 4.1: AMS ^{14}C radiocarbon age and calibrated ages of *Artemia urmiana* fecal pellets and bulk sediment from UL-2 sediment core. Calibrations were performed using Calib 8.2 (<http://calib.org/calib/calib.html>). Ages marked with a star (*) are from Sari et al al (2024).

Core ID	Material	Depth (m)	^{14}C Ages (yr BP)	Calibrated ^{14}C Ages (cal yr BP)
UL2	Pellet	4	6200 ± 40	7090 ± 50
*UL2	Bulk	5.03	7543 ± 35	8360 ± 50
*UL2	Bulk	6.01	10631 ± 64	12650 ± 70
UL2	Pellet	8.53	18740 ± 110	22680 ± 250
UL2	Pellet	9.44	21610 ± 140	25900 ± 220
*UL2	Bulk	10.10	22389 ± 71	26720 ± 160
UL2	Pellet	12.53	25100 ± 281	29420 ± 590
UL2	Pellet	13.43	26700 ± 260	30900 ± 560
UL2	Pellet	16	31850 ± 410	36190 ± 850
*UL2	Pellet	17.46	33000 ± 487	37660 ± 1350
UL2	Pellet	19.5	36280 ± 800	41200 ± 1360
*UL2	Bulk	19.90	37154 ± 224	41920 ± 390
UL2	Pellet	21.75	40079 ± 309	43240 ± 440
*UL2	Pellet	22.84	42268 ± 1246	44980 ± 2090
UL2	Pellet	23.8	45000 ± 4000	48070 ± 5290
*UL2	Pellet	24.76	45144 ± 1725	47690 ± 3750

Radiocarbon dates from core UL-2 (Table 4.1) allow the construction of a robust age-depth model for the last 50 cal ka BP (Figure 4.7). According to core chronology, the average sedimentation rate of the core between 24.76 m and 9.98 m depth is about 0.62 mm/year (47690 ± 3750 cal BP to 24460 ± 500 cal BP), between 9.98 m and 6.01 m core depth the sedimentation rate decreases to about 0.34 mm/year (MIS 2), and the sedimentation rate further decreases to about 0.25 mm/year between 6.01 m and 5.03 m (MIS 1).

Radiocarbon ages are in stratigraphic order and range from 47690 ± 3750 cal BP to 7090 ± 50 cal BP, thus covering marine isotope stages 3 and 2 (MIS 3 and MIS 2) from the Pleistocene to the Holocene.

4.1.3 Physical properties

The sediment core's magnetic susceptibility (MS) record exhibits multiple excursions towards high (100 SI) and low values (5 SI) (Figure 4.8). The lowermost section of the core (U1 and U2 between 24.8 m - 18.8 m) is characterized by low MS values, with only a few minor peaks and higher values. A notable increase in MS values is observed towards the core's middle section, within Unit 3, and is commonly linked to terrigenous minerals. MS values decrease dramatically from 9.8 m towards the core's top, with some relatively higher peaks occurring at several depths. The gamma density (GD) record documents high lithofacies variations across the sediment core, with the maximum GD value being 1.66 g/cm^3 and the minimum being 1.59 g/cm^3 .

4.1.4 Geochemical analysis

The sediment core's μ -XRF elemental composition analysis, which includes measurements of K, Fe, Ti, Mn, Sr, Fe/Mn, Ca/Ti, Sr/Ca, and TOC distribution, is presented in Figure 4.8. The analysis revealed noteworthy fluctuations in elemental profiles, with K, Fe, Ti, and Mn displaying analogous patterns characterized by relatively low values across the core. The Fe-Mn ratio throughout the core is predominantly low.

Unit 1: The lowermost coated grain dominant part of the sediment core displays distinct geochemical characteristics, as evidenced by lower values of K, Fe, Ti, and Mn, as well as relatively higher values of Ca/Ti and Sr/Ca ratios. Notably, a significant

decline in concentrations of K, Fe, Ti, and Mn is observed between depths of 23 m and 22.9 m, while the Ca/Ti and Sr/Ca ratios remain relatively stable. Above 22.9 m, concentrations of K, Fe, Ti, and Mn gradually increase until a sudden drop occurs at a depth of 21.7 m. These trends in Fe, Ti, and Mn concentrations show a decreasing pattern, while Ca/Ti exhibits a slight increase, consistent with the variations observed in the total organic carbon (TOC) content.

Unit 2: The later part of the fecal pellet dominant interval (21 m - 20 m) displays a gradual increase in K, Fe, Ti, and Mn content, positively correlating with Sr/Ca and TOC content. However, below 20 m, the concentrations of K, Fe, Ti, and Mn decrease significantly until 19.5 m. In the upper coated grain-dominated interval (19.5 m - 18.8 m), Ca/Ti, Sr/Ca, and TOC values are low, while K, Fe, Ti, and Mn reach high values. Sr values at the core bottom gradually decrease until 18.8 m, where a sharp decline occurs, even at lower Sr values between 18.8 m and 18.2 m. At 18.8 m, K, Fe, Ti, and Mn values decrease sharply and then gradually increase until 18.2 m, where another sharp decrease is observed. Between 18.2 m - 16.4 m, the overlying part of the unit displays high values in Ca/Ti, K, Fe, Ti, and Mn, with strong fluctuations. In contrast, Sr/Ca and TOC content have lower values. The top layer of the unit begins with lower K, Fe, Ti, and Mn.

Unit 3: This unit displays a pattern of increasing K, Fe, Ti, and Mn values in the terrigenous mineral-dominated interval located at the bottom of the unit (15.8 m - 14 m), while the Sr profile exhibits high values with notable fluctuations between 18.2 m and 14.6 m. The diagenetic gypsum layer at 14.6 m - 14.3 m causes a drop in K, Fe, Ti, and Mn values, while another significant decrease in Sr content is observed between 14.6 m and 13.4 m. The fecal pellet-dominated layers in the middle part of the unit (14.3 m - 12.8 m) demonstrate relatively high Ca/Ti, Sr/Ca, and TOC content, while the terrigenous mineral-dominated layers exhibit high K, Fe, Ti, and Mn values. Sr values gradually increase, then decrease at 13.4 m and 12.2 m, respectively. At 12.8 m, a sharp decrease is observed in the profiles of K, Fe, Ti, Mn, and Sr/Ca, which then increase again at 12.2 m. This upward trend continues within the upper terrigenous-dominated layer, where K, Fe, Ti, and Mn values increase while Sr/Ca and TOC values decrease. The Sr profile exhibits another sharp increase between 12.2 m and 11 m, followed by a similar increase between 11 m and 9.8 m.

Unit 4: This core part is characterized by elevated total organic carbon (TOC) content. The Ca/Ti, Sr/Ca, and TOC values significantly increase between 9.8 m and 9.2 m, whereas the K, Fe, Ti, and Mn profiles show a decrease in this interval, as expected. The lower values of these elements vary systematically in response to lithofacies changes in the element profiles observed between 9.2 m and 7.4 m. Additionally, the Sr values in this unit display low values with strong fluctuations, with minor Sr peaks corresponding to the gypsum dominant layer. The highest concentrations of K, Fe, Ti, and Mn are observed between 7.4 m and 6.8 m core depth, signifying a lithofacies change in this interval.

Unit 5: The K, Fe, Ti, and Mn concentrations significantly decrease between 6.8 m - 6.2 m, inversely correlated with Ca/Ti and Sr/Ca ratios. Sr values, however, gradually decrease from 7.2 m to 6.2 m. Until an abrupt shift at 3.8 m, Sr values remain low. Above this level, the K, Fe, Ti, and Mn values gradually increase with positively correlated Sr/Ca and TOC values. The rest of the unit is represented by another systematically significant fluctuation in the element profiles up to 4.4 m. This systematic fluctuation ends with a sharp decrease at 4.4 m. Above this level, the K, Fe, Ti, and Mn values gradually increase with positively correlated Sr/Ca and TOC values. The top of the core is characterized by the rich fecal pellet layers, which correspond primarily to the relatively high TOC content. Notably, the highest TOC values (2.3 wt%) are observed between 18.8 m - 18.2 and 4.2 m - 3.8 m. Additionally, the top of the core between 3.8 m - 3.2 m displays high K, Fe, Ti, Mn, and Sr values.

4.1.5 Palynological analysis

Pollen data of core UL-2 are documented here as AP and NAP curves (Figure. 4.8).

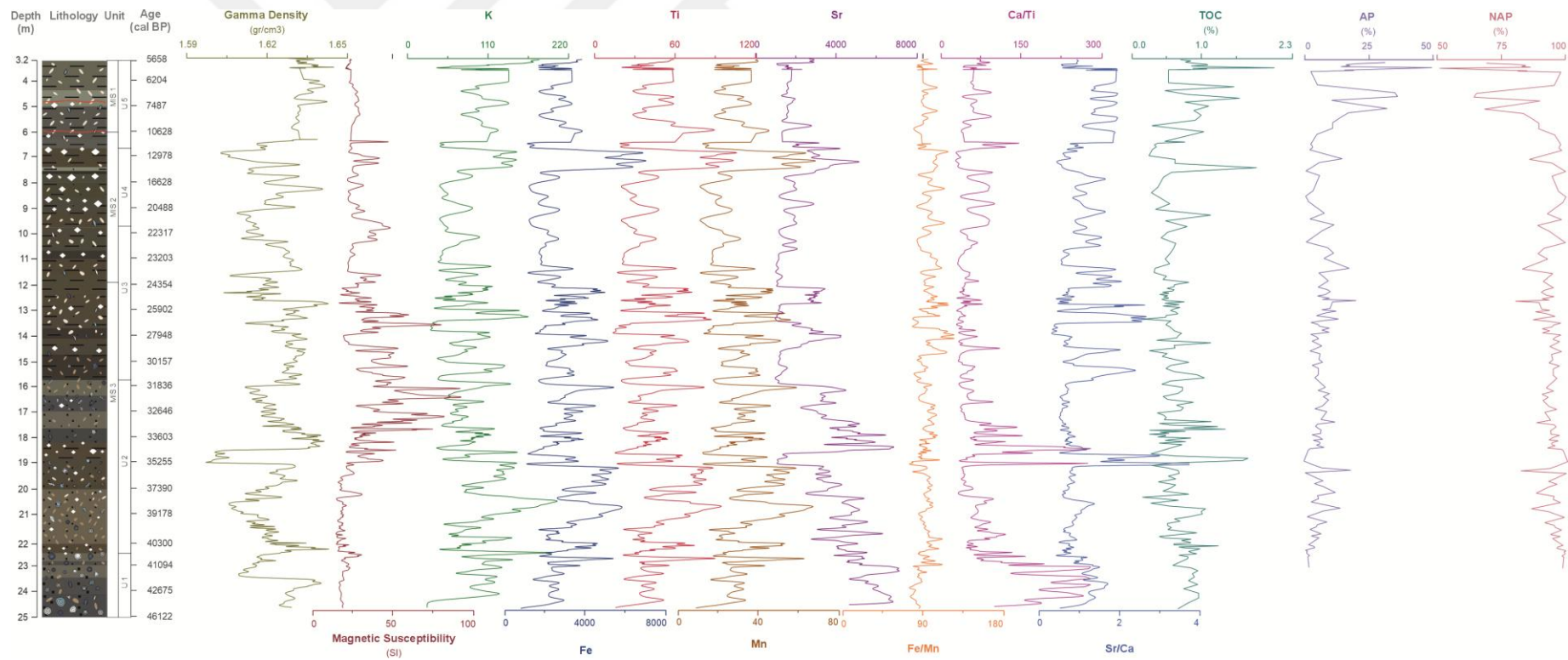


Figure 4.8: Urmia Lake; lithology, gamma density, magnetic susceptibility, μ -XRF geochemical element and element-ratio profiles (K, Fe, Ti, Mn, Sr, Fe/Mn, Ca/Ti, Sr/Ca), TOC content and AP-NAP (Depth).

4.2 Lake Level Fluctuation Controls on Formation, Types, and Abundance of Coated Grains in Hypersaline Lakes; Urmia Lake (NW Iran) Case Study

The distribution of coated grains throughout the core exhibits remarkable variability. While coated grains predominate in the lowest part of the core (between 25 m and 22.5 m), they are increasingly found together or intercalated with fecal pellets and other sedimentary constituents in the middle layers (between 22.5 m and 15.8 m). Notably, coated grains were also observed in the uppermost layers (6.2 m, 5.9 m, 5 m, and 3.7 m) with low concentrations (Figure 4.9). The coated grains exhibit significant variations in their overall abundance, shape, color, nucleus type, internal structure, cortex thickness and microfabrics, and frequency and thickness of lamellas.

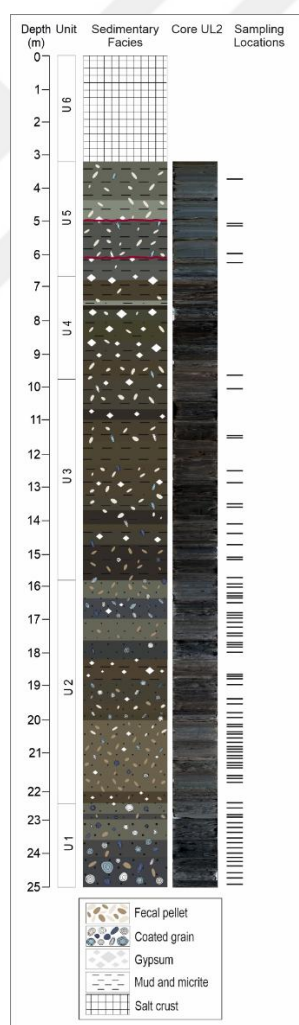


Figure 4.9: Lithostratigraphy of the studied sediment core showing sedimentary units (Unit 1 to Unit 6) and analyzed sample depth.

4.3 Core Description and Sedimentary Constituents

Visual observations and sedimentological analysis indicate that the sediment core exhibits substantial constituent variations. The sedimentary sequence is composed of biogenic mud (micrite) and sand (mainly fecal pellets of *Artemia urmiana* and rarely shell fragments), terrigenous fragments and minerals (quartz, feldspar, pyroxene, volcanic lithics, volcanic glass, and clay), coated grains, diagenetic sulfate minerals (mostly gypsum), and evaporite minerals (salt crust).

4.3.1 Core description

Six major sedimentary units were identified to provide a concise overview of the sedimentary units based on variation in type, abundance, and distribution of sedimentary constituents along the core (Figure 4.9). Table 4.2 summarizes their characteristics and depth ranges within the core description (Detailed core description given in chapter 4.1.2). Notably, the sedimentary record exhibits two sharp unconformities at Units 4 and 5. The lower unconformity at 6.07 m is marked by the transition to fresh fecal pellet-rich greenish mud, while the second unconformity at 4.90 m is characterized by a 0.10 m thick sand layer with diagenetic sulfate minerals, where fecal pellets are notably absent. These unconformities were identified based on sharp changes in color, lithology, physical characteristics, and gaps in the chronological record.

4.3.2 Sedimentary constituents

Diagenetic gypsum: Gypsum is a prevalent diagenetic constituent exhibiting variations in shape and size throughout the core. An exemplary instance of the coarsest transparent gypsum crystal (4.6 cm in length) is discerned at a depth of 8.5 m in association with the brown clay layer (Unit 4). Fine-grained gypsum crystals ranging from 1 to 2 mm are commonly observed below 6 m depth along the core, with a pronounced abundance occurring between 7.4 m and 8.6 m (Unit 4). Gypsum as early diagenetic cement is associated with coated grains-dominated layers (Unit 2). In some instances, gypsum grains can serve as the nuclei of coated grains (Unit 1).

Table 4.2 : A brief overview of the sedimentary unit's characteristics and depth ranges in the core.

Unit	Depth (m)	Characteristics
Unit 1	25 - 22.5	Dark grey coarse-grained sand with coated grains and reworked shell fragments.
Unit 2	22.5 - 15.8	Brown to greenish-grey mud with coated grains, fecal pellets, diagenetic sulfate minerals, and reworked shell fragments.
Unit 3	15.8 - 9.8	Brown mud with terrigenous minerals (quartz, feldspar, pyroxene, volcanic lithics, volcanic glass, clay), and diagenetic gypsum. Occasional small fecal pellets and infrequent coated grains.
Unit 4	9.8 - 6.8	Brown mud dominated by diagenetic gypsum (large crystals up to 4.6 cm) and olive-gray mud dominated by fecal pellets, and infrequent coated grains. Unconformity at 6.07 m.
Unit 5	6.8 - 3.2	Greenish-gray mud with an increase of fresh, soft, cream fecal pellets, rare diagenetic gypsum, and coated grains. Unconformity at 4.90 m.
Unit 6	3.2 - 0	Primary evaporite deposits (salt crust).

Fecal Pellet: Fecal pellets with aragonite and calcite mineralogy derived from *Artemia urmiana* are significant biochemical constituents in the Urmia Lake sedimentary record. They are distributed along the core but are abundant in the upper part of the sediment core (Unit 5; Figure 4.9) and exhibit moderate to good preservation. Eardley (1938) described aragonite-coated brine-shrimp fecal pellets, which he called "rod-shaped" ooids, in Great Salt Lake sediments. The fecal pellets demonstrate a distinct capsule shape, occurring as either whole and intact or fragmented pieces, with sizes ranging from silt to very coarse-grained sand fractions. They display diverse colors, including cream, brown, orange, dotted, and dark gray. Their color and internal texture change with depth in the sediment core (Figure 4.9). The fecal pellets often serve as nuclei for the formation of coated grains.

Terrigenous fragments and minerals: Terrigenous fragments and minerals in the sediment include quartz, pyroxene, volcanic lithics, volcanic glass, and clay minerals. The abundance of clastic minerals transported by rivers is relatively low. Brown-colored clay minerals prevail in the middle of the core (Units 2-4).

Primary evaporite minerals: The evaporite minerals (salt crust) with 3.2 m thickness constitute the core's uppermost part. It was deposited within the lake basin over the past two decades (between 1996 and 2017) due to extreme water level fall and evaporation (Figure 4.9).

Coated Grains: Coated grains are frequent in the studied core and show various shapes, sizes, and colors. They are sand-sized grains composed of a nucleus surrounded by concentric carbonate layers called the cortex. The nucleus of coated grains predominantly consists of fecal pellets, subsidiary amounts of shell fragments, gypsum, and terrigenous fragments and minerals such as quartz or volcanic lithics.

4.4 Coated Grain Morphology and Distribution

The shape of the available nuclei controls the overall external morphology of the resulting coated grains, which are typically elongated, subspherical, and angular; they vary in size from less than 118 μm to 1245 μm . The coated grains exhibit a remarkable diversity of colors, encompassing white, gray, orange, dotted, blue, and dark blue shades (Figure 4.10A-F). Blue ones are dominant in prevalence among these coated

grains, followed by white-coated grains as the second most common variant. On the other hand, orange-coated grains are exclusively encountered at specific depths, namely 8.53 m, 9.44 m, 16.12 m, 18.59 m, and 18.73 m (Figure 4.10E). Dotted-coated grains are comparatively rare and primarily associated with cream-colored fecal pellet nucleated coated grains (6.23 m, 23.55 m, and 23.97 m; Figure 4.10F). A prominent feature observed among the coated grains is the presence of concentric lamination, which displays variations in color, number and thickness.

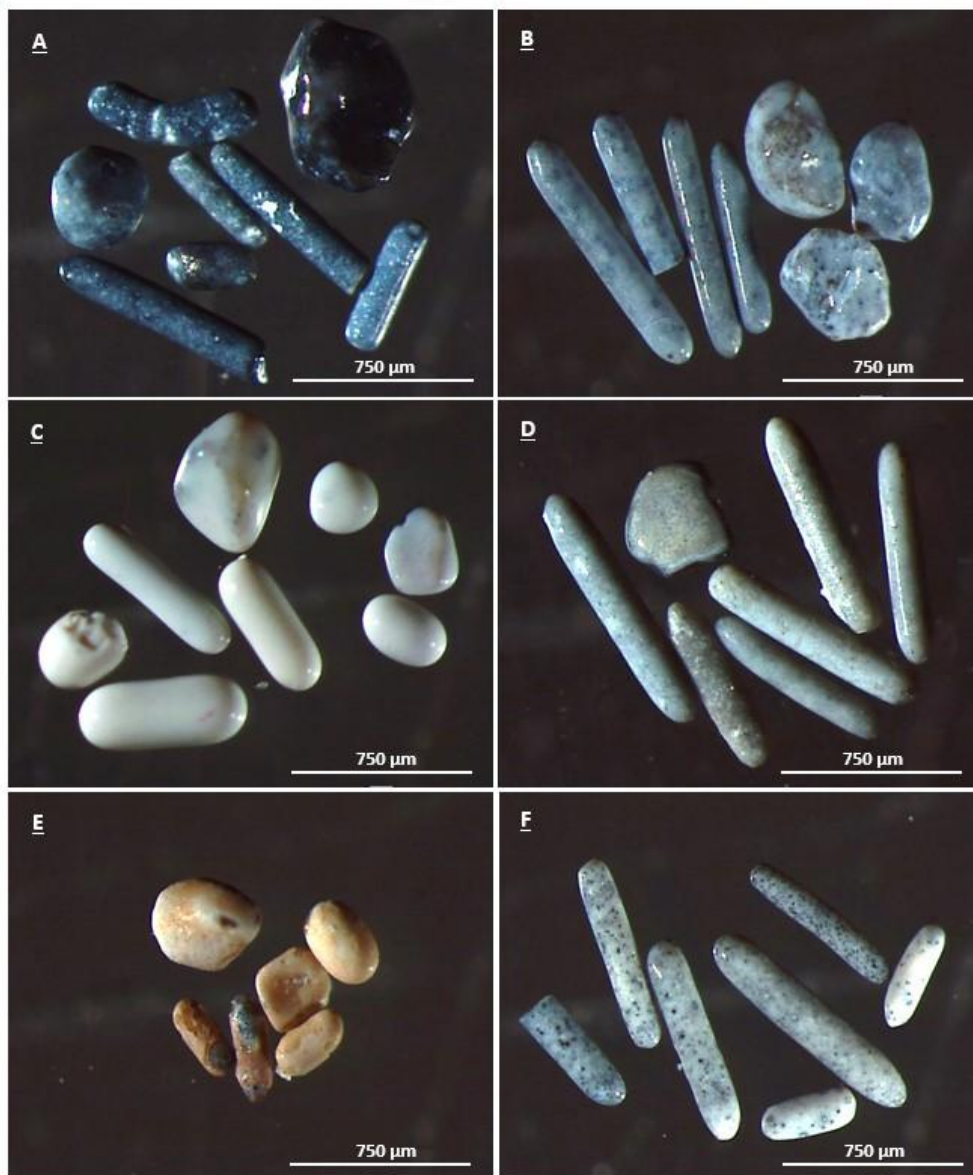


Figure 4.10: Representative coated grains in different colors, sizes, and shapes from different core depths. A) Dark blue coated grains from 24.76 m, B) Blue-coated grains from 23.05 m, C) White-coated grains from 18.73 m, D) Gray-coated grains from 24.37 m, E) Orange-coated grains from 16.12 m, and F) Dotted coated grains from 23.55 m.

We thoroughly examined the two-dimensional morphological characteristics of coated grains, specifically emphasizing their rectangularity, roundness, ellipsoidal configuration, and overall irregularity. The analysis extended to assess the rectangularity and roundness ratios associated with these grains. The comparison revealed that detrital nuclei of coated grains exhibited a higher degree of rectangularity in morphological characteristics. Conversely, coated grains with fecal pellet nuclei tended to favor ellipsoidal shapes. Although the dominant coated grain shape transitioned gradually towards an elliptical form due to the increasing prevalence of fecal pellets as available nuclei from the bottom core up to 16 m, no correlation was generally observed between sediment depth and coated grain shapes (Figure 4.11).

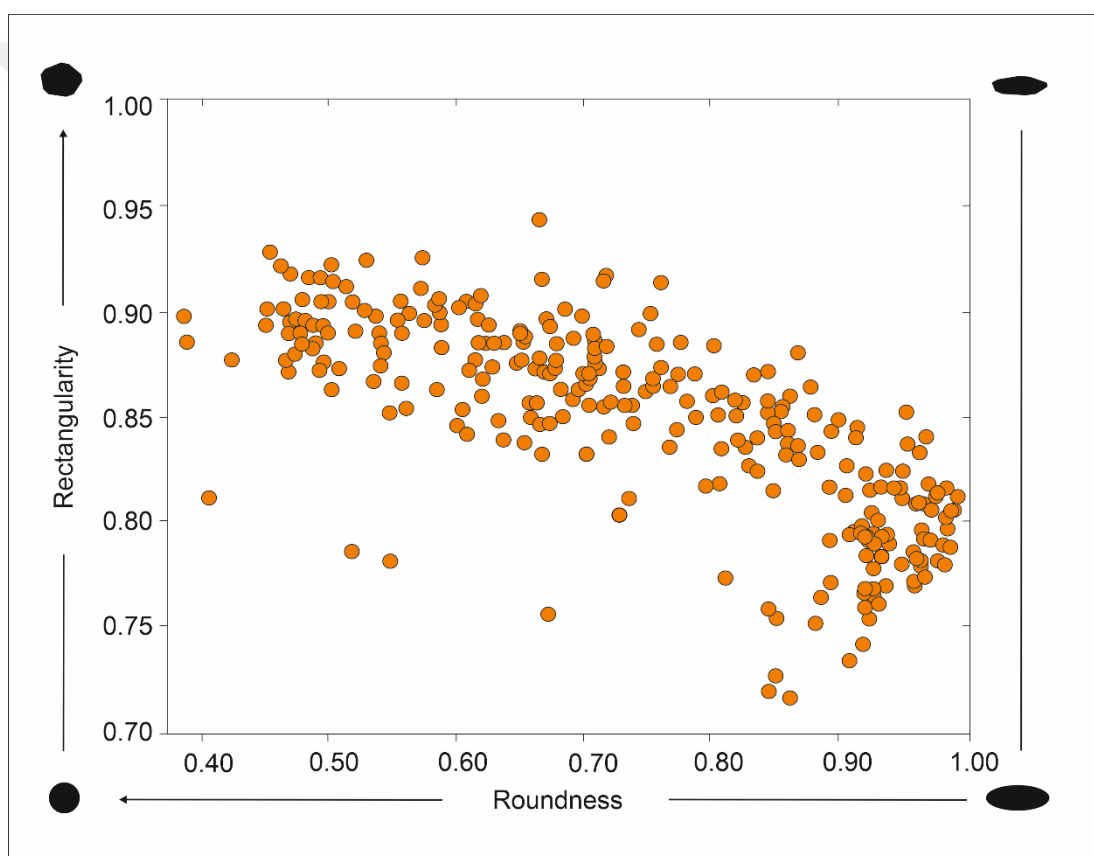


Figure 4.11: Comparison of rectangularity and roundness parameter changes of coated grains.

The vertical distribution of coated grains in the sediment core reveals distinct patterns at different depths. In the lowermost section (25 m - 22.5 m), there is a notable presence of coated grains displaying diverse colors and shapes formed around detrital grains, shell fragments, and fecal pellets. Moving upward, there is a decrease in abundance between 21.25 m and 20.89 m, followed by a resurgence at 19.73 m. At this depth,

though smaller, prevalent capsule shapes with dark blue coloration are observed, reaching a maximum of $\sim 600\ \mu\text{m}$ in size. Abundance decreases between 17.98 m and 16.95 m, followed by a reappearance with increased morphological diversity. Notably, in this interval, the coated grains show a slight enlargement, with capsule shapes measuring up to $770\ \mu\text{m}$ and spherical forms reaching $670\ \mu\text{m}$ in size. Above 16.26 m, where coated grains are no longer dominant, there is a gradual diminishment in the size of gray to blue capsule-shaped grains, reaching $470\ \mu\text{m}$. Furthermore, between 15.16 m and 9.44 m, rare instances of small, mostly broken coated grains appear, displaying a distinct white to blue coloration, with a size measurement of $\sim 400\ \mu\text{m}$. The sedimentary composition in the core reveals a significant scarcity of coated grains, with fecal pellets dominating the sediment constituents. Importantly, concentrations of gray to dark blue capsule-shaped grains are observed at specific levels within the core, at 6.23 m, 5.93 m, 5.38 m–5.06 m, and 3.94 m–3.67 m, reaching a maximum measured size in the long axis of $1245\ \mu\text{m}$.

4.5 Microfabric and Cortex Characteristics

The SEM photomicrographs captured along the sediment core reveal distinctive fabric features of coated grains. The cortices of coated grains exhibit a variety of microfabrics caused by different orientations of aragonite or calcite needles in the laminae, with some exhibiting randomly and tangentially arranged crystals (Figure 4.12).

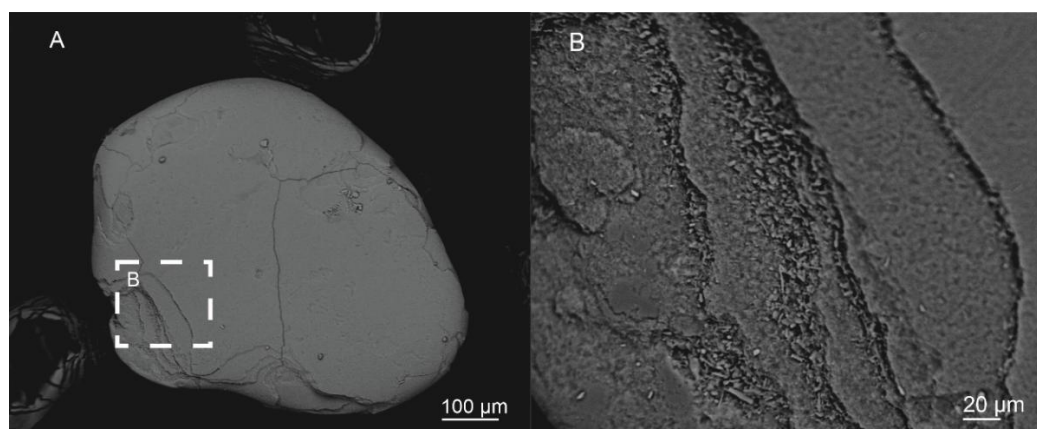


Figure 4.12: SEM photomicrographs of representative coated grains along the studied sediment core. A) Regular coated grain from 24.25 m depth characterized by a concentric laminar structure; B) Local magnification of A, showing typical microtextural characteristics; concentric laminations with randomly oriented crystals.

The SEM images of 280 coated grains selected from different depths indicate that grains with concentric coatings may exhibit randomly oriented crystals or subtle, unclear microfabric characteristics (Figure 4.12A, B). In some instances, radial-concentric fabrics were observed within MCG under polarizing microscope images.

The coated grain cortex exhibits differences in total thickness and thickness of individual laminae. Total thickness ranges from a minimum of 4 μm to 138 μm (Figure 4.13).

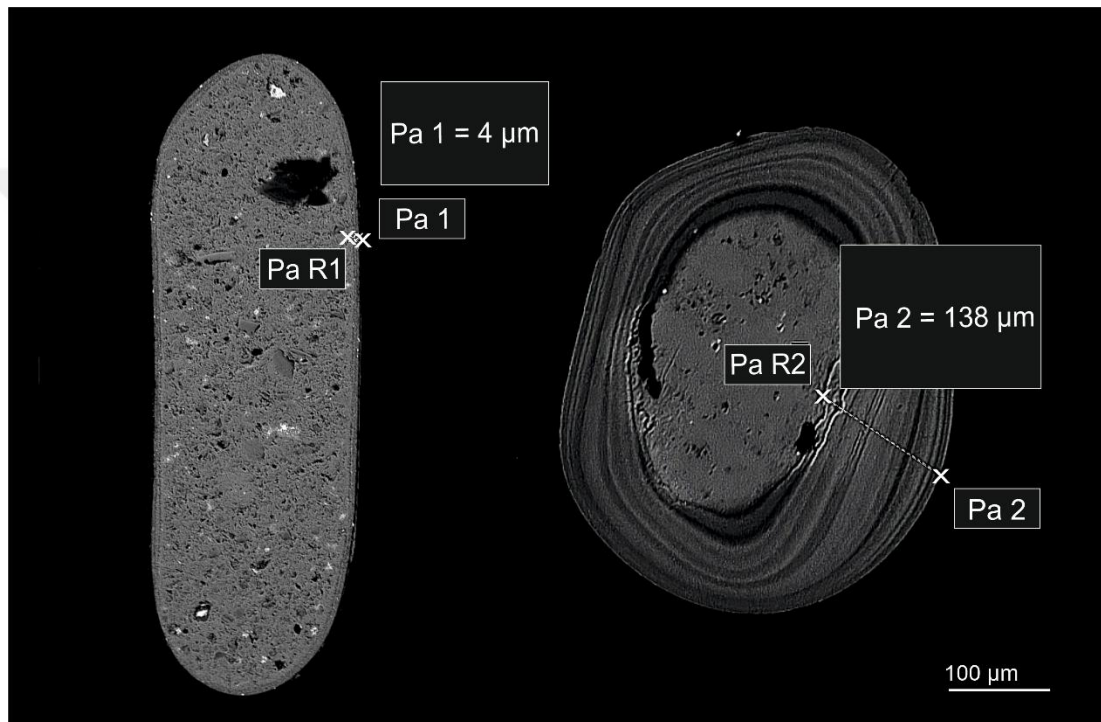


Figure 4.13: SEM photomicrographs of representative coated grains along the sediment core showing the minimum and maximum measured total cortex thicknesses at 16.12 m and 23.67 m, respectively.

4.6 Coated Grain Classification and Internal Structures

Examining the internal structures of two hundred sixty coated grains using SEM images revealed significant variability. Most coated grains exhibited a discernible pattern of alternating light and dark laminations (Figure 4.14). These cortical laminations display variability in thickness, adhering to the contour of the nucleus and transitioning from its original shape to a more rounded form. The shift from light to dark laminae is sharp, and the boundary between them is well-defined. However, dark-

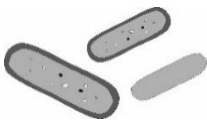
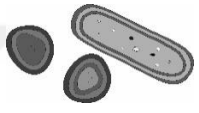
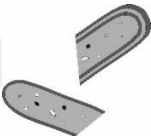
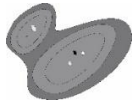
to-light laminae boundaries are frequently transitional and occasionally appear blurred. Notably, light laminae in the coated grain cortex tend to be thicker.

The thickness of laminae in coated grains varies, exhibiting variability, with some grains displaying only a few laminae (Figure 4.14A-D) and others featuring multiple laminae (Figure 4.14E-O). The concentric layers surrounding the amorphous nucleus are generally uniform, with undulating inner layers along the nuclei boundaries, occasionally interrupted by discontinuous cortex sections (Figure 4.14K). While most coated grains typically had centered nuclei, eccentric types were also observed (Figure 4.14L). Coated grains with complex and irregular nuclei exhibit a correspondingly intricate and irregular lamination pattern (Figure 4.14M). Some coated grains typically display a complex internal structure (Figure 4.14N). The nucleus of these grains comprises larger irregular clastic particles surrounded by micritic masses, exhibiting concentric laminations containing smaller particles, with different growth phases distinguished by the orientations of laminations around the multiple nuclei. In most cases, lamination closely follows the contour of a nucleus, with thin dark layers separating each successive layer.

The classification of coated grains based on their macroscopic and microscopic features revealed distinct varieties into five major types: superficial, regular, compound, broken, and patchy coated grains (Table 4.3).

A typical superficial grain characterized by thin cortical lamination covering a homogeneous fecal pellet nucleus is occasionally observed (Figure 4.14A-D). In some instances, it displays an uneven cortex thickness and a homogeneous interior (Figure 4.14B). The superficial type is common but generally occurs as regular coated grains. Regular coated grains typically exhibit multiple concentric layers around a nucleus, with transitions from following the nucleus's shape to a more rounded form being dominant (Figure 4.14E-O). Similarly, a broken grain might feature a pellet nucleus, displaying a comparable cortex structure and a homogeneous nucleus (Figure 4.14P). Patchy-coated grains show irregular and discontinuous laminations surrounding a nucleus (Figure 4.14R). A compound grain with the cortex of the coated grains forming the nucleus exhibits a notably darker appearance (Figure 4.14S), a compound grain wrapping two capsule-shaped coated grains (Figure 4.14T). Additionally, they can also be observed resembling grapestones (Figure 4.14U).

Table 4.3: Main types of coated grains based on their macroscopic and microscopic characteristics.

Type	Nucleus	Cortex	Abundance	Distribution	Wave Energy	Schematic	Figure
Superficial	Fecal pellet, detrital grains, shell fragments	Concentric Thin or incomplete coating	High	Mostly observed in the upper core above 16.26 m.	High		Figure4. 14 A-D
Regular	Fecal pellet, detrital grains	Concentric Numerous lamination	High	Mostly observed in the lower core below 16.26 m.	High		Figure 4.14 E-O
Broken	Fecal pellet	Concentric Multiple fragmented or partially cracked	High	Occurring sporadically throughout the core	High		Figure4. 14 P
Patchy	Detrital grain, fossil fragments	Irregular Poorly developed or uneven lamination patterns Concentric	Low	Prevalent below 23.83 m	Low		Figure 4.14 R
Compound	Fecal pellet, detrital grains Multiple nuclei	Formed through coalescence or progressive expansion of new coatings	Low	Prevalent below 22.86 m	Moderate- to Low		Figure 4.14 S-T

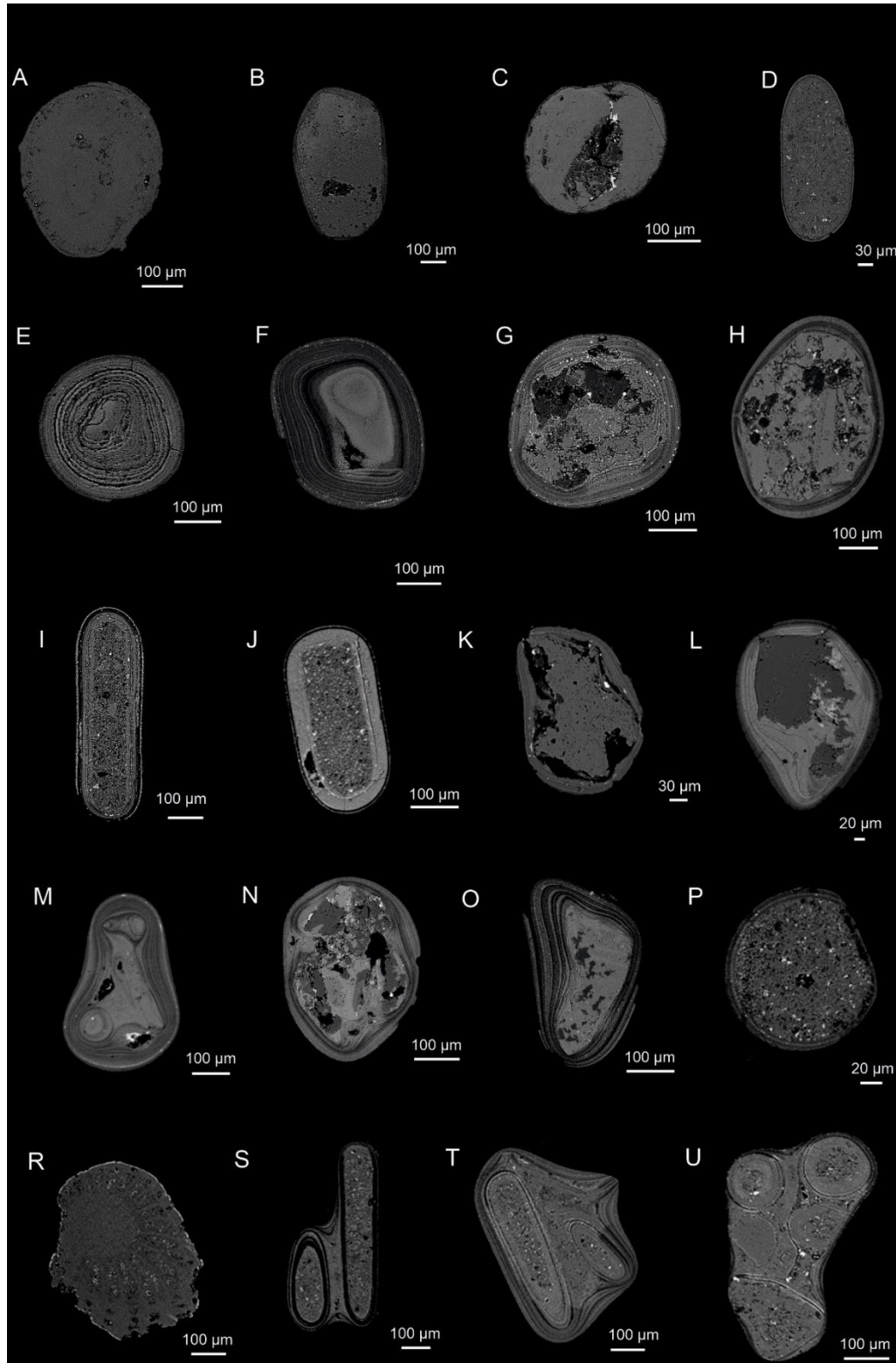


Figure 4.14: SEM photomicrographs of representative textural characteristics of coated grains along the studied sediment core: A-D) Superficial coated grains (depths; 12.32 m, 6.23 m, 3.94 m, 15.89 m), E-O) Regular coated grains (depths; 12.32 m, 24.25 m, 22.86 m, 22.54 m, 21.75 m, 21.32 m, 16.12 m, 19.73 m, 18.10 m, 17.38 m, 16.45 m), P) Broken coated grain (top view, depth; 22.27 m), R) Patchy coated grain with a foraminifera nucleus (depth; 23.67 m) S-T) Compound coated grains (depths; 23.55 m, 24.76 m) and U) Grapestone (depth; 24.53 m).

4.7 Mineralogy and Geochemical Composition

The mineralogical and geochemical composition of coated grains, investigated by a combination of XRD and SEM-EDS analysis, demonstrated that they predominantly comprise calcium carbonate (CaCO_3), with trace amounts of other elements that potentially substitute for the calcium ions. Our primary focus in the analysis was sediment depths below 16 m, where coated grains dominate.

4.7.1 X-ray diffraction (XRD) analysis

XRD analysis of the coated grains revealed that they are composed primarily of carbonate minerals, with calcite being the dominant mineral, followed by aragonite and quartz. The silicate minerals, mostly quartz, are mainly found in the nuclei of the coated grains. Ten samples were systematically collected and analyzed from depths with high concentrations of coated grains: 16.31 m, 16.85 m, 17.98 m, 18.73 m, 19.73 m, 20.49 m, 21.47 m, 22.65 m, 23.55 m, and 24.37 m. The overall mineral abundance showed negligible variations across the samples. (Table B1; Figure B3-12). Notably, the presence of gypsum peaks was only observed at one level, possibly originating from the nucleus of the coated grains collected at a depth of 21.47 m (Figure B9).

4.7.2 SEM-EDS geochemical analysis

SEM images revealed that the cortex of coated grains comprises repeating laminations of light-to-dark colors. Spot measurements of the thinner dark laminations using SEM-EDS through a gold-coated sample showed that the elemental composition was predominantly C. In contrast, the light laminations mainly comprised Ca, O, and some Si content (Figure 4.15).

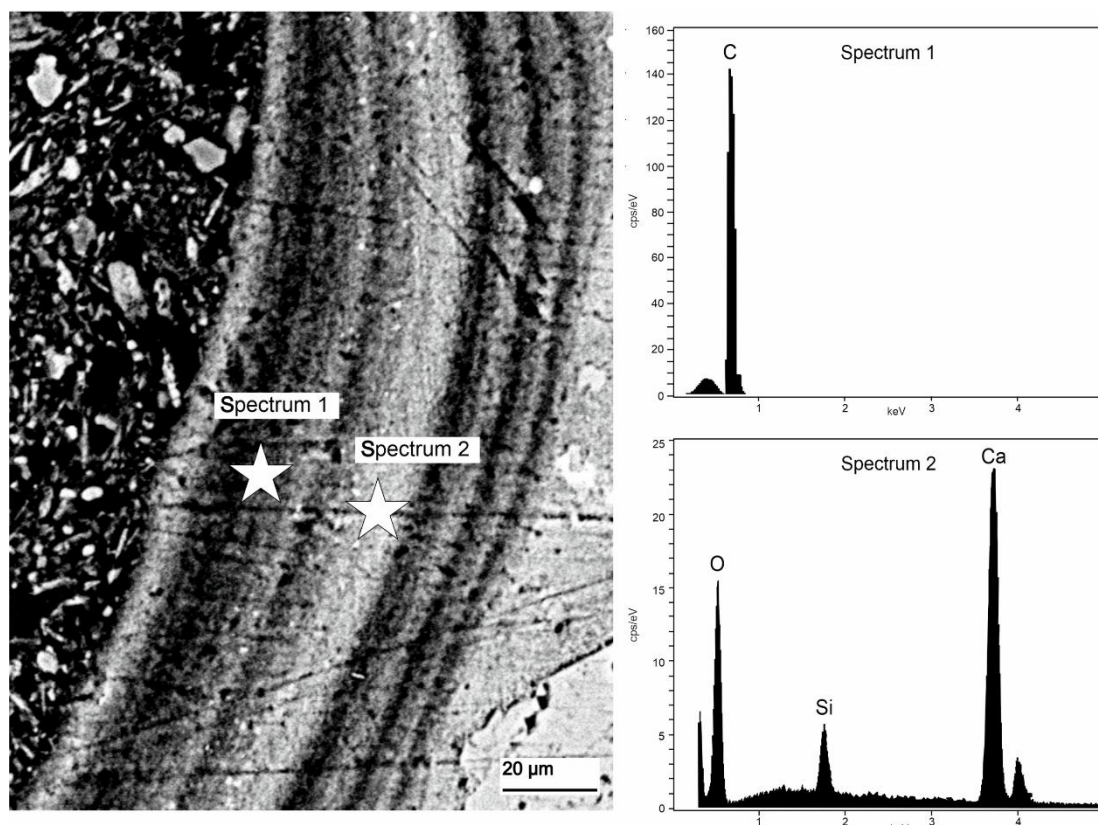


Figure 4.15: Qualitative analyses of a gold-coated representative coated grain with fecal pellet nucleus from 16.32 m, showing the elemental composition of dark and light laminae of cortex containing C, Ca, Si, and O, respectively. The low hump in Spectrum 1 represents a minor contribution from O and Au.

SEM-EDS geochemical analyses of the representative coated grains below 16.45 m revealed a relatively homogeneous cortex composition dominated by carbonate-rich laminae (average CaO =86.3 wt%) with admixed silica (average SiO_2 =2.4 wt%) and other elements namely MgO , Al_2O_3 , Na_2O , FeO , TiO_2 , SrO and S (average other elements=11.3 wt%; Table B3). Out of the 280 grains analyzed, only a few of them exhibited the presence of FeO (2 grains), TiO_2 (1 grain), ZrO_2 (4 grains), SrO (2 grains), and S (1 grain) within their cortex composition (Figures B1-2). The maximum proportions of primary cortex elements display diverse average concentrations, with CaO reaching 100% and SiO_2 a maximum of 12%. The maximum proportions of other cortex elements, collectively representing a spectrum of components, exhibit variability in their composition, including MgO at 0.26%, Al_2O_3 at 0.67%, Na_2O at 1.92%, TiO_2 at 3.45%, SrO at 2.64%, and S at 4.26%.

The nucleus of coated grains, as revealed by SEM-EDS, exhibits variations in elemental composition, including maximum concentrations of primary elements such

as CaO at 92.45%, SiO₂ at 93.03%, MgO at 21.2%, Al₂O₃ at 24.15%, Na₂O at 25.9%, and FeO at 20.02%. Elements such as TiO₂, K₂O, and S were observed in fewer grains across different depths, with the maximum concentrations of TiO₂ (43.09% in a sample at 19.95m), K₂O (7.44%), and S (9.64%) found in the analyzed samples (Table B4).

SEM images of coated grains often reveal fecal pellets in their nucleus (Figure 4.16A), and the detected elements generally exhibit a consistent trend with varying proportions. The SEM-EDS analysis of a regular coated grain with fecal pellet nuclei indicates a prominent elemental peak, showcasing significant quantities of Ca, along with trace amounts of Si, Mg, Al, and Fe (Figure 4.16B). The elemental map illustrates the random distribution of detected elements within the coated grain, providing a comprehensive view (Figure 4.16C). Additionally, a line scan through the coated grain highlights the random arrangement of the mentioned elements (Figure 4.16D).

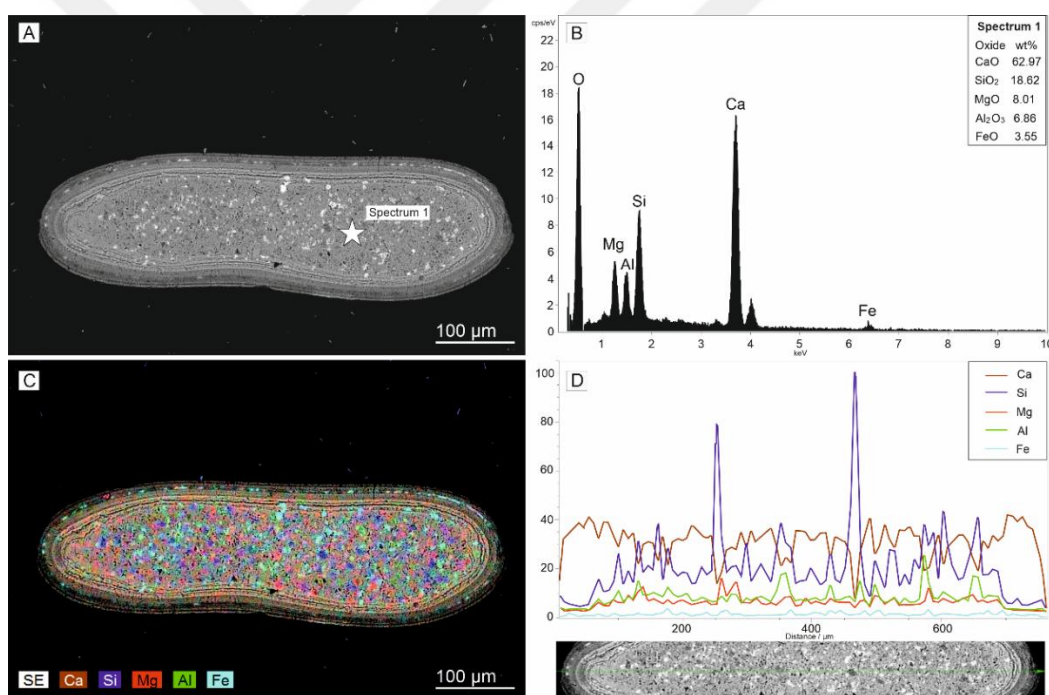


Figure 4.16: Qualitative analyses of SEM-EDS A) SEM image of a representative regular coated grain with fecal pellet nucleus from 19.73 m, showing the elemental composition revealed by B) Spot measurement C) Element map and D) Line scan.

Changes in elemental composition below 16.45 m along the sediment core are presented for the nucleus and cortex based on spot measurements from representative coated grains (Figure 4.17).

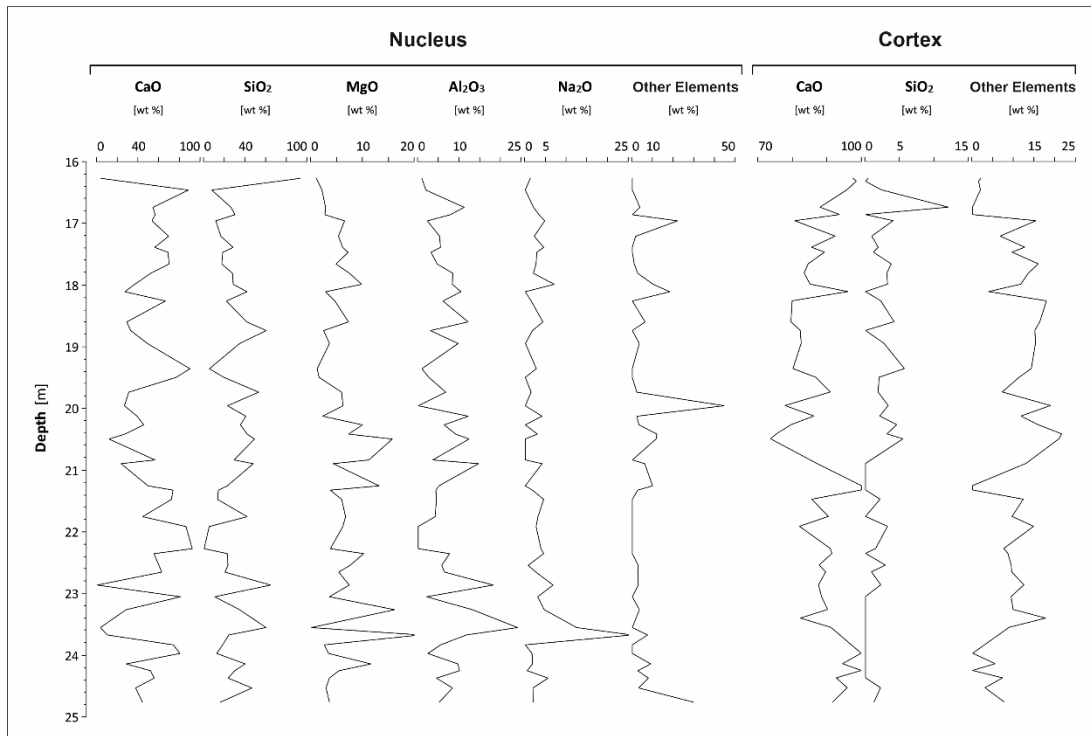


Figure 4.17: Major element distribution in coated grains along the core. Values in weight % oxides.

4.8 Modern Beach Coated Grains

Accumulations of modern coated grains (MCG) can be frequently observed along the western and northwestern shores of Urmia Lake, showcasing a distinct and predominant dark gray color (Figure 4.18A). These modern coated grains resemble those found within the sediment core. Nevertheless, the beach sediments notably exhibit an increased clastic material and evaporite minerals (Figure 4.18B). The thin section acquired from the modern beach sand has unveiled the internal characteristics of coated grains (Figure 4.18C). The thin section shows the prevalence of coated grains featuring tangentially or randomly oriented concentric lamination. This aligns with our findings from the SEM images of 280 coated grains in the sediment core (Figure 4.18D, E). Additionally, the presence of radially oriented concentric laminations has also been identified (Figure 4.18F, G).

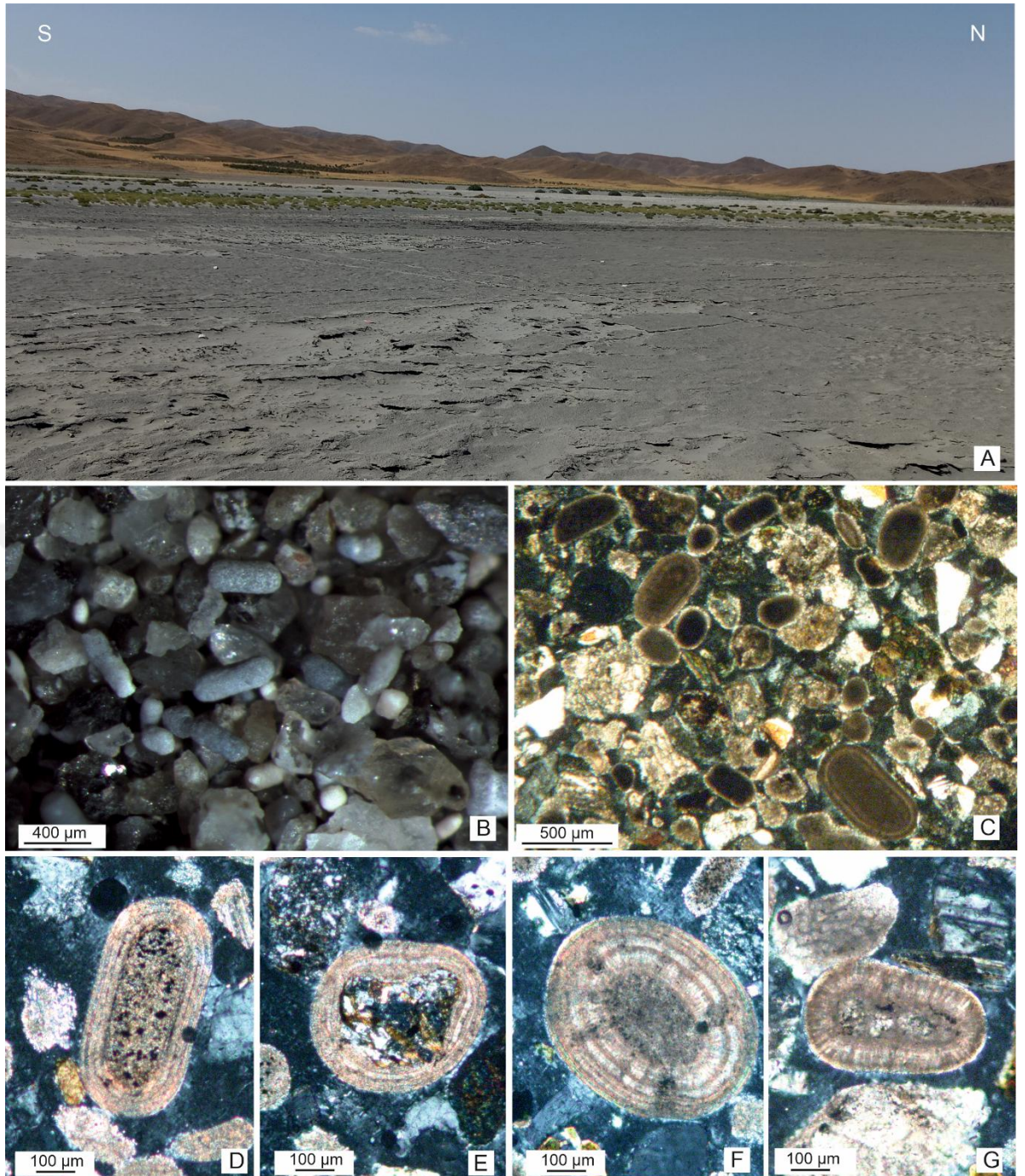


Figure 4.18: A) Notable dark gray sand predominantly consisting of coated grains. B) Sieved loose sediment. C) General representation of a thin section. D-E) Coated grain with tangential lamination. F-G) Coated grain with radial lamination.



5. DISCUSSION

5.1 Late Quaternary paleoclimate and paleoenvironment reconstruction using multiproxy approach in Urmia Lake (NW Iran)

The Ca/Ti μ -XRF profile derived from Urmia Lake sediments provides a high-resolution record of lake level fluctuations and geochemical changes, critical for understanding paleoclimate dynamics during MIS 3 and beyond. Calibrated using radiocarbon dating, this profile reveals intervals of enhanced chemical sedimentation and fluctuating terrigenous inputs correlating with key global climatic events. The $\delta^{18}\text{O}$ data from Lake Van (Çağatay et al., 2014) and the NGRIP ice core curve (NGRIP, 2004) provide complementary records that contextualize these local lake dynamics within broader hemispheric patterns. Periods such as the Younger Dryas (YD) cooling and Bølling-Allerød (B-A) warming are evident in these records, highlighting rapid climatic transitions. Additionally, the Ca/Ti profile and isotopic trends align with Dansgaard–Oeschger (DO) and Heinrich (HE) events, which are known for driving abrupt temperature and hydrological shifts in the Northern Hemisphere. These correlations underscore the sensitivity of Urmia Lake to regional and global climatic forcings, making it a valuable site for reconstructing paleoclimatic connections during the Late Pleistocene.

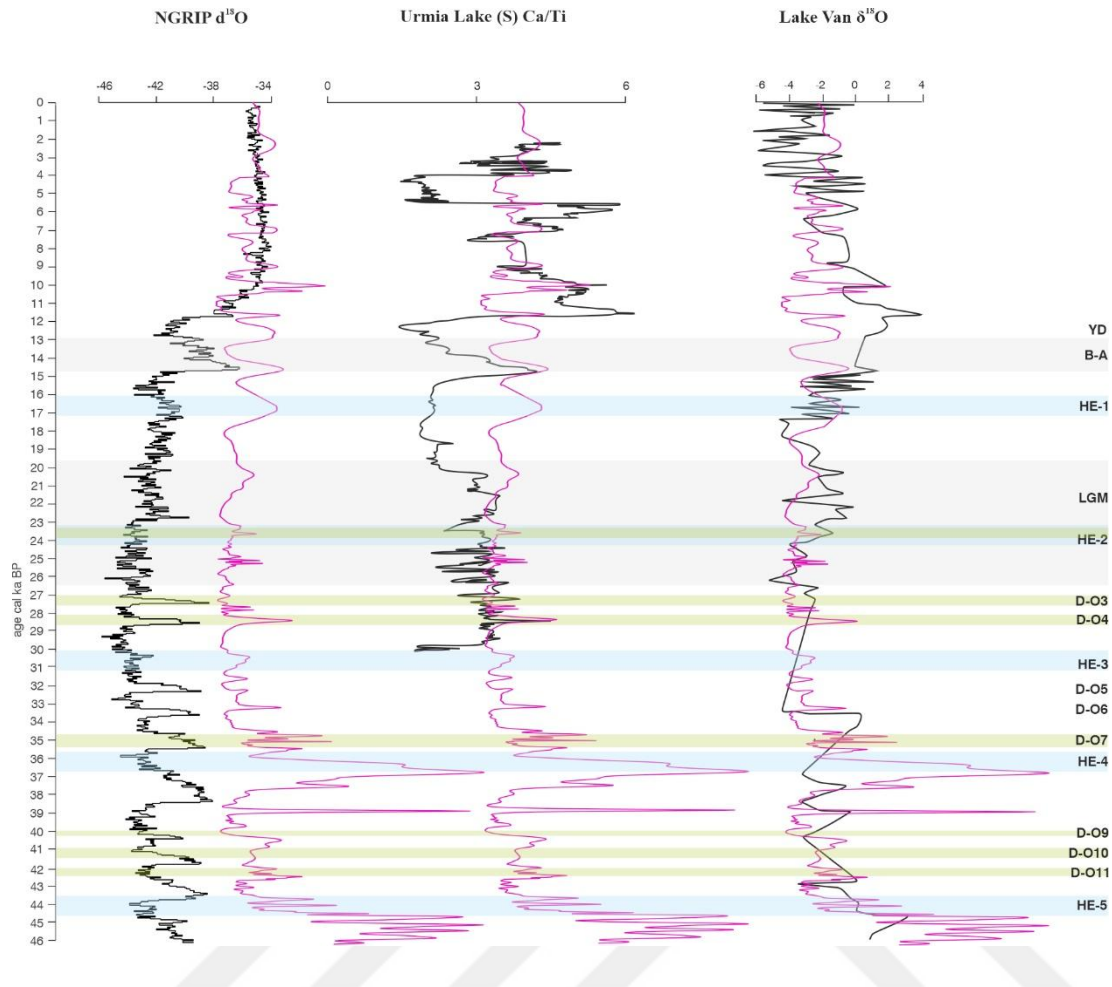


Figure 5.1: Ca/Ti μ - XRF profile by ^{14}C age: Lake Urmia: Ca/Ti from Urmia Lake (Kong et al., 2023), $\delta^{18}\text{O}$ data from Lake Van (Çağatay et al. 2014) and NGRIP curve (NGRIP, 2004). Abbreviations: YD -Younger Dryas cooling, B-A – Bølling-Allerød warming, LGM– Last Glacial Maximum, DO - Dansgaard–Oeschger events, HE- Heinrich events.

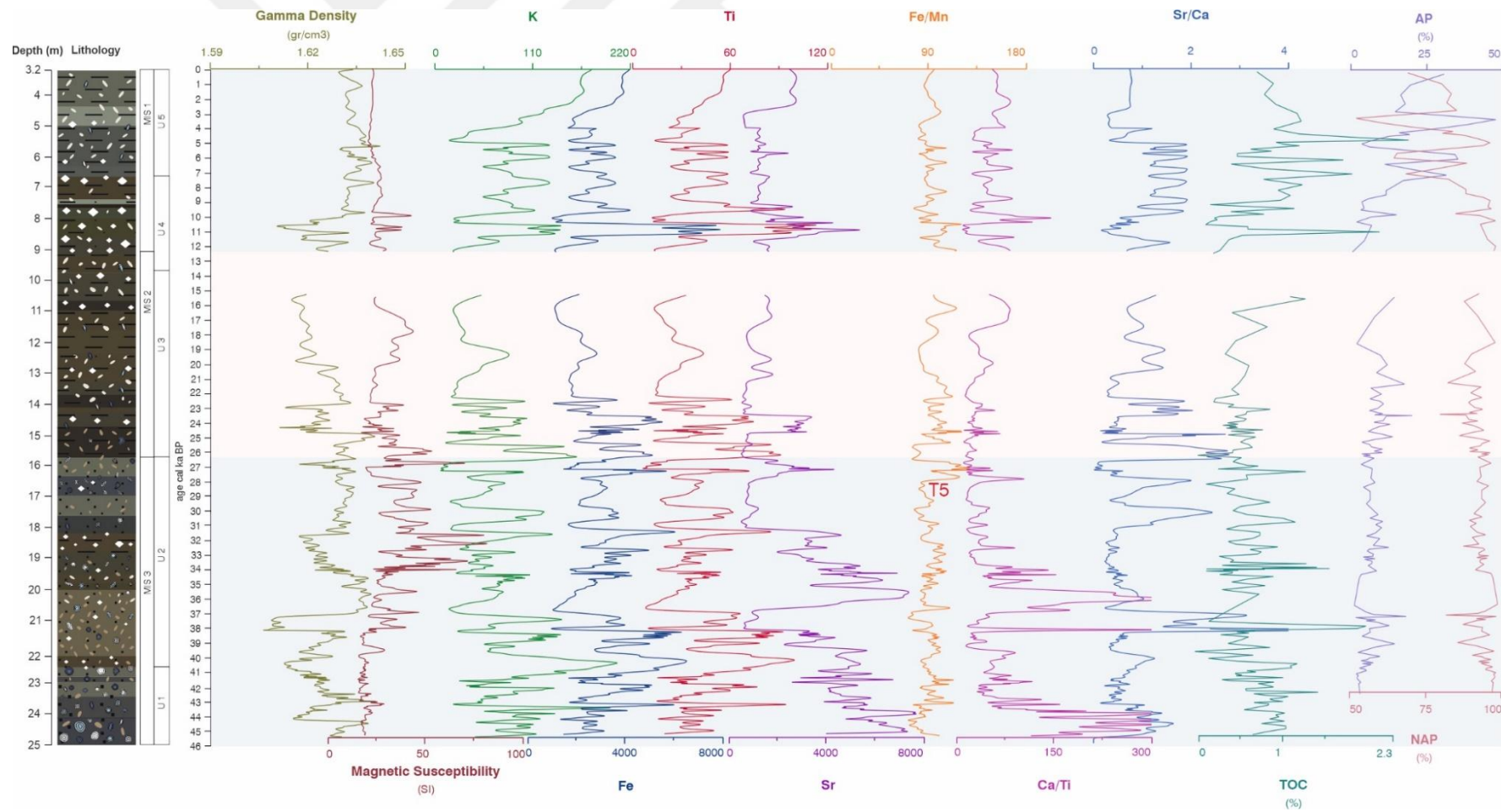


Figure 5.2: Urmia Lake; lithology, gamma density, magnetic susceptibility, μ -XRF geochemical element and element-ratio profiles (K, Fe, Ti, Mn, Sr, Fe/Mn, Ca/Ti, Sr/Ca), TOC content and AP-NAP (Age).

5.1.1 Sedimentary components as relative lake level indicators

Analysis of lithological units, sedimentology, and stratigraphy, alongside confirmation of multi-proxy data, presents strong evidence of significant and climatically influenced fluctuations in Urmia Lake's levels over the past 50 cal ka BP. In examining sedimentary components as indicators for lake level variations, a correlation emerges, with coated grains associated with low lake levels, while fecal pellets are linked to periods characterized by higher lake levels.

5.1.2 Lake level changes over the last ~50 cal ka BP

5.1.2.1 The MIS 3 (50 - 29 cal ka BP)

The global climate during MIS3 was characterized by episodic climatic oscillations, alternating cold stadials, and warm interstadials driven by millennial-scale changes in atmospheric circulation. These fluctuations are reflected in Urmia Lake's sedimentary record. The core base aligns with the onset of MIS 3 (50–41.7 cal ka BP), with a general trend of lake level lowering apparent, consistent with cooler and drier conditions relative to earlier periods. The reduction in biological activity during this time is indicated by low fecal pellet counts and the presence of volcanic lithics, coated grains, and reworked shell fragments. Together, these proxies point to an environment dominated by physical weathering and sediment reworking rather than active carbonate deposition. Short-lived wet phases are evident in increased chemical weathering proxies, such as elevated Ca/Ti and Sr/Ca ratios, reflecting transient increases in precipitation likely driven by intensifications of westerly winds (Sharifi et al., 2023; Sarı et al., 2024). These geochemical trends, consistent with TOC content, suggest the dominance of chemical sedimentation under shallow lake conditions. The formation of coated grains, often with fecal pellet, detrital, or shell nuclei, signifies wave-dominated shallow water settings conducive to carbonate precipitation under high ionic supersaturation. Variability in coated grain nuclei and terrigenous sediment influx highlight episodic shifts in lake levels and sediment supply (Salehipour Milani et al., 2021). These findings align with similar observations from Lake Van, where abrupt transgressive events occurred during MIS 3, likely linked to climatic shifts or meltwater input (Çağatay et al., 2014).

Coarse-grained coated grains and reduced fecal pellet abundance further underscore the predominance of chemical over biological sedimentation during early MIS 3. However, fecal pellets, when present, acted as nuclei for elongated coated grains, reinforcing the interplay between biogenic and chemical processes in sediment formation. Isotopic data, though limited in coverage, suggest stable low lake levels during this interval. The positive covariance between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values reflects a precipitation-evaporation balance under arid conditions, with intermittent fluvial contributions potentially driving transient increases in lake levels. Comparable isotopic trends in Urmia Lake and nearby Lake Van corroborate regional climatic synchronicity during MIS 3 (Çağatay et al., 2014; Sarı et al., 2024). Lake Van in Turkey displays parallel evidence of moisture influx during interstadials, emphasizing a shared sensitivity to atmospheric changes across the region. However, the sedimentary and isotopic records from Lake Van capture more pronounced interstadial moisture events, potentially due to its proximity to the Mediterranean moisture source. In contrast, mid-latitude systems, such as the Great Salt Lake in North America, experienced less dramatic variability during MIS3, highlighting regional differences in hydrological responses to global climatic drivers.

5.1.2.2 The MIS 2 (29 -12 cal ka BP)

MIS2, encompassing the Last Glacial Maximum (LGM), represents one of the most arid and cold periods globally. For Urmia Lake, this stage marked a prolonged period of low lake levels and increased salinity, reflecting severely reduced precipitation and heightened evaporation. The sedimentary record during this interval is dominated by large sulfate crystals, indicating hypersaline conditions, while the absence of fecal pellets suggests a significant decline in biological activity. Increased detrital inputs, driven by intensified erosion under sparse vegetation cover and strong seasonal winds, further underscore the harsh conditions. Geochemical data also support these changes, where reduced Ca/Ti and Sr/Ca ratios point to limited chemical weathering processes in the catchment. The chemical composition of the sediment core shows similar trends to the mineralogical composition. High TOC content corresponds to the fecal pellet abundance. Terrigenous mineral-dominated layers commonly have high density and magnetic susceptibility values. During MIS 2 (29-12 cal ka BP), the lake reached its lowest point, potentially revealing the lake floor with brown mud containing volcanic

lithics, volcanic glass, and detrital grains alongside an increased prevalence of diagenetic sulfate minerals, particularly evident in Units 3 and 4. The sediment color transition from gray to brown (15.8 m–9.8 m) indicates a gradual decline in water levels during the late MIS 3 and early MIS2, leading to complete lake desiccation and partial lake bed exposure. Whether uncoated or as nuclei for coated grains, fecal pellets are typically fragmented, signifying the recycling of deposited pellets from the exposed lake. The limited occurrence of coated grains, fecal pellets, and detrital fragments within them emphasizes the significant influence of terrigenous sediments, which play a dominant role in deposition.

Furthermore, the presence of rounded diagenetic sulfate minerals suggests recycling. The aridity event, identified by an increase in diagenetic sulfate minerals, mainly gypsum, in the sediment record during the late MIS2 (9.8 m–6.8 m), coincides with the appearance of brown sediments. This suggests a brief period of oxidation, characterized by high evaporation rates, hyper-saline conditions, and low lake levels, perhaps associated with a temporary lake dry-out. A playa-lake condition prevailed during MIS 2, as already described by Kelts and Shahrabi (1986). Despite the prevailing aridity, brief wetter intervals are detectable in the sediment record through transient increases in fecal pellet counts and carbon isotopic variations. These short-lived phases may correspond to episodic intensifications of the Indian Ocean Monsoon or shifts in the westerly circulation. On a regional scale, lakes such as Zeribar and Van exhibit similar low lake levels during the LGM, but Lake Van appears to show an earlier and more consistent moisture recovery post-LGM. This may reflect differences in topography and local hydrological dynamics. Globally, contrasting examples include Lake Bonneville in North America, where glacial meltwater contributed to a high lake level during the LGM, highlighting the unique effects of local hydroclimatic factors in different regions.

5.1.2.3 The MIS 1 (12 cal ka BP to recent)

MIS1 encompasses the transition from glacial to interglacial conditions and includes the Holocene and Anthropocene periods. This stage saw significant warming and hydrological changes that reshaped Urmia Lake's paleoclimate and environment. MIS 1 (12 cal ka BP–Recent) witnessed a rapid rise in the level to a high lake level, as indicated by deposits abundant in micrite and fresh cream pellets and the almost

absence of diagenetic sulfate minerals, terrigenous minerals, and coated grains fostering optimum ecological conditions for *Artemia urmiana*, the organism absorbs organic carbon from algae. It dissolves organic and inorganic carbon from lake water, accumulating them as fecal pellets. During the Early Holocene (12–6.4 cal ka BP), the relatively warm climate around the lake would have promoted organic productivity, as inferred from the higher total organic carbon (TOC) content in the core corresponding to the rich fecal pellet layers with the particularly low magnetic susceptibility measurements. The Younger Dryas (~12.9–11.7 cal ka BP), a brief cold reversal, is evident in Urmia Lake's sediment record as a regression phase, with declining fecal pellet counts and increased salinity indicating reduced lake levels. Following this, the early Holocene brought wetter conditions during the Holocene Climatic Optimum (9 cal ka BP–5 cal ka BP). Sediments from this period show higher fecal pellet abundances and isotopic evidence ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of an improved precipitation-evaporation balance. *Artemia urmiana*'s critical role in absorbing calcium cation and carbonate and bicarbonate ions during periods of high lake levels restricts the availability of free ions, essential for carbonate chemical precipitation and coated grain formation in Urmia Lake. In this distinctive environment with limited clastic materials, fecal pellets emerge as the predominant sedimentary component. These changes correspond to intensified westerly and monsoonal contributions, resulting in a high lake level for Urmia Lake and aligning with similar trends observed in Lake Van and other regional systems. This finding is supported by the pollen record in the sediment core, which implies a greater percentage of arboreal vegetation (AP ratio in Figure 5.1). The previous studies based on the pollen records from Urmia Lake also documented a general trend towards more humid conditions during the Early Holocene (Djamali et al. 2008).

The Late Holocene, however, saw a gradual decline in precipitation, leading to progressive lake shrinkage. This period was punctuated by climatic events such as the Medieval Warm Period and the Little Ice Age, which caused further oscillations in lake levels. The Anthropocene marks a sharp departure from these natural cycles. Over the past three decades, Urmia Lake has lost 90% of its surface area due to human activities, including dam construction, groundwater extraction, and agricultural expansion. This rapid desiccation contrasts starkly with the more gradual natural fluctuations observed in earlier periods, making the lake a striking example of

anthropogenic environmental degradation. The rapid lowering of the lake level has resulted in the deposition of thicker layers of halite, exceeding 3.2 m, indicating a profound shift from a terrigenous-biochemical hypersaline lake to a chemical playa environment (Mohammadi et al., 2019, 2021, 2023). Comparisons with other systems reveal similar trajectories in response to Holocene climatic drivers, such as the synchronous low lake level in Lake Van during the Holocene Climatic Optimum. However, Lake Van's decline in water levels was less dramatic, likely due to differences in watershed management and climatic buffering from its geographic location.

5.1.3 Climate records: global and regional comparisons

Lake Urmia, one of the world's largest hypersaline lakes, shows episodic water level changes influenced by both climatic and anthropogenic factors. During the Last Glacial Maximum (LGM, ~29.9–20.2 cal ka BP), sediment records indicate relatively high water levels, following a prolonged low stand around 30 ka BP. This suggests wetter regional conditions associated with broader climatic trends (Kong et al., 2022; Tudryn et al., 2021). In contrast, the Younger Dryas (~12.8–11.7 cal ka BP) is marked by a sharp regression, reflecting arid conditions with heightened salinity (Sarı et al., 2023; Sharifi et al., 2023). The significant transition from the Younger Dryas to the Early Holocene, akin to that observed in Urmia Lake, has been documented across various locations, including the North Greenland Ice Core (NGRIP, 2004), several Middle Eastern lakes such as the Dead Sea (Enzel et al., 2003), Lake Van (Çağatay et al., 2014), Lake Mirabad (Wasylikowa et al., 2006), Lake Zeribar (Wasylikowa et al., 2006), and the Caspian Sea (Kroonenberg et al., 2007). Additionally, speleothem records from caves such as Soreq Cave in Israel (Bar-Matthews et al., 1999) and Sofular Cave in Turkey (Fleitmann et al., 2009) corroborate these findings. Between 60 and 34 cal ka BP, Lake Van's water level was generally lower than today, with interruptions due to transgressive episodes linked to Dansgaard-Oeschger events around 57, 53, 46, and 35 cal ka BP. These episodes showed elevated $\delta^{18}\text{O}$, Ca/Fe, TOC, and TIC values. Initial lake level rises from meltwater input were followed by evaporative drops, indicated by positive $\delta^{18}\text{O}$ excursions. The mid-Holocene (~11.8–5.6 kyr BP) saw a resurgence of lake levels, corresponding to wetter conditions likely linked to global insolation maxima (Kong et al., 2022). However, recent decades have

witnessed catastrophic declines in Lake Urmia's size, with nearly 90% of its surface area lost due to dam construction, agricultural water diversion, and reduced precipitation. This dramatic reduction exemplifies the significant impact of human activity, contrasting with the relative stability of earlier natural fluctuations (Sharifi et al., 2023; Tudryn et al., 2021).

Lake Van, located in eastern Turkey, also provides a robust paleoclimate record through laminated sediments and carbonate isotopic analysis. High water levels during interglacial periods, such as MIS 5 and MIS 1, correspond with increased precipitation and reduced evaporation (Çağatay et al., 2014). These periods are characterized by high organic carbon and low detrital influx, indicating stable, wetter conditions. Conversely, water levels dropped significantly during glacial and stadial periods, associated with arid conditions and increased sediment deposition (Çağatay et al., 2014; Sharifi et al., 2023). The lake's sensitivity to North Atlantic climatic systems, including Dansgaard-Oeschger events, further underscores its role as a key regional climate archive (Sharifi et al., 2023). Regional comparisons reveal that Lake Van's records align well with other systems like Urmia Lake and Lake Zeribar, emphasizing coherent hydrological responses to global and regional climatic drivers (Kong et al., 2022; Tudryn et al., 2021). Lake Zeribar, though smaller, complements these findings by offering localized insights into climatic variability in the Zagros Mountains. Its sediment cores indicate high water levels during the LGM (~26–21 cal ka BP), attributed to increased precipitation. This contrasts with mid-Holocene aridity (~7.8–7.5 cal ka BP), during which lake levels dropped (Wasylikowa et al., 2006; Tudryn et al., 2021). Stabilization of lake levels around 6 cal ka BP suggests reduced climatic variability, consistent with Lake Van and Urmia trends during the same period (Kong et al., 2022; Sharifi et al., 2023).

Salinity is a critical proxy in these hypersaline lakes, reflecting the balance between water input and evaporation. The geochemical signals preserved in sediments, such as changes in carbonate precipitation and elemental ratios, provide detailed evidence of past climatic conditions (Kong et al., 2022; Çağatay et al., 2014). For instance, elevated salinity during arid phases corresponds with lower water levels and increased evaporative loss, while wetter phases show reduced salinity and higher water levels.

The records from these lakes collectively highlight the interplay of global and regional climatic forces. Periods such as the Younger Dryas and the mid-Holocene are marked by synchronous hydrological responses, reflecting the influence of systems like the North Atlantic Oscillation, monsoonal patterns, and Mediterranean circulation (Çağatay et al., 2014; Sarı et al., 2023). However, the main difference between natural variability and recent anthropogenic impacts is particularly evident in Urmia Lake. While earlier fluctuations were driven by climatic conditions, the Anthropocene period has seen unprecedented changes due to human activity, including water management practices and land use changes (Sharifi et al., 2023; Tudryn et al., 2021).

5.2 Lake Level Fluctuation Controls on Formation, Types, and Abundance of Coated Grains in Hypersaline Lakes; Urmia Lake (NW Iran) Case Study

5.2.1 Coated grain origin, formation, and distribution

Coated grains are distributed across various environments, ranging from marine to freshwater, with their formation influenced by biological, chemical, and physical processes. The origin of coated grains is extensively researched and debated, typically involving understanding the factors that affect their genesis and growth. These grains typically form through accretion, influenced by biological and physiochemical processes, potentially involving microbial activity in lacustrine environments (e.g., Duguid et al., 2010; Diaz et al., 2015, 2017; Trower et al., 2017). While the exact mechanisms may vary based on specific geological and environmental contexts, the general pattern involves accretion with a gradual mineral or organic material buildup around a central nucleus, forming distinct concentric layers. Coated grain formation is primarily controlled by factors such as water supersaturation, microbial activity, water chemistry, agitation and wave action, and the nature of the substrate, influencing the precipitation and concentric layering of minerals around the nuclei. (e.g., Duguid et al., 2010; Flügel, 2010; Pacton et al., 2012; Diaz et al., 2015; Trower et al., 2018; Wang et al., 2023).

Coated grains are typically found in shallow lake environments with adequate energy to facilitate sediment transport (grain flow, saltation, and suspension) and grain-to-grain collision processes but not enough to cause erosion or fragmentation by direct precipitation around any available nuclei (e.g., Trower et al., 2017; Sipos et al., 2018).

Hydrodynamics, particularly wave activity, is considered a primary factor influencing the distribution of coated grains. The hydrodynamic force on the lake shore influences the thickness of coats, as particles from the lake shore, subject to intensified wave action, undergo multiple cycles of carbonate precipitation, increasing carbonate coat thickness (Hao et al., 2022). The diversity of coated grain types in sedimentary environments arises from the intricate interplay of multiple physical processes, such as sediment transport, mixing, compaction, diagenesis, and biological activity, leading to shifts in coated grain characteristics and distribution (Trower et al., 2018). The origin and distribution of distinct grain types across various depositional environments could signify varying energy levels within the surroundings spanning from low to high, as exemplified in the Clevedon Lake Oolites of southwest England (Milroy and Wright, 2002). The transportation mechanisms of coated grains result in substantial mixing resembling the characteristics of coated grains discovered in the Great Salt Lake (Eardley 1938; Kahle 1974).

The distinctive conditions of the shallow hypersaline waters in Urmia Lake provide a unique setting conducive to the formation of coated grains, as first reported by Kelts and Sharabi (1986), resembling those found in the Great Salt Lake; these coated grains exhibit concentric layers of calcite or aragonite around nuclei composed of quartz, feldspar, dolomite grains, or polished fecal pellets. Amini et al. (2010) noted that coated grains originated in the basin margin, where wind-induced waves generated a relatively high-energy sub-environment. Sharifi et al. (2018) observed coated grains featuring a carbonate or siliciclastic core with multiple concentric layers of aragonite crystals in core sediments and on the modern shore of the Shahi Peninsula. Additionally, Mohammadi (2024) reported that *Artemia urmiana*, through the absorption of calcium ions and their deposition in fecal pellets, leads to a depletion of calcium in lake water, which in turn affects the mineralogy of salt crusts by inhibiting gypsum formation. Several other researchers also documented the presence of coated grains around Urmia Lake (Mohammadi, 2005; Stevens et al., 2012; Mohammadi et al., 2019, 2021; Tudyryn et al., 2021). Modern accumulations of coated grains are frequently seen along the western and northwestern shores of Urmia Lake (Figures. 2.1 and 4.10; Mohammadi, 2024). The diverse morphologies exhibited by these grains, encompassing variations in color, size, shape, and internal texture, are influenced by the availability of nuclei such as fecal pellets, terrigenous fragments and minerals,

reworked shell fragments, and occasionally authigenic gypsum within the depositional environment.

The critical control on the morphology of coated grains depends on the types of nuclei present, leading to the reported five discernible typologies (Table 4.3). The elemental composition of the nucleus primarily reflects the conditions during the initial formation of the coated grains. Figure 4.17 illustrates the down-core variations in elemental composition between the nucleus and cortex of selected coated grains, highlighting the geochemical heterogeneity associated with their formation. Analysis of these coated grains reveals that CaO and SiO₂ show an inverse relationship, while the concentrations of MgO, Al₂O₃, and Na₂O vary independently in the nucleus. The inverse relationship between CaO and SiO₂ in the nucleus suggests that shifts between carbonate-dominated and siliciclastic-dominated environments strongly influenced the initial stages of coated grain development. The variations in MgO, Al₂O₃, and Na₂O in the nucleus likely reflect environmental changes, such as increased erosion and the transport of clay minerals during periods of lower lake levels. These elements are often associated with weathering products from the surrounding catchments. These become more prominent in the sediment record when water levels are lower, exposing larger lakebed areas to sediment influx. Higher MgO concentrations in the cortex during low water levels suggest that the lake's salinity fluctuated in response to changes in the water budget, promoting the formation of high-Mg calcite or dolomite. Wind and wave activity linked to lake level fluctuations frequently displace these grains, resulting in mixed successions and settling patterns similar to the processes observed in the Great Salt Lake. This relative high-energy environment is further supported by fluctuations in lake levels, ultimately contributing to the varied proportions of coated grains along the sediment core of Urmia Lake.

5.2.2 Coated grain lamination, growth, and environmental impact

Microbial organic matter and residual algae constitute the biogenic materials in sediments, with physiochemical processes playing a dominant role in cortex accretion in most modern coated grains, while the abundance of algal features highlights the importance of biochemical processes in their growth (e.g., Folk and Lynch, 2001; Duguid et al., 2010; Diaz et al., 2015; O'Reilly, 2017). The relative importance and role of microorganisms in forming coated grains are highly variable and may play both

constructive and destructive roles during cortex deposition (Mariotti et al., 2018; Flannery et al., 2019; Vennin et al., 2019; Siahi et al., 2017; Batchelor et al., 2018). These microbial communities contribute to the growth through various mechanisms, including the acquisition of organic signatures, microbial heterotrophic degradation of organic matter, and the association of organic matter with mineral phases during accretion (Mariotti et al., 2018; O'Reilly et al., 2017; Flannery et al., 2019; Siahi et al., 2017; Batchelor et al., 2018). Several studies have suggested that coated grains, for example, in Lake Geneva, are formed through microbial precipitation of low-Mg calcite, indicating the influence of biological processes in their formation (Davaud and Girardclos, 2001; Plée et al., 2008; Plée et al., 2010; Pacton et al., 2012; Ariztegui et al., 2012). Pacton et al. (2012) revealed that microbes stimulate early carbonate precipitation around the nucleus and control the overall cortex formation. Carbonate precipitation is often initiated through the metabolic activities of microorganisms, but it can also occur without the direct involvement of living microorganisms. The association of carbonate precipitation with degraded organic matter is linked to chemical processes resulting from the death and decay of microorganisms (e.g., Reitner, 2004; Pei, 2022). Coated grains exhibit lamination caused by biologically induced chemical changes, producing an alternation of dark and lighter carbonate laminae (Suarez-Gonzalez and Reitner, 2021). The presence of dark organic-rich and light carbonate-rich laminae within the cortex indicates the presence of alternating layers of organic material and inorganic carbonate minerals.

The formation of concentric laminae in Urmia Lake-coated grains is closely linked to both chemical and biological activity. Typical laminated patterns in coated grains appear as an alternation of dark organic-rich laminae and light carbonate-rich laminae (Figure 4.9), suggesting periodic variations in water chemistry and biogenic production. Urmia Lake's high salinity levels provide an ideal environment for the growth of halophytic algae, which serve as a crucial food source for *Artemia urmiana*. However, when the lake saline conditions exceed the tolerance threshold of *Artemia urmiana*, there is a consequent increase in the algae population. This phenomenon, commonly known as an algal bloom, leads to the characteristic red coloration of the lake during specific periods in dry seasons and results from various environmental factors such as extremely high evaporation, elevated water temperatures, and low water movement (e.g., Mohebbi and Seidgar, 2019; Mohammadi et al., 2021). The

proliferation and subsequent death of algae in Urmia Lake have significant consequences on the accumulation of organic matter, which is readily observable through the internal structures of coated grains. When the algae overgrow and decay rapidly, the resulting organic accumulation appears as dark layers in contrast to the light carbonate layers of the coated grains (Figure 4.14). The examination of coated grains collected from the lake sediment reveals a distinct gradient of color change from dark to light in the light-carbonate lamination.

In contrast to this gradient, the dark-organic laminae have sharp boundaries. They are often thinner than light-carbonate laminae, indicating the presence of a process that replaces the slower carbonate coating with the short and rapid precipitation of organic matter. The involvement of algae in organic matter production suggests a constructive biological activity. In contrast, intact cortices and the absence of microboring structures indicate a lack of destructive roles (Figure 4.12). The algal bloom and consequent dark laminae form in arid conditions when water becomes over-saturated due to high evaporation. In contrast, biological processes are prominent in the light, carbonate-rich layers formed during lake-level rise and recovery periods. These fluctuations in lamination also reveal dry and humid periods, highlighting the interaction between long-term or seasonal climate and dynamic aquatic ecosystems that once dominated.

5.2.3 Impacts of lake level fluctuations on coated grain formation

The paleoenvironmental history of Urmia Lake can be understood through a series of changes in sedimentary processes, sediment types, and the influence of water levels on the formation of coated grains. Urmia Lake has experienced significant fluctuations in water levels over time, leading to the formation of different types of coated grains, controlling their temporal and spatial abundance.

Phase 1– High Lake Level: *Artemia urmiana*, the primary inhabitant of Urmia Lake, plays a crucial role in the genesis of coated grains. During relatively high lake levels and optimum ecological conditions for *Artemia urmiana*, the organism consumes algae, thereby obtaining organic carbon.

It dissolves organic and inorganic carbon from lake water, accumulating them as fecal pellets. *Artemia urmiana*'s critical role in absorbing calcium cation and carbonate and bicarbonate ions during periods of high lake levels restricts the availability of free ions, essential for carbonate chemical precipitation and coated grain formation in Urmia Lake (Mohammadi et al., 2021; Lak et al., 2022; Mohammadi, 2024). In this distinctive environment with limited clastic materials, fecal pellets emerge as the predominant sedimentary component. Consequently, minimal coated grain formation begins with the availability of nucleus-forming fecal pellets. This does not imply that *Artemia urmiana* fecal pellets control the formation of all coated grains. However, in the Urmia Lake environment, where clastic materials are limited, these fecal pellets often serve as initial nuclei for some coated grains. The observable formation of coated grains is minimal in the coastal zone, and the settling of fecal pellets in relatively deeper waters remains undisturbed. (Figure 5.3A).

Phase 2–Lake Level Falling: As the water level falls and the salinity of the lake water intensifies, the environmental conditions are unfavorable for *Artemia urmiana*. At the same time, halophytic algae thrive and undergo a flourishing bloom. In the absence of *Artemia urmiana* to absorb ions, the water undergoes supersaturation (Mohammadi et al., 2021; Lak et al., 2022). As the water levels gradually diminish, wave dynamics shift toward the lacustrine interior, sustaining the accretionary growth of coated grains in the wave-influenced zone. In Phase 2, the previously formed limited coated grains in Phase 1 become progressively exposed. During this phase, early diagenetic cement-type gypsum develops alongside the existing coated grains within the exposed region, occasionally encasing them. The mixture of diagenetic gypsum, fecal pellets, terrigenous grains, and coated grains is recycled and transported to the wave-affected area. This transportation may result in the fragmentation of some coated grains, forming broken coated grains. In this transitional phase, sediments in the deeper parts of the lake are still primarily composed of pellets, eventually transported to the wave-affected area and forming capsule-shaped coated grains (Figure 5.3B).

Phase 3–Low Lake Level: During low lake level, a mixture of sedimentary components, including clastic minerals, fecal pellets, diagenetic gypsum, and broken coated grains eroded from the shoreline, becomes exposed within the wave action zone of Phase 2 paleo-coast. The former shoreline, distant from wave dynamics, restricts

sediment transport, minimizing the influx of new materials. Material transfer from nearshore areas to the wave-affected lake section endures through erosion and reworking, sustaining the ongoing coated grain formation process. As the lake water level significantly declines, the pellets in the deeper lake sections undergo micritization and salt crust development, forming a sedimentary layer that blankets the lakebed. The lack of new pellet production means no nuclei material is available from the deeper-water source. This leads to the cessation of material transport from these relatively deeper lake regions (Figure 5.3C).

The fluctuating water levels of Urmia Lake have led to the formation and mixture of coated grains at different depths, with high lake levels initiating available nuclei for coated grain formation by *Artemia urmiana* fecal pellets, falling lake levels exposing and transporting previously formed coated grains, and low lake levels resulting in a complex assemblage of coated grains, fecal pellets, clastic material, marginal shell fragments, diagenetic gypsum, and broken coated grains eroded from the shoreline.

The formation of coated grains in the wave-affected zones varies depending on the available nuclei (Figure 5.3). Some of these coated grains develop during the initial phase, forming the superficial coated grains. These grains progressively accumulate additional layers through ongoing accretionary processes, generating the most prevalent coated grain type, referred to as regular. Nevertheless, some previously transported coated grains may experience degradation and reworking, ultimately forming broken coated grains. Compound grains in the Urmia Lake's sediment record suggest that adjacent coated grains coalesced during growth, indicating a development process supported by the absence of available nuclei. Among these coated grains, those with angular shapes with poorly developed laminations, commonly called patchy coated grains, experienced slower growth rates, with less turbulence and more stability, in contrast to the more agitated conditions that initially fostered their development.

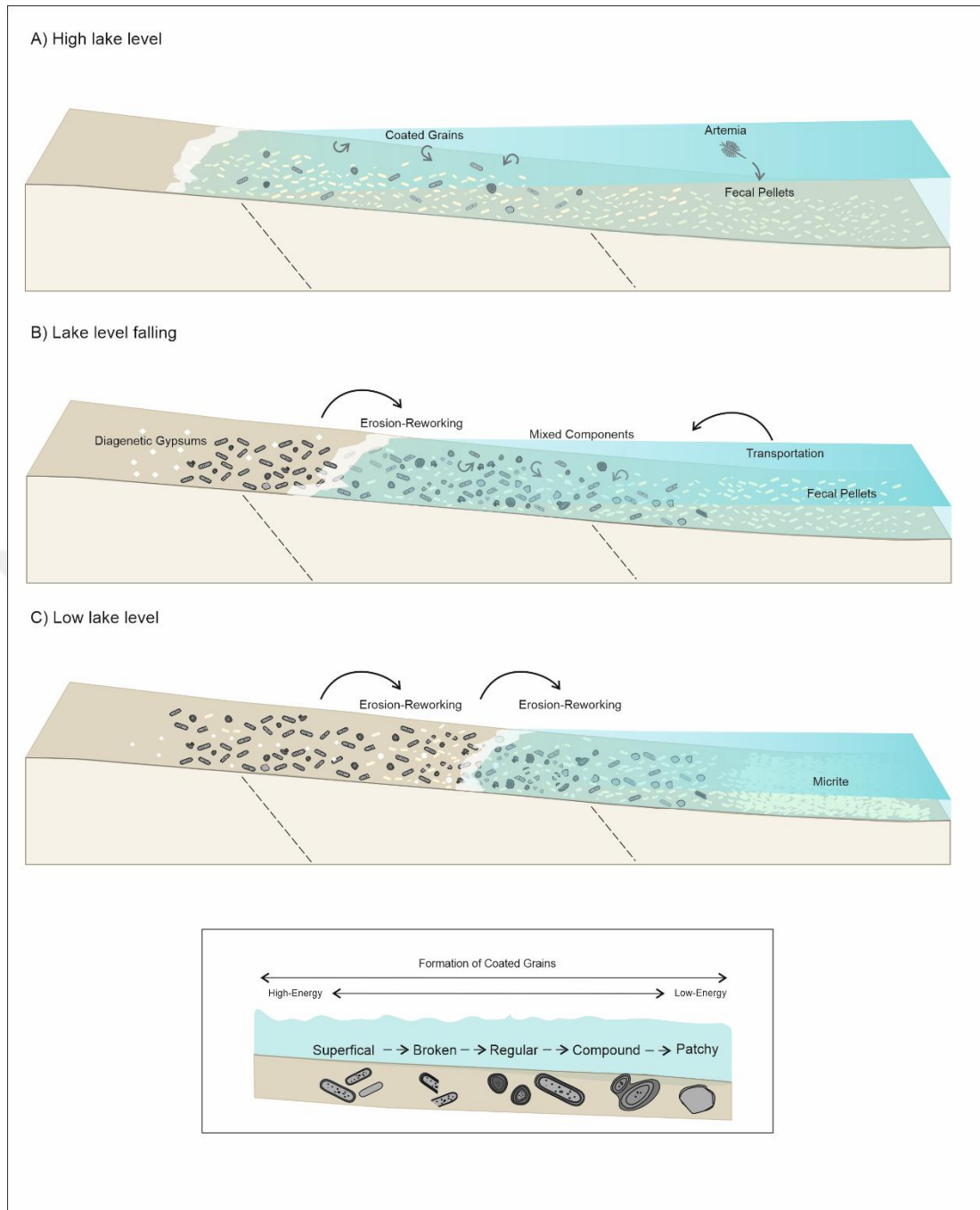


Figure 5.3: Urmia Lake coated grains and their proposed depositional stages: (a) high lake level, (b) lake level falling, and c) low lake level.

5.2.4 Sedimentary environment, coated grains, and lake level history

The sediment core retrieved from Urmia Lake exhibits diverse terrigenous sediments from the surrounding catchment area into the lake and authigenic minerals directly corresponding to the lake water ionic concentrations. They are significant indicators of the lake's past environmental conditions. While coated grains provide valuable

insights, their chronological interpretations should be cautiously approached and supplemented with additional proxy data to understand the lake's depositional history better. Detailed stratigraphy of the studied core reveals an alternation of dominant sedimentary constituents, including coated grains, fecal pellets, diagenetic gypsum, terrigenous fragments and minerals, and salt crust. The variations in the type and abundance of these sedimentary constituents provide compelling evidence of the lake's remarkable sensitivity to climatic variations and water-level fluctuations. Sari et al. (2024) dated core UL2 using the ^{14}C age from fecal pellets and bulk sediments, which we also used in our study. These dates were not adjusted for the reservoir effect. Core chronology goes back to 50 cal ka BP and covers the upper parts of MIS 3 (Figure 5.4). Radiocarbon dating within this time range is subject to uncertainties. Even a tiny amount of young-carbon contamination, which is difficult to detect, can make ages appear much younger. Furthermore, if the dated grains have been reworked or there is a significant radiocarbon reservoir in the water, the dates may not accurately represent the deposition age. Therefore, the ancient ages from the core should be regarded as approximate, and further work is needed to refine the chronology.

During the upper part of the MIS3 (48-29 cal ka BP), a gradual decline in lake level is evidenced by an abundance of coated grains and reworked shell fragments from marginal fresh and brackish water swamps and deltas. Notably, the period from 48 to 33 cal ka BP was particularly conducive for dominant coated grain formation on the northwestern part of the lake (Units 1-2). The abundance and type of coated grains are valuable proxies for the lake-level reconstruction. As they form in the shallow water with the wave effect, their presence suggests that the lake may have experienced a prolonged period of low water levels with high levels of ionic super-saturation water concerning carbonate and bicarbonate anions, along with the presence of nuclei and high-energy, shallow agitated water conditions required for the formation of coated grains. The supply of coated grain nuclei exhibits spatiotemporal variability in their distribution patterns. The pronounced abundance of detrital nuclei and reworked shell fragment nuclei indicate a significant influx of terrigenous sediment. The decreased lake water level is associated with transporting predominantly reworked shell fragments from marginal water swamps, lake terraces, and adjacent foraminifera-bearing formations (Salehipour Milani et al., 2020). The majority of the coated grains present in Units 1 and 2 (Figure 5.4) display a prevailing tendency towards a more

spherical to angular shape, strongly suggesting that the morphology of these grains is markedly different from those present in the remaining sediment core due to the terrigenous constituent abundance. The transition to elongated coated grains in Unit 2 signifies a substantially reduced terrigenous sediment influx over time.

During MIS 2 (29-12 cal ka), the lake reached its lowest point, potentially revealing the lake floor with brown mud containing volcanic lithics, volcanic glass, and detrital grains alongside an increased prevalence of diagenetic sulfate minerals, particularly evident in Units 3 and 4. The sediment color transition from gray to brown in Unit 3 (15.8 m–9.8 m) indicates a gradual water level decline during the late MIS 3 and early MIS2, leading to complete desiccation of the lake and partial exposure of the lake bed. Whether uncoated or as nuclei for coated grains, fecal pellets are typically fragmented, signifying the recycling of deposited pellets from the exposed lake. The limited occurrence of coated grains, fecal pellets, and detrital fragments within them emphasizes the significant influence of terrigenous sediments, which play a dominant role in deposition. Furthermore, the presence of rounded diagenetic sulfate minerals suggests recycling. The late MIS2 Unit 4 (9.8 m–6.8 m) is marked by a low lake level and partial exposure of the lake floor.

The subsequent period, MIS 1 (12 cal ka BP-Recent), witnessed a rapid rise in the lake level, as indicated by deposits abundant in fresh cream pellets and the almost absence of sulfate minerals and coated grains (Unit 5), fostering optimal conditions for *Artemia urmiana*. The presence of coated grains is restricted to specific depths (6.23 m, 5.93 m, 5.38 m–5.06 m, and 3.94 m–3.67 m), indicating their limited abundance. *Artemia urmiana* is a pivotal factor influencing grain formation characteristics in Urmia Lake. *Artemia urmiana* absorption of calcium, carbonate, and bicarbonate ions results in limited availability of free ions crucial for developing coated grains (Mohammadi, 2005; Mohammadi et al., 2019, 2021; Lak et al., 2022). On the other hand, *Artemia urmiana* provides fecal pellets as a nucleus for coated grain in Urmia Lake. Despite the presence of conducive factors, such as a turbulent environment at considerable depths, the inhibitory role of *Artemia urmiana* appears to be a significant factor in preventing the formation of coated grains (Mohammadi et al., 2021).

The lake's modern state, characterized by a low lake level, is represented by a prominent 3.20 m salt crust corresponding to the last 25 years. This crust signals a

transition from a terrigenous-biochemical hypersaline lake to a chemical playa (Figure 5.4; Mohammadi et al., 2019, 2021; Mohammadi, 2024).

The lake level/water depth fluctuation curve presented in Figure. 5.4 for the past ~50 cal ka demonstrates a strong alignment with regional paleoclimate records, validating the use of coated grains as reliable proxies for lake dynamics during this period. Pollen data from Djamali et al. (2008) provide a long-term view of vegetation and climate changes in the Urmia Basin. During the Last Glacial Maximum (LGM) (Clark et al., 2009), their findings indicate a predominance of steppe vegetation, reflecting arid conditions. This is consistent with our lake level curve, which depicts lower lake levels during the LGM, corroborating the dry climate inferred from the sparse vegetation. The gradual transition towards wetter conditions from the late Pleistocene into the early Holocene, marked by an increase in arboreal taxa such as *Quercus* and *Juniperus*, is also mirrored in our lake level curve as a significant rise in water levels, reflecting the onset of more humid conditions.

Further support for these climatic shifts comes from the $\delta^{18}\text{O}$ data of Stevens et al. (2012), which indicate an increase in humidity and lake levels following the LGM. Our lake level curve similarly records a pronounced rise in water levels starting around 14 cal ka, corresponding to the deglaciation and into the Holocene, suggesting a positive hydrological balance during this period. The sensitivity of the lake system to abrupt climatic changes is highlighted by the Younger Dryas event, which is captured in both the $\delta^{18}\text{O}$ record and our lake level curve as a distinct decline in water levels, indicating a brief return to arid conditions. Tudryn et al. (2021) provide additional sedimentological evidence using magnetic susceptibility and carbonate content. Higher magnetic susceptibility values in their dataset, associated with increased erosion and lower lake levels, are consistent with the lower water levels observed in our lake level curve during the LGM.

In contrast, higher carbonate concentrations indicate more stable and wetter conditions, which match well with increased lake levels in our reconstruction during the early Holocene, supporting the interpretation of favorable climatic conditions. The Holocene portion of our lake level curve strongly aligns with the paleo-rainfall reconstruction by Sharifi et al. (2023), which identifies periods of increased rainfall between 10 and 6 ka. Similarly, Sari et al. (2024), using the same sediment core as our

study and employing fecal pellet abundance as a primary proxy, provide a detailed account of lake level fluctuations.

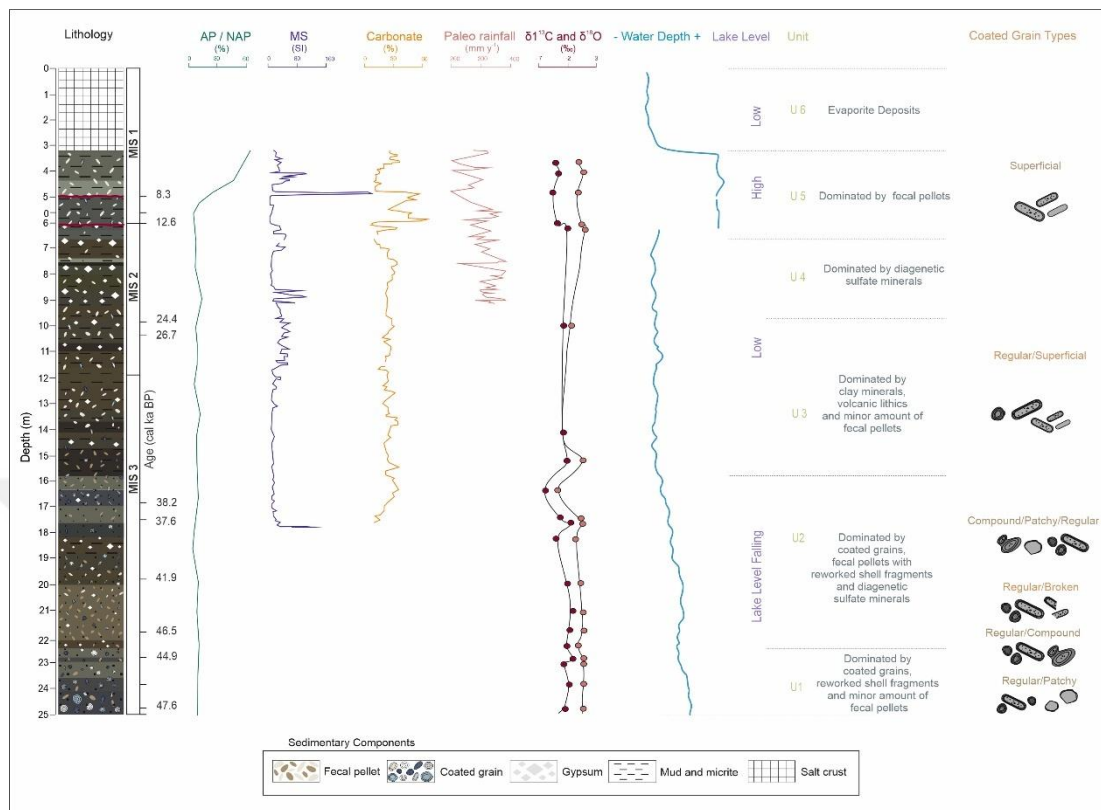


Figure 5.4: Simplified lithostratigraphy of the sediment core. Fecal pellets and bulk sediments cal Pollen data (Djamali et al., 2008), $\delta^{18}\text{O}$ records (Stevens et al., 2012) magnetic susceptibility and carbonate data (Tudryn et al., 2021), paleo-rainfall data (Sharifi et al., 2023), and calibrated ^{14}C ages for pellets and bulk sediments and lake-level fluctuation curve from (Sarı et al., 2024). Sedimentary units (Unit 1 to Unit 6), with summarized descriptions and dominant coated grain types along the sediment core, are from this study.

5.2.5 Comparison of the Urmia Lake and Great Salt Lake coated grains

Coated grains were first reported by Kelts and Shahrabi (1986) in Urmia Lake, showing striking similarities to those found in the Great Salt Lake. These grains are particularly abundant near Golman-Khaneh and exhibit concentric bands of radial aragonite surrounding nuclei typically composed of quartz, feldspar, or dolomite grains. In other regions of Urmia Lake, sand bars predominately feature single-layer aragonite-coated fecal pellets. Lankarani et al. (2017) conducted a study characterizing the latest Holocene surficial deposits in the Golman-Khaneh area of Urmia Lake. They found these deposits are primarily composed of well-sorted, medium to coarse-grained

sandy-coated grains, displaying superficial and concentric coatings. These microfacies resemble those commonly encountered in ooidal shoals within carbonate systems. Sharifi et al. (2018) investigated these coated grains in Urmia Lake. They observed that, in most cases, the grains are polished fecal pellets of *Artemia urmiana* covered with a single layer of radial aragonite crystals. However, in the lower half of the long cores, they found grains composed of multiple concentric layers of aragonite crystals around a carbonate or siliciclastic core, similar to what we observed in our sediment core.

The sediments along the shorelines of the Great Salt Lake have been extensively studied (Eardley, 1938; Sandberg, 1975; Pedone and Norgauer, 2002; McGuire, 2014; Bouton et al., 2016; Paradis, 2019; Lincoln et al., 2022 and Paradis et al., 2024), focusing on their distribution, composition, mineralogy, and internal structures. While there are notable differences between the two lakes, such as their geographical locations and surrounding environments, the coated grains found in their sediments share many similarities in size, shape, and composition. However, the coated grains in Urmia Lake exhibit distinct variations in coloration, unlike those commonly observed in other lacustrine environments. The sediment core studied from Urmia Lake displays a wide range of colors, which may be attributed to subtle changes in the elemental composition of the coated grains, differing from the characteristics of many other coated grains. Additionally, organic matter in both lakes is essential as an adhesive during cortex accretion.

Great Salt Lake-coated grains have garnered attention as analogs for their formation, showing diverse cortical fabrics, including radially oriented needles and concentric layers (Eardley, 1938; Sandberg, 1975). They typically form on fecal pellets or quartz nuclei and differ from marine coated grains found in environments like Caribbean carbonate platforms, which lack the radial microfabric, possibly due to differences in sediment transport energy (Kahle, 1974; Heller et al., 1980). The orientation of crystals and the microfabric of coated grain cortices exhibit variations influenced by environmental factors and chemical and physical conditions. Although they resemble each other in many aspects, the predominant microfabrics diverge between the Great Salt Lake and Urmia Lake, with the coated grains in the Great Salt Lake characterized

by radial carbonate cortices. Coated grains with tangential and randomly oriented crystal structures exist in the Great Salt Lake but lack volumetric significance.

Conversely, SEM images of 280 coated grains in Urmia Lake reveal fabric patterns deviating from radial orientations. These grains, characterized by well-defined concentric coatings, may display subtle or unclear microfabric features with indistinct characteristics. It is worth noting that previous research has reported coated grains with radial features in Urmia Lake (Kelts and Sharabi, 1986; Sharifi et al., 2018). The Lake modern coated grains also display radial orientations (Figure 4.12).

Additionally, polarizing microscope images of a thin section from the modern lake beach sample revealed radial-concentric fabrics in some instances (Figure 4.12F, G). The reason for our potential oversight could be the scarcity of these features or the possibility that microfabrics are more discernible through polarizing microscope images. The radial orientation of crystals in coated grains may be due to a combination of factors, including hydrodynamic conditions, biological activity, mineral composition, and diagenetic processes. Further research and analysis of these factors in sedimentary environments are essential to fully understand the mechanisms underlying the observed differences in microfabric formation.

The coated grains in Urmia Lake and Great Salt Lake develop under distinct environmental conditions influenced by water levels, chemistry, and variations in biogenic activity. While both lakes are hypersaline and contain similar carbonate deposits, the factors controlling grain formation may differ. In Urmia Lake, shifts in water levels and the influence of organisms such as *Artemia urmiana* are key drivers. In contrast, Great Salt Lake is more affected by hydrodynamic forces, chemical saturation, and microbial contributions.

5.2.6 Significance of coated grains in hypersaline lake level fluctuations

Compared to other sedimentary components, coated grains' spatial distribution and prevalence can be a reliable indicator of historical water level fluctuations. Variations in water levels play a crucial role in shaping sediment composition and affect the presence of different organisms, sedimentation patterns, and the overall dynamics of ecosystems. The effects of water level fluctuations on the formation of coated grains

in lakes are multifaceted and have been studied across various geographical locations. Milroy and Wright (2002), in their comprehensive analysis of an Upper Triassic lake oolite in southwest England, shed light on the origins, transport processes, and diagenesis of ooids, emphasizing their role as indicators of diverse depositional environments. Great Salt Lake is a well-known site that provides a valuable model for understanding the processes behind coated grain formation and serves as a significant archive of environmental changes. Paradis (2019) conducted a comprehensive study establishing the growth rates and chronology of coated grains in the Great Salt Lake. She used them as high-resolution environmental archives, addressing their biogenicity through microbial analysis, and employed them as lake-level indicators.

Mischke et al. (2019) explored the Holocene salinity history of Lake Lop Nur in NW China using a combination of ostracods, foraminifera, ooids, and stable isotope data, highlighting the unique presence of ooids resembling those found in hypersaline environments such as the Great Salt Lake and Urmia Lake and suggesting their potential as stratigraphic markers for understanding past lake level changes. Lincoln et al. (2022) further investigated the unique features of Great Salt Lake coated grains and Mg-silicate presence, suggesting microbial involvement, which is valuable for recognizing such mineral associations in ancient lake deposits. Their presence offers insights into environmental changes as they form in shallow water with the wave effect during transgression and regression periods. Similarly, Semmani et al. (2022) showcased the importance of ooids in understanding lake-level changes. Their study of lacustrine carbonate succession in the Vistrenque Basin, Southeastern France, not only illuminated the oolitic saline lake margins but also delved into the complex mechanisms of lake transgressions within interconnected saline lake systems using the abundance of coated grains along with other sedimentary components as an indicator.

6. CONCLUSIONS AND FUTURE PROSPECTS

6.1 Synthesis of Key Findings

This study has comprehensively reconstructed Late Quaternary paleoenvironmental and paleoclimate dynamics in Urmia Lake, a hypersaline basin in northwestern Iran. Utilizing a 25-meter sediment core (UL2) from the northern part of the lake, the research employed a suite of high-resolution multiproxy analyses—including sedimentological, geochemical, and morphological approaches—to unravel the depositional history and hydrochemical variability of the lake over the past ~50 cal ka BP.

The findings reveal that Urmia Lake has experienced three major stages of lake level fluctuations, driven by regional and global climatic variations. These stages—characterized by periods of low, intermediate, and high lake levels—are recorded in the sedimentary composition and stratigraphy. Coated grains emerged as a particularly valuable proxy, offering insights into the interplay between lake hydrodynamics, biogeochemical cycles, and climatic conditions. Their mineralogy, internal structures, and distribution patterns reflect critical shifts in water salinity, ion concentrations, and depositional energy levels, demonstrating their utility as indicators of past environmental changes.

In parallel, the biogenic components, notably *Artemia urmiana* fecal pellets, provided additional evidence of the lake's ecological responses to fluctuating water levels. Their abundance in certain stratigraphic intervals underscores their role in modulating sediment composition and highlights the close coupling between biological and chemical processes in hypersaline systems. Geochemical proxies, such as elemental ratios (Ca/Ti, Sr/Ca, and Fe/Mn) and total organic carbon (TOC) content, further illuminated the dynamic interplay between endogenic carbonate production, terrigenous input, and salinity-driven mineral precipitation.

6.2 Implications for Paleoenvironmental Research

The research underscores the significance of hypersaline lake systems as sensitive archives of paleoclimate and paleoenvironmental changes. The multiproxy approach adopted here demonstrates the value of integrating sedimentary, geochemical, and biological indicators to achieve a nuanced understanding of environmental variability. The findings contribute to the broader body of knowledge on arid and semi-arid regions, offering critical insights into the climatic and hydrological evolution of the Middle East over the Late Quaternary.

Moreover, this study highlights the potential of coated grains as robust paleoenvironmental proxies in Urmia Lake and other hypersaline systems globally. This research advances our understanding of carbonate sedimentology in extreme environments by elucidating their formation mechanisms and depositional patterns. It enhances the interpretive frameworks for reconstructing past climatic and hydrochemical conditions.

6.3 Future Directions

While this study provides a robust framework for interpreting Urmia Lake's Late Quaternary history, several avenues for future research remain. These include:

1. **Higher-resolution age modeling:** Refining the chronological framework through additional radiocarbon dating and other isotopic techniques would enable more precise correlations with global climate events.
2. **Expanded geographical scope:** Comparative studies of sediment cores from different parts of the lake could capture spatial heterogeneity in depositional processes and hydrological responses.
3. **Role of microbial activity:** Investigating the microbial contribution to carbonate precipitation and coated grain formation could provide deeper insights into the biogeochemical dynamics of hypersaline systems.

6.4 Final Remarks

This thesis reconstructs the depositional and hydrological history of Urmia Lake, contributing to a deeper understanding of the mechanisms governing hypersaline lake

systems and their responses to climate variability. The findings illuminate the region's environmental past and offer valuable perspectives for addressing contemporary challenges, including lake desiccation and ecological degradation, in the context of ongoing climate change and anthropogenic pressures.

This research bridges the gaps between sedimentology, paleoclimatology, and environmental science, providing a foundation for future multidisciplinary studies of hypersaline lake systems worldwide.





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APPENDICES

APPENDIX A: XRD analysis of bulk sediments

APPENDIX B: SEM-EDS and XRD analysis of coated grains



APPENDIX A: XRD analysis of bulk sediments

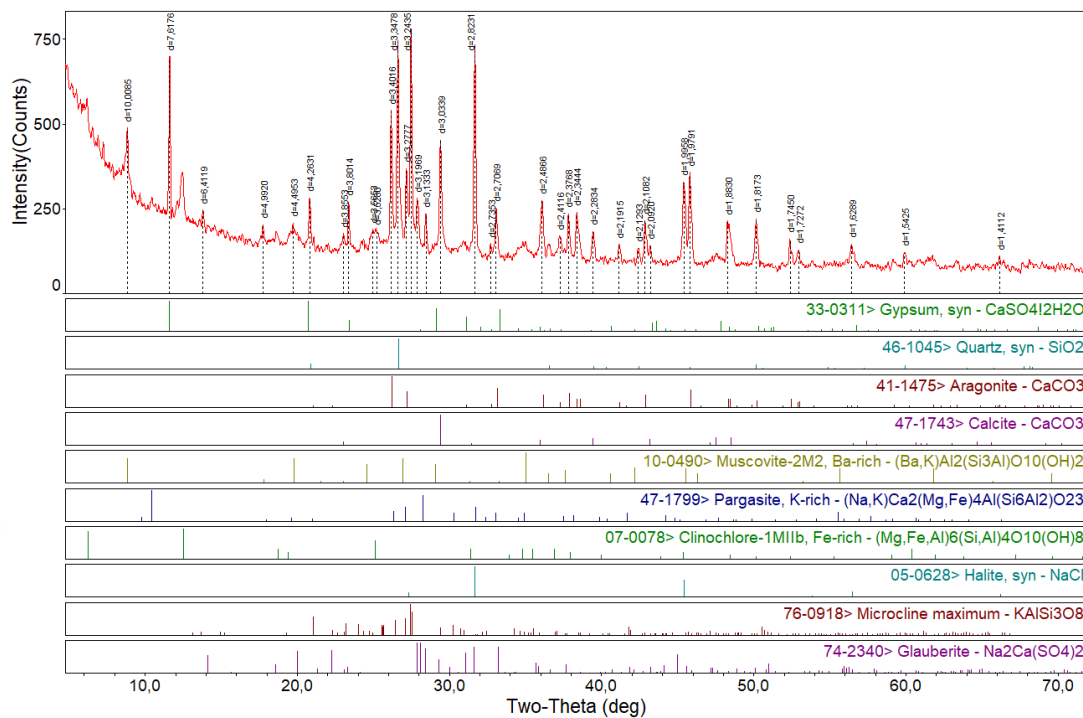


Figure A.1: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 3.53-3.55 m.

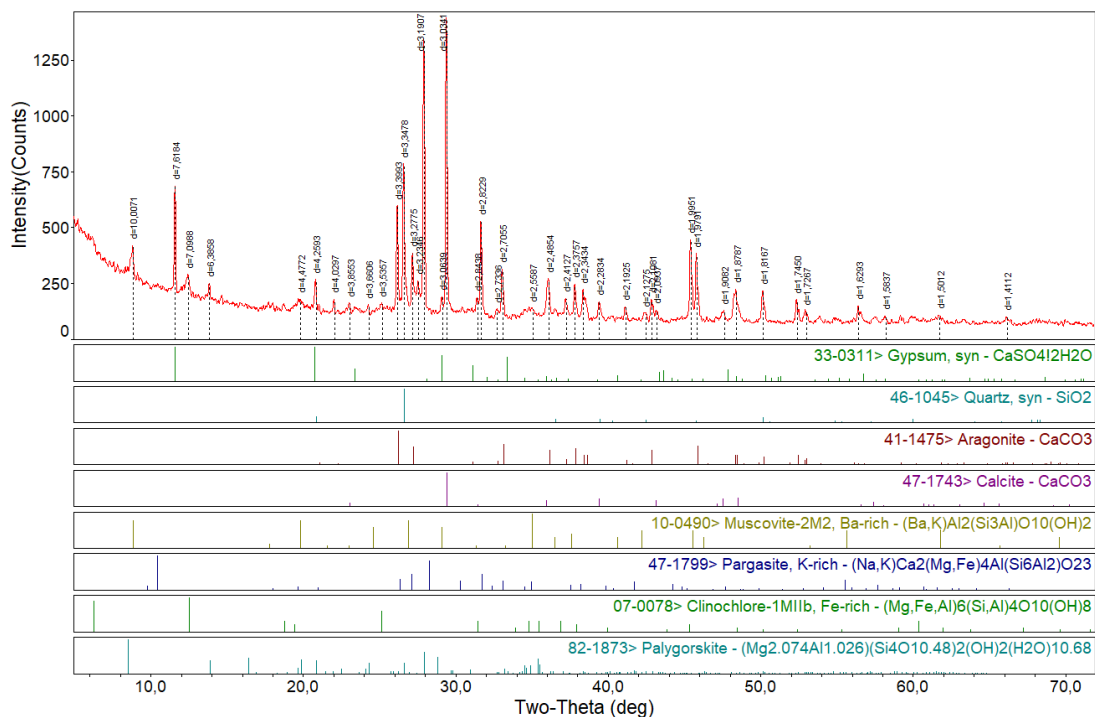


Figure A.2: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 5.05-5.07 m.

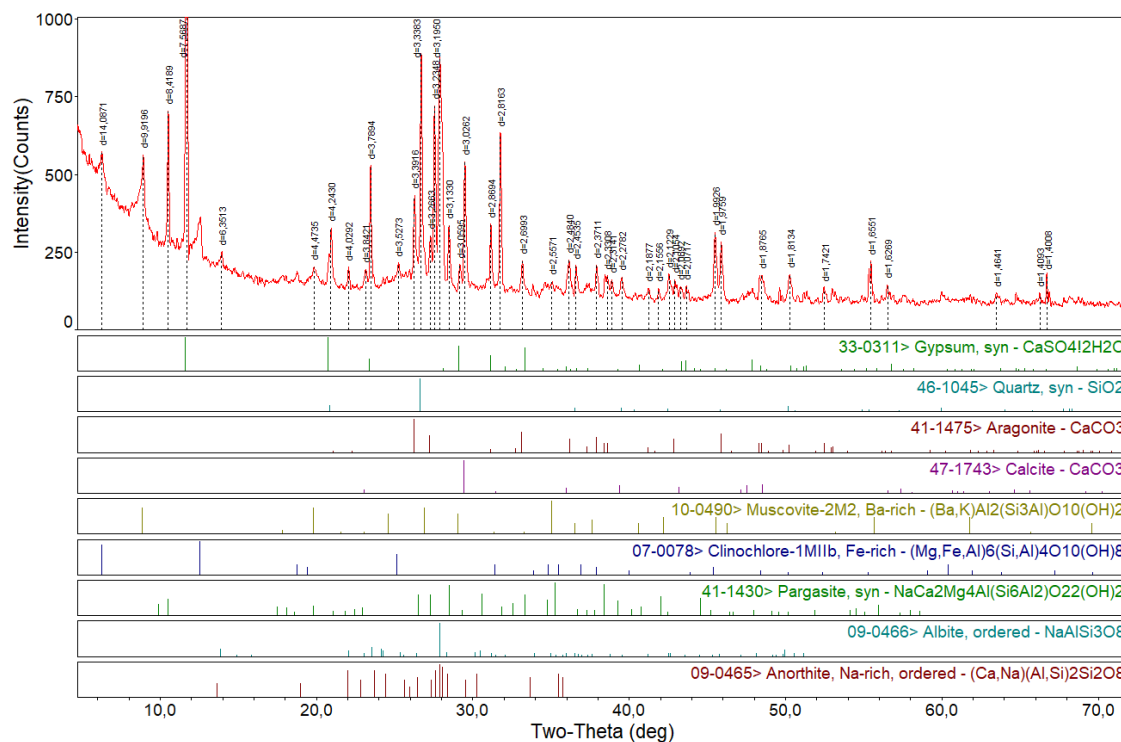
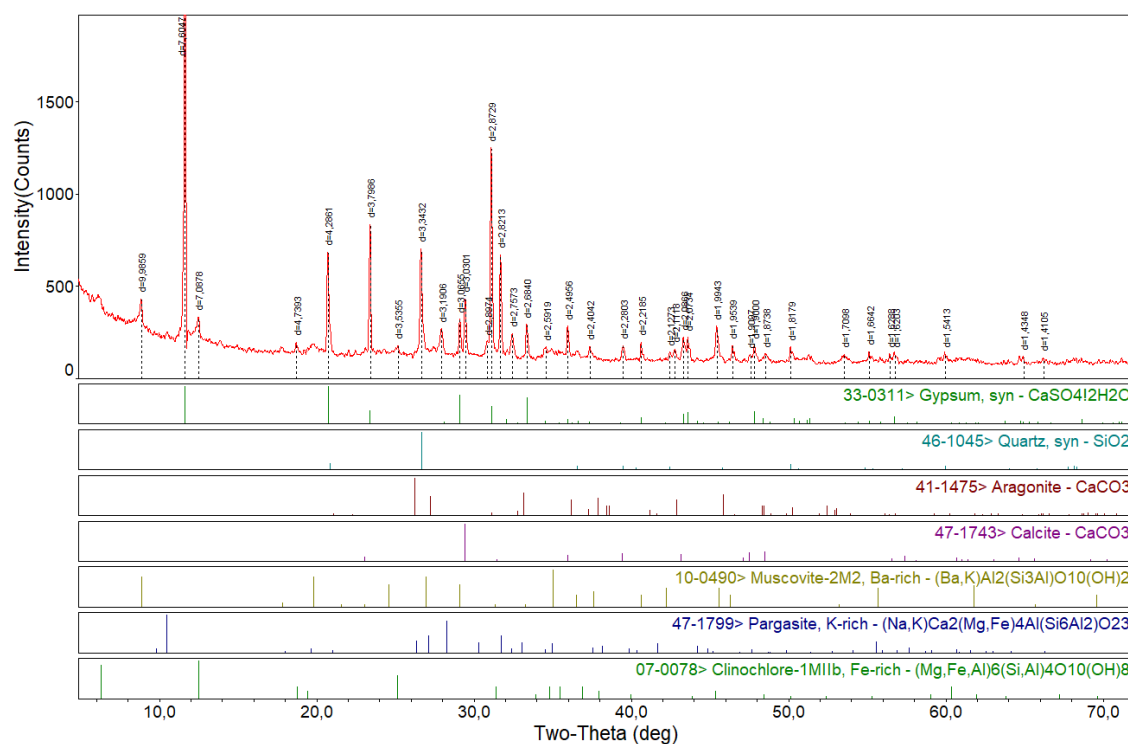


Figure A.3: X-ray diffractometric pattern of bulk sediment from Urmia Lake at



a depth of 6.25-6.27 m.

Figure A.4: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 6.85-6.87 m.

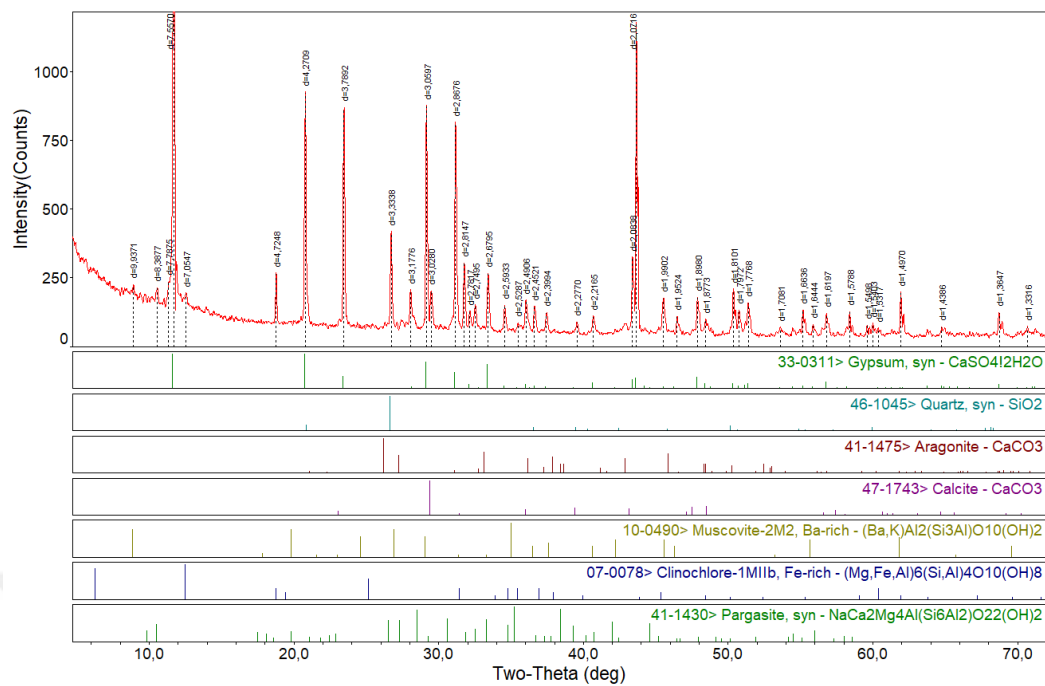


Figure A.5: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 7.85-7.87 m.

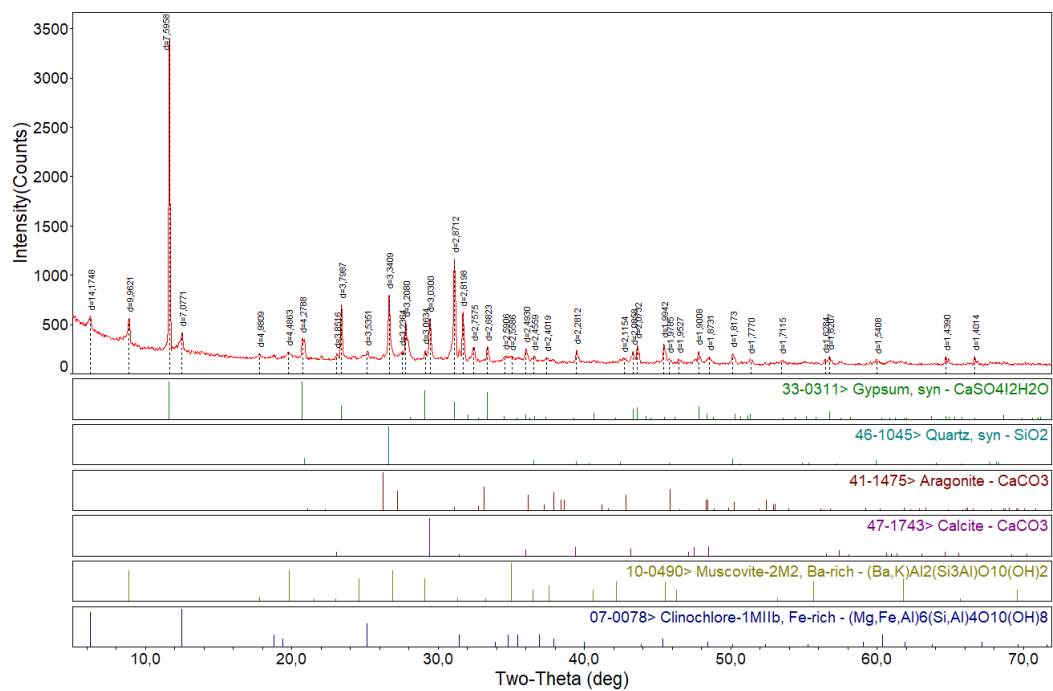


Figure A.6: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 8.35-8.37 m.

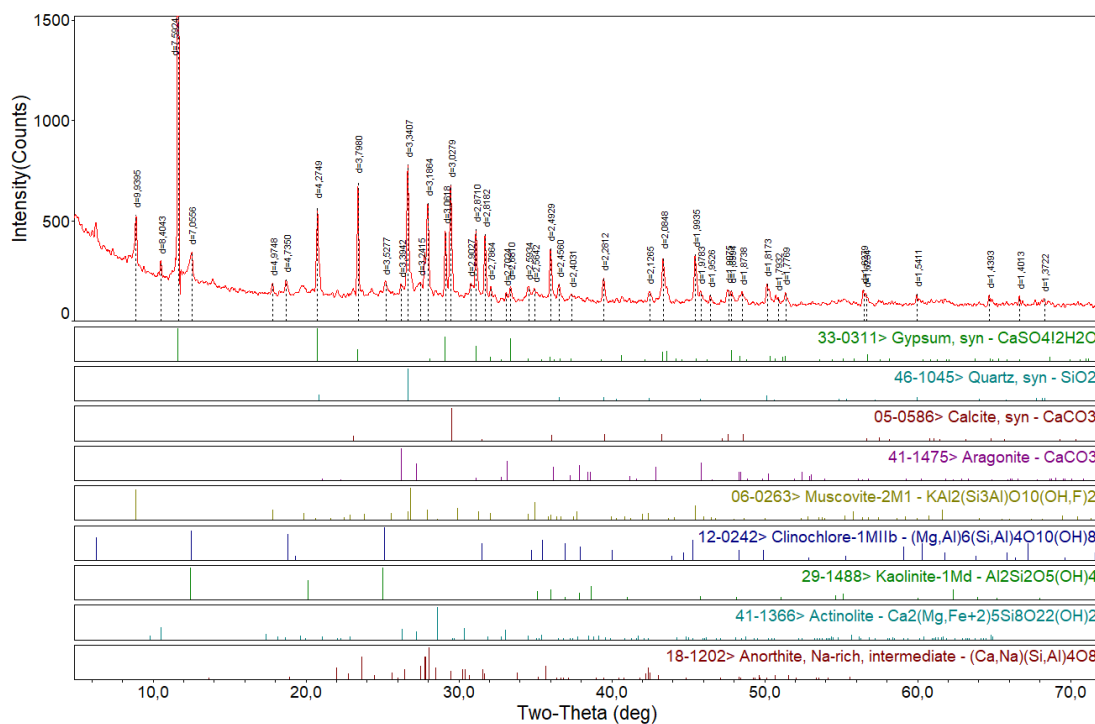


Figure A.7: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 11.95-11.97 m.

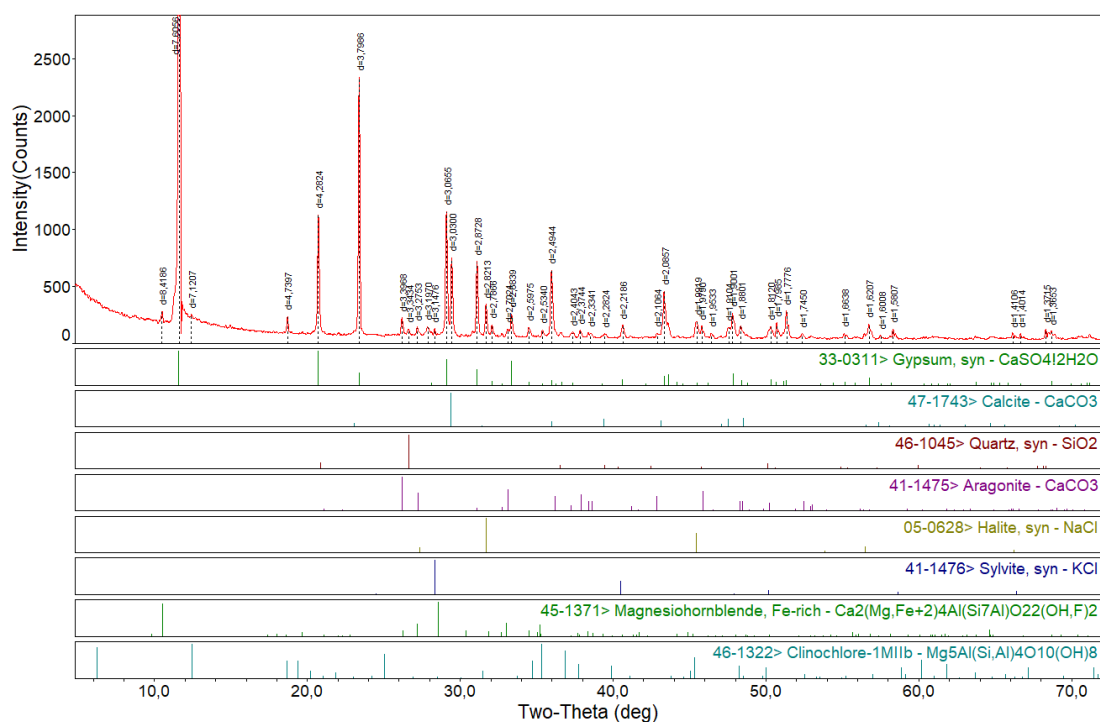


Figure A.8: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 18.25-18.27 m.

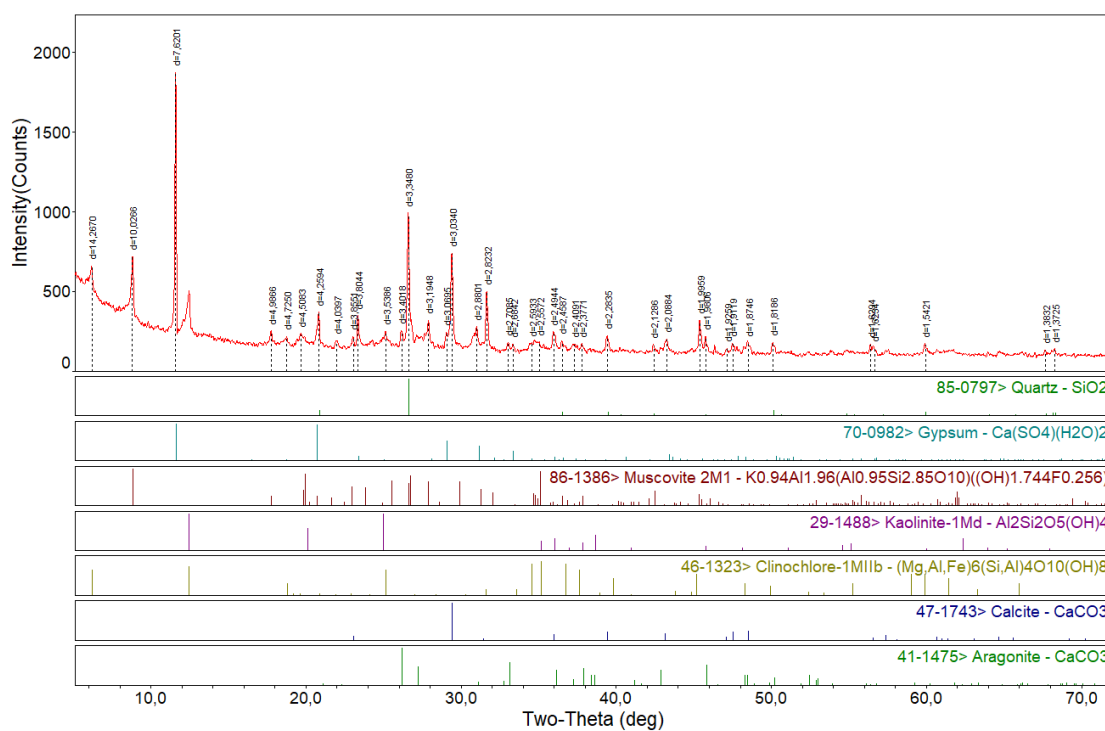


Figure A.9: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 18.55-18.57 m.

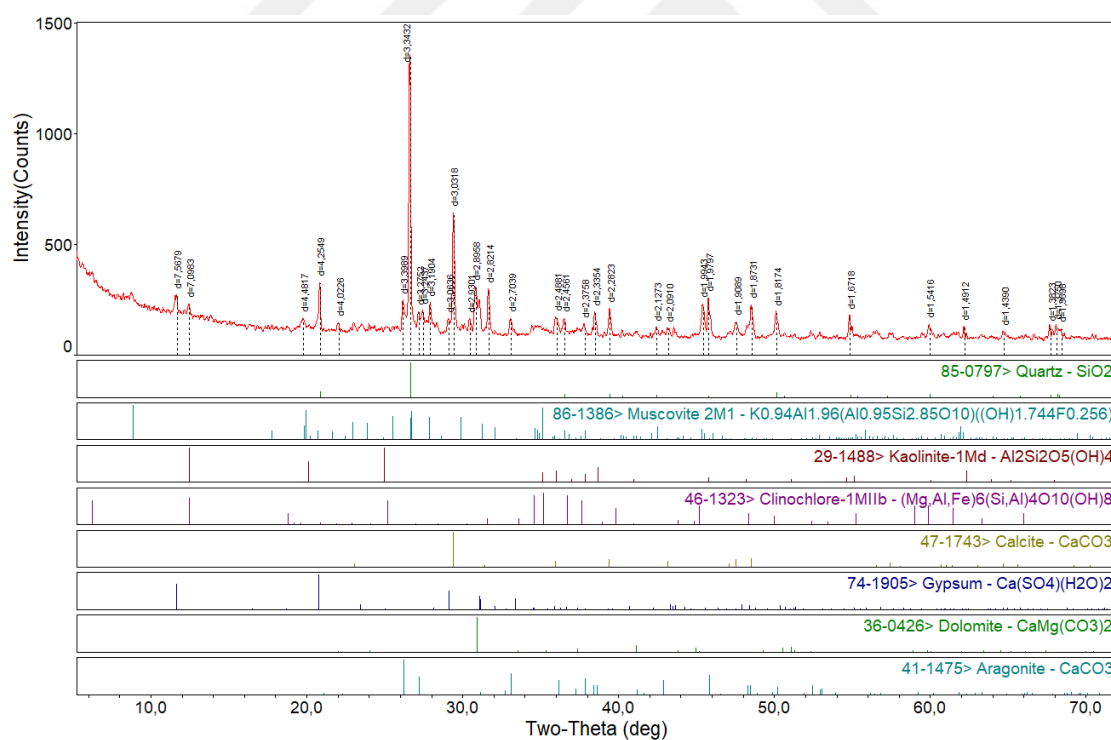


Figure A.10: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 19.35-19.37 m.

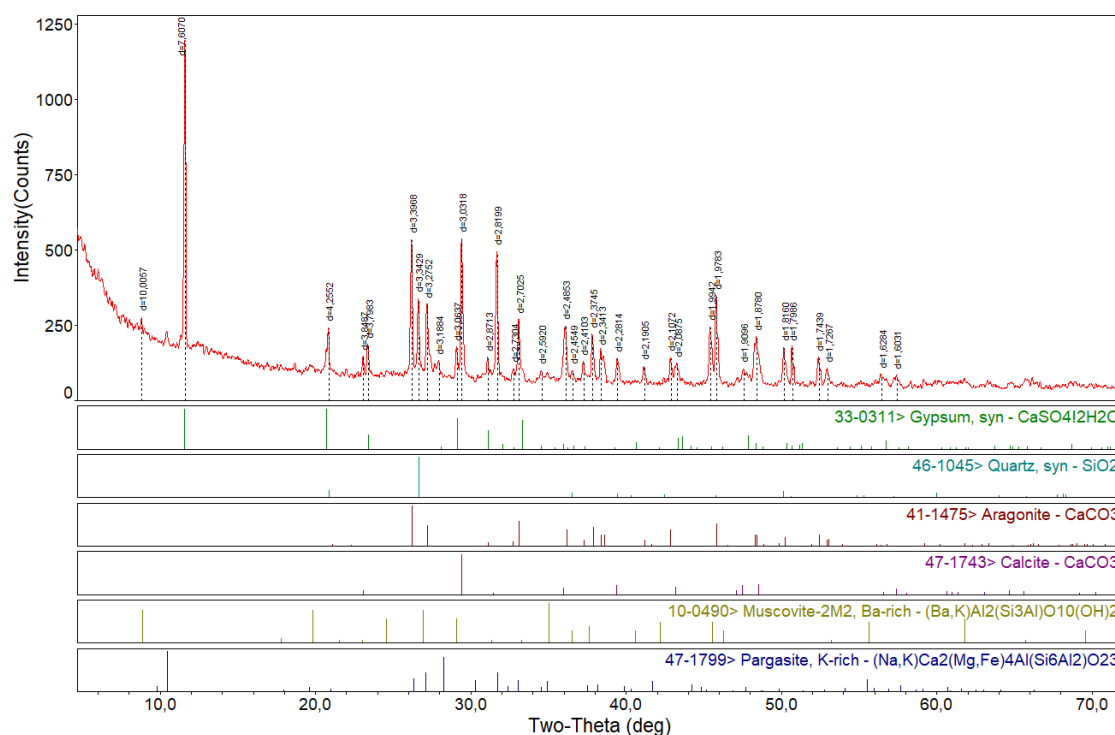


Figure A.11: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 23.85-23.87 m.

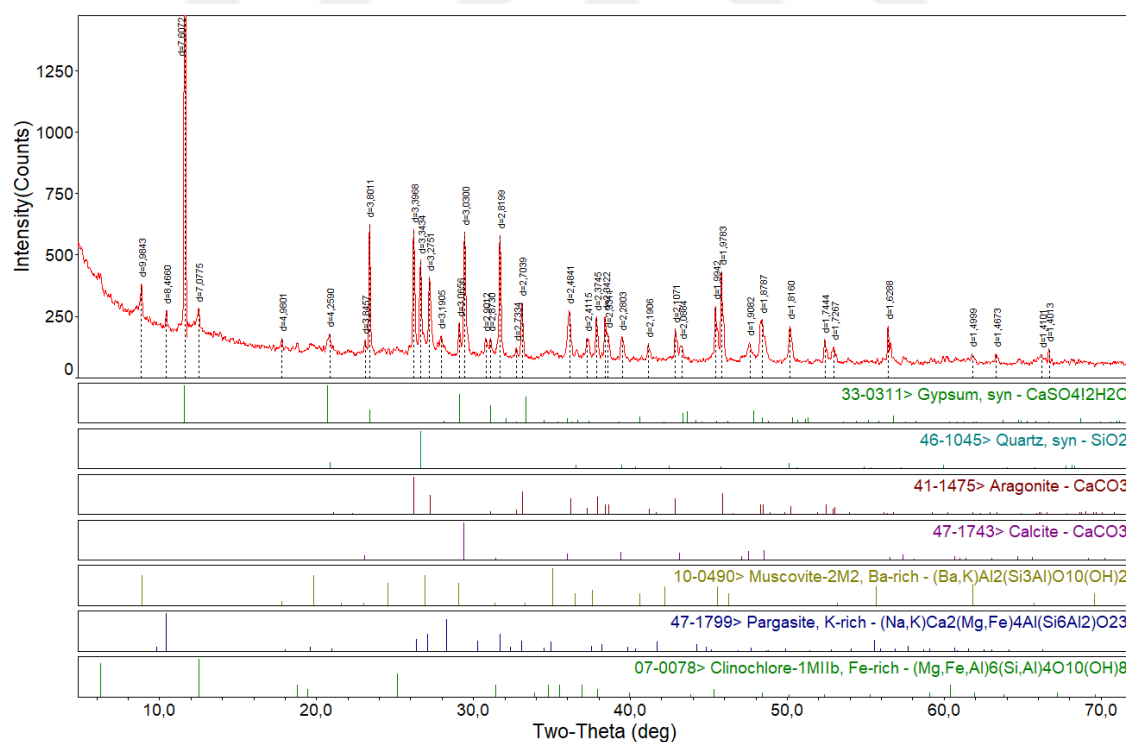


Figure A.12: X-ray diffractometric pattern of bulk sediment from Urmia Lake at a depth of 24.45-24.47 m.

APPENDIX B: SEM-EDS and XRD analysis of coated grains

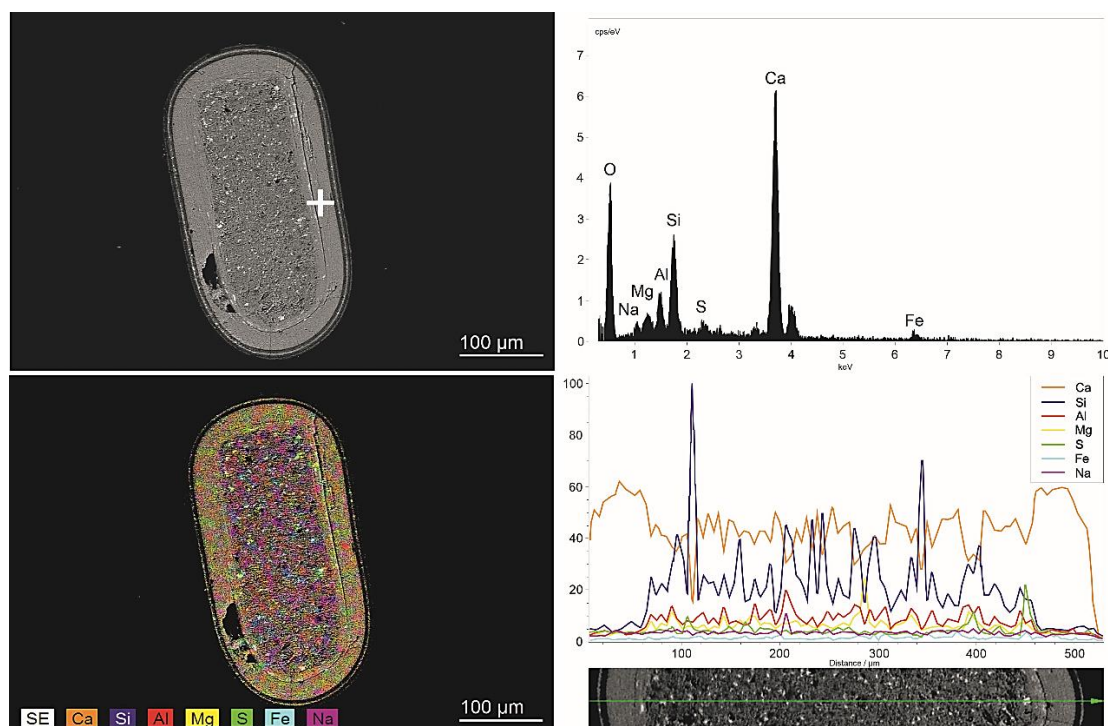


Figure B.1: Qualitative analyses of representative regular coated grain with broken fecal pellet nucleus from 21.32 m, showing the elemental composition revealed by the spot measurement, line scan, and element map.

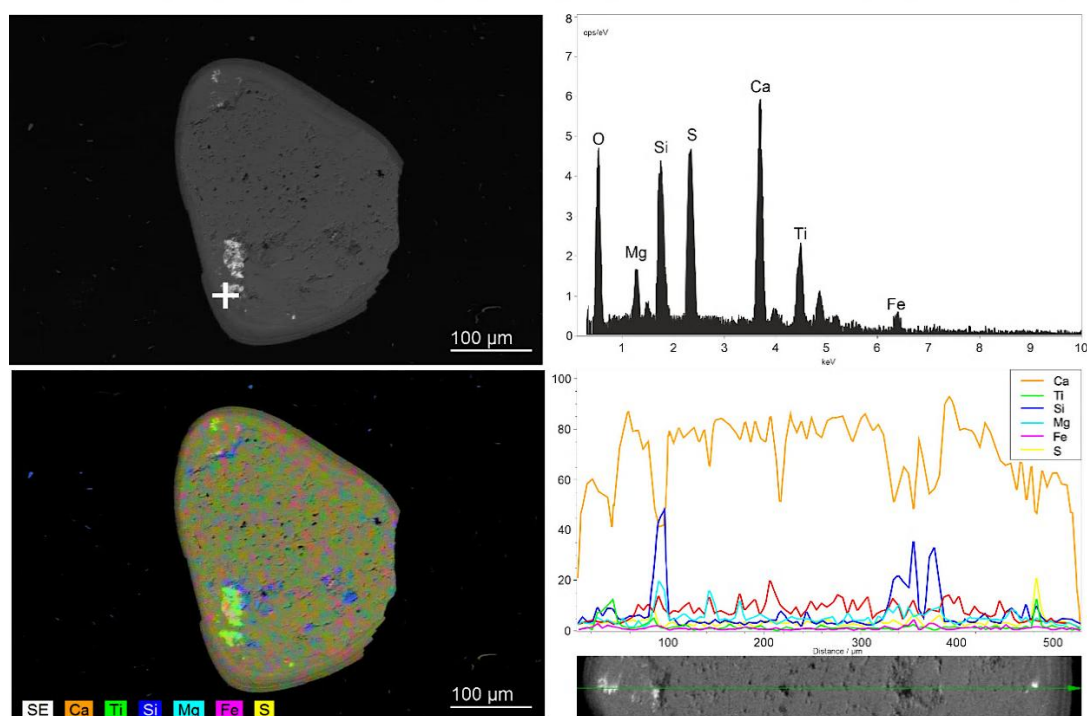


Figure B.2: Qualitative analyses of representative patchy coated grain from 19.95 m, showing the elemental composition revealed by the spot measurement, line scan, and element map.

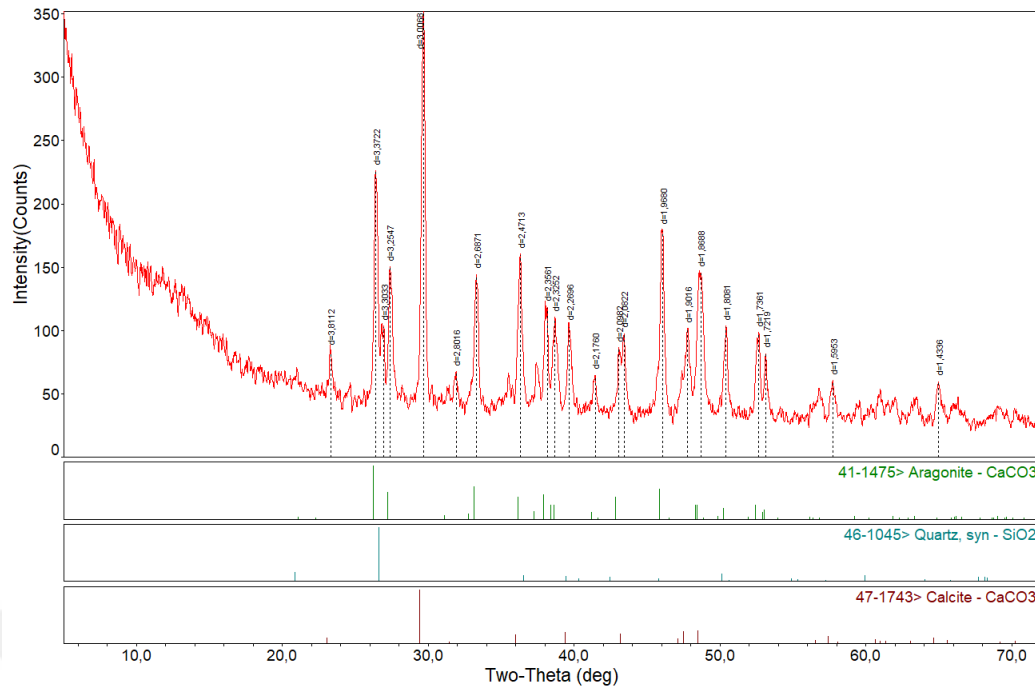


Figure B.3: X-ray diffractometric pattern of Urmia Lake coated grain from 16.31m. The identified minerals are calcite, aragonite, and quartz.

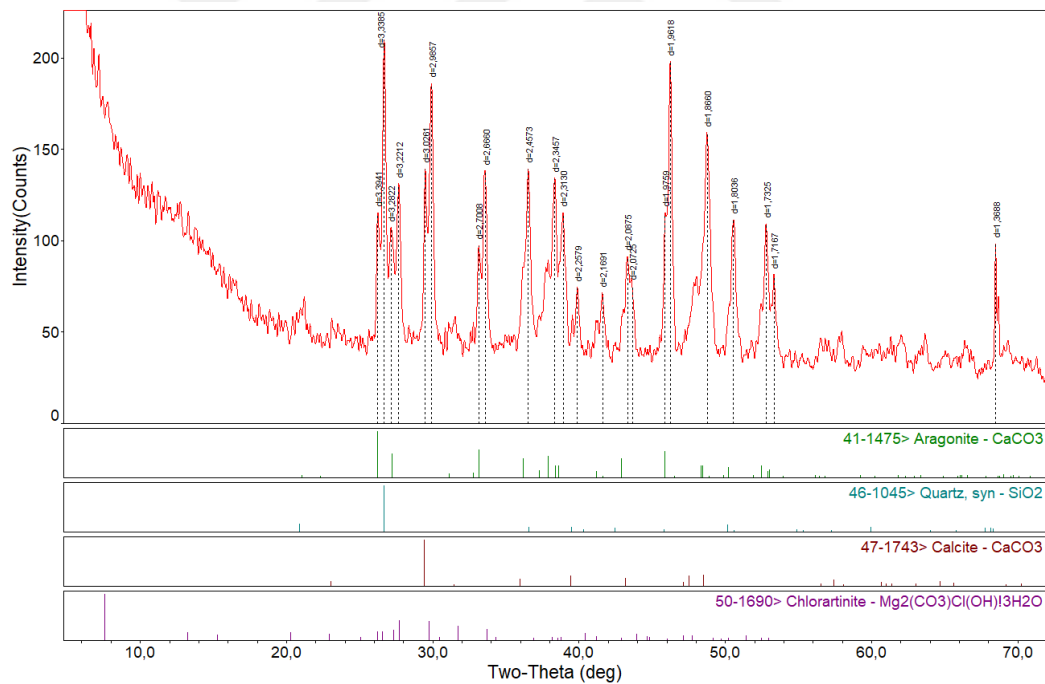


Figure B.4: X-ray diffractometric pattern of Urmia Lake coated grain from 16.85 m. The identified minerals are calcite, aragonite quartz, and chlorartinite.

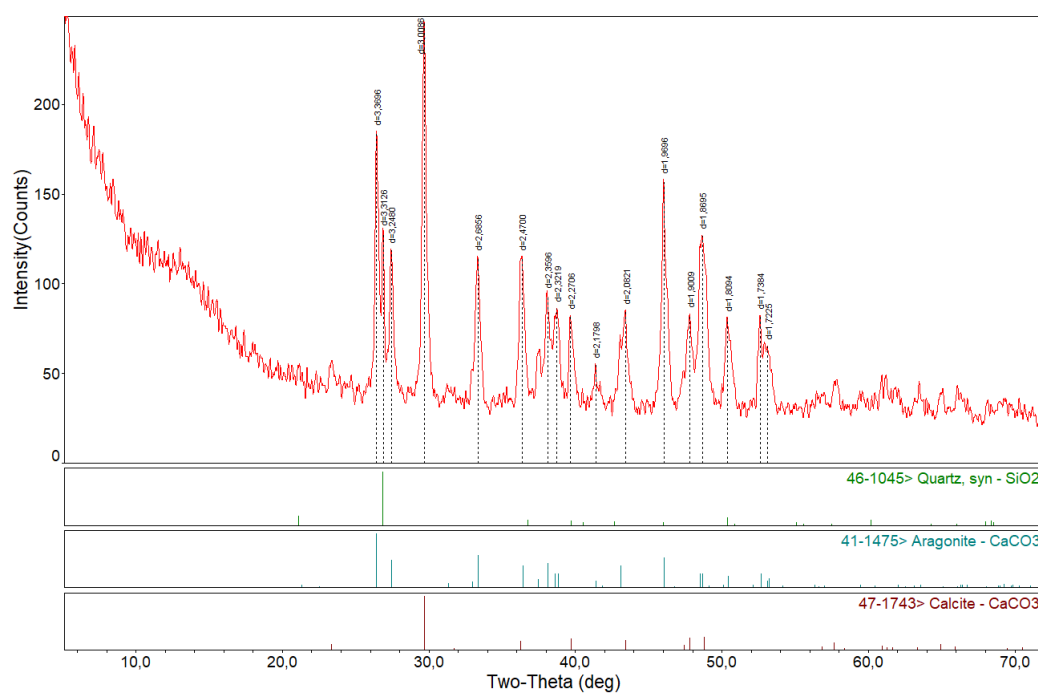


Figure B.5: X-ray diffractometric pattern of Urmia Lake coated grain from 17.98 m. The identified minerals are calcite, aragonite, and quartz.

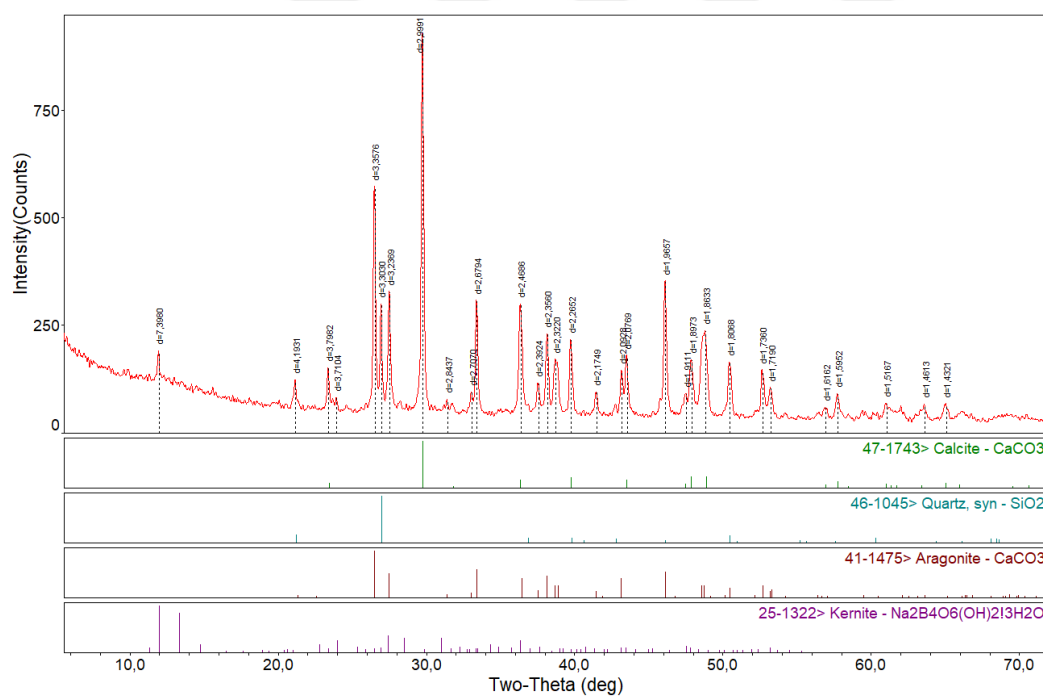


Figure B.6: X-ray diffractometric pattern of Urmia Lake coated grain from 18.73 m. The identified minerals are calcite, aragonite, quartz, and kernite.

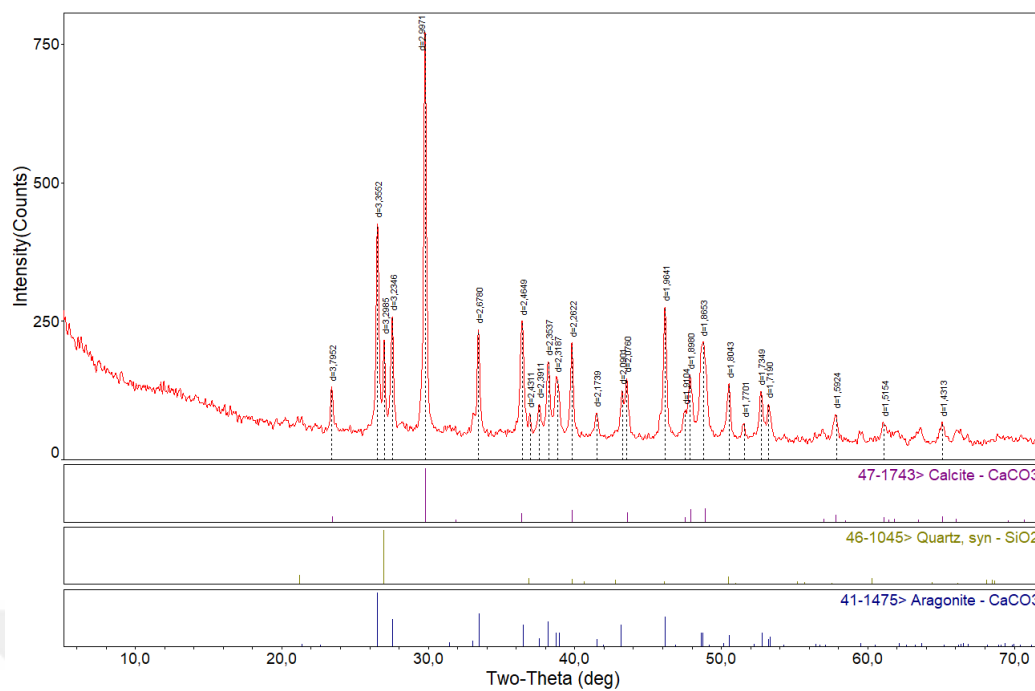


Figure B.7: X-ray diffractometric pattern of Urmia Lake coated grain from 19.73 m. The identified minerals are calcite, aragonite, and quartz.

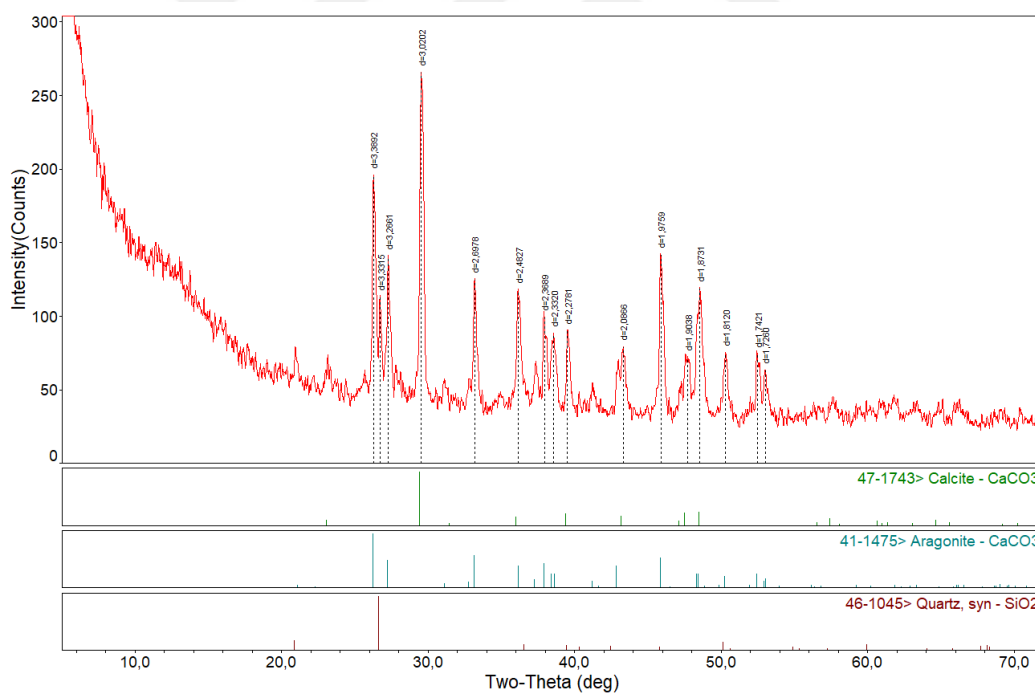


Figure B.8: X-ray diffractometric pattern of Urmia Lake coated grain from 20.49 m. The identified minerals are calcite, aragonite, and quartz.

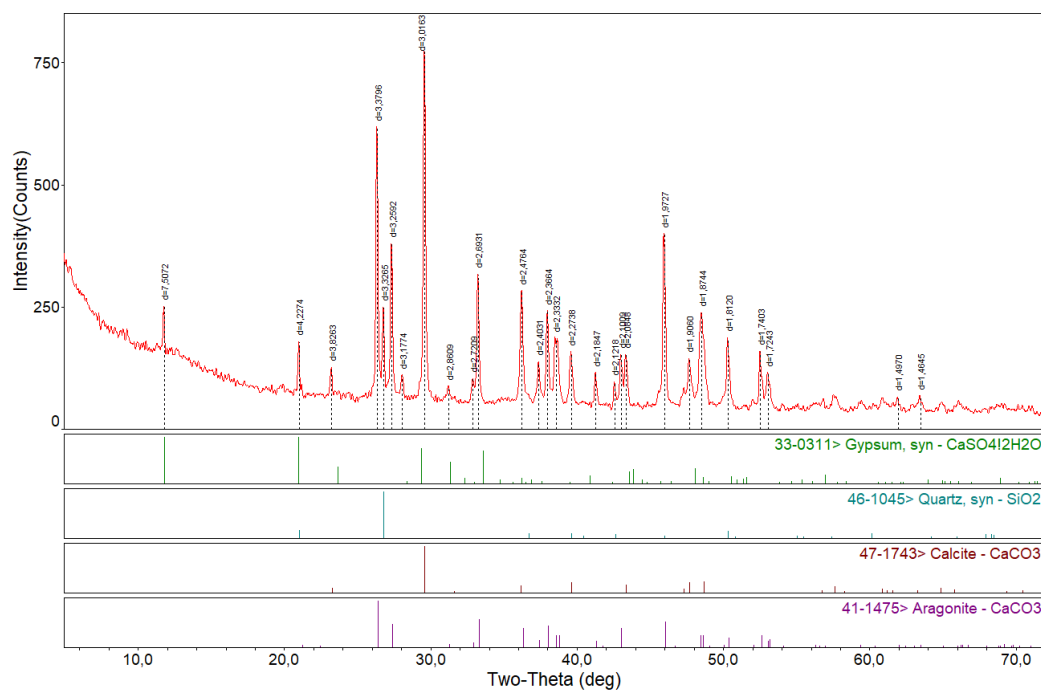


Figure B.9: X-ray diffractometric pattern of Urmia Lake coated grain from 21.47 m. The identified minerals are calcite, aragonite, quartz, and gypsum.

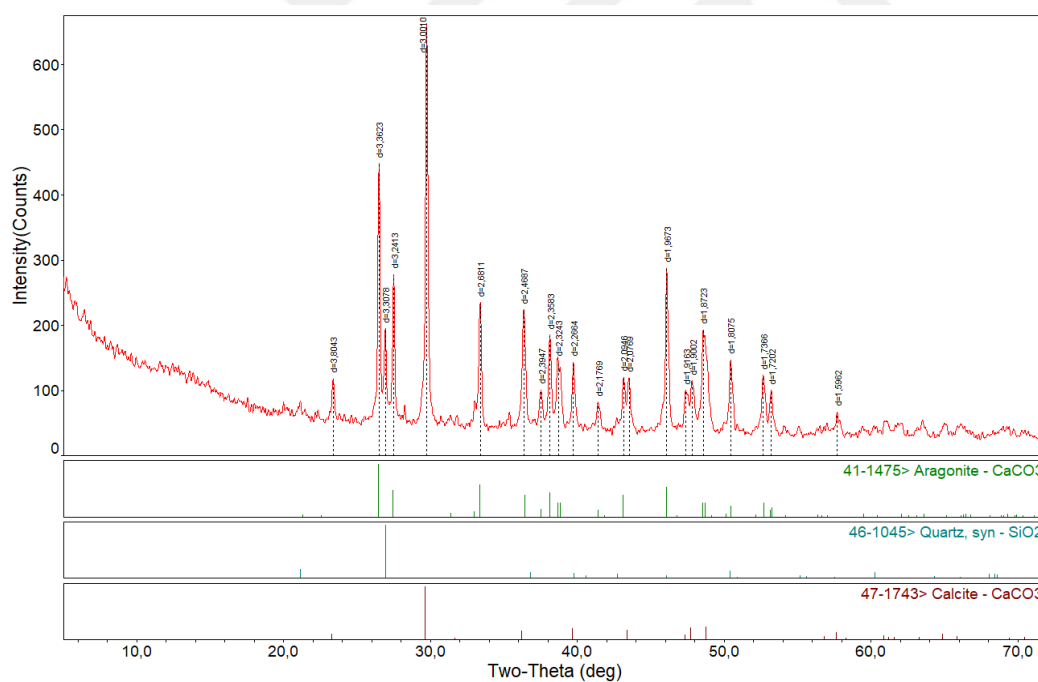


Figure B.10: X-ray diffractometric pattern of Urmia Lake coated grain from 22.65 m. The identified minerals are calcite, aragonite, and quartz.

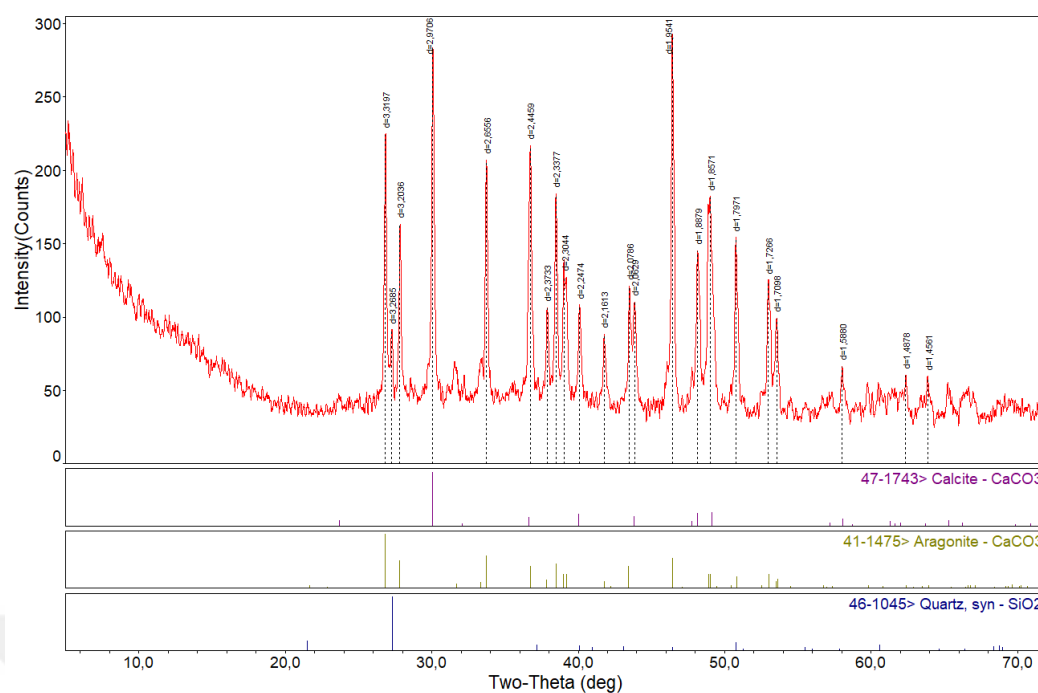


Figure B.11: X-ray diffractometric pattern of Urmia Lake coated grain from 23.55 m. The identified minerals are calcite, aragonite, and quartz.

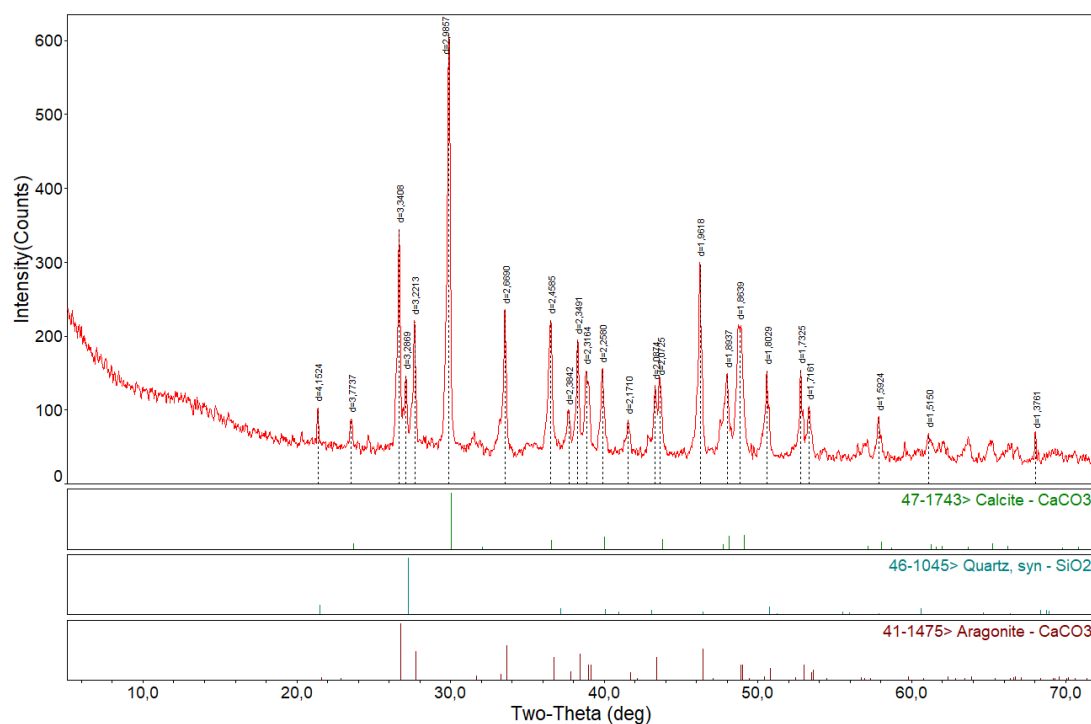


Figure B.12: X-ray diffractometric pattern of Urmia Lake coated grain from 24.37 m. The identified minerals are calcite, aragonite, and quartz.

Table B.1: XRD results of coated grains from different depths along the sediment core.

Depth (m)	Sample compositions
16.31	calcite, aragonite and quartz
16.85	calcite, aragonite quartz and chlorartinite
17.98	calcite, aragonite and quartz
18.73	calcite, aragonite, quartz and kernite
19.73	calcite, aragonite and quartz
20.49	calcite, aragonite and quartz
21.47	calcite, aragonite, quartz and gypsum
22.65	calcite, aragonite and quartz
23.55	calcite, aragonite and quartz
24.37	calcite, aragonite and quartz

Table B.2: Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
3.94	1.226	0.816	0.997	652.64	0.994	0.793	0.962	0.789
3.94	1.696	0.59	0.994	1547137	0.987	0.881	0.864	0.575
3.94	1.131	0.884	1	93893	0.999	0.787	0.978	0.853
3.94	6.325	0.158	0.999	4999315	0.973	0.886	0.383	0.157
3.94	5.332	0.188	0.998	9797053	0.932	0.811	0.402	0.174
3.94	5.064	0.197	0.999	2171198	0.988	0.896	0.466	0.197
5.06	1.799	0.556	0.998	468591	0.989	0.843	0.855	0.537
5.06	1.596	0.626	1	274481	0.998	0.846	0.91	0.62
5.06	4.67	0.214	0.999	6696951	0.955	0.896	0.475	0.21
5.06	3.899	0.257	0.992	8327963	0.956	0.786	0.512	0.254
5.06	4.446	0.225	0.999	1463681	0.991	0.905	0.514	0.224
5.06	3.931	0.254	0.999	3031.51	0.977	0.866	0.552	0.247
6.23	4.957	0.202	0.997	3764965	0.955	0.894	0.447	0.194
6.23	6.499	0.154	0.999	4975.97	0.968	0.899	0.376	0.152
6.23	2.027	0.493	1	137768	0.998	0.856	0.819	0.493
6.23	2.443	0.409	0.996	1828497	0.964	0.872	0.726	0.396
12.32	2.044	0.489	0.999	164394	0.995	0.773	0.807	0.485
12.32	2.998	0.334	1	175205	0.995	0.863	0.678	0.331
12.32	2.226	0.449	1	30545	0.999	0.851	0.8	0.449
15.89	2.182	0.458	1	109498	0.998	0.818	0.801	0.453
15.89	2.631	0.38	1	131466	0.997	0.855	0.728	0.376

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
15.89	3.063	0.326	1	175917	0.996	0.85	0.654	0.322
15.89	1.965	0.509	0.998	420655	0.989	0.827	0.824	0.499
15.97	2.106	0.475	0.999	282456	0.992	0.839	0.814	0.472
15.97	2.756	0.363	0.988	1363201	0.968	0.755	0.667	0.355
15.97	1.333	0.75	0.995	685819	0.994	0.815	0.943	0.733
16.12	2.96	0.338	0.996	974135	0.981	0.832	0.663	0.336
16.12	1.205	0.83	1	52469	0.999	0.818	0.965	0.808
16.12	1.061	0.942	1	0	1	0.772	0.956	0.79
16.12	3.455	0.289	0.999	1253006	0.986	0.853	0.6	0.288
16.12	3.304	0.303	1	890222	0.989	0.885	0.619	0.295
16.12	3.507	0.285	0.999	2090469	0.982	0.877	0.609	0.282
16.12	2.443	0.409	1	164032	0.998	0.865	0.764	0.409
16.12	1.721	0.581	1	104461	0.999	0.848	0.895	0.577
16.12	1.308	0.764	1	112056	0.999	0.824	0.945	0.738
16.12	2.801	0.357	1	18397	0.999	0.871	0.706	0.356
16.12	2.886	0.346	1	178118	0.998	0.858	0.686	0.346
16.12	2.874	0.348	1	790631	0.989	0.862	0.691	0.342
16.12	2.747	0.364	1	270358	0.998	0.832	0.698	0.363
16.12	2.905	0.344	0.999	980882	0.989	0.847	0.661	0.34
16.26	1.8	0.556	1	51595	0.999	0.829	0.864	0.554
16.26	2.917	0.343	0.989	5315961	0.935	0.839	0.632	0.319
16.26	1.384	0.723	0.992	1369994	0.985	0.761	0.925	0.689
16.31	1.344	0.744	0.998	1931052	0.991	0.804	0.92	0.678
16.31	2.439	0.41	1	2331.99	0.983	0.892	0.738	0.407
16.31	2.447	0.409	1	1056555	0.987	0.803	0.723	0.403
16.31	1.282	0.78	1	152359	0.999	0.775	0.962	0.769
16.31	2.721	0.367	1	208448	0.997	0.855	0.71	0.367
16.31	1.606	0.623	1	58.6	1	0.823	0.917	0.622
16.45	1.612	0.62	0.999	554746	0.995	0.763	0.881	0.611
16.45	1.882	0.531	1	234217	0.997	0.837	0.856	0.524
16.45	1.008	0.992	0.992	6323.43	0.971	0.741	0.914	0.745
16.73	3.398	0.294	1	918283	0.993	0.859	0.615	0.294
16.73	2.616	0.382	1	1203267	0.992	0.847	0.734	0.38
16.73	2.216	0.451	1	234933	0.999	0.835	0.804	0.449
16.85	1.097	0.911	0.987	1763391	0.983	0.769	0.934	0.733
16.85	1.007	0.993	1	6287	1	0.781	0.972	0.86
16.85	2.323	0.43	1	291355	0.996	0.841	0.714	0.416
16.85	3.339	0.299	1	629211	0.995	0.873	0.623	0.296
16.85	2.81	0.356	1	461.39	0.994	0.868	0.696	0.354
16.85	2.371	0.422	1	542247	0.996	0.87	0.769	0.421
16.85	4.212	0.237	1	775.69	0.996	0.881	0.537	0.237
16.85	3.138	0.319	1	1195342	0.991	0.877	0.646	0.316

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
16.85	2.381	0.42	1	769533	0.994	0.836	0.762	0.412
16.95	2.874	0.348	1	418852	0.995	0.888	0.687	0.347
16.95	2.732	0.366	1	461152	0.995	0.876	0.705	0.364
16.95	2.431	0.411	1	375397	0.996	0.885	0.752	0.41
16.95	2.363	0.423	1	296099	0.996	0.856	0.7	0.406
16.95	3.317	0.301	0.999	1096976	0.985	0.885	0.627	0.299
16.95	1.578	0.634	1	0	1	0.814	0.921	0.63
17.05	3.076	0.325	1	303892	0.996	0.897	0.668	0.324
17.05	1.055	0.948	0.993	2488142	0.976	0.766	0.917	0.772
17.05	1.46	0.685	0.997	351257	0.996	0.824	0.933	0.679
17.2	2.967	0.337	0.998	1468872	0.989	0.872	0.669	0.334
17.2	1.396	0.716	0.995	1490248	0.967	0.872	0.839	0.597
17.2	3.469	0.288	1	1914725	0.981	0.905	0.603	0.285
17.38	1.231	0.812	1	0	1	0.77	0.956	0.797
17.38	2.357	0.424	0.999	718451	0.989	0.9	0.748	0.418
17.38	1.923	0.52	1	53653	0.999	0.853	0.848	0.519
17.38	1.427	0.701	1	124925	0.999	0.816	0.94	0.695
17.38	2.067	0.484	0.993	1009883	0.991	0.836	0.823	0.483
17.38	3.411	0.293	0.999	1380048	0.983	0.905	0.607	0.293
17.46	2.294	0.436	0.999	803617	0.988	0.914	0.757	0.42
17.46	1.909	0.524	1	145268	0.997	0.86	0.856	0.52
17.65	2.081	0.481	1	28081	1	0.85	0.815	0.479
17.65	1.219	0.821	0.999	246444	0.997	0.791	0.963	0.787
17.65	2.754	0.363	0.999	2437374	0.988	0.865	0.698	0.362
17.65	1.953	0.512	0.999	4414054	0.986	0.836	0.821	0.486
17.65	2.022	0.495	1	9216	1	0.858	0.837	0.492
17.65	1.57	0.637	1	599.69	0.997	0.794	0.903	0.625
17.65	1.891	0.529	1	248049	0.997	0.833	0.858	0.528
17.65	2.004	0.499	1	77934	0.999	0.843	0.845	0.498
17.65	1.911	0.523	0.996	644006	0.991	0.824	0.831	0.517
17.8	2.204	0.454	0.998	671833	0.99	0.817	0.791	0.449
17.8	2.32	0.431	1	33529	1	0.844	0.768	0.431
17.8	3.447	0.29	1	1094826	0.988	0.841	0.604	0.288
17.8	1.09	0.918	0.999	1207954	0.994	0.785	0.955	0.776
17.8	1.232	0.812	1	0	1	0.806	0.967	0.799
17.98	3.746	0.267	1	2538306	0.988	0.895	0.582	0.267
17.98	3.103	0.322	1	715513	0.997	0.877	0.659	0.322
17.98	1.215	0.823	1	398.01	0.997	0.811	0.947	0.793
17.98	1.175	0.851	1	28497	1	0.765	0.923	0.726
17.98	1.01	0.99	1	0	1	0.812	0.989	0.945
17.98	3.767	0.265	1	2285524	0.989	0.897	0.57	0.262
18.1	3.125	0.32	1	1179.15	0.993	0.874	0.659	0.316

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
18.1	2.533	0.395	1	559885	0.994	0.889	0.703	0.391
18.10	1.546	0.647	0.999	1902763	0.988	0.771	0.889	0.628
18.25	1.982	0.504	1	1023	1	0.846	0.843	0.503
18.25	2.412	0.415	1	282814	0.997	0.886	0.771	0.414
18.25	4.37	0.229	0.999	5022488	0.962	0.873	0.504	0.228
18.59	3.266	0.306	0.998	339924	0.996	0.848	0.629	0.305
18.59	1.293	0.773	0.999	1153.48	0.995	0.801	0.924	0.74
18.59	1.716	0.583	0.999	484591	0.994	0.754	0.846	0.555
18.73	3.571	0.28	1	2259364	0.982	0.901	0.582	0.274
18.73	2.041	0.49	1	189446	0.998	0.87	0.83	0.487
18.73	1.249	0.8	1	0	1	0.792	0.968	0.788
18.73	1.615	0.619	0.997	1893299	0.987	0.757	0.842	0.585
18.73	1.997	0.501	1	361985	0.996	0.858	0.84	0.498
18.94	3.715	0.269	1	525588	0.997	0.883	0.583	0.268
18.94	2.254	0.444	0.998	500925	0.997	0.885	0.797	0.442
18.94	1.171	0.854	1	87955	1	0.779	0.978	0.841
18.94	3.073	0.325	1	241424	0.999	0.871	0.662	0.325
18.94	1.245	0.803	0.999	800817	0.993	0.762	0.923	0.76
18.94	1.91	0.523	0.991	879.31	0.987	0.84	0.832	0.519
18.94	3.769	0.265	1	1493.63	0.975	0.912	0.567	0.262
18.94	3.229	0.31	1	377704	0.994	0.876	0.644	0.308
18.94	1.091	0.916	1	0	1	0.8	0.979	0.885
19.35	4.322	0.231	0.999	4159142	0.972	0.891	0.517	0.224
19.35	1.169	0.855	1	404972	0.998	0.78	0.946	0.767
19.35	1.117	0.895	1	15502	1	0.797	0.98	0.874
19.35	1.649	0.606	1	166336	0.998	0.827	0.903	0.599
19.35	1.532	0.653	1	133656	0.999	0.817	0.928	0.651
19.49	4.865	0.206	1	1652.78	0.988	0.906	0.475	0.203
19.49	1.888	0.53	1	130146	0.998	0.855	0.849	0.524
19.73	1.877	0.533	1	133681	0.999	0.835	0.863	0.53
19.73	1.211	0.826	1	25144	1	0.788	0.976	0.814
19.73	2	0.5	1	0	1	0.851	0.839	0.498
19.73	4.347	0.23	1	1127344	0.995	0.925	0.524	0.23
19.73	2.52	0.397	1	130333	0.999	0.87	0.751	0.395
19.73	2.845	0.352	0.999	1281817	0.989	0.902	0.681	0.35
19.73	1.239	0.807	0.999	465244	0.996	0.759	0.915	0.732
19.73	3.089	0.324	1	443534	0.997	0.857	0.658	0.324
19.73	1.135	0.881	1	246268	0.998	0.791	0.96	0.814
19.95	4.113	0.243	0.999	1775445	0.985	0.898	0.532	0.243
19.95	3.497	0.286	1	1025196	0.984	0.845	0.597	0.28
19.95	1.343	0.744	1	44175	1	0.768	0.926	0.729
20.12	3.848	0.26	1	195401	0.998	0.927	0.569	0.26

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
20.12	3.086	0.324	1	0	1	0.873	0.666	0.324
20.26	3.744	0.267	1	0	1	0.864	0.58	0.266
20.26	3.123	0.32	1	1015.78	0.99	0.838	0.649	0.318
20.41	3.124	0.32	0.998	1266275	0.988	0.857	0.652	0.319
20.41	2.334	0.428	1	180657	0.997	0.858	0.775	0.425
20.49	5.7	0.175	0.999	1956089	0.985	0.877	0.419	0.171
20.49	2.691	0.372	1	757064	0.989	0.916	0.662	0.354
20.83	5.079	0.197	1	1546127	0.989	0.877	0.461	0.196
20.83	2.443	0.409	1	647961	0.989	0.811	0.73	0.403
20.83	3.35	0.298	1	859778	0.992	0.874	0.622	0.298
20.89	3.363	0.297	1	341521	0.997	0.868	0.616	0.295
20.89	2.639	0.379	1	106074	0.998	0.855	0.734	0.378
20.89	3.266	0.306	1	197.45	0.999	0.885	0.632	0.305
21.25	1.793	0.558	1	0	1	0.852	0.876	0.557
21.25	1.414	0.707	1	671322	0.997	0.79	0.92	0.695
21.25	1.121	0.892	1	10965	1	0.789	0.982	0.874
21.25	2.805	0.357	0.999	579968	0.993	0.942	0.661	0.35
21.25	2.787	0.359	1	1410823	0.991	0.882	0.704	0.358
21.32	1.023	0.977	1	394252	0.998	0.84	0.964	0.863
21.32	1.388	0.72	0.999	408139	0.997	0.796	0.907	0.707
21.32	1.736	0.576	0.999	252921	0.998	0.864	0.873	0.573
21.32	2.483	0.403	1	1109411	0.993	0.874	0.756	0.397
21.32	2.14	0.467	1	110731	0.999	0.857	0.816	0.466
21.47	3.23	0.31	1	531707	0.996	0.891	0.645	0.309
21.47	3.762	0.266	1	2003815	0.984	0.89	0.553	0.265
21.69	3.025	0.331	1	786834	0.994	0.897	0.666	0.33
21.69	3.061	0.327	1	928195	0.994	0.893	0.669	0.326
21.69	2.914	0.343	1	640207	0.995	0.898	0.693	0.342
21.75	3.549	0.282	1	1432446	0.986	0.903	0.598	0.278
21.75	1.15	0.87	0.997	4907368	0.984	0.753	0.919	0.7
21.75	1.174	0.852	1	15525	1	0.852	0.948	0.787
21.75	5.163	0.194	0.999	3666409	0.973	0.901	0.448	0.192
21.91	4.868	0.205	1	1137703	0.994	0.883	0.486	0.205
21.91	2.52	0.397	1	186891	0.999	0.869	0.751	0.396
21.91	1.458	0.686	1	190243	0.999	0.787	0.925	0.662
22.27	1.475	0.678	1	230484	0.999	0.792	0.932	0.676
22.27	1.318	0.759	0.999	2154396	0.988	0.784	0.918	0.708
22.27	5.049	0.198	1	1775232	0.991	0.886	0.474	0.196
22.27	2.526	0.396	1	419764	0.997	0.865	0.749	0.395
22.27	1.502	0.666	1	94098	0.999	0.795	0.926	0.663
22.27	2.431	0.411	0.996	1715927	0.982	0.863	0.744	0.403

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
22.27	1.327	0.753	0.999	1036599	0.993	0.817	0.889	0.689
22.35	1.414	0.707	0.999	443754	0.996	0.798	0.913	0.676
22.35	1.201	0.833	0.991	5895378	0.961	0.715	0.856	0.664
22.54	2.339	0.428	1	425728	0.996	0.87	0.782	0.424
22.54	2.755	0.363	1	382169	0.995	0.886	0.705	0.363
22.54	1.214	0.824	1	84242	1	0.779	0.962	0.772
22.54	4.167	0.24	1	2202115	0.991	0.875	0.535	0.239
22.54	4.033	0.248	1	1890308	0.986	0.852	0.543	0.245
22.65	3.81	0.262	1	1526878	0.989	0.904	0.579	0.261
22.65	1.76	0.568	1	52222	1	0.843	0.889	0.567
22.65	4.755	0.21	1	1503341	0.993	0.917	0.489	0.21
22.65	5.004	0.2	1	5118924	0.972	0.902	0.46	0.195
22.65	3.065	0.326	1	306913	0.997	0.873	0.661	0.326
22.65	1.442	0.694	1	172894	0.999	0.79	0.932	0.689
22.86	3.706	0.27	0.994	2375647	0.967	0.854	0.555	0.269
22.86	1.897	0.527	1	63814	0.999	0.831	0.853	0.525
22.86	3.026	0.331	0.999	686882	0.988	0.847	0.669	0.326
22.86	1.005	0.995	1	0	1	0.806	0.986	0.905
23.05	1.64	0.61	1	44.42	1	0.84	0.909	0.605
23.05	1.29	0.775	0.996	147271	0.997	0.833	0.959	0.765
23.05	3.148	0.318	0.999	1274132	0.988	0.888	0.649	0.315
23.05	4.702	0.213	1	2166098	0.989	0.873	0.488	0.208
23.05	4.987	0.201	1	219762	0.999	0.89	0.474	0.201
23.05	5.04	0.198	1	1416017	0.99	0.894	0.465	0.196
23.26	4.768	0.21	0.998	3995544	0.983	0.881	0.469	0.209
23.26	2.655	0.377	1	608.9	0.995	0.865	0.726	0.373
23.26	2.186	0.457	1	497459	0.995	0.859	0.798	0.455
23.4	5.193	0.193	1	1248969	0.993	0.919	0.464	0.192
23.4	3.516	0.284	1	559613	0.997	0.897	0.612	0.284
23.4	4.029	0.248	0.999	3861.8	0.975	0.867	0.531	0.239
23.4	5.419	0.185	1	1356167	0.995	0.929	0.449	0.184
23.4	5.336	0.187	1	1094.66	0.994	0.923	0.459	0.186
23.4	3.49	0.287	1	519422	0.997	0.885	0.615	0.287
23.55	5.019	0.199	1	2163955	0.986	0.872	0.463	0.196
23.55	3.289	0.304	0.999	3355802	0.973	0.894	0.619	0.304
23.55	2.281	0.438	1	401343	0.994	0.85	0.783	0.431
23.55	5.084	0.197	1	1381343	0.991	0.89	0.464	0.194
23.55	4.761	0.21	1	2946806	0.984	0.885	0.486	0.204
23.55	3.353	0.298	0.999	2841011	0.976	0.908	0.614	0.295
23.67	4.773	0.21	1	1131182	0.994	0.905	0.489	0.209
23.67	4.45	0.225	0.996	1396578	0.99	0.915	0.499	0.222
23.67	2.723	0.367	1	101297	0.999	0.857	0.718	0.367

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
23.83	4.755	0.21	1	255813	0.999	0.906	0.494	0.21
23.83	5.11	0.196	0.998	2347873	0.986	0.919	0.466	0.195
23.83	4.656	0.215	0.997	1218723	0.992	0.876	0.492	0.214
23.97	3.671	0.272	0.999	875186	0.993	0.906	0.581	0.269
23.97	2.152	0.465	1	618851	0.993	0.862	0.805	0.459
23.97	1.304	0.767	1	64175	0.999	0.806	0.968	0.763
24.14	3.448	0.29	1	862376	0.989	0.873	0.607	0.286
24.14	2.698	0.371	1	879471	0.992	0.884	0.712	0.367
24.14	3.97	0.252	1	1297732	0.991	0.9	0.558	0.25
24.14	1.13	0.885	0.99	6896984	0.963	0.751	0.875	0.709
24.14	1.181	0.847	1	0	1	0.809	0.963	0.811
24.14	4.242	0.236	1	1435439	0.99	0.886	0.535	0.235
24.14	1.447	0.691	1	318188	0.998	0.782	0.926	0.678
24.14	4.54	0.22	1	1569633	0.988	0.864	0.497	0.219
24.14	4.892	0.204	1	1530804	0.99	0.894	0.482	0.201
24.14	4.287	0.233	1	1557102	0.989	0.89	0.534	0.231
24.25	4.91	0.204	1	2283454	0.989	0.917	0.48	0.203
24.25	4.43	0.226	0.999	1483309	0.991	0.901	0.523	0.226
24.25	4.739	0.211	1	1610733	0.992	0.891	0.493	0.211
24.25	1.14	0.877	0.998	1282057	0.995	0.813	0.9	0.707
24.25	1.162	0.86	1	443226	0.998	0.79	0.934	0.742
24.25	1.016	0.984	0.999	829434	0.996	0.733	0.904	0.728
24.25	1.094	0.914	0.995	2829525	0.981	0.795	0.926	0.71
24.25	1.481	0.675	0.996	4736663	0.986	0.795	0.904	0.661
24.37	3.169	0.316	1	2161009	0.985	0.886	0.647	0.308
24.37	2.835	0.353	0.999	872168	0.992	0.85	0.679	0.348
24.37	3.749	0.267	0.998	4984555	0.967	0.781	0.543	0.252
24.37	1.336	0.748	1	0	1	0.808	0.959	0.743
24.37	1.091	0.917	0.998	1951472	0.989	0.837	0.949	0.8
24.37	3.079	0.325	1	776438	0.993	0.87	0.666	0.322
24.37	1.757	0.569	1	171858	0.998	0.833	0.879	0.565
24.37	1.907	0.525	0.999	698473	0.994	0.815	0.844	0.524
24.37	1.32	0.758	1	86679	0.998	0.769	0.935	0.712
24.53	1.117	0.896	0.999	1099418	0.991	0.794	0.931	0.733
24.53	1.354	0.739	0.992	4033357	0.978	0.791	0.888	0.659
24.53	1.122	0.891	0.996	1763898	0.987	0.777	0.922	0.751
24.53	2.69	0.372	1	603399	0.996	0.917	0.715	0.369
24.53	4.523	0.221	1	1700676	0.991	0.913	0.508	0.221
24.53	3.058	0.327	1	284931	0.998	0.885	0.674	0.326
24.53	1.087	0.92	0.999	835141	0.996	0.813	0.97	0.841
24.53	2.66	0.376	1	1091091	0.993	0.916	0.713	0.371
24.53	4.715	0.212	1	1327503	0.993	0.923	0.497	0.211

Table B.2 (continued): Morphometric analysis of selected coated grains along the sediment core.

Depth (m)	LTWR	WTLR	CONV	CONC	SOLI	RECT	ROUN	SPHE
24.76	1.545	0.647	0.971	7325661	0.945	0.718	0.841	0.553
24.76	4.125	0.242	1	763051	0.993	0.896	0.549	0.242
24.76	2.992	0.334	1	2312.48	0.989	0.877	0.672	0.324
24.76	1.562	0.64	0.979	6050431	0.955	0.725	0.845	0.552
24.76	1.029	0.972	0.999	885.35	0.996	0.794	0.96	0.812
24.76	1.226	0.816	1	20037	1	0.815	0.979	0.811
24.76	4.838	0.207	1	1024281	0.994	0.894	0.489	0.205
24.76	4.166	0.24	1	291956	0.997	0.905	0.552	0.239
24.76	1.262	0.793	0.999	988891	0.993	0.788	0.927	0.743

Table B.3: SEM-EDS cortex major element composition of selected coated grains along the sediment core. Values in weight % oxides.

Depth (m)	CaO [wt.-%]	SiO ₂ [wt.-%]	Other elements [wt.-%]
16.45	80.25	0.00	19.75
16.73	87.93	12.07	0.00
16.85	93.66	0.00	6.34
16.95	80.55	4.03	15.42
17.20	92.37	0.91	6.72
17.38	85.45	1.85	12.69
17.46	89.25	1.15	9.60
17.65	88.71	3.75	7.54
17.80	83.31	3.11	13.57
17.98	85.05	3.21	11.74
18.10	96.10	0.00	3.90
18.25	79.82	2.22	17.96
18.59	79.47	4.17	16.36
18.73	82.16	2.69	15.16
18.94	82.45	2.25	15.30
19.35	80.04	5.67	14.29
19.49	86.67	1.99	11.34
19.73	90.93	1.84	7.23
19.95	77.73	3.31	18.96
20.12	86.18	2.07	11.75
20.26	79.51	4.56	15.93
20.41	75.21	3.13	21.66
20.49	73.52	5.46	21.02
20.83	27.90	21.45	50.65
20.89	87.02	0.00	12.98
21.25	100.00	0.00	0.00
21.32	100.00	0.00	0.00
21.47	85.53	2.13	12.35
21.75	90.39	0.00	9.61
21.91	81.93	3.21	14.86
22.27	90.93	1.48	7.59

Table B.3 (continued) : SEM-EDS cortex major element composition of selected coated grains along the sediment core. Values in weight % oxides.

22.35	91.41	0.00	8.59
22.54	87.68	2.90	9.41
22.65	89.61	0.87	9.53
22.86	87.51	0.00	12.49
23.05	88.38	2.23	9.39
23.26	90.14	0.00	9.86
23.40	82.20	0.00	17.80
23.55	91.10	0.00	8.90
23.97	99.96	0.00	0.04
24.14	99.99	0.00	0.01
24.25	99.98	0.00	0.02
24.37	93.80	0.00	6.20
24.53	91.74	2.19	6.07
24.76	92.07	1.25	6.68

mean CaO [wt.-%]	mean SiO ₂ [wt.-%]	mean other elements [wt.-%]
86.35	2.38	11.27

Table B.4: SEM-EDS nucleus major element composition of selected coated grains along the sediment core. Values in weight % oxides.

Depth (m)	CaO [wt %]	SiO ₂ [wt %]	MgO [wt %]	Al ₂ O ₃ [wt %]	Na ₂ O [wt %]	FeO [wt %]	TiO ₂ [wt %]	K ₂ O [wt %]	S [wt%]
16.26	3.85	93.03	1.01	0.89	1.22	0.00	0.00	0.00	0.00
16.45	88.68	7.37	2.10	1.85	0.00	0.00	0.00	0.00	0.00
16.73	54.32	26.04	2.78	11.17	2.00	1.32	0.00	2.37	0.00
16.85	56.26	29.94	2.66	7.79	3.35	0.00	0.00	0.00	0.00
16.95	53.28	11.25	6.49	2.21	4.73	17.26	0.00	0.00	4.78
17.2	69.44	16.27	5.29	5.21	2.18	1.60	0.00	0.00	0.00
17.38	55.89	28.10	6.11	5.40	4.49	0.00	0.00	0.00	0.00
17.46	68.90	18.03	7.18	3.10	2.80	0.00	0.00	0.00	0.00
17.65	69.89	17.11	4.82	4.60	2.62	0.64	0.32	0.00	0.00
17.8	52.11	27.52	7.43	8.38	1.96	1.03	0.00	1.30	0.27
17.98	36.44	28.26	9.81	8.29	7.05	10.14	0.00	0.00	0.00
18.1	26.93	41.66	2.77	10.39	0.00	11.03	3.45	3.77	0.00
18.25	66.42	21.54	4.60	6.00	1.44	0.00	0.00	0.00	0.00
18.59	28.74	41.38	7.24	12.13	4.29	3.84	0.00	1.00	0.57
18.73	32.61	60.32	2.40	2.93	1.74	0.00	0.00	0.00	0.00
18.94	48.87	34.44	3.55	9.69	0.04	1.08	0.00	2.33	0.00
19.35	90.21	5.06	1.15	0.87	2.69	0.00	0.00	0.00	0.00
19.49	76.65	19.22	1.54	2.60	0.00	0.00	0.00	0.00	0.00
19.73	30.75	53.03	5.91	6.69	1.42	2.20	0.00	0.00	0.00

Table B.4 (continued): SEM-EDS nucleus major element composition of selected coated grains along the sediment core. Values in weight % oxides.

19.95	26.46	22.65	6.18	0.00	0.00	1.62	43.09	0.00	0.00
20.12	38.89	40.45	2.23	12.18	4.07	2.19	0.00	0.00	0.00
20.26	45.27	35.27	9.97	6.27	0.00	3.23	0.00	0.00	0.00
20.41	27.01	41.75	7.25	9.09	2.94	6.03	3.81	2.12	0.00
20.49	11.47	48.88	15.76	12.35	0.00	11.53	0.00	0.00	0.00
20.83	56.26	29.02	11.20	3.52	0.00	0.00	0.00	0.00	0.00
20.89	23.20	47.75	4.26	14.66	4.09	4.25	0.00	1.80	0.00
21.25	49.43	22.49	13.21	5.01	0.00	9.85	0.00	0.00	0.00
21.32	73.78	13.86	3.71	4.28	1.73	2.65	0.00	0.00	0.00
21.47	72.17	13.00	5.93	4.41	4.48	0.00	0.00	0.00	0.00
21.75	44.24	41.89	6.68	4.11	3.08	0.00	0.00	0.00	0.00
21.91	86.35	4.86	6.15	0.00	2.64	0.00	0.00	0.00	0.00
22.27	92.45	0.00	3.73	0.00	3.81	0.00	0.00	0.00	0.00
22.35	55.17	22.53	10.22	7.62	4.47	0.00	0.00	0.00	0.00
22.54	60.05	23.12	7.55	5.69	0.70	1.85	0.00	1.05	0.00
22.65	62.78	20.22	5.35	6.41	2.58	2.08	0.00	0.59	0.00
22.86	0.00	64.64	7.40	18.25	6.77	1.02	0.00	1.92	0.00
23.05	81.27	10.18	3.52	2.02	3.01	0.00	0.00	0.00	0.00
23.26	28.06	34.44	16.23	13.17	4.62	3.48	0.00	0.00	0.00
23.55	3.21	60.13	0.00	24.15	12.51	0.00	0.00	0.00	0.00
23.67	9.92	23.87	21.20	11.67	25.90	0.00	0.00	7.44	0.00
23.83	73.97	18.05	2.55	5.44	0.00	0.00	0.00	0.00	0.00
23.97	80.52	12.13	3.38	2.34	1.64	0.00	0.00	0.00	0.00
24.14	28.20	39.90	11.59	9.63	1.73	7.08	0.81	0.95	0.00
24.25	51.81	29.62	5.39	10.03	0.47	1.22	0.00	1.47	0.00
24.37	55.42	23.25	3.53	4.42	5.54	0.00	7.84	0.00	0.00
24.53	37.39	46.46	2.88	8.33	1.85	2.43	0.00	0.65	0.00
24.76	43.98	15.78	3.54	5.12	1.92	20.02	0.00	0.00	9.64



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PUBLICATIONS AND PRESENTATIONS ON THE THESIS:

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