Mudrock Resistivity Reversal in the Riserless Section of Deep-Water Well, Western Black Sea: A Geological Phenomenon Unrelated to Shallow Hazards

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Abstract: ***Uncertainty related to Shallow Hazards associated with overpressure just beneath the seabed in the deep water Western Black Sea prompted drilling of a riserless pilot hole in the top hole section of an exploration well as a mitigation measure. The riserless section indicated mudrocks of low resistivity to the extent of as low as 0.2 ohm-m. The pilot and the main holes revealed that the pore pressures estimated from these low mudrock resistivities were much higher than actual pore pressures. However, the benign well behavior invalidated the pore pressure estimates, signifying it as a false alarm. Therefore, it is imperative to investigate what causes the significant lowering of mudrock resistivity. Understanding the geological history of the region holds the key to the underlying process that shaped the electrolog response. Analogues were consulted, and the geological history of the Black Sea was studied to explain the low resistive mudrocks just beneath the seabed. With periodic saline water incursions through the Bosporus Strait in the Pliocene to recent sediments of the Black Sea, as documented in various studies, it is not unusual for the unconsolidated mud rocks to be influenced by the salinity of the incursions from the Mediterranean Sea. The sediments, characterized by their softness and porosity, along with the percolation of the weight of seawater above them, contributed to the retention of the denser saline water within the interstices. Hence, the resistivity responses are subdued. The outflow from the Black Sea is characterized by lower temperatures and reduced salinity, allowing it to float above the warmer, saltier inflow from the Mediterranean. This phenomenon arises from variations in density attributed to differences in salinity, resulting in the formation of a substantial anoxic layer situated well beneath the surface waters. Therefore, the lower mudrock resistivities are not the reflection of higher pore pressures but only the imprint of the preservation of environmental conditions of that geological period. These shallow formations just beneath the seabed are inferred to be connected to the seabed and therefore of hydrostatic pressures, with the overburden pressure being borne by the rock framework. This indicates that the environment of deposition plays a key part in the pressure generation in the Black Sea Basin, and understanding it is important for predicting the pore pressures. This attempt will serve as a platform for future ventures in the Black Sea.***

Keywords: Low resistivity, pore pressure, shallow hazards, salinity, pilot hole, main hole, Bosporus, Mediterranean

1. Introduction

The Black Sea is an extensive deep-water basin that reaches depths exceeding two kilometres. It is encircled by continental landmasses, with the stable European platform to the north, the Caucasus Mountains to the northeast, the Lesser Caucasus and Pontides Mountains to the south, the Balkanide Mountains to the southwest, and the Moesian Platform to the west[1]. Deep water drilling is challenging given the narrow drilling window, which is a function of the diminishing difference between the formation fracture initiation pressure and formation pore pressure[2], Deepwater hydrocarbon exploration drilling only began in the Black Sea less than 20 years ago[3].

Shallow flow hazards are generally encountered before the installation of the marine riser. Consequently, if the formation begins to flow uncontrollably, it poses a safety threat to the rig and risks damaging the well structure and affecting the adjacent seafloor[4]. The cost of geological uncertainty is that such unwarranted incidents could wipe out large investments. Integrating safety in everything we do and every decision we make guides the relentless pursuit of the objective of no harm to people and no significant incidents, which is called Goal Zero. All activities and decisions in Shallow hazards monitoring are governed and geared towards achieving Goal Zero. In situations where uncertainty in shallow hazard interpretation is significant during the exploration of uncharted areas, it is prudent first to drill a pilot hole as a due diligence approach and gather insights to effectively proceed with drilling the main hole.

An exploration well drilled in the deep waters of Turkey Offshore in the Black Sea, close to the DSDP wells 380 and 380A (Figure 1) in the riserless section of the pilot hole, indicated the presence of low-resistivity mudrocks having resistivity as low as 0.2 ohm-m with no scope for checking on the drill cuttings as the drill cuttings and mud return were to the seabed. The pore pressure estimated from these mudrock resistivities in real time was higher than the actual pore pressures, which were invalidated by the benign well behaviour. As the pilot hole was incident-free, the main hole was taken up, and it also recorded similar mudrock resistivities. Therefore, it is required to investigate what causes the significant lowering of mudrock resistivity in the drilled shallow sequence.

2. Shallow Hazards of the Deep Waters

Numerous geological hazards exist in shallow formations linked to oil and gas exploration and development in deep-water environments. Shallow hazards present dangers to drilling activities. In deep-sea settings, the seabed may display unstable inclines, leading to slumping, sliding, and the formation of sinkholes. Below the seabed, numerous threats

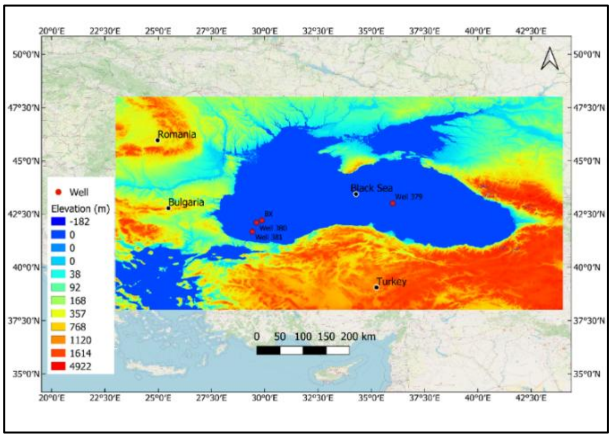

Figure 1: Deep water Exploration well location BX in the Black Sea, southeast of Bulgaria[5]

to drilling arise from shallow water and gas flows, as well as hidden channels and splays containing water and gas (Figure 2). Furthermore, active faults, gas clouds, chimneys, and plumes contribute to these risks, along with dissociating gas hydrates and lateral pressure transfer effects could increase pressures in shallower areas. Shallow flow hazards are generally experienced prior to the installation of the marine riser. If the formation begins to flow uncontrollably, it presents a safety risk to the rig and may damage the well structure, as well as impact the surrounding seafloor. Shallow water flow is particularly alarming, as it can lead to the buckling of casing strings and significant sand buildup on the seafloor. Moreover, an uncontrolled release of water or gas into the ocean can have severe environmental repercussions. Abnormal pore pressure can result in water flow and the accumulation of gas and gas hydrates, potentially impacting drilling safety. Consequently, accurately predicting pore pressure in shallow deep water formations is of significant importance.

Due to the significant uncertainty and the inherent wildcat characteristics of this Black Sea well, the drilling of a pilot hole riserless just below the seabed sediments, coupled with the collection of real-time high-resolution seismic data and dedicated real-time pore pressure predictions to reduce the associated risks, was implemented. During the riserless drilling, the low mudrock resistivity was recorded, and the pore pressure transform indicated overpressures. This created a unique situation in what otherwise would be a benign well. One of the first rules in geology is to step back and detach from preconceived ideas of what it is supposed to be and figure out the bigger picture.

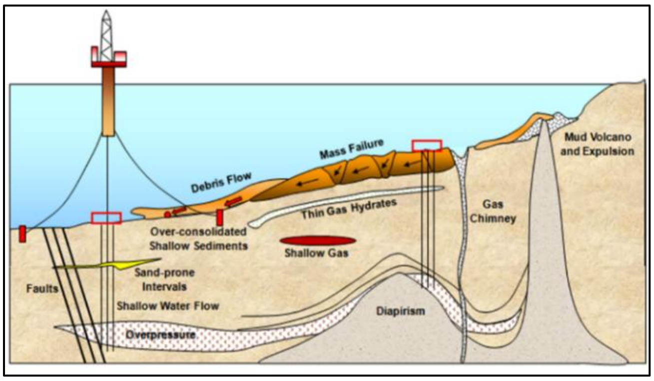

Figure 2: Modified from International Centre for Geohazards, Norwegian Geotechnical Institute (NGI)[6]

3. Pilot Hole Drilling

Figure 3 (a) shows the log response of the pilot hole in the deep water well drilled at a water depth of 2110m. The continuous drop in resistivity is evident from the normal compaction trend line, coloured in black, which reaches 0.2 ohm-m at 2600m TVD. The pore pressures derived from these mudrock resistivities are much higher than the equivalent circulating density and even exceed the predicted high-case pore pressure(Figure 3 (b)). The well behaviour does not suggest that the pore pressure estimates are accurate, and the riserless section could be drilled event-free.

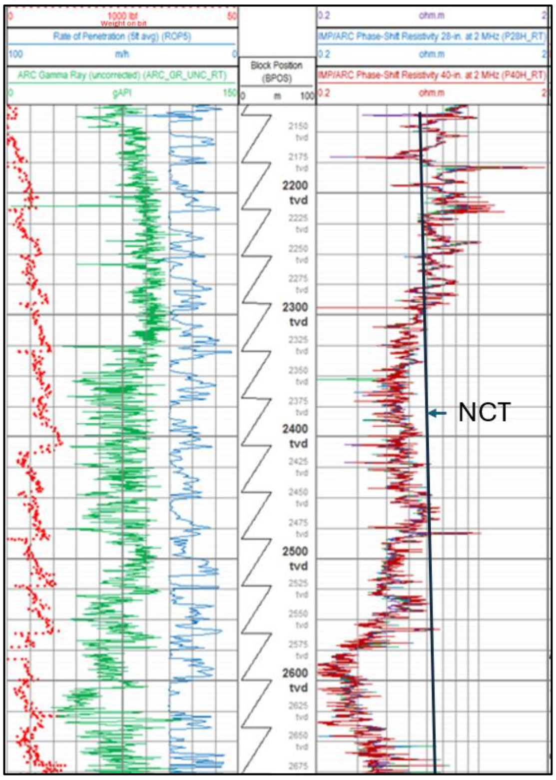

Figure 3: (a) LWD response in the pilot hole, notice the decreasing resistivity with depth and reaching 0.2 ohm-m.

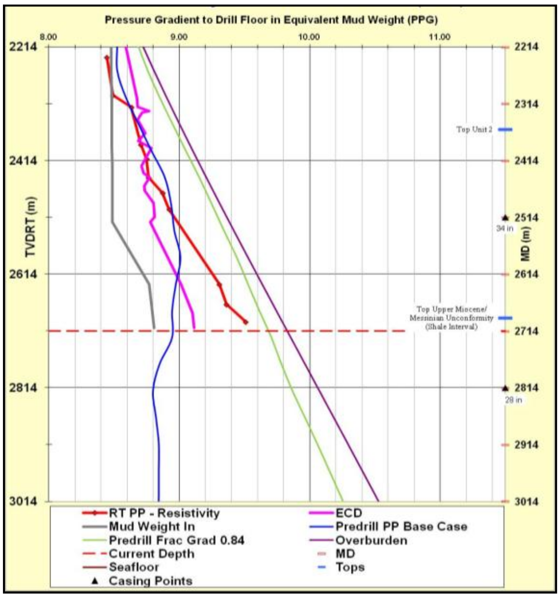

Figure 3: (b) Pore Pressure plot of the pilot hole, note that the pore pressure exceeds the ECD.

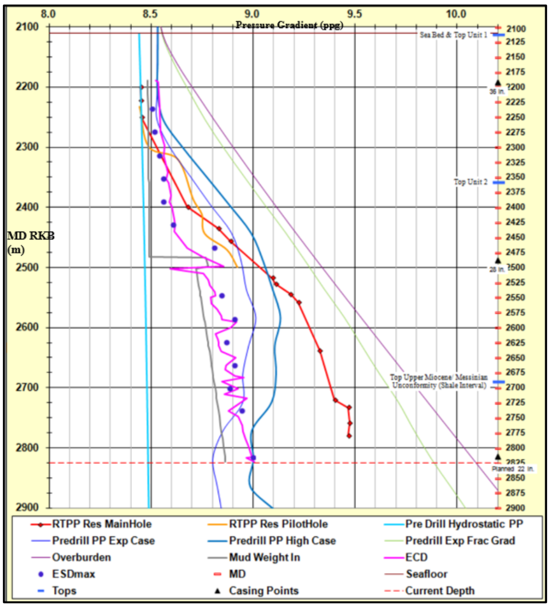

Figure 4: (b) Pore Pressure plot of the mainhole, note that the pore pressure exceeds the ECD

4. Main Hole Drilling

Despite the high log-based pore pressure prediction, the lack of threatening well safety events in the pilot hole prompted the go-ahead with the mainhole drilling. The log response in the main hole is also similar, and the pore pressure estimates derived from these mudrock resistivities are no different from those in the pilot hole (Figures 4 (a) and (b)).

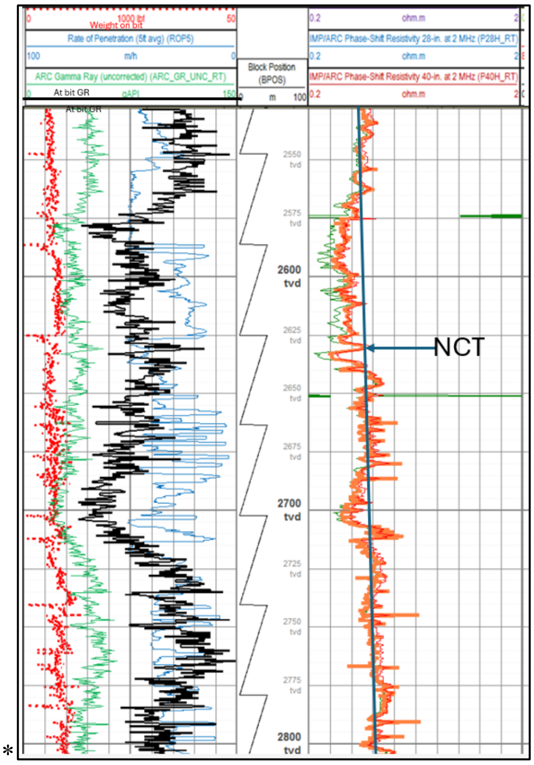

Figure 4: (a) LWD response (main hole) with decreasing resistivity with depth reaching 0.2 ohm-m.

5. Stratigraphy

As the drilling in this section was riserless, no samples were available for examination. However, reference can be taken from DSDP 380 well drilled about 30 km away. The stratigraphy is as follows (Figure 5). The occurrence of Diatomaceous marls, calcareous oozes, and diatomaceous clays is noted. The lithology described is expected to have higher resistivities than those recorded in the well section, even with some disseminations of ore minerals like pyrite and siderite. This is evident from the approximate resistivity ranges that will be discussed later in Section 7 and represented in Figure 6.

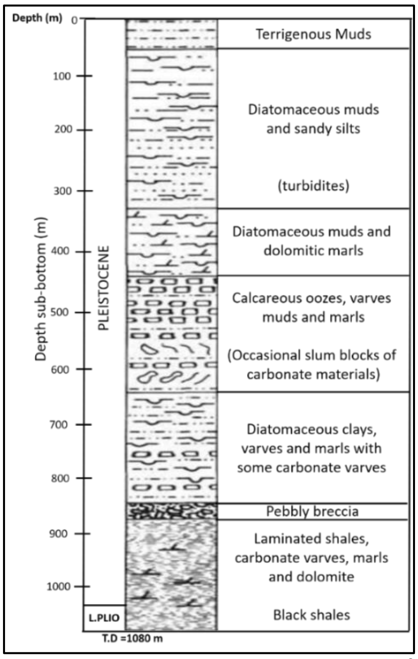

Figure 5: Litho-column at DSDP-380[8]

The following lithology descriptions are from the DSDP 380 core, which covered depths from mudline to 1073.5 m. Pyrite is mentioned in all of the cored intervals, up to 30% by volume

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at depths of 380-389.5 m below mudline; this would certainly lead to low resistivities. Since pyrite often occurs as pore-lining material, providing a continuous circuit throughout the formation, even 1% can provide low-res values. Glauconite is explicitly mentioned in only two intervals, 275.5-285.0 and 332.5-342.0 m, but "heavy minerals," which could include glauconite, are also mentioned frequently. Pyrite was formed when sufficient sulphate ions were reduced by bacterial action into sulphide ions. The presence of sulfate ions in the waters of the Black Sea, primarily sourced from the influx of seawater, has led to the interpretation that significant pyrite found in Black Sea cores serves as a marker for marine-brackish conditions[7].

6. Analogue

The power of geological analogues to stimulate and seed new play ideas and validating assumptions used in probabilistic assurance of new opportunities are widely accepted as the oil and gas industry's "best practice". The well-known parable depicting a group of blindfolded individuals encountering an elephant for the first time serves as an insightful visual metaphor for understanding the significance of geological analogues[9] (Figure 6). This scenario resembles three blind individuals groping an elephant, with each one feeling a distinct part of its body and claiming that only their interpretation is accurate[10]. Each individual touches a distinct part of the elephant's body, describing it according to their personal experience. The lesson of the parable illustrates that our interpretations of observations are often shaped by our own limited and subjective experiences, which can lead us to draw erroneous conclusions.

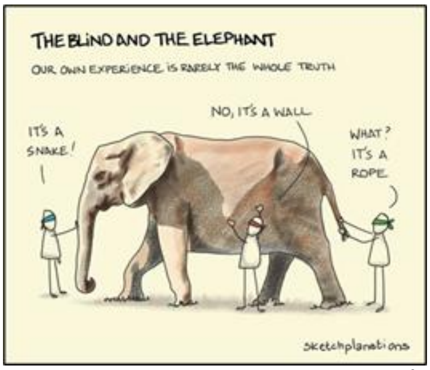

Figure 6: The blind and the elephant[9]

In other areas, low electrical resistivities of the same order have been observed. The Sea of Galilee, located within a deep pull-apart basin in the northern part of the Dead-Sea Transform, is a freshwater lake, into which saline water emerges through onshore and offshore springs and flux from the lake's sediments. The electrical resistivities of 1.0 and 0.2 ohm-m are detected at depths of ~10 m below the lake bottom in most of the lake area[10]. Resistivity values in the subsurface of the Sea of Galilee lower than 1.5 ohm-m may be attributed only to saline water because no lithology in the vicinity can have such low resistivity unless saturated with saline water[11].

Keeping in view this analogy, in view, a post-drill analysis of the geological history of the Black Sea and its relationship with the adjoining areas was carried out to comprehend the cause for the reduction in shale resistivity and the false alarm from real-time pressure prediction unsupported by well behaviour, which is the best direct indicator.

7. Explanation for the occurrence of low resistivity mudrocks

Resistivity logs assess the types of fluids contained within reservoir rocks by evaluating the efficiency with which these rocks conduct electricity. Because fresh water and oil are poor conductors of electricity, they have high resistivities. By contrast, most formation waters are salty enough that they conduct electricity with ease. Thus, formation waters generally have low resistivities. Mudrocks are impermeable but have high ineffective porosity. Electrical resistivity is generally a nonlinear function of porosity and connectivity. When unconsolidated and soft, the water in which the sediments are laid could attain saturation and predominantly affect the measured resistivity. The physics of the rocks will then depend on the porosity and connectivity. The electrical conduction in the rocks is mainly, but not exclusively, caused by electrolytes that circulate within the pore system

The factors that determine the resistivity of a rock or sediment are 1) porosity, 2) pore fluid(s) resistivity, and 3) percentage of conducting minerals (clays, graphite, sulphides) contained within the mineral grains. The approximate resistivity ranges for sedimentary rocks and glacial sediments are depicted in Figure 7. Under certain conditions, these ranges may be larger than those depicted in the figure. It is important to observe that the resistivity ranges for sandstone and sand and gravel intersect. Additionally, the resistivity range for till partially overlaps with that of sandstone, sand, and gravel.

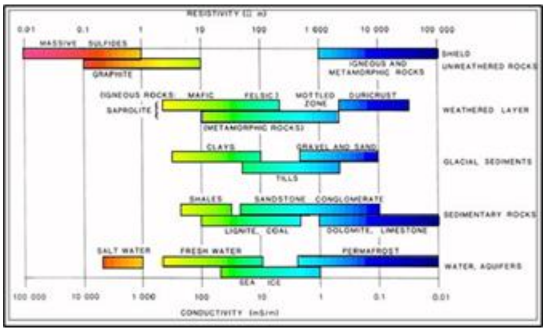

Figure 7: Approximate resistivity ranges for sedimentary rocks and glacial sediments[12]

In conductivity terms, which is the reciprocal of resistivity, the conductivity variation between igneous, sedimentary, and ore minerals are shown in Figure 8.

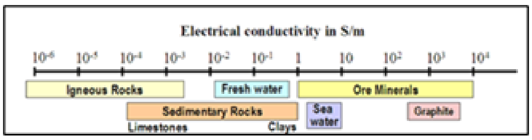

Figure 8: Approximate resistivity ranges for sedimentary rocks and glacial sediments[13]

The low resistivity to the tune of 0.2 ohm.m in both the pilot and main holes below is unrelated to pore pressures, as the well behaviour does not support the overpressure predicted by the resistivity transformed with values in the 0.2 ohm.m range. Therefore, it is surmised that the fall in resistivity could

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be related to the geological history of the Black Sea, where the formation water becomes quite saline not too far below the seabed and gets preserved by the pile of mudrocks. Hence, an attempt has been made to understand the geology of the area from the available published literature.

The most recent sediment column at the well to be deposited was the argillaceous lacustrine deposit under similar brackish water and anoxic conditions. Anoxic conditions would mean very little/no input from terrestrial environments and hence suggest the uniformity of salinity throughout the lacustrine section. The shallow sediments in the first 100-200 m may be less compacted and may have some communication with the seabed, maintaining similar cold temperatures (Figure 9). This may be more with depth, sediment/rock loses porosity, and also the thermal conduction increases with temperature. evident from the possible occurrences of gas hydrates.

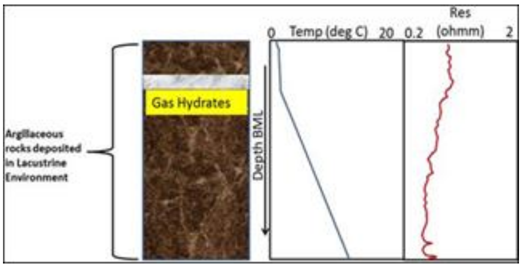

Figure 9: Argillaceous sediments close to the seabed

There could be several reasons for the decrease in Resistivity with depth in the near-seabed deep water sediments. The most plausible reasons could be:
1) In Deepwater environments, the seabed temperature is about 4ºC or colder and corresponds to the highest density in the water column. Below the mud line, with the geothermal gradient starts to play, the sediments get warmer, the charged ions have greater mobility, and the resistivity tends to decrease.
2) The rapid decrease in resistivity of shallow mudrocks, observed mostly in deep-water settings, is primarily due to temperature. The temperature at the seafloor in deep water is cold, hovering close to the freezing point. Hence, gas hydrates form on the sea floor and within the very shallow sediments. The temperature begins to increase within a few hundred feet, and resistivity increases again as sediments compact and porosity decreases. Generally, cold rocks have higher resistivity than warm rocks.
3) The admixture of fresh water from rainfall/ glacial melt with saline connate water from initial deposition in a marine or brackish water environment can result in decreasing resistivity with depth.
4) The presence of ore minerals like pyrites and siderites in large concentrations could reduce resistivity.

In short, it is influenced by the influx of fresh and saline water, sea level fluctuations, and temperature changes. Therefore, geological history holds the key to the process. Geological thoughts centre on the notion of processes that shaped the environment of deposition through time and space. Therefore, a perusal and collation of the geological history from the work of several authors has been attempted to examine the likely cause of lowering mudrock resistivity.

8. Geological History

8.1 Evolution of the Black Sea

The Black Sea has historically captivated geologists and oceanographers due to its distinctive history and environment. It is thought to be a remnant of the Tethys Sea, which existed before the significant splitting and separation of continents approximately 200 million years ago. Additionally, the Black Sea's environment is remarkable as it is the largest body of anoxic water globally[14]. The Black Sea basin is characterized as a back-arc basin that emerged during the Early Cretaceous to Early Paleogene period, coinciding with the northward subduction of the Neo-Tethys beneath the Balcanides–Pontides volcanic arc[15]. In-depth deep reflection seismic studies reveal the presence of two extensional sub-basins, which are divided by a significant continental uplifted block known as the Andrusov or Mid-Black Sea Ridge[16]. The Western Black Sea Basin was formed through a rifting phase during the Late Barremian to Early Albian, which was succeeded by substantial subsidence and the formation of oceanic crust from the Cenomanian to Maastrichtian periods[17]. Conversely, the Eastern Black Sea Basin developed as a result of rifting in the Late Paleocene, followed by the emplacement of oceanic crust in the Middle Eocene[18].

The Black Sea is one of the world's best examples of a small oceanic basin that formed by rifting of a pre-existing active continental margin related to subduction northward from Triassic–Miocene time. The Black Sea is commonly recognized as an extensional back-arc basin that formed along the northern active margin of the Tethys Ocean, which experienced northward subduction from the Triassic to the Miocene period. It is believed to be a remnant of the old Tethys Sea, which existed before the major separation of the continents about 200 million years ago. Since that time, it may have been a site of continuous deposition. Since about 120 million years ago, the area has been a sea basin, with extremely dynamic development and huge sediment accumulation up to 13 km of bottom sediment thickness in the central part of the basin. The basin has two components with different timing and orientation of extension, with rifting beginning probably in the Late Palaeocene (about 55 Ma ago), the Eastern and Western Black Sea basins. Significant alterations in sea levels and, as a result, profound transformations in land morphology, substantial sediment accumulation in the deeper regions of the sea, and changes in environmental conditions have transpired throughout the geological history of the Black Sea. The Quaternary period was particularly marked by remarkable changes, primarily influenced by global glaciation and deglaciation events. During these changes, the Black Sea level behaviour was influenced by the restricted connection with the Mediterranean Sea through the Bosphorus. The current configuration of the Bosphorus was formed during the Holocene epoch through the linkage of the southern basin with the northern stream. Erosion and faulting have deepened the barrier and the stream valley in the north, resulting in a strait that connects the Black Sea to the Mediterranean[4].

Quaternary sediments found in the Black Sea provide insights into the geological and climatic events that have transpired in the eastern Mediterranean region. The boundaries of the

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Black Sea basin have undergone frequent changes throughout the Quaternary period. Over the past two million years, the Mediterranean Sea has maintained a continuous exchange with the Atlantic Ocean; however, its link to the Bosphorus has been intermittently severed and reconnected. During periods of continental glaciation, the water level of the Black Sea would drop below the Bosphorus sill, leading to a freshening of the waters and transforming the area into a vast inland lake. Conversely, during interglacial phases, rising water levels in the Mediterranean Sea and the Sea of Marmara would re-establish this connection, resulting in the formation of sapropels and sediments that arise from geocatastrophic events within the Black Sea environment[19].

It is connected with the Mediterranean Sea by the narrow Bosphorus, which has a sill depth of about 50 meters. The Bosphorus is a rather narrow (0.76 – 3.6 km large) and shallow strait (presently 32 – 34 m at the sill) restricting the two-way water exchange between the brackish Black Sea (the salinity of the Black Sea water is about 17‰ at the surface and 22 ‰ at the bottom) and the very saline Mediterranean Sea (38 – 39 ‰)[20]. This shallow sill has caused environmental conditions within the Black Sea to be altered considerably during the Quaternary through Pliocene eustatic sea-level changes. As sea levels fluctuated during glacial and interglacial periods, the Black Sea alternately connected with and disconnected from its marine source, transitioning between marine, brackish, and freshwater environments. These primarily climate-controlled environmental changes have influenced sedimentation processes and the deposition of freshwater, brackish to marine microfossils[21,22]. During the most recent Quaternary glaciation, the Black Sea transformed into a giant freshwater lake. Research studies on piston cores from DSDP wells in the Black Sea have demonstrated that Holocene variations in salinity within the Black Sea were synchronous events, associated with global eustatic changes[23]. During periods of low global sea levels, the Black Sea existed as a freshwater lake, cut off from the Mediterranean. In contrast, during high sea level periods, like the present, a link to the open ocean is formed, resulting in the Black Sea being brackish. Deep-sea drilling cores reveal that the depositional environments of the Black Sea have undergone multiple transformations. The presence of nannofossils and diatoms suggests several instances of marine incursions, during which the Black Sea transitioned to a brackish marine state[24]. Given that these events must have occurred in a geologically instantaneous manner, the horizons characterized by sudden changes in salinity, as suggested by floral ecology, can be regarded as chronostratigraphic markers.

The timing and origin of the deep Black Sea basin remain subjects of debate. For instance, Muratov proposed that its history can be categorized into three distinct periods[25]. During the Mesozoic and Paleogene, a relatively shallow basin existed in the Black Sea region, bordered by deep geosynclinal depressions to the north and south. The second period was marked by the presence of several deep basins in the central, northern, western, and eastern sections of the Black Sea, which accumulated sediments throughout the Oligocene and Miocene. In the third period, encompassing the Pliocene and Pleistocene, the current deep basin of the Black Sea was established.

8.2 Black Sea Salinity Crisis of the Pleistocene

The fluctuations of sea levels in the Black Sea, especially at the Bosporus Straits, have been the focus of considerable geological research. Scholars have investigated how variations in sea levels affected the link between the Black Sea and the Mediterranean, influencing environmental and hydrological conditions over millennia. During periods of low global sea levels, the Black Sea existed as a freshwater lake, cut off from the Mediterranean. In contrast, during high sea level periods, such as the current day, a link to the open ocean is formed, resulting in the Black Sea becoming brackish. Deep-sea drilling cores reveal that the depositional environments of the Black Sea have undergone numerous transformations; the presence of nannofossils and diatoms suggests multiple marine incursions when the Black Sea transitioned to a brackish marine state, highlighting sudden shifts in salinity. The Black Sea salinity crisis occurred in the Pleistocene and represented a hypersaline episode of the type presently developed in the Great Salt Lake rather than a salt deposition (Figure 10). Such a mechanism would give additional support for the assumption of a major unconformity[26].

As per Ross, D.A., et al., the freshwater section noted in Site 379 was present but strongly attenuated[8]. It reaches a low salinity level of 16.5°/oo and does not extend below about 40 metres. After several breaks in slope, a smooth increase in salinity to about 98°/oo is obtained. This increase in salinity and Ca and Mg confirms the previous evidence that a hypersaline stage existed in the Black Sea, but did not reach the point of depositing significant concentrations of solid evaporites. The interstitial water program revealed that the dominant pore water feature at the site is a gradual increase in salt content with depth, reaching a maximum of approximately 98% salinity in the deepest investigated strata.

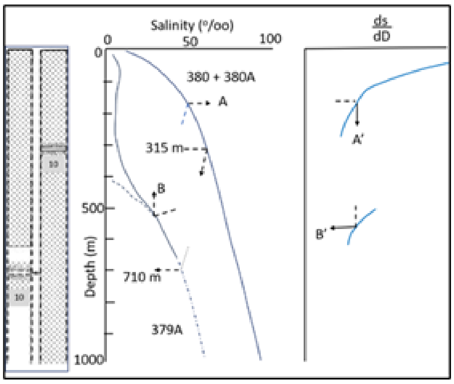

Figure 10: Salinity versus depth curves and their first differential[26].

This indicates a brine or evaporite source well below the penetrated strata and appears to require considerable time to allow diffusion to smooth the curves.

8.3 Black Sea Eustatic Level Changes

The most widely accepted hypothesis based on data from the deep basin floor sediments holds that post-glacial inflow of Mediterranean water into the isolated freshwater lake of the Black Sea began 9000 years ago. As saline spills periodically flowed to the basin floor, they created a dense accumulation of layered brackish water at the bottom, which ultimately became anoxic over time. Ryan etal in 1997 proposed the abrupt drowning of the Black Sea shelf around 7150 years ago[27]. The surface of the lake went down 100m below the outlet, and then, when the Mediterranean Sea rose to the Bosporus spillway, salt water poured through the spillway into the Black Sea and filled and submerged the exposed shelf extensively. Interpreting the seismic profiles in the area south of Ukraine, they identified an erosional unconformity that truncated an underlying glacial-age alluvial and delta deposit when the Black Sea became a giant freshwater lake. Approximately 8,000 years ago, the water level of the Marmara Sea is believed to have risen sufficiently to initiate a two-way flow. This hypothesis is supported by various pieces of evidence, including the differing ages of sapropel deposits found in the eastern Mediterranean Sea and the Black Sea, the presence of buried barrier islands that have retreated on the Black Sea shelf, and an underwater delta located in the Marmara Sea near the Bosporus Strait, which is made up of sediments from the Black Sea. The exploration well in our study also depicts alternations of mudrock resistivity in both the pilot and main holes (Figures 3a and 4a).On the ground, a geological survey revealed a buried erosional surface strewn with shelly gravel composed entirely of bleached fragments of the freshwater molluscs eroded from underlying coquina-bearing sand and clay layers that contain abundant leafy plant material, fluvial gastropods, desiccated cracks, and roots, suggesting a marshy coastal environment. The indicator used most assertively as a proxy for salinification is the δ18O/δ16O ratio of the carbonate component. The hydrological equilibrium of the Black Sea is determined by the inflow from rivers and the exchange with the Mediterranean Sea via the Bosporus Strait. The connection with the Mediterranean Sea has been repeatedly interrupted over the last 3 Ma, causing the Black Sea to oscillate between lacustrine and marine conditions. Badertscher et al suggest that the connection between the two seas has been open for a significant period, at least twelve times, since 670,000 years ago[28]. Ryan et al interpreted the instantaneous submergence of the Black Sea as a consequence of Mediterranean waters' invasion over the Bosporus spillway caused by reduced riverine input and evaporation in the Black Sea[27].

Figure 11 on the Left shows the Ryan and Pittman catastrophic flood hypothesis suggests that there were two Holocene evaporative draw-downs of a freshwater Black Sea ‘lake’, which were followed by a deluge of seawater around 7.2 ka BP (RP1) or 8.4 ka BP (RP2). On the Right: The gradual flood hypothesis proposed by Hiscott et al. indicates a strong yet declining outflow from the Black Sea since approximately 11 ka BP, leading to the deposition of sapropel in the Marmara and Aegean seas, along with a progressively increasing inflow of Mediterranean water over the southwestern Black Sea shelf after around 9.5 ka BP[29].

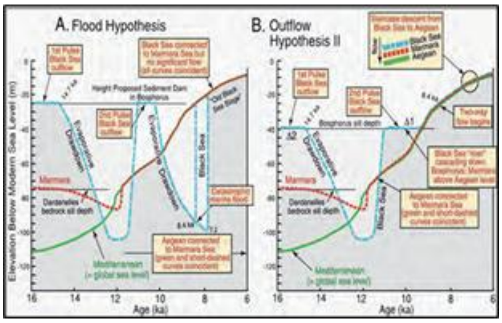

Figure 11: Inflow and flood models for the Black Sea with the Mediterranean Sea[30]

Another viewpoint presented in Figure 12 illustrates the reconstructed levels in the Mediterranean (M) and the Black Sea (B) and their connection/isolation through the Bosporus spillway (S). The figure on the left portrays a gradual inflow model of Degenes and Ross[23], with the first connection envisaged around 9000 years BP. The depth of the spillway deepened slowly as the global eustatic level rose and leading to an acceleration in the salinity of the Black Sea. The catastrophic flood model envisages the Mediterranean breaking through a barrier in the inlet at 7150 years BP and rapidly flooding a partly evaporated freshwater Black Sea.

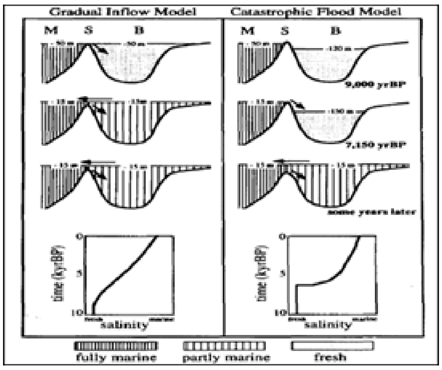

Figure 12: Inflow and flood salinity models for the Black Sea with the Mediterranean Sea[27]

8.4 Division among the Geologist Fraternity

Sediment analysis has shed light on historical sea-level variations, illustrating how geological structures have changed over time. The Black Sea’s distinctive anoxic deep waters and sediment layers act as crucial records of past environmental transitions. The low resistivity mudrocks are the result of this effect. Certain studies indicate that during times of reduced sea levels, the Black Sea became disconnected from the Mediterranean, effectively turning into a freshwater lake. As global sea levels increased, the Bosporus sill permitted Mediterranean waters to inundate the Black Sea, resulting in a profound transformation of its ecosystem.

Throughout geologically recent periods, the Black Sea has experienced intermittent connections to the global ocean via narrow, shallow straits located at both ends of the Marmara Sea (Figure 13). Its surface area has fluctuated significantly in response to climatic variations and changes in sea level. During glacial periods characterized by low global sea levels, the Black and Marmara seas became isolated from the Mediterranean, transforming into inland lakes. The marine reconnection was restored during high global sea levels. The difference in opinion among geologists was on the exact positioning of the waxing and waning of the sea level that caused the connection and reconnection of the Black Sea with the Mediterranean Sea through the narrow Bosporus Strait, the Marmara Sea, and the Aegean Sea.

Critics of the deluge hypothesis are based on two primary arguments. The first argument centers on the water level of the Black Sea: if the rate and extent of the Black Sea's rise were moderate, or if it even exceeded the rise in the Aegean basin (with water flowing from the former to the latter upon their reconnection, as it does currently), or if the straits had already opened (at a level lower than present) and the two basins were connected at the time of the proposed flood, then the catastrophe hypothesis is rendered invalid. The second argument pertains to the absence of archaeological evidence that one would anticipate from a flood, including its effects on geology, wildlife, or human populations. Since the conclusion of the last glacial period, the global sea level has increased by 120 metres (390 feet)[31]. The flood hypothesis is based on the geomorphological changes of the Bosporus since the termination of the glacial age[32]. The region surrounding the Black Sea has experienced periods of isolation and reconnection numerous times over the past 500,000 years[28]. This is now evident from the mudrock resistivity recorded in the riserless holes.

Figure 13: Black Sea to Mediterranean Sea link[31]

9. Geological Model and Shallow Hazard Perspective

The detailed analysis of the geological history indicates that the reduced abnormal mudrock resistivity is the result of the geological history of alternate saline incursions and freshwater riverine input, causing a two-way flow regime in the Black Sea that controlled the hydrological balance rather than the prevalence of overpressure. The history of isolation and marine reconnection of the Black Sea impacts the mudrock resistivity. The occurrence of sulfate ions in the Black Sea waters, mainly derived from the influx of seawater, has resulted in marine-brackish conditions. This understanding contributes to enhanced safety and improved drilling efficiency in deep water exploration wells. Therefore, while drilling the riserless section, it would be prudent to rely more on the well behaviour than the mudrock resistivity-based pore pressure prediction, as drill cuttings and mud return are only upto the seabed. It is about time to adopt the cost-prohibitive mud recovery method in riserless drilling.

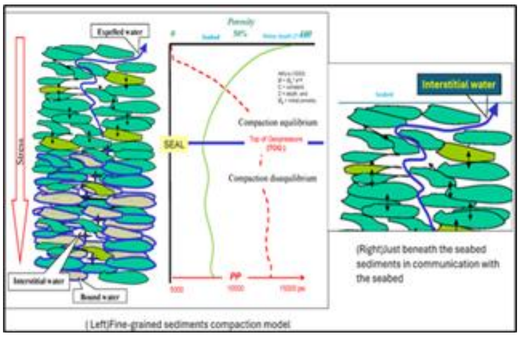

Figure 14: Sediments just beneath the seabed in communication with the seabed[33]

A conceptual geological model illustrates the dewatering and compaction of shale and fine sediment within the youngest stratigraphic sequence located just beneath the seabed during the process of sedimentation (Figure 14). It is important to note that above the anticipated seal, formation fluid (water) is moving upward (hydrodynamically) towards the sea floor as a result of increasing stress (indicated by the left arrow)[28]. Beneath the seal, water becomes trapped in the pore space (leading to excess pressure) in addition to the irreducible bound water. In the porosity versus pore pressure plot (to the right), one can observe the similarity between the porosity reduction curve and the increasing pressure during compaction and beyond. On the right in Figure 14, the sediments just beneath the seabed are in communication with the seabed and have been laid in seawater, with intermittent connections to the Black Sea and the Mediterranean. The unconsolidated sediments retain saline water in their interstices, being completely saturated with seawater. When fluid pathways exist due to high porosity, the electrical resistivity is generally small. As it is connected to the seabed and shallower than the fluid retention depth, the pore pressure is hydrostatic, with the full weight of the overburden being borne by the rock framework. The occurrence of sulfate ions in the Black Sea waters, mainly derived from the influx of seawater, has resulted in considerable pyrite and siderite in the top hole sequence of Pliocene to recent age.

The riserless drilling of the upper section before installing the marine riser in deep water wells requires careful oversight. The lower abnormal mudrock resistivity inverts into overpressures, but in the shallow sands did not flow during drilling with seawater. These shallow formations just beneath the seabed are inferred to be connected to the seabed and therefore of hydrostatic pressures, with the overburden pressure being borne by the rock framework. This indicates that the environment of deposition plays a key part in understanding and predicting the pressure distribution in a basin. This attempt will serve as a platform for future ventures in the Black Sea.

10. Concluding Remarks

With saline water incursions occurring periodically in the Pliocene to recent sediments of the Black Sea, it is not unusual for the unconsolidated mudrocks to be influenced by the salinity of these incursions from the Mediterranean Sea. Given that the sediments are soft and porous, percolation occurs, and the load of seawater above retains the denser saline water saturating the interstices, resulting in subdued resistivity responses. Therefore, the lower resistivities in the mudrocks do not reflect higher pore pressures but merely indicate the preservation of the environmental conditions of that geological period and signify a false alarm while drilling. There is no shallow hazard concern related to overpressures in this deep-water area just beneath the seabed. Integrating this geological study amid the uncertainty in log-based pore pressure prediction will be immensely important for planning future exploration wells in the Black Sea, ensuring safe and cost-effective drilling.

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