

# A Seismic Facies Analysis to Determine the Relative Age and History of the Al Idrissi Mud Volcano from Offshore Larache Located in the NW Moroccan Atlantic Margin

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## Abstract

Formed on top of the Gulf of Cadiz, the Al Idrissi mud volcano is the shallowest and largest mud volcano in the El Arraiche mud volcano field of the northwestern Moroccan margin. The development and morphology of mud volcanoes from the El Arraiche mud volcanoes group have been studied at a large scale. However, the time interval related to their formation period still needs to be better understood. In this regard, we interpreted and analyzed the seismic facies from the 2D reflection data of the GEOMARGEN-1 campaign, which took place in 2011. The aim was to identify the seismic sequences and draw the Al Idrissi mud volcano system to determine the formation period of the Al Idrissi mud volcano. And as a result, the Al Idrissi mud volcano system is made of both buried and superficial bicone and was identified along with the Upper Tortonian to Messinian-Upper Pliocene facies. As the initial mud volcano extrusive edifice, the buried bicone was formed in the Late-Messinian to Early-Pliocene period. However, the superficial bicone, as the final extrusive edifice, was included in the Late Pliocene. In this case, the timing interval between the buried and superficial bicone is equivalent to the Late-Messinian to Upper-Pliocene period. Therefore, the latter corresponds to the Al Idrissi mud volcano formation period.

## Keywords

Northwestern Moroccan Margin, Al Idrissi Mud Volcano, 2D Reflection Data from the GEOMARGEN-1 Campaign, Seismic Signatures Analysis, Formation Period

## 1. Introduction

Mud volcanoes are positive topographic features that result from the extrusion of mud and fluids deep below the seafloor [1]. They are mostly associated with diapirs or active faults. Their mud breccia includes rock fragments from the deep levels, water, and fine-grained sediments [2]. In this way, the mud volcanoes provide information on the inaccessible deep stratigraphical facies. Additionally, mud volcanoes can accumulate a huge amount of gas hydrates (considered as new source of energy) [3]. This indicates that the oil/gas reserves are leaky on the location of mud volcanoes [4]. These geological structures are found everywhere on Earth, but are mostly located along the active continental margins with high sedimentation rates and the accretionary wedges like in the Gulf of Cadiz and the North-West Moroccan Atlantic margin [5].

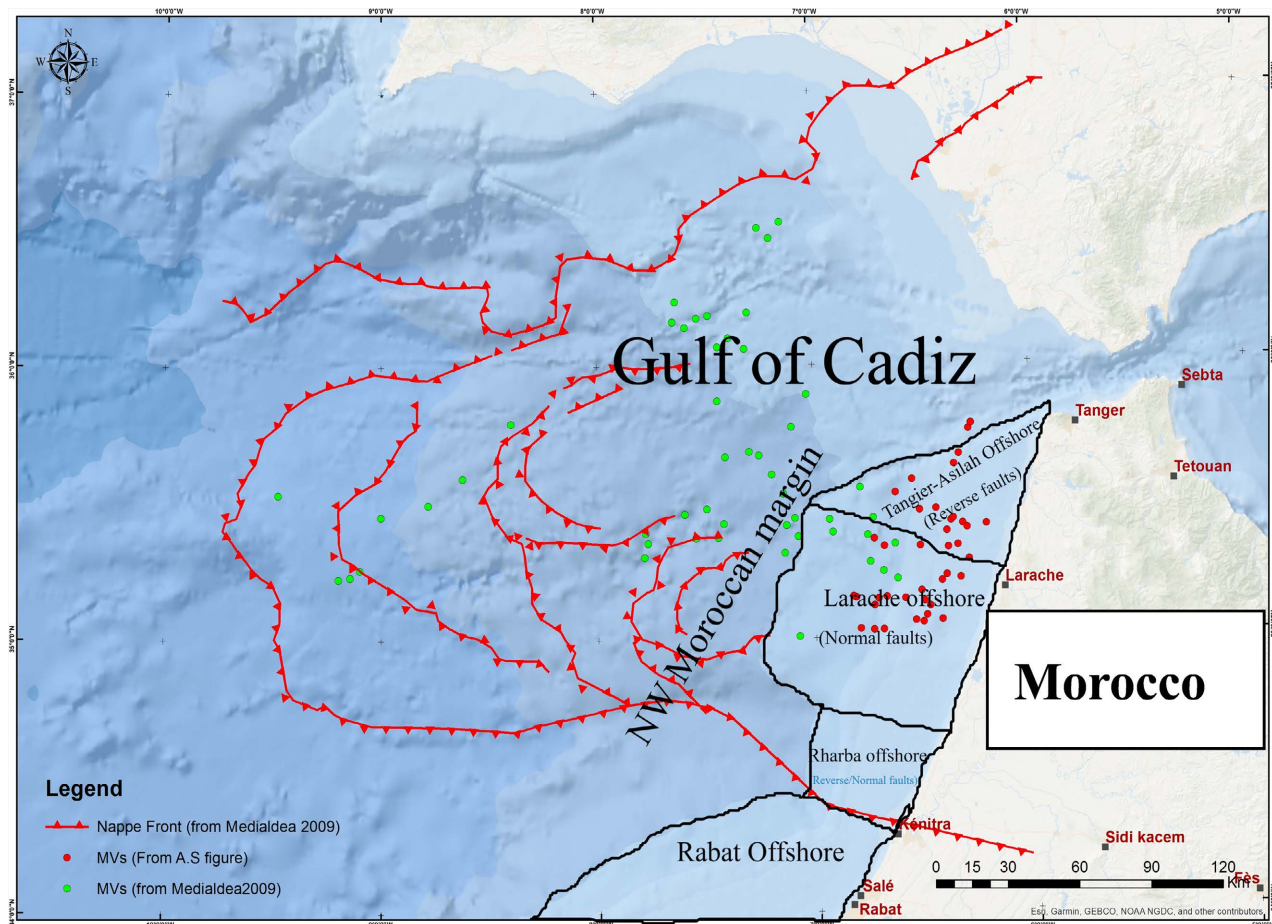
In the Gulf of Cadiz, mud volcanoes were discovered for the first time in 1999 [3] [6]. They have been investigated at a large scale by domestic and outside universities, and certain organizations such as UNESCO (e.g.: TTR14) and the Moroccan Network in charge of Marine Sciences (REMER) [3] [6] [7]. Most active mud volcanoes can be found on the Moroccan Atlantic margin [8]. The most investigated in this location is the El Arraiche mud volcanoes group. The latter is made of the south-Eastern continuation side of the Spain-Moroccan mud volcanoes field [9] [10]. The mud volcanoes group is found at the top of the accretional wedge known as Prerifaine Nappe of Morocco in the offshore Larache [10]. According to previous literature [11] [12], these mud volcanoes were formed based on the upward flow of fluids and mud from the overpressured levels of the accretional wedge. This overpressure mechanism in the Gulf of Cadiz is believed to be caused by the Plio-Quaternary oblique convergence motion [10] [12]. The subsidence tectonic regime that took place since the Cenozoic played an important role in the initiation of the mud volcanism in the Gulf of Cadiz and in the study region (El Arraiche Field) in particular [9]. The mud volcano activity in the El Arraiche mud volcanoes field are well known to be under the control of normal faults within the Pliocene basin [11]. In this case, the Al Idrissi mud volcano is the biggest mud volcano in this El Arraiche mud volcanoes group [10].

In the Gulf of Cadiz, the mud volcanoes' development, morphology, and source of their mud breccia have been widely documented [11] [12]. However, the time interval corresponding to their formation period is still poorly known. This study aims to determine the Al Idrissi mud volcano system and the time interval of the Al Idrissi mud volcano based on the seismic facies analysis. The relative age relationships concept and the seismic signatures (amplitude, for example) are the critical base of this assessment. As matter of fact, the remainder of the paper is given as follows: Section 1 describes the Al Idrissi mud volcano regional setting. Section 2 presents the seismic data from the GEOMARGEN-1 campaign and the methodology to be used in the determination of the Al Idrissi mud volcano's time interval. Section 3 includes the description of the seismic sequences

within the study and the architecture of the Al Idrissi mud volcano system. Section 4 represents the discussion part which correlates both seismic sequences and the Al Idrissi mud volcano system and concludes the relative interval corresponding to the formation period of the Al Idrissi mud volcano. Section 5 made the general conclusion of this research paper.

## 2. Regional Setting

The North-West Atlantic Moroccan Margin is a part of the Gulf of Cadiz which is located between Rabat and Tangier on the South-side of the Gulf of Cadiz (**Figure 1**). It is among the oldest margins on Earth [13]. The margin was formed through the central Atlantic rifting mechanism which took place from Triassic to lower Jurassic around 180 to 200 Ma [14] [15] [16] [17]. The non-volcanic margin type is conjugate to the Nova Scotia margin from North America [13]. The geological setting of the Moroccan margin is characterized by the extensional normal faults, detached synclinal and anticline folds. The latter are located accordingly to the main structural domains represented by Tangier-Asilah offshore, Rharb Bassin offshore, Rabat offshore, and the Larache offshore [18].



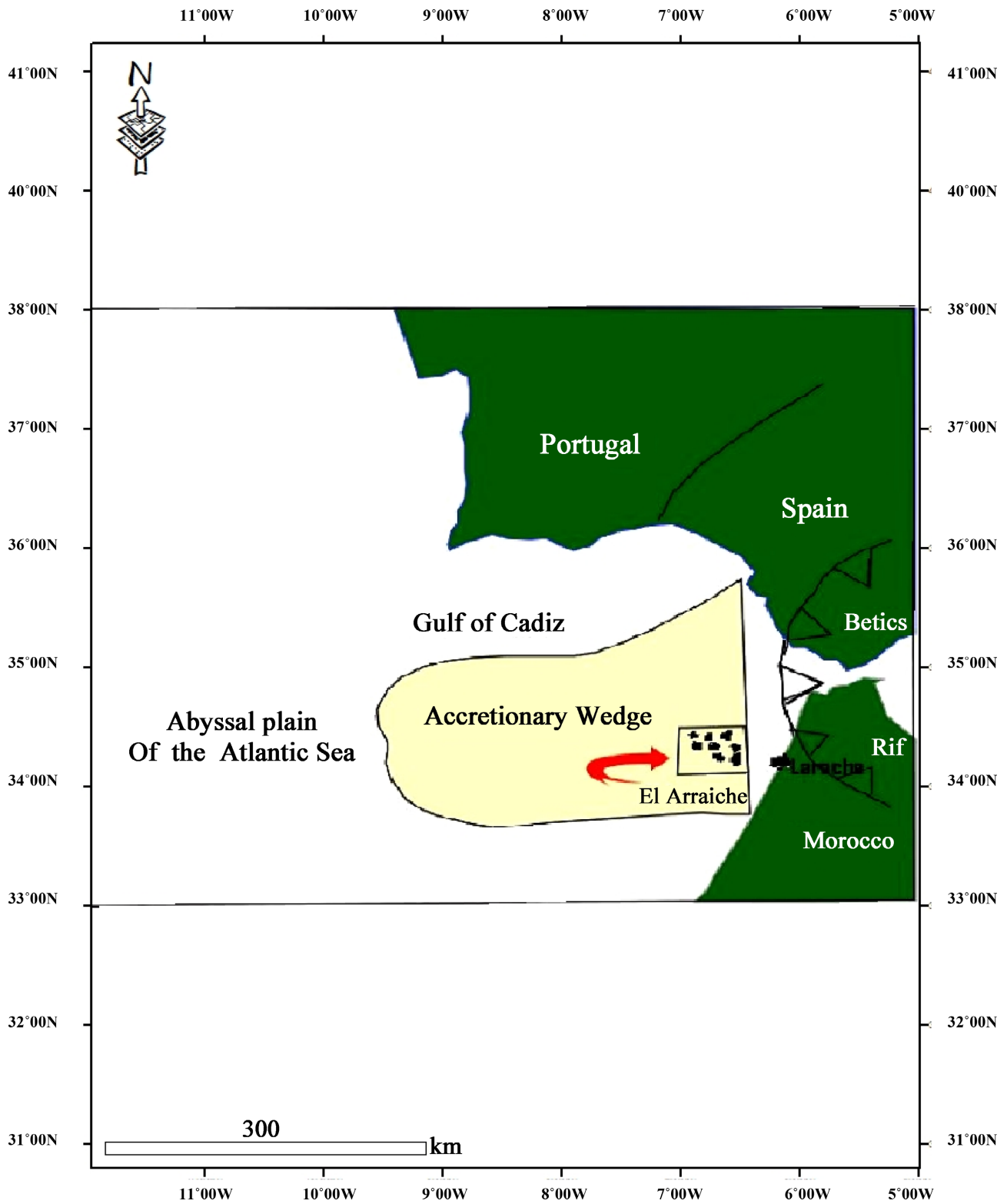
**Figure 1.** NW Morocco Atlantic margin and its different structural domains. The Legend recognizes nappe Front, the mud volcanoes discovered in the past (in green color) [12] and the recent discovered mud volcanoes (in red color) [18].

The Larache offshore where the El Arraiche mud volcano field is located, it is characterized by a distensif system [18]. The offshore is found in the Pliocene extensional basin made by the Upper Miocene-Pliocene sedimentary sequences [10]. In the Eastern side of the Larache offshore, the anastomic normal faults together form the system of extensional normal faults overlying the accretional wedge structure or the Prerifaine Nappe of Morocco [14] [16]. The latter is mainly composed of Triassic salts, shallow-marine carbonate (Mesozoic marine sedimentary unit), and the Middle Miocene clay and shales [16] formed from an interaction between the Alboran domain together with Eurasian and African passive margins in the Middle Miocene [14]. The accretional wedge structure was implanted in the late Tortonian [16] as a consequence of the westward movement of the Gibraltar Arc [14]. It has been affected significantly by the increased subsidence that took place in the late Miocene to lower Pliocene as a consequence of the extensional collapse of the Cadiz Nappe [14]. The subsidence has opened space for the deposition of the turbidite systems (Messinian deposits) in the deep NE-SW trending basins [16] [18]. This is similar to the case of the Plio-Quaternary facies in the Larache offshore and along the Moroccan margin in general [16]. Besides, the Plio-Quaternary NW-NE oblique convergence motion between African and Iberian continental plates reactivated the extensional normal faults and control the location and morphology of the diapiric structure (Triassic salts and Miocene shales diapirs) within the accretional wedge structure [19] [20]. These reactivated normal faults and the diapiric activity have influenced the formation of mud volcanoes found within the Larache offshore and the Gulf of Cadiz in general [12]. In this regard, the El Arraiche mud volcanoes group is one of the examples under the effect of normal faults and diapiric activities in the study region [9].

The El Arraiche mud volcano group is located at the Moroccan margin. It is found on top of the accretion wedge structure but outside of the Cadiz Nappe (the main olistostrome unit occupying the center of the complex olistostrome unit) [9]. The field is made of 8 mud volcanoes situated at water depth which varies from 200 to 700 m [9] [10]. The mud volcanoes' activities are fully controlled by a normal faults system [5] [9]. The Lazarillo de Tormes and don Quichote represent the smallest mud volcanoes in the group with a diameter of 500 m and 25 m high respectively. Whereas the Al Idrissi mud volcano represents the largest mud volcano in the field with a diameter of 5.3 m and height of 225 m (Figure 2).

The Al Idrissi mud volcano is the most active in the Gulf of Cadiz [11]. It is located at a water depth of 420 m near the self-edge [10]. The mud breccia within the mud volcano is made of claystone of 1 cm and 0.5 m rocks clasts composed of sandstones to siltstones with some cemented foraminifera and biotritus [9] [11]. The rock clasts are sourced from the Upper Miocene and Pliocene-aged sediments. The exotic limestone, claystone, and sandstones which are typically for the mud volcano deposits indicate the deep source related specifically to the accretionary wedge structure (or Prerifaine Nappe of Morocco) [18]. Based on the symme-

trical morphology and large size of the Al Idrissi mud volcano, it is clear that the mud volcano formation is related to the diapiric activity.



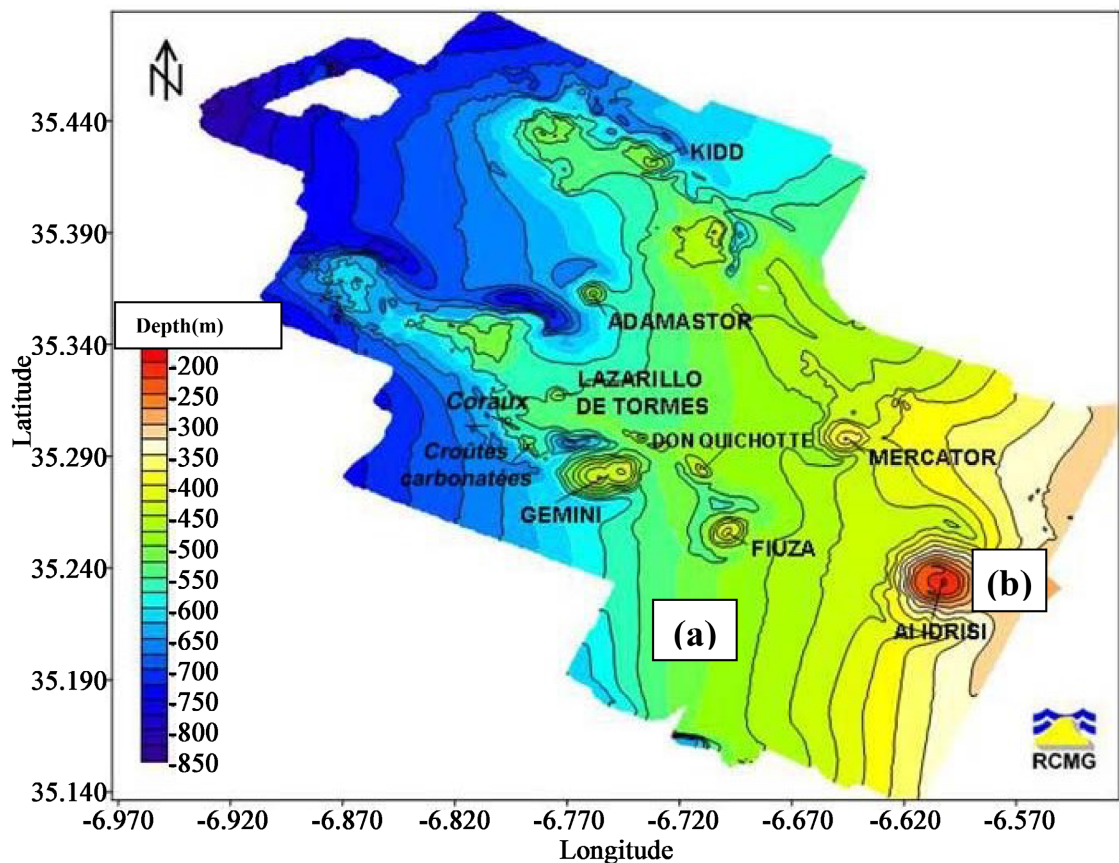
**Figure 2.** The map shows the accretionary wedge and the position of the El Arraiche mud volcanoes group in the Gulf of Cadiz (modified from [5] [21]).

### 3. Material and Methods

The 2D seismic data used in this work is a part of the G14 seismic line from the GEOMARGEN-1 research project that took place in 2011. The GEOMARGEN-1 campaign aimed to study the tectonic and sedimentary structure of the Gibraltar Arc system in the Gulf of Cadiz region. The seismic data were obtained using an Air Guns G-GUN II de Sercel of 10 m depth and recorded via an SEG-D streamer SSAS Multichannel Sentinel Sercel type with 480 channels and 8 hydrophones per channel. Therefore, the seismic image resulting from the research project allowed us to analyze the different seismic sequences based on seismic parameters such as chaotic, transparent, amplitude, continuity, and discontinuity [12] [13] [22]. Furthermore, the thickness of each seismic facies and the depth of each major unconformity on the seismic image (Figure 3) was calculated by converting the Two Wave Travel Time (TWTT) in milliseconds (ms) into thickness and depth in meter (m), based on the equation below (modified in [22]):

Equation (1):

$$\text{Depth} = \left( T_w (\text{en ms TWTT}) * V (\text{m/s}) (\text{water thickness in m}) \right) / 2 + \left( T_s (\text{ms TWTT}) * V (\text{m/s}) (\text{sediments thickness in m}) \right) / 2$$



**Figure 3.** (a) Bathymetric map of the El Arraiche mud volcanoes field [18]; (b) The Al Idrissi mud volcano, which represents the giant mud volcano in the El Arraiche mud volcanoes group.

$T_w$  and  $T_s$  represent the time of the seismic reflections in water and sediments. In this case, the used velocity in water and sediments is equivalent to 1500 m/s and 2000 m/s respectively [23] [24] [25].

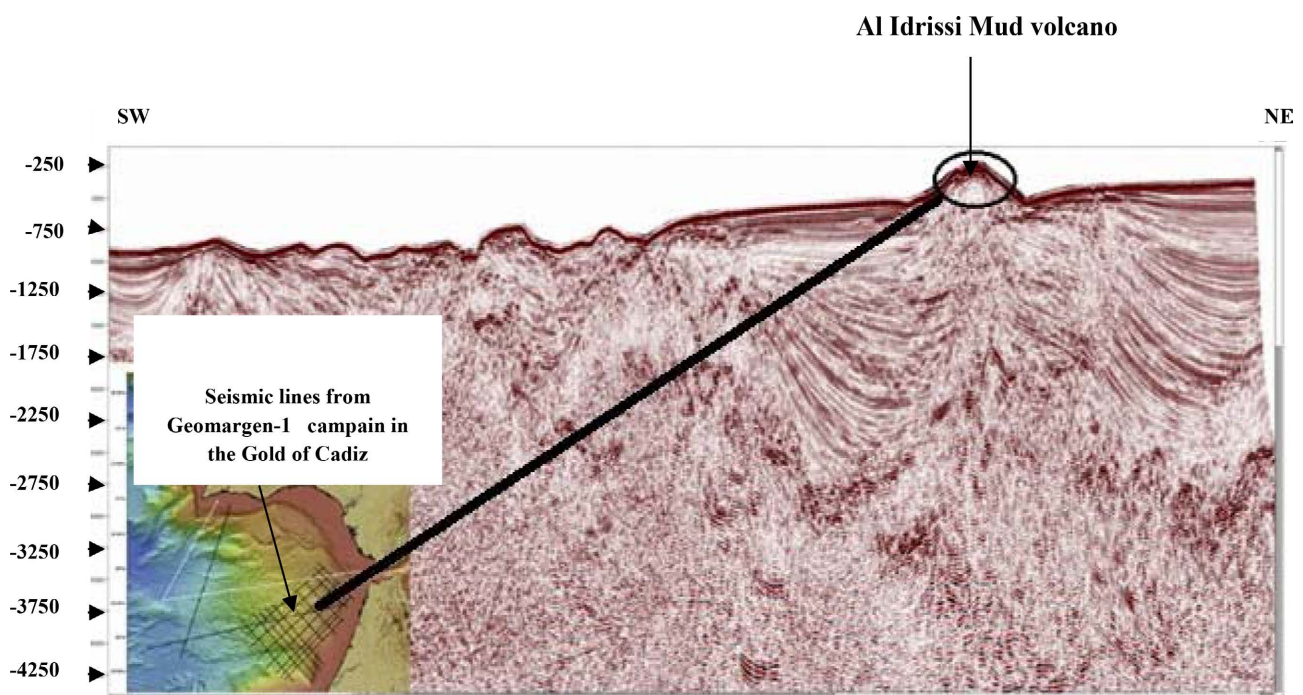
The time-depth curve of the LAR-1 well (**Figure 4**) was crucial to our analysis. The LAR-1 well was extracted from a water depth of 274 m near Larache City by the Burmah company towards the end of the year 1974 [8] [18]. This well represents a unique well that exists in the offshore Rabat-Tangier. Consequently, its time-depth curve was used to fix the seismic section on the sonic log from the study region which allowed us to build a geological model of the concerned study area and identify the geological time scale related to each seismic facies crossed by the mud volcano system.

## 4. Results

### 4.1. Seismic Sequences of the Al Idrissi Mud Volcano

The seismic sequences analysis plays an important role in the determination of the interval of time corresponding to the formation period of a mud volcano. The main issue resides in the identification of the different sedimentary cycles within the seismic profiles. The correlation between the identified seismic sequences and the mud volcano system helps to assess the time interval corresponding to the formation period of a mud volcano [26].

The Seismic signatures (higher or lower amplitude, transparent, continuous, and discontinuous seismic reflections) analysis was used to trace the regional reflectors. The sonic logs of the LAR-1 well [18], and the previous regional characteristics



**Figure 4.** The 2D Multichannel seismic profile corresponds to the GM-14 seismic line from the GEOMARGEN-1 campaign that took place in 2011. The seismic image shows the Al Idrissi mud volcano and its surrounding environment.

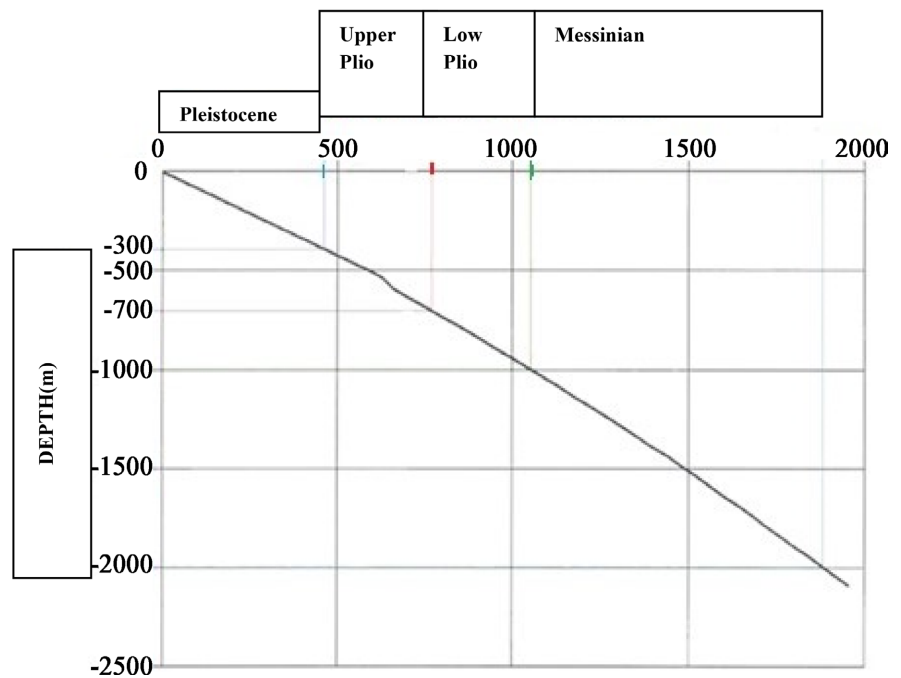
detailed in Roberts 1970 and Rodriguez-Suarez 2005, both were used to determine the geological time scale of each regional sequence. Therefore, the Prerifaine Nappe of Morocco at the base and the Supra Nappe facies on the top were identified (Figure 5). In our case, the Supra Nappe includes the Upper Tortonian-Lower Messinian as the regressive facies, and the Early Messinian to Pliocene-Quaternary (Early and Late Pliocene-Quaternary) as the transgressive ones toward the South-Western margin (Figure 6). We present below the detailed information of each sedimentary sequence from the study area.

#### ***The Prerifaine Nappe Facies:***

The accretional wedge structure or the Prerifaine Nappe of Morocco shows high amplitude and chaotic seismic reflections. It is highly deformed into diapiric structures which are related to the complex deformation that has been known by the sequence [16] [25]. The Prerifaine Nappe has been deposited in the Gulf of Cadiz since the late Tortonian time [25]. The extensional collapse that began in the Late Tortonian together with the roughly N-E compressional tectonic regime has created inter-diapiric basins (upper foredeep basins) [27]. These basins have opened space for the deposition of the Supra Nappe facies [25].

#### ***The Supra-Nappe Unit:***

The Supra-Nappe unit is made of progradation (regressive)-aggradational sedimentary sequences including the Upper Tortonian and the Early Messinian facies both prograding toward NE location, and the Upper Messinian to the Late Pliocene deposits as the aggradational sedimentary deposits. These facies have contributed significantly to the evolution of the Gibraltar arc [14]. The Upper



**Figure 5.** A time-depth curve of the LAR-1 well extracted in [18], and has been used to calibrate our findings.

Tortonian-Messinian facies are the main deposits forming the Miocene Supra-Nappe unit [14] [18].

***The Miocene Supra-Nappe Facies: Messinian (Early&Late Messinian) and the Upper Tortonian facies.***

The Miocene Supra-Nappe facies includes the Upper Tortonian Facies, the Early Messinian, and the Late Messinian deposits. It shows the continuous internal reflectors with high reflectivity or discontinuous and disorganized reflectors as in the chaotic facies. It is affected by faults inherited from the Prerifaine Nappe [18]. The conjugate faults trending NW-SE, and E-W, and SE-NW normal faults are responsible for the subsidence of this unit [14] [18].

The Upper Tortonian unit overlying the accretionary wedge has been recognized as a syn-sedimental sequence to the Prerifaine Nappe of Morocco by the fact that this unit touches the front of the Nappe [16]. This is well visible on the Southwestern margin of the seismic image (Figure 6). In this regard, the Upper Tortonian unit (UT unit) touches directly the front of the Prerifaine Nappe. On the seismic image (Figure 5), the Upper Tortonian facies is characterized by an interaction of transparent and discontinuous seismic reflections. It occupies the inter-diapiric depressions above the Prerifaine Nappe with 1125 m (sediments velocity: 2000 m/s and 1.125 s TWTT as sediments thickness) thick on the SW and 250 m (2000 m/s sediment's velocity and 0.25 s TWTT as sediments' thickness) above diapir. However, at the NE margin, the facies represents the thickness of 1100 m (sediment velocity: 2000 m/s and 1.1 s TWTT as sediments thickness). Sedimentary, the Upper Tortonian unit is made of plastic grey dominated by glauconite and pyrite [16].

The Messinian unit on top of the Upper Tortonian facies is subdivided into two transgressive-regressive sedimentary deposits. The Early Messinian facies (EM) is a regressive sedimentary facies prograding toward the NW location of the southwestern foredeep basin (or inter-diapiric depression). In this area, the facies represent the thickness of the sediments of 225 m (2000 m/s sediment's velocity and 0.225 s TWTT as sediment's thickness). However, in the NE margin, the sediment unit shows the sediment thickness of 425 m (2000 m sediment's velocity and 0.525 s TWTT as sediment's thickness in second) above the diapiric rim and 350 m (2000 m sediment's velocity and 0.350 s TWTT as sediment's thickness) in the foredeep basin at North-Eastern location. Seismically, the Early Messinian facies is characterized by semi-parallel, continuous to semi-continuous and high amplitudes of seismic reflections. These kinds of seismic parameters are descriptive seismic behaviors for turbidite deposits [26]. On the contrary, the Upper Messinian deposit is a transgressive facies retrograding toward the South-western Location of the seismic image. It is characterized by oblique, semi-continuous (in the SW inter-diapiric depression), continuous (in the NE inter-diapiric depression), and high amplitude seismic reflections. The facies represents the sediment thickness of 275 m (2000 m sediment's velocity and 0.275 s TWTT as sediment's thickness in second) in SW inter-diapiric depression while 525 m (2000 m sediment's velocity and 0.525 s TWTT as sediment's thickness in second) above the diapiric

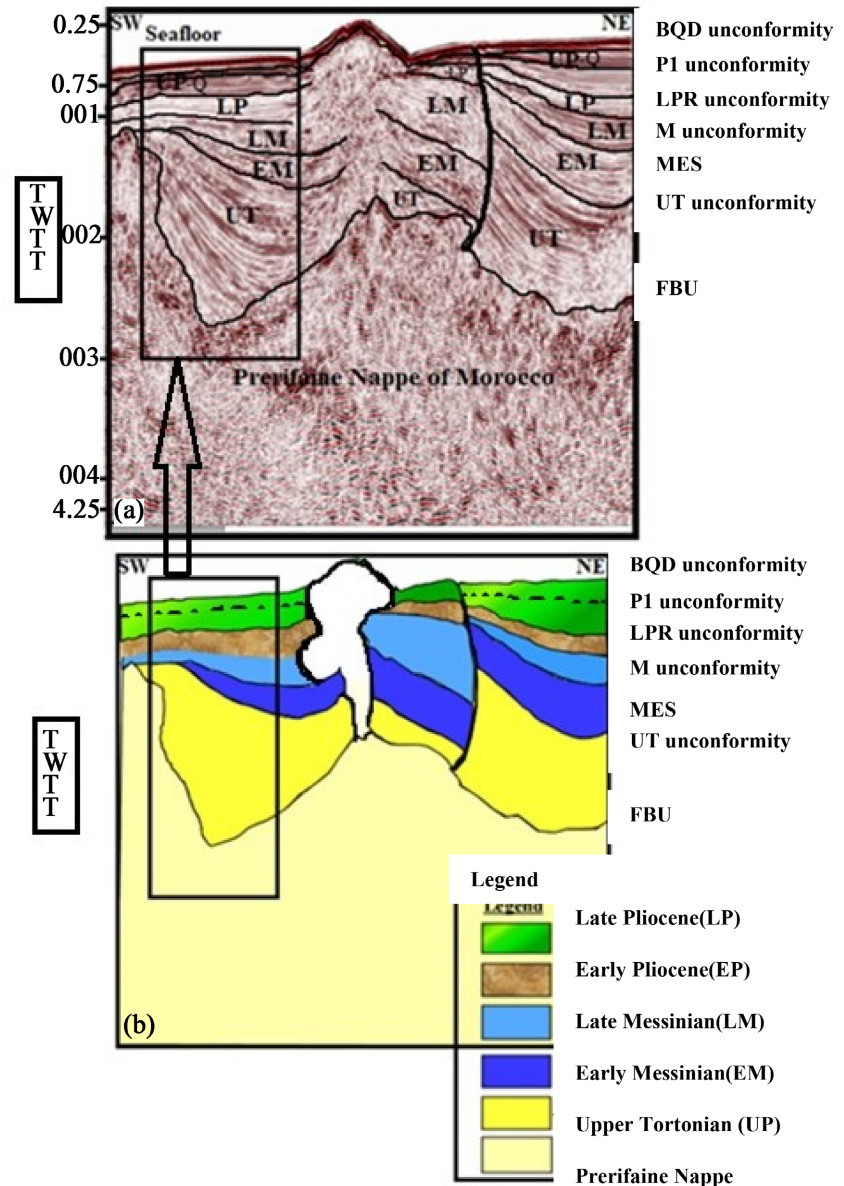
rim (**Figure 5**). However, in the NE foredeep basin, the Messinian facies represents the sediment thickness of about 275 m (2000 m sediment's velocity and 0.275 s TWTT as sediment's thickness in second). In summary, the Early and the Late Messinian facies are differentiated by the retrograde-prograding sedimentary deposits. They both represent the Guadiana sands which correspond to the turbidite deposits from the north margin of the Gulf of Cadiz to the foredeep [16] [26]. Furthermore, the sediments facies contain a higher quantity of gas with economic potential [16] [26]. Besides, the Pliocene sedimentary deposits overlying the Messinian facies made the continuation of the recognized turbidity system [16].

#### ***The Early and the Late Pliocene Facies.***

The Early Pliocene facies (EP) is a part of the aggradational sedimentary deposits of the Supra Nappe Units. It overlies the Upper Messinian facies. Seismically, the Early Pliocene facies is characterized by transparent, parallel, and low amplitude seismic reflectors. It has an average thickness of 225 m (2000 m/s sediments velocity and 0.225 s TWTT as sediments thickness) at SW margin while 75 m and 150 m as sediments thick above diapir and at NE margin successively. The Late Pliocene sediments from the top of the Lower Pliocene show very high amplitude, continuous, parallel to semi-parallel seismic reflections. It has an average thickness of 250 m thick (sediments velocity: 2000 m/s, and sediments' thickness of 0.25 s TWTT) at SW margin while 0 to 400 m above diapir and NE margin successively. Lithologically, the lower Pliocene is made of clays and interbedded andy clays from hemipelagic and turbidite deposits [28] [29].

Based on the seismic signatures of each seismic sequence, the time-depth curve of the LAR-1 well [18], the previous studies related to the existing regional characteristics in the Gulf of Cadiz [14] [18] [33] and the Alboran domain [26] [30], we have determined five essential major discordances separating the identified seismic sequences. The latter include Messinian erosional surface (MES: 5.6 Ma) which separates the Early (EM) and the Late Messinian deposits (LM) [29], the Messinian unconformity (5.5 Ma) separating Messinian facies and the Early Pliocene deposits, the Intra-lower Pliocene unconformity (LPR: 4.2 Ma), the Intra Upper Pliocene unconformity (P1: 3.6 Ma), and the base of the Quaternary (BQD: 2.6 Ma). On top of these essential major unconformities, we added the Upper Tortonian-Messinian Unconformity (UT unconformity) which is an erosional discordance recognized as the sequence boundary between the Upper Tortonian and the Early Messinian sequence [29]. At the second, we have the boundary between the accretion wedge structure (Prerifaine Nappe of Morocco) and the Upper Tortonian facies (UT unit). The latter has been interpreted as the basal foredeep unconformity (BFU) [14] [18]. It is well visible on the seismic image due to the chaotic behavior of the Prerifaine Nappe of Morocco (**Figure 6**).

Therefore, for the seismic analysis to be complete, the description of the mud volcano system should be the main focus of the following chapter. There is a strong connectivity between the seismic sequences, their major discordances,



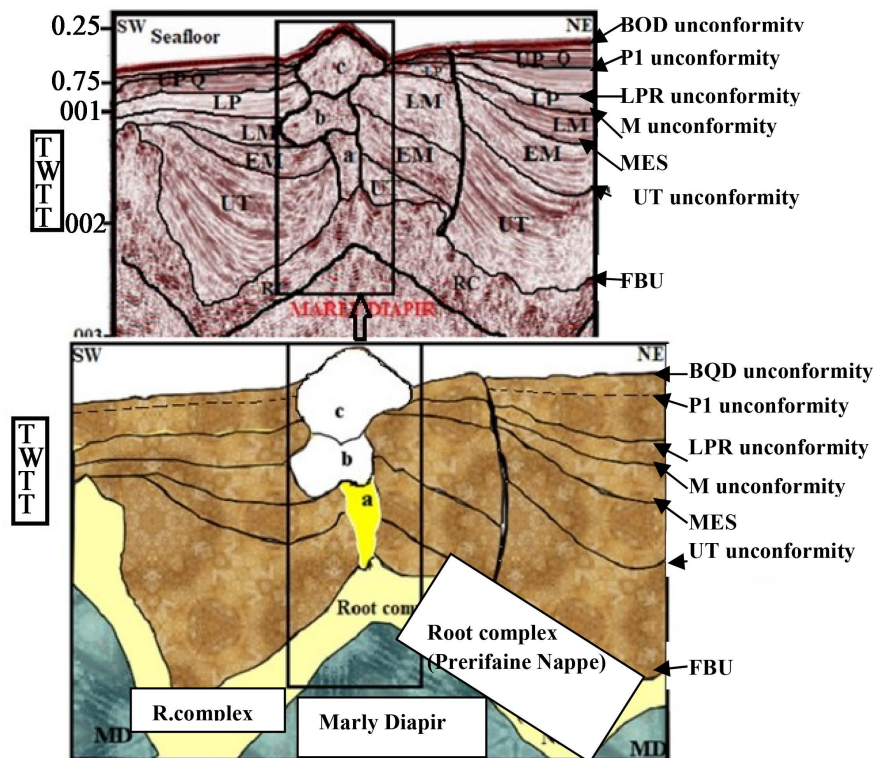
**Figure 6.** The different seismic sequences within the Al Idrissi mud volcano's seismic image, and the major unconformities between the seismic facies (modified from [14] [18] [33]). (a) The seismic sequences within the seismic profile of the Al Idrissi mud, (b) the Ultra-high resolution image of the Al Idrissi mud volcano showing clearly the seismic sequences and their major unconformities, and was modified via Canvas x 16 software. From the base to the top, the seismic sequences include the Prerifaine Nappe of Morocco and the Supra-Nappe successively. The Supra-Nappe facies is formed by: the Upper Tortonian or Syn-Olistostrome Unit (UT Unit); the Early Messinian deposits (EM), the Late Messinian facies (LM), the Lower Pliocene (LP), and Upper Pliocene-Quaternary (UP-Q). The identified major discordances include the basal foredeep Unconformity (BFU or delimitated unconformity); the UT erosional unconformity; the Messinian erosional surface (MES) (between Lower and Upper Messinian), Messinian Unconformity (found between Messinian and Lower Pliocene facies, Intra lower Pliocene unconformity (LPR), the Intra Upper Pliocene unconformity (P1), and the Base of the Quaternary which is known as the Upper limit of the Upper Pliocene facies. Besides, the NW-SE and SE-NW listric normal faults connect the deep Prerifaine Nappe to the seafloor surface [14] [18].

and the mud volcano system when the mud volcano's relative age issue is addressed [26].

#### 4.2. The Architecture of the Al Idrissi Mud Volcano System

The Al Idrissi mud volcano system is made of two vertically stacked bicones, a downward-tapering cone (DTC), and the root complex overlying the deep Marly diapir (Figure 7). These systems are all connected by the deep SE-NW listric normal fault which is common to the mud volcanoes formed at the higher deep diapirs [10].

The superficial and the buried bicones represent the extrusive edifices of the Al Idrissi mud volcano system. They both represent chaotic reflections and are stacked vertically together. The chaotic reflectivity behavior of the bicones is related to the presence and movement of mud and sands throughout the bicones [26]. Generally, both extrusive edifices indicate the different eruption episodes that underwent the Al Idrissi mud volcano along with its formation. The buried bicone (c) in which the base begins at depth of 1137.5 m (velocity in water: 1500 m/s and Tw: 0.55 s TWTT, velocity in sediments: 2000 m/s and Ts: 0.725 s TWTT) from the SW margin just above the Messinian erosional surface (MES) symbolizes the initial extrusive edifice of the mud volcano. However, the superficial bicone (b) which begins at the Intra lower Pliocene Unconformity (LPR)



**Figure 7.** The Al Idrissi mud volcano system: (a) Downward-tapering cone (DTC); (b) Buried bicones, (c) Superficial bicones. At the base of the mud volcano system, we find the source of fluids and mud which is represented by the root complex (RC), and the Marly Diapir which helps the moving upward of mud and fluid.

represents the final mud volcano extrusive edifice. Besides, the buried bicone is connected to the root system by a Downward-tapering cone (DTC) (a). The latter is the mud volcano intrusive edifice which is recognized as the feeder or connector of the initial extrusive edifice (buried bicone at the top) to the root complex [26]. It allows the moving upward of mud and fluids from the source to the buried bicone. On the seismic image, the DTC shows the chaotic seismic reflections which may be related to the mud and sand substances passing through it.

The root complex made the base of the Al Idrissi mud volcano system. This represents the Upper part of the Prerifaine Nappe of Morocco just below the Upper Tortonian Unit (UT) (Figure 6). Its seismic reflectivity is similar to that of the buried and superficial bicones. However, the root complex is more chaotic compared to other areas of the Prerifaine Nappe. This may be explained by the fact that the sedimentary facies holds a huge quantity of mud and fluids. On the other hand, the deep Miocene marly diapir is found below this root complex and has resulted from the deformation of the Prerifaine Nappe of Morocco [12]. This deformation has been influenced by the rapid subsidence that took place since Cenozoic [31] [33]. In summary, the Marly diapir facilitates the upward movement of fluids and mud from the root complex to the downward-tapering cone (DTC).

## 5. Discussion of Results

The purpose of this study is to estimate the time interval related to the formation period of the Al Idrissi mud volcano. The understanding of the seismic sequences of the study area with the Al Idrissi mud volcano system made the base of this research. In this case, the findings from this study show a mud volcano system with one buried bicone overlying the Messinian erosional surface (5.6 Ma) at the depth of 1137.5 m and the superficial bicone above the Intra-Lower Pliocene unconformity (4.2 Ma) (see Figure 6). Both bicones are stacked vertically together with a short dormant period. They are all connected through one feeder system which overlies the Prerifaine Nappe of Morocco and passing through the Supra-Nappe Units (the Upper Tortonian to the Late Pliocene-Quaternary facies) to the surface. Furthermore, the root complex at the base of the feeder complex system is made of the most chaotic Upper part of the Prerifaine Nappe of Morocco just above the deep marly clay diapirs or underneath the Upper Tortonian Facies (UT Unit) (see Figure 6). The SE-NW listric normal fault plays an important role in the moving upward of the mud breccia from the source (root complex) to the surface. This kind of architecture found within the Al Idrissi mud volcano system could be a common architecture to the mud volcanoes formed on the top of the deep mud diapirs. The same type of mud volcano system has been found in the TASYO mud volcano and was formed similarly [11].

On the other side, the first formed mud volcano extrusive edifice represents

the initial phase and corresponds to the starting period of the diapiric activity [11] [26] which has been recognized as the Early Pliocene in the Gulf of Cadiz [12] [32]. In this research paper, the initial phase is related to the formation of the buried bicone formed in the Late-Messinian Early-Pliocene timing interval by the fact that both facies (Late Messinian-Early Pliocene facies) touch the front of the concerned bicone (Figure 6). The final phase resulted in forming the superficial bicone in the Late Pliocene. Therefore, the two stacked bicones explain the fact that the Al Idrissi mud volcano underwent two eruptional phases of mud and fluids from the overpressured Prerifaine Nappe of Morocco [11]. Furthermore, tectonics has been the main factor controlling the architecture of the mud volcano system [10]. It plays an important role by overpressuring the source material which leads to the generation of fluids and mud forming the mud volcano extrusive edifices [9] [10] [11]. The rapid subsidence is the initial tectonic regime in the study area and has taken place in the Late Messinian-Early Pliocene timing interval [16] [18]. The latter corresponds exactly to the formation period of the buried bicone. Besides, this tectonic regime has never affected the morphology of the buried bicone which is in a similar case as the Late-Messinian Early-Pliocene sedimentary facies [24]. Nevertheless, the short dormant period between the buried bicone and the superficial bicone could be related to the rapid decrease in the subsidence rates in the Early Pliocene [16]. On the other side, compression tectonics has been possibly the main actor to an overpressure of the accretional wedge which resulted in the formation and the development of mud volcanoes in the Gulf of Cadiz [12] [31]. In this case, the well-known tectonics of this kind is known as the Oblique convergence motion which took place in the Late Pliocene-Quaternary [13] [33] [34]. This timing interval includes the formation period of the superficial bicone. Consequently, the latter could have resulted from the reactivation of the buried bicone influenced by this oblique convergence motion.

Therefore, it has been proposed that the formation period (measured in terms of relative age) of a mud volcano corresponds to the timing interval between the initial extrusive edifice (or the initial buried bicone) of a mud volcano system and the latest formed extrusive edifice (superficial bicone) [35]. In this case, the buried bicone formed in the Late-Messinian Early-Pliocene timing interval, and the superficial bicone in the Late Pliocene, made us conclude that the relative age of the Al Idrissi mud volcano corresponds to the Late Messinian-Upper Pliocene period.

Overall, this research paper is limited to the time interval corresponding to the formation period of the mud volcano through relative age's relationships. According to our estimated results, we found out that the Al Idrissi mud volcano is older than the mud volcanoes from the West Alboran domain (or Ceuta drift) where the activity of the oldest mud volcano in the region began in the mid-Pliocene [26]. Nevertheless, any error that could be associated with our estimated results may be related to the use of the low seismic reflections data and the incoherent reflectivity in the seismic image because of the faulting system

(e.g., NW-SE listric normal at NE margin). The latter made it harder in separating the seismic sequences mostly the root complex from the deep marly diapir in the Prerifaine Nappe of Morocco. Furthermore, the use of the time-depth curve of the LAR-1 well (see **Figure 4**) as the only one available stratigraphical data has been also part of our challenges. This is because the time-depth curve does not recognize the Messinian erosional surface (MES) which is considered as the initial point of reference of the estimated results. On the other hand, the determined time interval and the Al Idrissi mud volcano system are the additional value to the existing information related to the Al Idrissi mud volcano.

## 6. Conclusions

We aimed to determine the time interval corresponding to the formation period of the Al Idrissi mud volcano thereby basing on the analysis of the seismic parameters applied on the 2D seismic image from the GEOMARGEN-1 research project. In this case, the amplitude, chaos, continuity, and discontinuity of the seismic reflections were the main seismic signatures used to identify the seismic facies within the seismic image. The latter was fixed on the sonic logs from the study area using the time-depth curve of the LAR-1 well. Therefore, along with the study, the following conclusions were made:

The Al Idrissi mud volcano has undergone two eruptional phases, and the Prerifaine Nappe of Morocco is the source of the Al Idrissi mud volcano's mud breccia. Furthermore, the two vertically stacked bicones where the buried bicone represents the initial extrusive edifice of the Al Idrissi mud volcano system were formed during the Late Messinian-Early Pliocene and has been initiated by rapid subsidence that took place since Cenozoic (Late Messinian-Early Pliocene). The superficial bicone as the final extrusive edifice of the Al Idrissi mud volcano system was formed in the late Pliocene under the influence of the Plio-Quaternary oblique convergence motion which overpressured the buried bicone. Together, these timing intervals related to the formation period of both stacked bicones helped us to conclude that the time interval related to the formation period of the Al Idrissi mud volcano is equivalent to the Late Messinian-Upper Pliocene time.

Finally, the assessment of the time interval or geological range corresponding to the formation period of the Al Idrissi mud volcano has been the motivation in the recognition of the Al Idrissi mud volcano system (to be among the new pieces of information in the study area) and in the understanding of the series of events that have marked the formation period of the concerned mud volcano (e.g., different episodes undergone the Al Idrissi mud volcano during its formation period). Although, our manuscript has succeeded and come up with an interval of time related to the formation period of the Al Idrissi mud volcano, its numerical age (or absolute age) is still the lacking information like it has been the case to many others mud volcanoes in the Gulf of Cadiz. The latter requires some radiometric dating technics [36] which is not part of our agenda. We,

therefore, recommend the next research projects to fulfill the gap.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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