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Comparison between Mud Volcanoes from the NW Moroccan Atlantic and Moroccan Mediterranean Margins Using Seismic and Bathymetric Data, Morocco

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Abstract

This work compares mud volcanoes from the NW Moroccan Atlantic Margin and the Ceuta Drift in the Mediterranean Moroccan Margins. Through the analysis and interpretation of high-resolution seismic data combined with existing research, the study explores the distinct formation mechanisms and the structural characteristics of mud volcano systems in these regions. The NW Moroccan Atlantic Margin, influenced by the accretionary wedge and the strike-slip faulting associated with the Rif-Betic Arc tectonic movement, exhibits mud volcanoes formed primarily through the upward movement of mud diapirs along faults. In contrast, the Ceuta Drift is characterized by mud volcanoes formed on top of the seafloor-piercing mud diapirs, resulting from compressional-extensional tectonics and the Middle Miocene shale diapirs. This study highlights the key factors driving mud volcano formation, such as rapid subsidence and strike-slip fault activity on the NW Moroccan Margin, compared to tectonic compression and subsequent extension in the Ceuta Drift. By comparing these two different tectonic and geological environments, the article provides insights into the dynamics of mud volcano systems, their implications for hydrocarbon exploration, and their significance in understanding tectonically active regions.

Keywords: Mud volcanoes, NW Moroccan Margin, Ceuta Drift, Seismic data analysis, strike slip faults, Seafloor-piercing mud diapirs, Tectonic mechanisms.

1. Introduction

The submarine mud volcanoes are significant geological features found in various marine and terrestrial environments worldwide [1]. These structures, characterized by the expulsion of mud, fluids, and gases from deep underground, are often associated with tectonic activity and can provide valuable insights into subsurface processes and the potential for hydrocarbon exploration [1][2]. In the context of the Moroccan margins, two distinct regions— the NW Moroccan Atlantic Margin and the Ceuta Drift in the Mediterranean Moroccan Margin—host prominent mud volcano systems that offer unique opportunities to study these geological phenomena [3][4][5][6] [7][8].

The NW Moroccan Atlantic Margin, located along the Gulf of Cadiz, is shaped by complex tectonic interactions, including subduction, strike-slip faulting, and the westward movement of the Rif-Betic arc [4][5]. These processes have resulted in a diverse range of

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geological structures, including a significant accretionary wedge that influences the formation and distribution of mud volcanoes. In contrast, the Ceuta Drift, situated in the Southwestern Alboran Sea, is primarily influenced by the tectonic and geological history of the Alboran Basin [9] and the morphology of the pre-existing seafloor that has been under the control of the mud diapirs acting as barriers, in association with the Gibraltar arc and the semi-confined morphology of the Alboran sea [10]. The region's geological evolution, marked by alternating phases of extensional and compressional tectonics, has led to the development of distinct mud volcano systems associated with Middle Miocene shale diapirs [8].
The contrasting geological and tectonic histories of the Atlantic and Mediterranean regions lead to differing structural characteristics and formation processes of their mud volcano systems [2]. This study compares these systems along both the Moroccan margins using high-resolution seismic data and geological mapping. The aim is to examine their formation mechanisms, tectonic controls, and implications for hydrocarbon exploration. By integrating these datasets, the research enhances our understanding of how regional geodynamics influence mud volcanism and its potential for hydrocarbon resources.

2. Data and Method

This study utilizes high-resolution seismic datasets from two key surveys: the 2011 GEOMARGEN-1 survey, conducted in the Gulf of Cádiz, and the 2000–2001 ConocoPhillips surveys, which cover the Alboran Sea.
However, the key seismic features, such as amplitude variations and transitions between chaotic or continuous seismic reflections [11][12], were employed to delineate regional sedimentary layers. In this case, to establish the timing of these layers, the study integrates chronological constraints from previous works [3][4][13][14], which provide age models and stratigraphic correlations.

3. Mud volcanoes NW Moroccan Atlantic margin *:*

3.1. Regional settings

The NW Moroccan Atlantic margin is one of the continental margins of the Cadiz Gulf, located on the African side, and it is bounded from Tanger to Rabat (Figure 1). The geological complex of the NW Moroccan margin has been influenced by several tectonic events throughout its history, which has resulted in a diverse range of rocks and geological structures [15][16].

The more internal part of the margin is part of the Rif domain chacterized mainly by the flysh Magrhebides (Numidian unity) from the external zones of the Cordillera, the intrarif (internal units), external intrarif (El habt Unit), internal intrarif (external Tanger-Ketama Unit), and the more recent deposits(Upper Miocene-Quaternary), such as the Gharb basin (Between Larache and Kenitra) dominated by the Prerifaine Nappes [15][17]. The arrangement of these sedimentary facies has been under the control of the NW-SE convergence motion, known to be the first influential tectonic movement in the Gulf of Cad, in the Rif Betic arc and the Alboran domain [18][19][20]. Furthermore, the more external zone of the NW Atlantic margin is characterized by the large accretionary wedge formed by the westward movement of the Rif-Betic arc [21].This movement has been facilitated by dextral strike-slip faults in the Betic and sinistral strike-slip faults in the rift [4][15]. The deposition of this accretionary wedge has resulted in the strong Tortonian subsidence, which has strongly affected the sedimentary facies from the NW Atlantic margin, including the Pre-rifaine Nappes [15]. This latter tectonic has been the origin of the formation of mud diapir activities that have been the source of mud volcanoes available today in the Gulf of Cadiz and the NW Moroccan Margin in general [22][23].

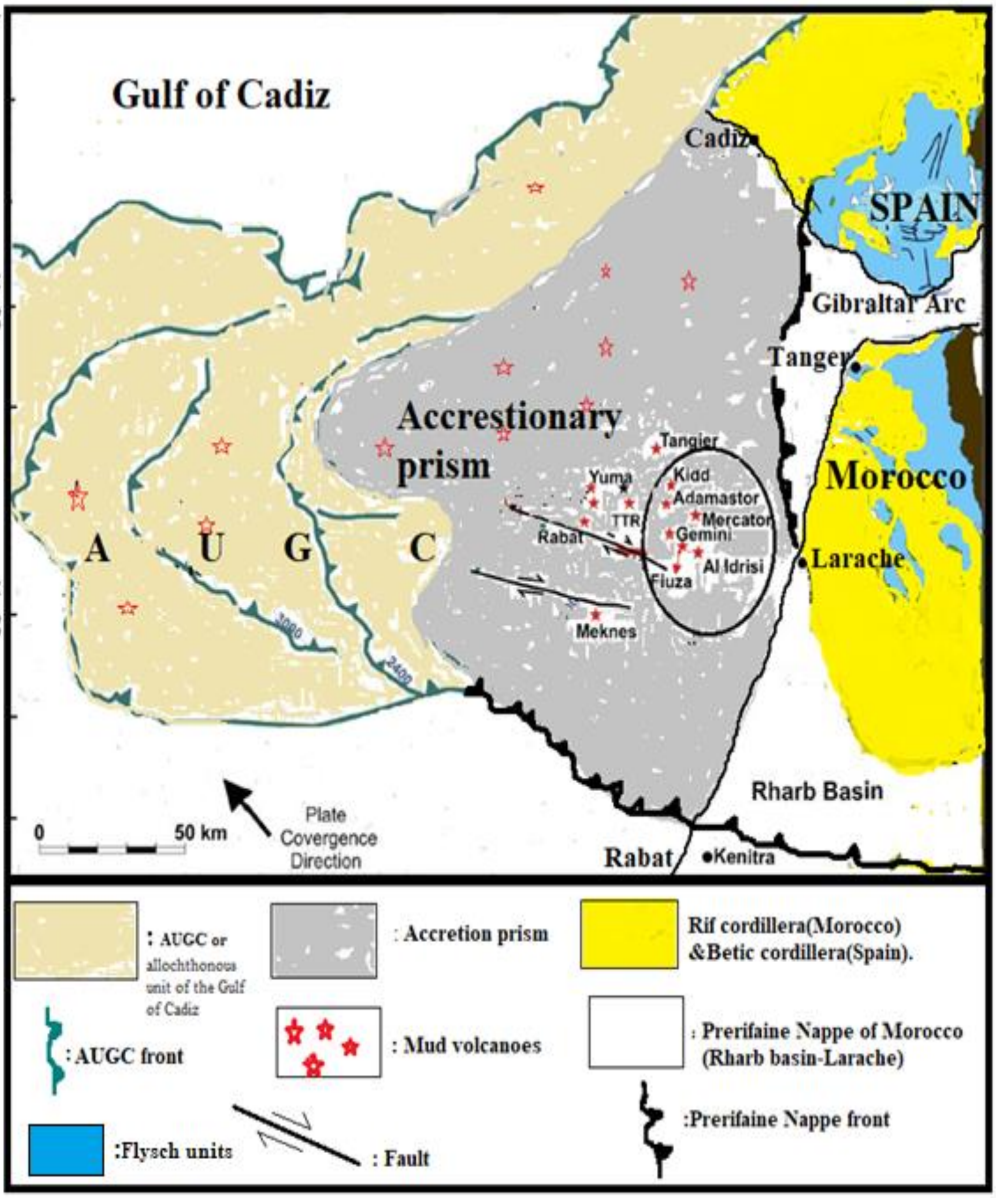

Figure 1 : Simplified geological map of the Gulf of Cadiz and the NW Moroccan margin (modified from[21],[23]). The red stars represent mud volcanoes found within the accretionary wedge and the circle represents the El Arraiche mud volcanoes field which is the most known and the biggest mud volcanoes field in the NW Moroccan margin and he Gulf of Cadiz in general.

3.2. Mud volcanoes systems of mud volcanoes from the NW Moroccan Atlantic margin

3.2.1. Literature review.

A mud volcano system is a term related to the description of the set of structures in association with the mud volcano and the feeder complex that connects the mud volcano to its source rock (or its source stratigraphic unit) [24].

In the Gulf of Cadiz, the first mud volcano in which the mud volcano system has been recognized is the Tasyo mud volcano, located on the Moroccan Atlantic margin at a water depth between 1000m and 2000m [13][14]. The mud volcano system of the latter includes the mud volcano on top of the seafloor and the feeder complex, made of buried bicones stacked together to form the cone on the surface, but with different sizes (Figure 2).

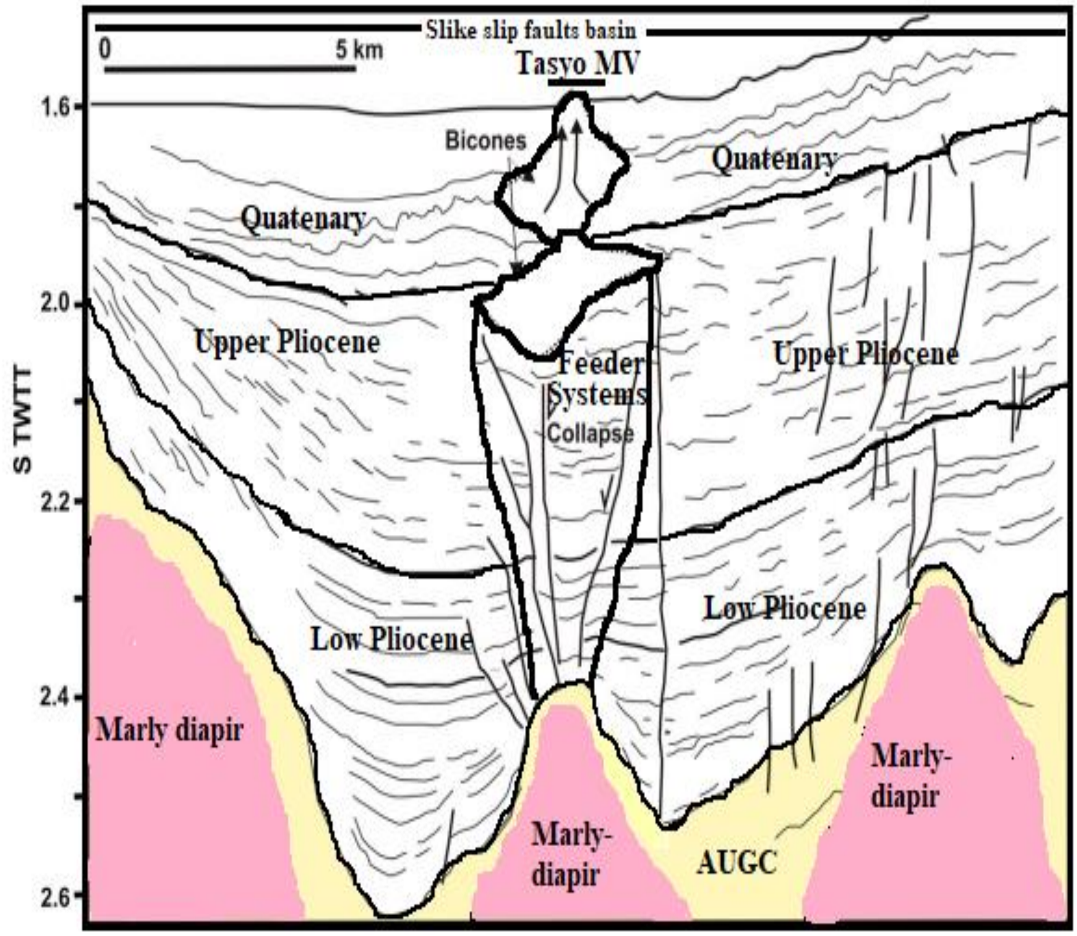

Figure 2 : The Tasyo mud volcano system is structurally controlled by marly diapirs, which serve as primary pathways for fluid escape. The feeder systems are composed of strike-slip faults and overlying biconic conduits. The Allochthonous Unit of the Gulf of Cádiz (AUGC), interpreted as the mobile shale source, overlain by Pliocene–Quaternary sedimentary facies (Modified from [14])

3.2.2. The Al Idrissi mud volcano system

On the other hand, we have analyzed the seismic data of the Al Idrissi mud volcano. As a reminder, the Al Idrissi mud volcano is the largest in the Gulf of Cadiz, located on the NW Moroccan Atlantic margin, specifically in the Larashe offshore area (Figure 3).

The mud volcano is part of the El Arraiche mud volcanoes field, located within a water depth between 200m and 1000m [13][25]. Furthermore, this El Arraiche field is described as the most dominant mud volcano group in the NW Moroccan margin, with eight mud volcanoes developed on top of the accretionary wedge [25][26].

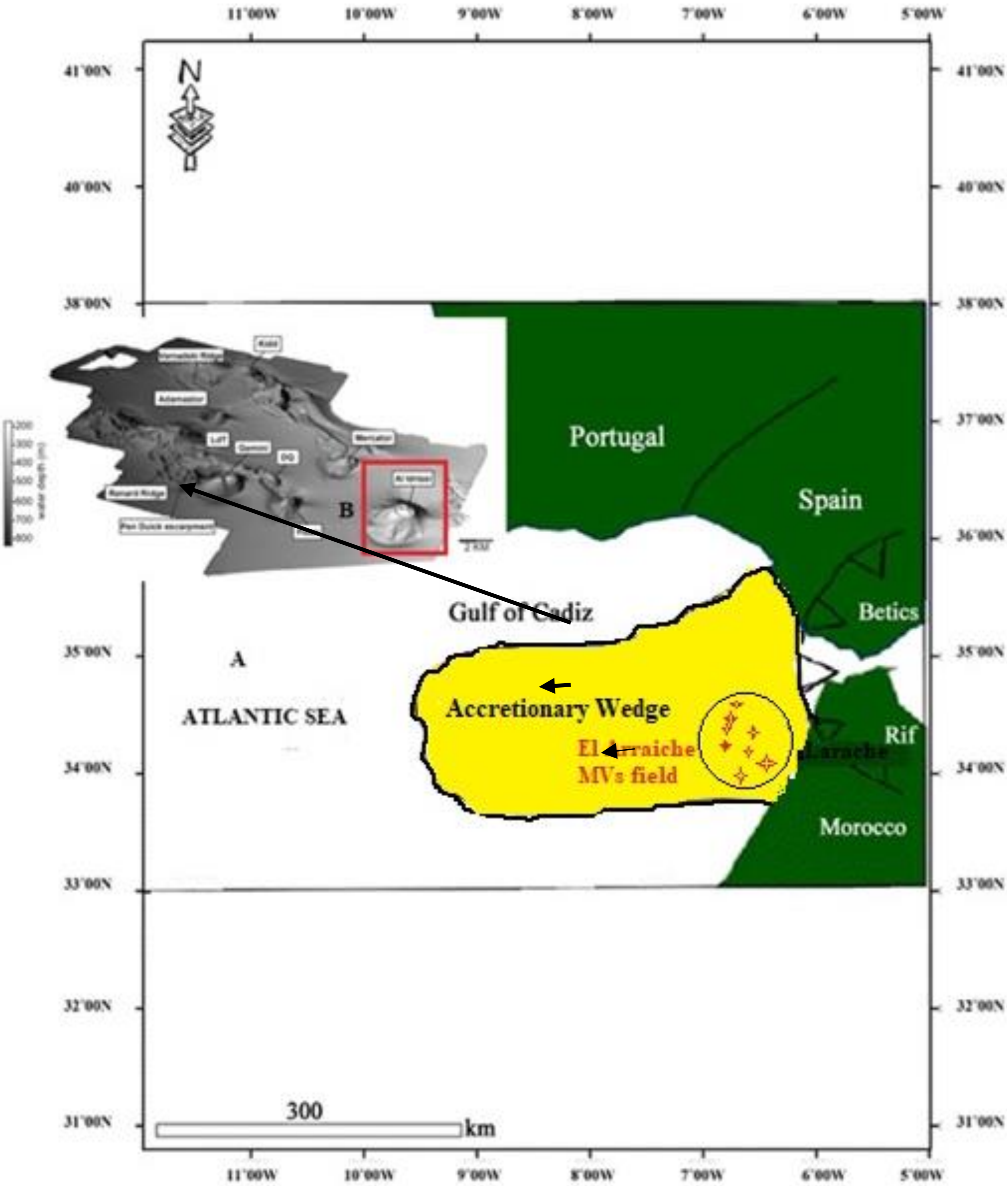

Figure 3 : The accretionary wedge and the El Arraiche mud volcano field (modified from[21][26] [25]]). **(A)** Location of the El Arraiche mud volcano group in the Gulf of Cádiz ; **(B)** El Arraiche mud volcano field, highlighting the Al Idrissi mud volcano (red box) within the complex. MVs = mud volcanoes.

Therefore, based on the seismic signatures analysis, the resulting Al Idriss mud volcano system shows both cone and buried bicones stacked together but with different sizes, and are connected to the mobile shale by the DTC or downtapering cone (Figure 4). In this case, the sedimentary cover consists of Upper Miocene to Quaternary edimentary facies, while the Prerifaine Nappes represent the plastic shale sedimentary facies (or mobile shale).

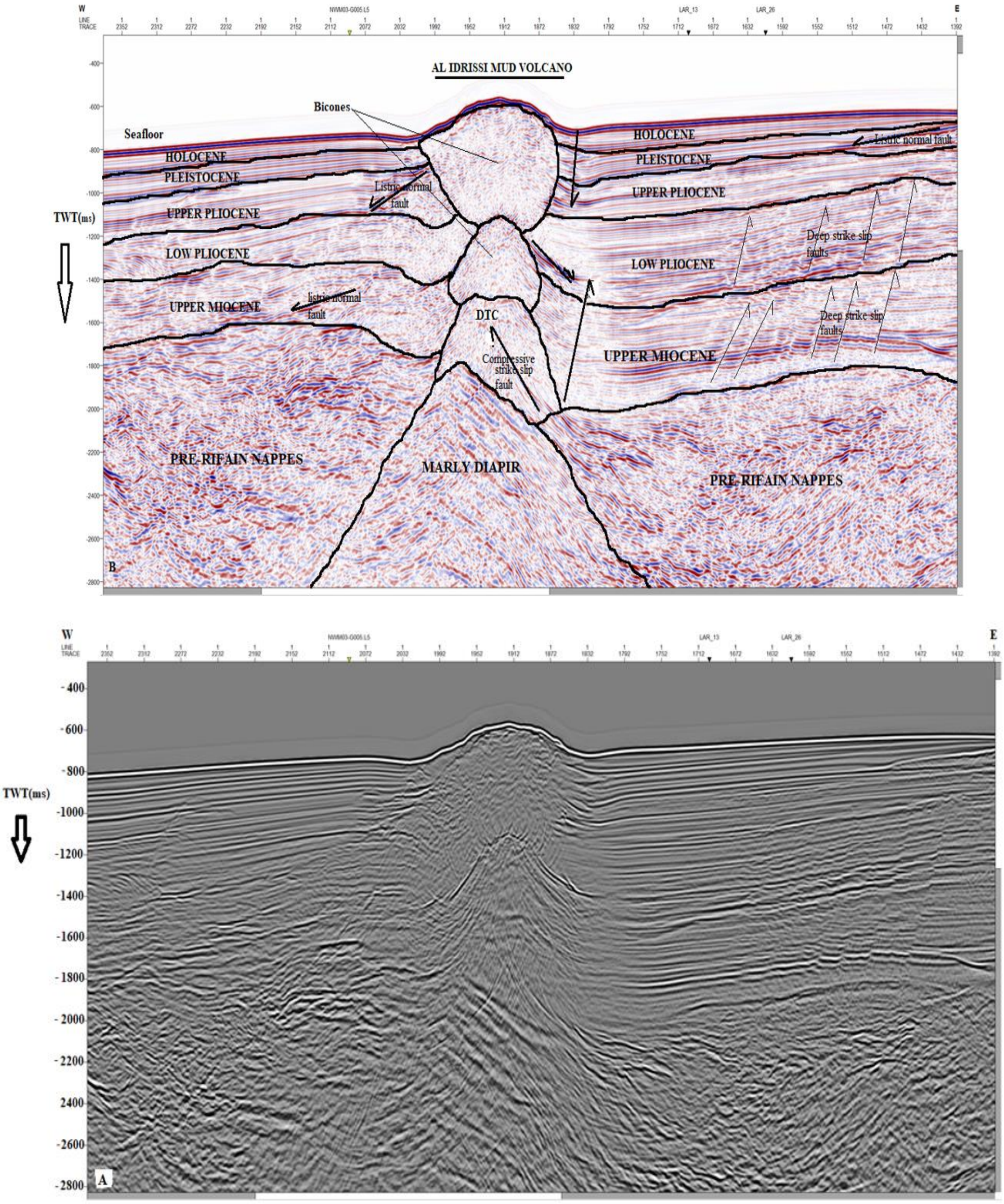

Figure 4 : simplified Al Idirssi mud volcano systems.A) The non-interpreted seismic data of the Al Idirssi mud volcano in greyscale, B) the interpreted colored seismic data showing the mud volcano systems, the plastic shale sedimentary unit (Prerifaine Nappes) and the sediment cover (Upper Pliocene to Quaternary)(Modified from[27][13]).DTC (Downtapering cone).

The upward movement of mud and fluids has been largely facilitated by the strike-slip faults, where mud volcanoes have been developed on top of these faults. However, the listric normal faults and the reverse ones within the accretionary wedge have played an important role, especially in putting the latter into contact with the complex feeder connecting the mud diapir from the source rock (Prerifaine Nappes and the Mud volcano on the surface. The sedimentary cover is rich in terms of thermogenic and biogenic gases, as observed in the mud volcanoes of the El Arraiche field [4] [26][28]. On the other hand, mud and fluid formed mud volcanoes in the Larache offshore, taking their source from the marl Nappes known as the Prerifaine nappes of Morocco, where the Middle Miocene marly mud diapirs have been developed in the late Tortonian. These marly diapirs played an important role in moving mud and fluid from the Prerifaine Nappes of Morocco. Therefore, the strict slip faults connect these marly mud diapirs to the seafloor surface where mud volcanoes are formed (Figure 4). The marly diapirs are composed of Miocene clay and marls and were formed from the Upper Miocene to the present. Their genesis has been related to the strong subsidence resulting from the deposition of the accretionary wedge [15]. The latter has been justified by the fact that these marly diapirs cut through the accretionary wedge, forming mud volcanoes on the surface. One thing to know is the fact that we use marly diapirs for mud volcanoes that have been formed in low water depth areas search us 350m water depth while for mud volcanoes formed in very deep water depths like 2000m water depth, their formation has been associated with Triassic salts diapirs that have been formed during the initial phase of the opening of the Atlantic Sea [29].

3.2.3. General Conceptual model of mud volcano system in the NW Moroccan Atlantic margin.

Therefore, based on both the Al Idrissi and Tasyo mud volcano systems, a simplified conceptual model of the most dominant mud volcano system and formation mechanism related to all submarine mud volcanoes from the NW Moroccan Atlantic margin is described in Figure 5 below.

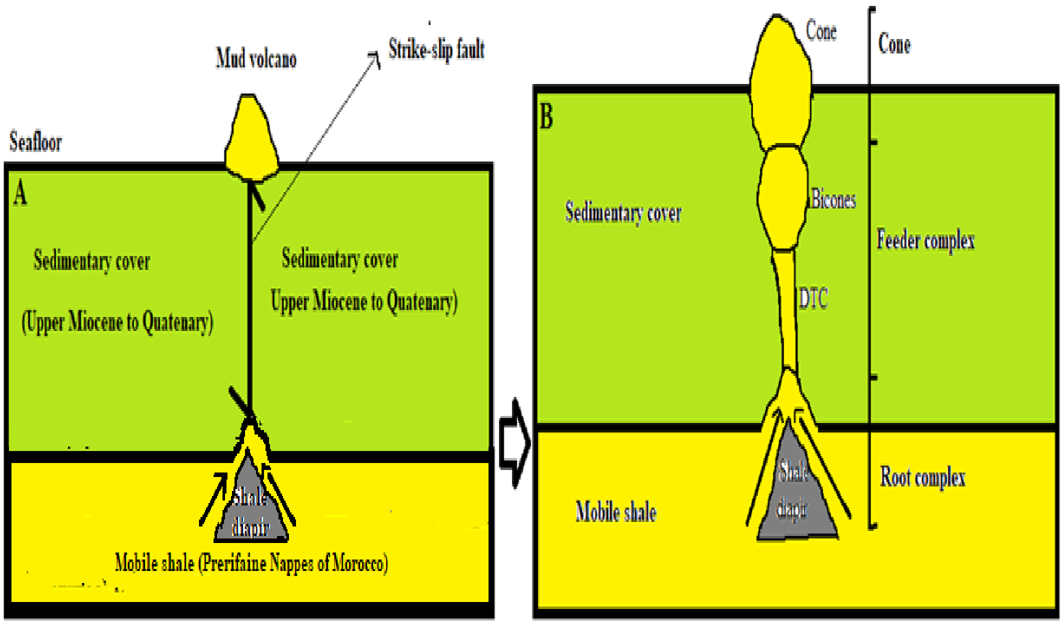

Figure 5 : Symplified formation mechanism and the general mud volcano system of mud volcanoes from NW Moroccan margin.A) the formation mechanism with **sinister** trike-slip fault connecting the mud volcano to its source (mobile shale).B) General Conceptual model of the mud volcano system with root complex, feeder complex (DTC and buried bicones) and the Cone at the Seafloor (Modified from [2][3][14]).

4. Mud volcanoes in the Ceuta drift (Moroccan Mediterranean margin)

4.1. Regional settings

The Ceuta Drift is situated at a water depth ranging from 200 to 700m on the Moroccan Mediterranean margin in the southwestern Alboran Sea (also referred to as the Mediterranean Sea) (Figure 6). Its geological complexity is closely linked to the tectonic and geological history of the Alboran domain, as the Ceuta Drift is part of the internal Rif zone within this domain. The formation of the Alboran Basin occurred between the early Miocene and late Tortonian, driven by extensional tectonics related to the general convergence between the African and Eurasian plates[30]. This basin formation was also influenced by significant thinning of the Alboran domain due to these extensional movements [3]. Following this extensional phase, a shift to convergence tectonics occurred from the late Miocene to the Holocene, rotating from a north-south (N-S) to a northwest-southeast (NW-SE) direction. This phase resulted in the formation of inverted normal faults, reverse faults, strike-slip faults, and folds within the Alboran Basin [30] [31].

The Alboran Basin is primarily characterized by a basement composed of metamorphic and volcanic rocks from the Betic and Rif internal zones [32]. This basement was deposited during the late Aquitanian-Burdigalian period and reaches a thickness of approximately 8 km in the western Alboran Basin [33]. Above this basement, Middle and Late Miocene deposits follow, separated by the Messinian major discordance, which marks the boundary between Miocene sediments and overlying Plio-Quaternary sedimentary facies.

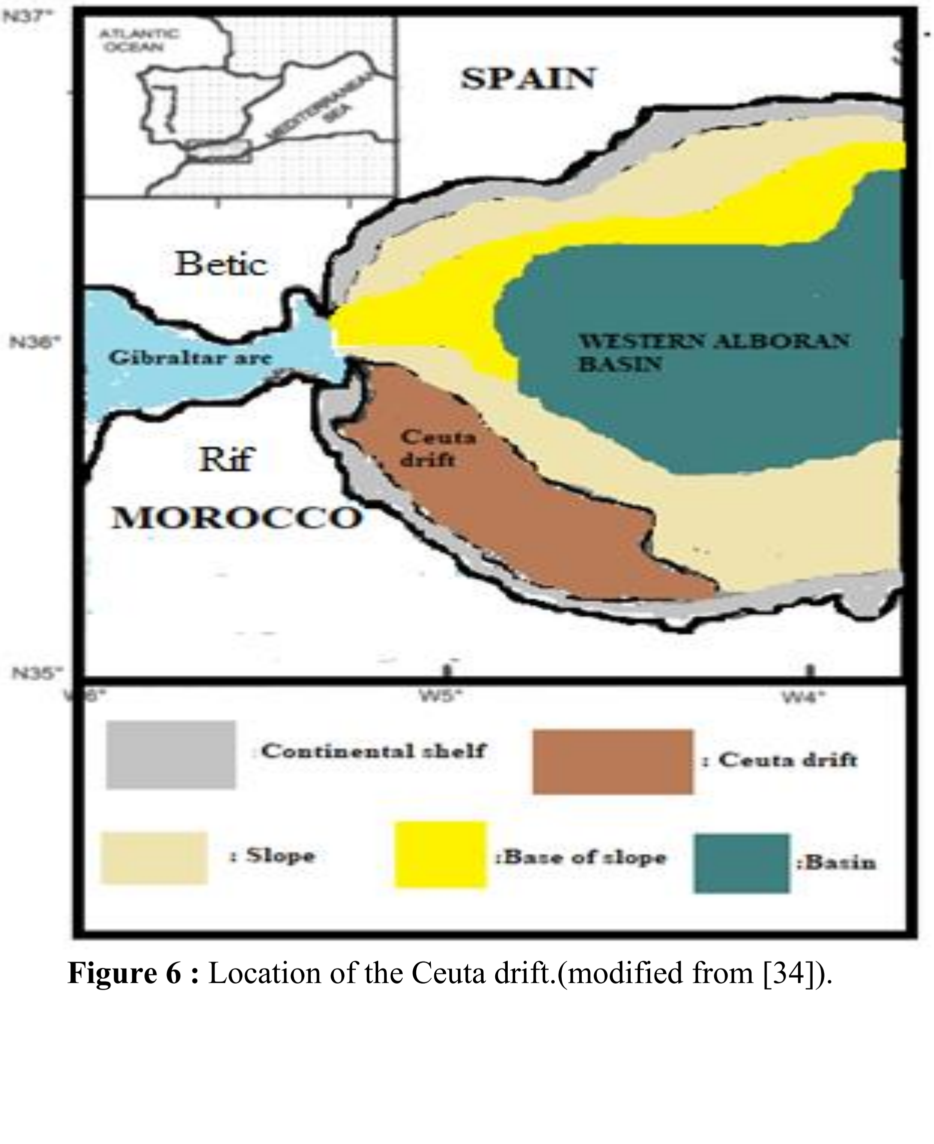

Figure 6 : Location of the Ceuta drift.(modified from [34]).

4.2. Mud volcanoes systems and formation mechanisms of mud volcanoes from the Ceuta drift

In the Alboran Basin, mud volcanoes are located exclusively in the western region, at water depths ranging from 330 to 1050 meters [3]. A total of 10 mud volcanoes have been discovered in this area, and most of their systems have been studied [3]. Based on the analysis of the bathymetric map from [3], we found that only 7 of these mud volcanoes are located in the Ceuta Drift, which is the focus area of this study (Figure 7).

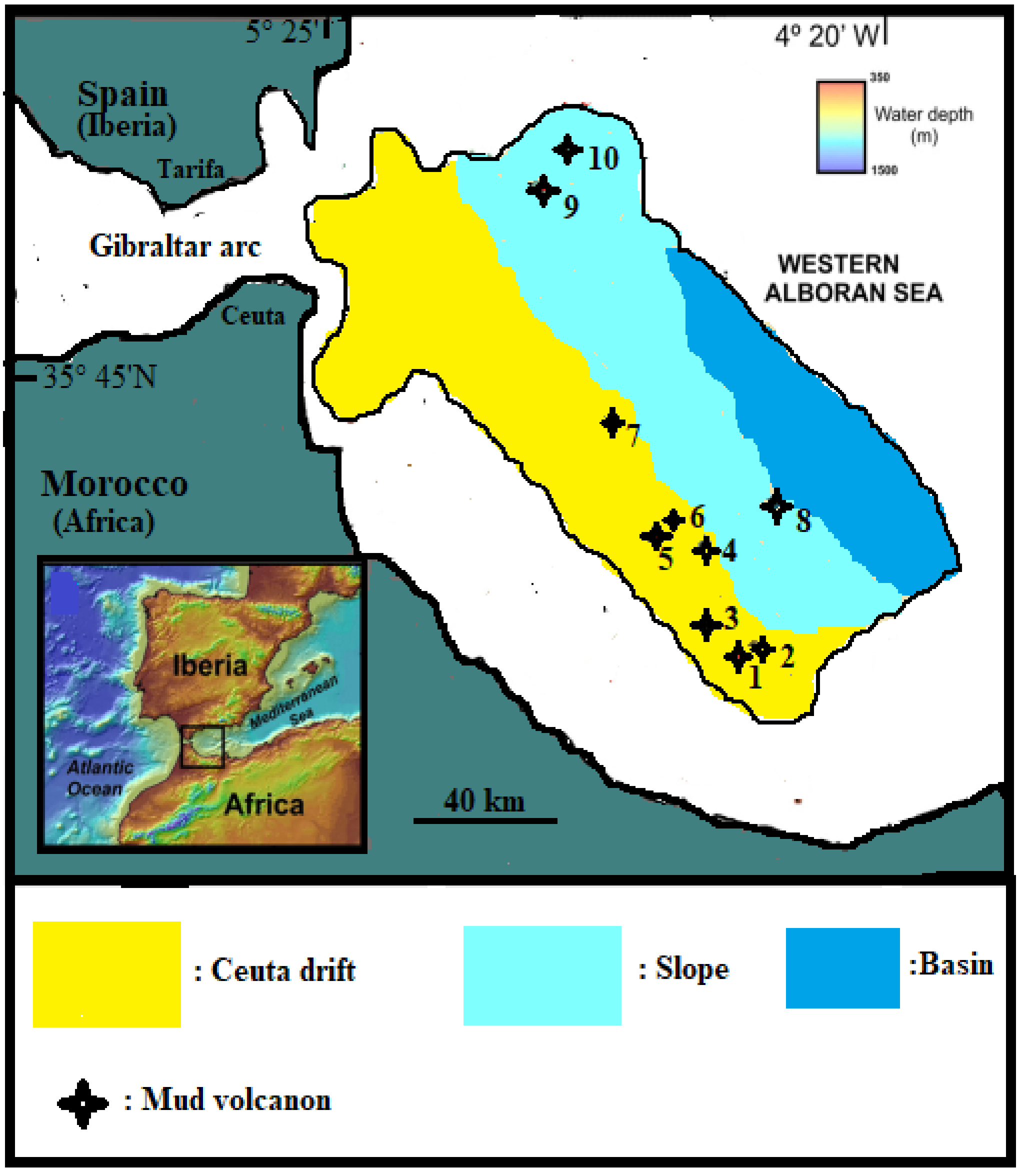

Figure 7 : The Location of mud volcanoes in the Ceuta drift :1) Mulhacen MV ,2) Dakha MV,3) Maya MV,4) Granada MV ,5) Ceuta MV,6) Tarifa MV,7) Carmen MV,8) Marrakech MV,9) Kalinin MV, and 10) Peregil MV (modified from [3]).

The conceptual model for the dominant mud volcano system in the Ceuta Drift (Figure 8) features a single stacked architecture comprising biconic structures and conical conduits of uniform dimensions. The Middle Miocene sedimentary facies, identified as the source rocks for these mud volcanoes [3][8], supply mud and fluid materials to the system. This model is consistent with documented mud volcanoes in the region, including Granada, Kalinin, Perejil, and Kalinin [3], where mud diapirs pierce through overlying strata to reach the seafloor, forming mud volcanoes at the seafloor surface [2][3].

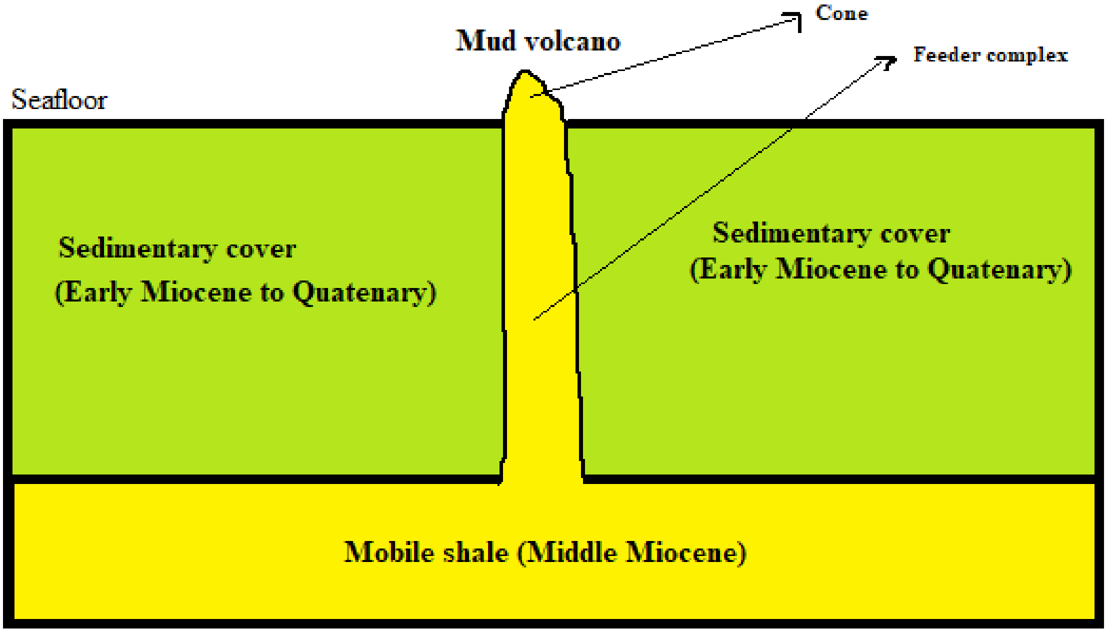

Figure 8 : A Cartoon simplifying the formation mechanism of mud volcanoes in the Ceuta drift and mud volcano system made of a cone and feeder complex with the same size (modified based on[2] [3]).

Furthermore, the source rocks for mud volcanoes in the Ceuta Drift are Middle Miocene facies, while the Late Miocene and Plio-Quaternary facies comprise the sedimentary cover of mud volcano systems in the study area [3][8]. As an example, we have identified a seafloor-piercing mud diapir in the NNE-SSW seismic profile of the Ceuta Drift (Figure 8). Additionally, Figure 9 presents an example of a mud volcano formed through the seafloor mud diapir process.

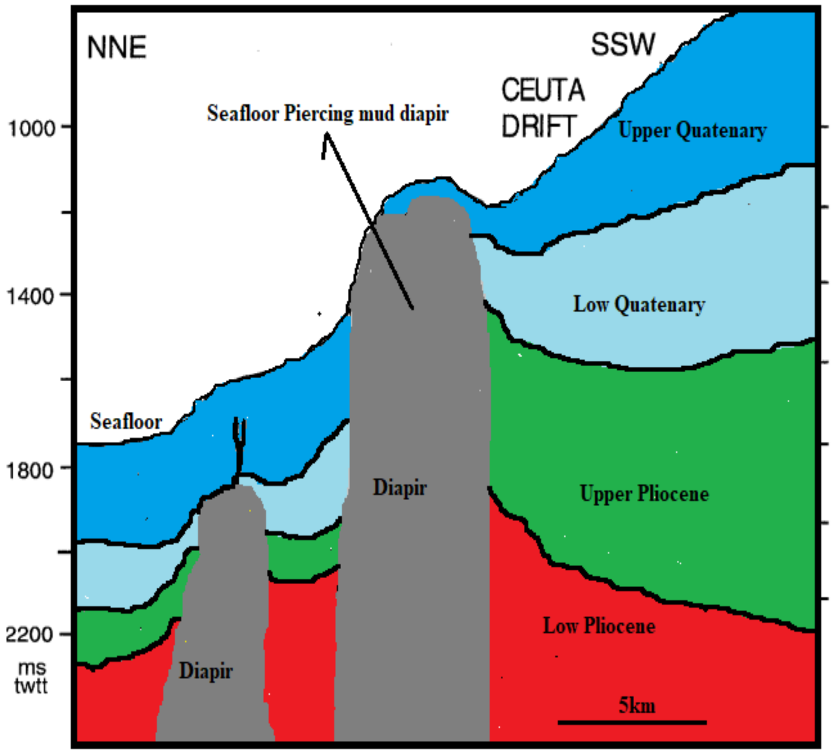

Figure 9 : Cartoon of the high resolution Pliocene-Quaternary seismic profile with one of the examples of the seafloor-piercing mud diapirs in the Ceuta drift (modified from [8].

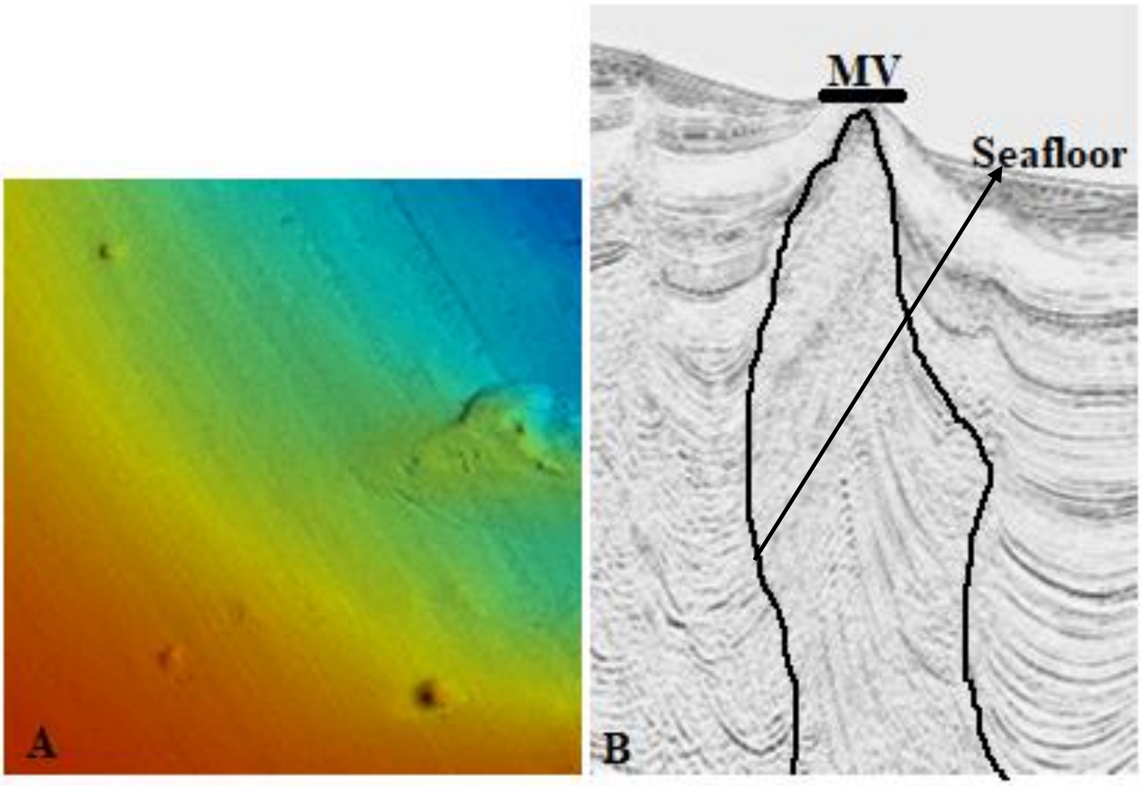

Figure 10 : An example of mud volcano (MV) formed through the seafloor piercing mud diapir formation mechanisms. The mud volcano is found in the South region of the Ceuta drift and the bathymetric data of the Ceutad drift (A) and the Seismic data (B) are some of the data that have been taken by ConocoPhillips oil company during their research projects conducted by 2000 and 2001 in the Alboran Sea.

The above conceptual model (Figure 8), is also related to the history of the formation of mud volcanoes in the Ceuta drift, which began with the formation of the Middle Miocene shale diapirs by the Neogene compression tectonic and the plastic shale layer that has been formed in the Middle Miocene [8]. These shale diapirs served as conduits of fluid from the Middle Miocene mobile shale or plastic shale sedimentary facies to the surface. The latter mud diapirs are classified as seafloor-piercing mud diapirs [2]. The second episode of mud volcanoes formation has been marked by the formation of the Late Miocene to Quaternary mud diapirs along the Pliocene-Quaternary sedimentary cover. We have recognized the latter as the piercing mud diapirs that ended up forming mud volcanoes on the surface. The mud volcanoes have been developed on top of mud diapirs [3][8]. However, it has been said that in order for a mud volcano to be formed, the seafloor-piercing mud diapir in the sedimentary cover has to [8]. In the same sense, the listric normal faults and reverse normal faults in the sedimentary cover played a crucial role for fluids and gas to reach the seafloor and form mud volcanoes [3][8].

5. Comparison and discussion: Formation Mechanisms and key factors, Mud Volcano Systems, Hydrocarbon Exploration and Global Comparisons.

5.1. Formation Mechanisms and key factors involved in mud volcano formation

Worldwide, there are two types of mud volcanoes: formation mechanisms [2].The first ones are mud volcanoes formed on top of the seafloor, piercing mud diapirs and the second ones are formed along the faults due to the overpressure of fluid from the deep areas to the surfaces [2][35]. In these two cases, the NW Moroccan Atlantic Margin is related to the second formation mechanism, where mud volcanoes form due to the upward movement of mud diapirs, often facilitated by strike-slip faults that act as conduits for the mud from deep underground to the seafloor (Figure3, A). This is related to the second mechanism of mud volcano formation. In contrast, the mud volcanoes from the Ceuta drift are the products of the seafloor-piercing mud diapirs representing the first formation mechanisms of mud volcanoes (Figure 8). The mud diapirs involved in the formation of mud volcanoes from the Ceuta drift have been developed from the source rocks as a result of the Neogene compression tectonic, and they went through several phases to reach the surface, including active, passive, reactive and collapse [8]. Furthermore, the collapse phase in the Upper Quaternary period, which has been associated with the extensional processes, has been the main phase behind the formation of the seafloor piercing mud diapirs and the mud volcanoes in the Ceuta drift [3] [8].

The key factors are divided into geological factors and tectonic factors, and they play a critical role in the formation of mud volcanoes [2]. Some of the geological factors include thick terrigenous sediments, rock density inversion, the presence of a plastic shale layer in the subsurface, gas accumulations in the deep subsurface, and abnormally high formation pressure. While the tectonic reasons include the rapid subsidence due to the high sedimentation rate of the sedimentary cover, the occurrence of diapiric structures, the occurrence of faults and lateral tectonic compression, etc [2]. In the NW Moroccan Atlantic Margin, the geological and tectonic settings are complex, involving rapid subsidence due to sedimentation rate of the accretionary wedge structure, strike-slip faults, and the movement of the Rif-Betic Arc [4][36]. These forces create pathways for mud and fluids to rise to the surface, forming mud volcanoes. The formation of mud volcanoes such as Youma, Ginisburg, Meknes and those from the El Arraiche mud volcanoes field from the NW Moroccan Margin has been related to the strike-slip faults activities with interaction of rapid subsidence due to the rapid sedimentation rate of the accretionary wedge structure [5] [36].This suggests that the strike-slip faults and the rapid subsidence force are the primary key factors in the formation of mud volcanoes in the NW Moroccan Atlantic margin.

In contrast, the formation of mud volcanoes in the Ceuta drift has been under the control of the recent tectonic activities dominated by the compressional forces, followed by extensional movements [3]. The initial compressional tectonics led to the formation of the Middle Miocene diapirs, while the subsequent extensional tectonics allowed these diapirs to pierce the seafloor and form mud volcanoes [3][8].Therefore, the tectonic history of the area determines the types of mud volcanoes that can be formed in the same location.

5.2. Formation mechanisms of mud volcanoes from the Moroccan Atlantic margin and the Ceuta drift

Mud volcanoes are formed primarily through two mechanisms: the seafloor-piercing mud diapir process and fault-related processes [2][35]. In the seafloor-piercing mechanism, mud erupts through the seafloor-piercing mud diapirs, creating a volcanic structure above [2]. In contrast, fault-related mud volcanoes arise from the movement of overpressured fluids from deep below the surface, which travel along fault lines[2]. The NW Moroccan Atlantic Margin exemplifies the second mechanism, where mud volcanoes are formed by the upward movement of mud diapirs [4][5][36]. This process is facilitated by strike-slip faults, which act as conduits for the mud to reach the seafloor from deep underground. (Figure 3, A).

In contrast, the Mud volcanoes in the Ceuta Drift are formed through the seafloor-piercing mud diapir mechanism (Figure 6). These diapirs originated from Middle Miocene source rocks due to Neogene compressional tectonics and underwent several stages—active, passive, reactive, and collapse—before reaching the surface [3] [8]. The collapse phase, occurring during the Upper Quaternary and driven by extensional processes, played a crucial role in the formation of seafloor-piercing mud diapirs and mud volcanoes in this region [3]. This highlights the significant influence of lateral compressional tectonics on the formation of mud volcanoes in the Ceuta Drift.

5.3. The key factors involved in the formation mechanisms.

The key factors influencing the formation of mud volcanoes can be divided into geological and tectonic factors, both of which play a crucial role [2]. Geological factors include thick terrigenous sediments, rock density inversion, the presence of a plastic shale layer in the subsurface, gas accumulations in the deep layers, and abnormally high formation pressures [2][35]. Tectonic factors, on the other hand, involve rapid subsidence due to high sedimentation rates, the occurrence of diapirs, fault activity, and lateral tectonic compression [2][35].

In the NW Moroccan Atlantic Margin, the geological and tectonic settings are complex. They feature rapid subsidence driven by the high sedimentation rate of the accretionary wedge, strike-slip faults, and the movement of the Rif-Betic Arc [4][36]. These factors create pathways for mud and fluids to rise to the surface, leading to the formation of mud volcanoes [36]. Specifically, mud volcanoes such as Youma, Ginsburg, Meknes, and those in the El Arraiche mud volcano field are linked to strike-slip fault activity combined with rapid subsidence due to the high sedimentation rate of the accretionary wedge [5][36]. This highlights that strike-slip faults and rapid subsidence are the primary factors driving the formation of mud volcanoes in the NW Moroccan Atlantic Margin.

In contrast, the formation of mud volcanoes in the Ceuta Drift is controlled by recent tectonic activities, dominated first by compressional forces, followed by extensional movements[3]. Initial compressional tectonics in the Middle Miocene led to the formation of diapirs, while subsequent extensional forces allowed these diapirs to pierce the seafloor, resulting in the formation of mud volcanoes [3][8]. The mud volcanoes formed in this way are rare Worldwide and unique [2].

In summary, the NW Moroccan Atlantic Margin and the Ceuta Drift represent two distinct mechanisms of mud volcano formation. In the NW Moroccan Atlantic Margin, the combination of strike-slip faults and rapid subsidence drives the formation of a mud volcano. In contrast, in the Ceuta Drift, a compressional-extensional tectonic sequence plays the dominant role in mud diapir formation and subsequent mud volcano activity. The geological and tectonic forces of these regions ultimately dictate the types of mud volcanoes that emerge.

Table 1: The differences in terms of formation mechanisms and key factors between the mud volcanoes from the NW Moroccan Atlantic margin and the Ceuta

Formation mechnisms/Keys factors	NW Moroccan Atlantic margin	Ceuta drift
Formation Mechanisms	Formed along faults	Developed on top of the seafloor-piercing mud diapir
Key factors	Rapid subsidence, fault activity, thick terrigenous sediments	Lateral compression tectonic, recent extentional mouvement, occurrence of diapirs

5.4. Mud Volcano Systems and Global Comparisons.

The mud volcano systems consist of both the surface volcano and the feeder complex, which connect the source of the mud to the seafloor [24]. In the NW Moroccan Atlantic Margin, these systems are characterized by complex structures, with cones and buried bicones of varying sizes (Figure 3, B). An example of mud volcanoes showing similar mud volcano systems is the Al Idirssi mud volcano from the El Arraich mud volcanoes field (Figure 2) and the Tasyon mud volcano [4]. These types of mud volcano systems are similar to those found in the South Caspian basin, where the Maykop formation (or Maykop sedimentary facies) has been the source of the mud and petroleum oil [24]. Therefore, these types of mud volcano systems (specifically in the NW Moroccan Atlantic margin) often exhibit dynamic structural complexity due to the varying tectonic forces acting on the margin [4][36].

Conversely, in the Ceuta Drift, the mud volcano systems are more uniform, with single-stack structures consisting of cones and a complex of feeders of similar size (Figure 8). These systems form as a result of the Middle Miocene shale diapirs, with mud volcanoes emerging as seafloor-piercing diapirs during the episodes of extensional tectonics [3][8].

5.5. Hydrocarbon Exploration and Mud Volcanoes

Mud volcanoes are often associated with hydrocarbon-rich areas, making them of interest for exploration [37]. The mud and gases expelled from these volcanoes can include hydrocarbons, providing valuable insights into subsurface oil and gas reservoirs [5][38]. In the NW Moroccan Atlantic Margin, the El Arraiche mud volcano field is known for the presence of thermogenic and biogenic gases (mostly methane gas in the form of gas hydrates) [5][26] [28]. In addition, the active mud volcanoes searched us Yuma, Ginsburg and Meknes, are significant for hydrocarbon exploration [36].

In the Ceuta Drift, the Middle Miocene shale diapirs are believed to act as conduits for hydrocarbon-rich fluids, mostly methane gas, further enhancing the region's potential for hydrocarbon exploration [3]. However, no scientific literature we have found recognizing the presence of hydrocarbon in the form of gas hydrate in the Ceuta drift, as has been the case in mud volcanoes from the NW Moroccan Atlantic margin and the Gulf of Cadiz in general [28].

6. Conclusion

In the formation of mud volcanoes, different factors have played a role depending on the region. On the NW Moroccan Atlantic margin, the primary factor has been the high sedimentation rate, while in the Ceuta Drift, lateral tectonic compression and extensional movements are the dominant forces.

Regarding the formation mechanisms, mud volcanoes on the NW Moroccan Atlantic margin have formed due to overpressure acting on fluidised sediment along dextral strike-slip faults, a common mechanism for mud volcanoes worldwide. In contrast, mud volcanoes in the Ceuta Drift have developed atop diapirs, which rise from deeper layers due to density inversion. This mechanism is less common and results in the formation of large seafloor-piercing mud diapirs, where both the cone and feeder complex of the mud volcanoes are of considerable size and share similar dimensions.

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