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Classification of mud volcanoes in the South Caspian Basin, offshore Azerbaijan

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Abstract

A 2D seismic grid in the South Caspian Basin, offshore Azerbaijan, is used to define the areal distribution of mud volcanoes and to make a classification of the mud volcanoes based on characteristic seismic features. A high concentration of mud volcanoes is observed at the southern part of the study area that coincides with the distribution of subsurface structures within the basin. Mud volcanoes with low relief (several tens of meters) are concentrated primarily in the northeastern portion of the study area; mud volcanoes with large vertical relief (greater than 200 m) are clustered in the southwest part of the basin. Mud volcano development in the South Caspian Basin is generally linked to faults, which in some instances are detached at the basement level. The seismic database allows us to determine the relative timing of mud flows and gives us valuable information about mechanisms of mud volcanism within the South Caspian Basin. The cycles of mud volcano activity coincides with time of high sedimentation rates, regional contraction episode and a major stage for hydrocarbon generation. Mud volcano formation within the South Caspian Basin is primarily controlled by compressional tectonic forces and overpressured sediments. Mud volcano activity may not always be related to the Maykop organic rich shale succession (Late Oligocene–Lower Miocene) but may also occur at shallower stratigraphic zones.

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Keywords: Mud volcanoes; South Caspian Basin; Seismic data

1. Introduction

Mud volcanoes are a natural phenomena that reflect regional geological processes. There are many global studies of mud volcanoes that reveal aspects of their origin, mechanism of formation and paleo-activity (Brown, 1990; Guliyev & Feizullayev, 1995; Jakubov, Ali-Zade, & Zeynalov, 1971; Kopf, 2002; Milkov, 2000). Mud volcanoes are mainly concentrated in systems of accretionary prisms where compressional settings and active fluid dynamics prevail. Thus, they are an important source of information about subsurface sediments and conditions.

Submarine mud volcanoes in southern Caspian Basin have previously been described and discussed by, amongst others (Ginsburg & Soloviev, 1994; Newton, Cunningham, & Schubert, 1980). The goal of this study is to interpret and classify mud volcanoes in the Azeri sector of the Caspian Sea using observations from 2D seismic data. This study provides a description of offshore mud volcanoes in an area of about 60,000 km^2 offshore Azerbaijan (Fig. 1). The source of data is 2D seismic coverage acquired in 1995 and 1998. Line spacing of the seismic lines vary from 5×5 to 2.5×2.5 km. Since there is a paucity of geologic samples from the offshore areas where mud volcanoes are observed, seismic data is vital for our understanding of the processes and mechanisms of their formation.

In this study, we map the location of the mud volcanoes and characterize them according to their height, shape and relation to structures. The relative time of paleoflows (paleoactivity) from the mud volcanoes is determined. Wedge-like features observed beneath the sea floor on the seismic reflection profiles are a manifestation of mud volcano activity in the past are also discussed.

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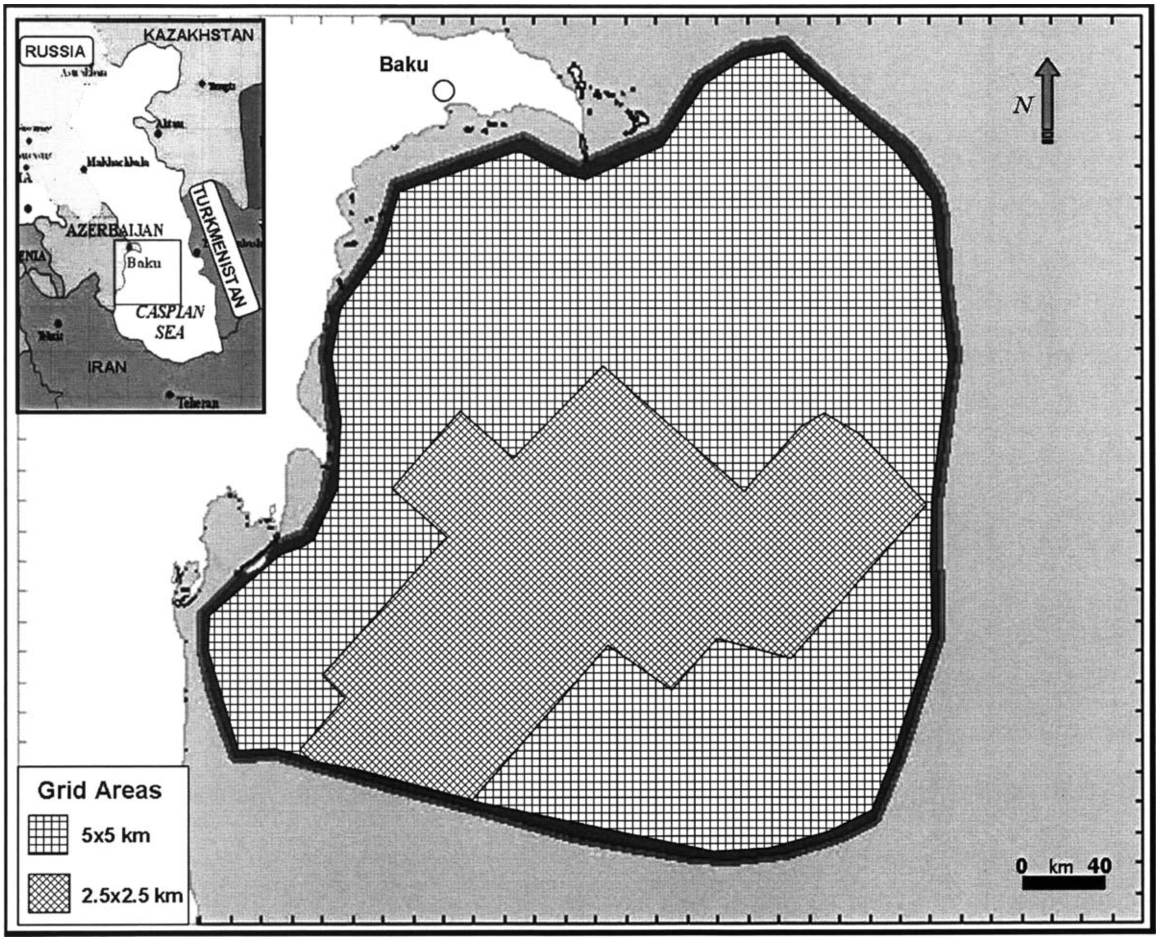

Fig. 1. Area of study with the 2D seismic data coverage.

2. Regional geology

2.1. Mud volcanoes

More than 30% of the world's known mud volcanoes are concentrated in the South Caspian Basin (Guliyev & Feizullayev, 1995). Favorable tectonic conditions and depositional settings caused the generation of large mud volcanoes in this region (Guliyev & Feizullayev, 2000). In places, they will be shown to be several kilometers across and reach several hundred meters in height. As a source of hydrocarbon gases they may provide sufficient supply of gases to the hydrosphere and atmosphere to possibly affect climate change (Kopf, 2002; Milkov, 2000). According to Guliyev and Feizullayev, the mud volcanoes may have a spatial and genetic relationship with oil and gas fields and thus may provide evidence of petroleum potential. This study shows that mud volcanoes are indeed located in regions where active hydrocarbon systems are present, but are not necessarily connected with fossil fuel accumulations. Mud volcanoes also impact drilling operations, rig installations and pipeline routings by their violent eruptions and instability of the surrounding gas saturated sediments (Milkov, 2000).

When integrated with the previous studies on mud volcanoes in the Caspian Sea observations from this study show that there are no evidence of mud diapirs observed in the seismic data. Most mud volcanoes in our study area are situated above anticlines that are complicated by faults. Their development occurs in stages, a result which is similar to mud volcano studies in other geographical regions.

Geologically, the South Caspian Basin is a relict fragment of the Tethyian Ocean with basinal subsidence up to 25–30 km being a result of collision connected with closure of the Tethys Ocean (Lerche, Bagirov, Nadirov, Tagiyev, & Guliyev, 1997). Very high sedimentation rates up to 1000 m/MA since the Middle Pliocene causes excessive fluid pressure within the sediments throughout the whole basin. Existence of overpressured sediments appears to be the key factor for the mud volcano formation and the mud volcanism in the basin (Lerche et al.; Nadirov, Bagirov, & Tagiyev, 1997).

2.2. Hydrocarbon occurrence

The main oil reserves have been discovered in the Middle Pliocene Productive Series (Fig. 2). Deposition of the Productive Series was initiated by a major fall in base level

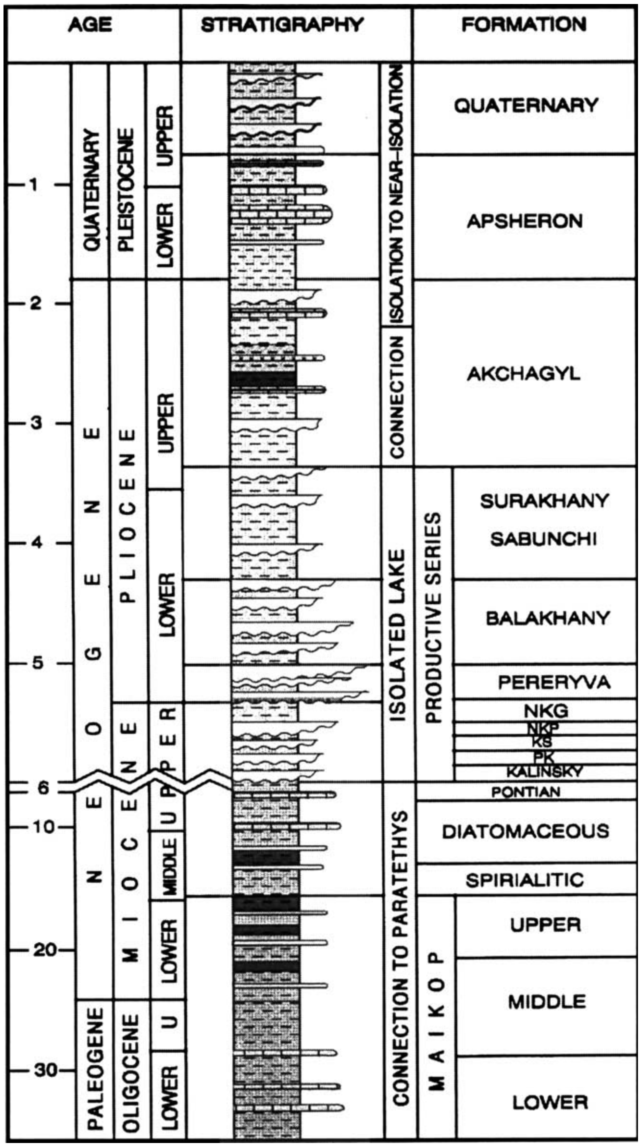

Fig. 2. Generalized stratigraphic column for the Azeri sector of the South Caspian Basin (Fowler et al., 2000).

during the Late Miocene. There are two distinctive groups of reservoir rocks within the Productive Series. One is the Early Productive Series—mainly quartz and rocks typical for Paleo-Volga deposits. The second is the Late Productive Series—less quartz, more feldspar, and fragments of both sedimentary and volcanic rocks typical for the Paleo-Kura sediments that are present in the southwest portion of our study area. Typical source rock for the basin is the organic rich Maikop shales. Their thickness, in some instances, reaches 8 km (Abrams & Narimanov, 1997; Belopolsky, Talwani, & Berry, 1998; Buryakovsky, Djevanshir, & Chilingar, 1995).

Hydrocarbon accumulations are mainly associated with structural traps. The variety of anticlinal folds, monoclines with various degrees of reverse faulting and fracturing creates favorable conditions for trapping of hydrocarbons with mud volcanoes penetrating most of the structures (Katz, Richards, Long, & Lawrence, 2000; Lerche et al., 1997).

3. Observations

3.1. Distribution and morphology

The analysis of the seismic lines reveals 99 mud volcanoes within the study area (Fig. 3). There is a large concentration of mud volcanoes in the southern part of the examined area. Towards the north and northeast, these morphological features on the sea floor become less dense. Approximately 75% of the mud volcanoes coincide with the distribution of present day anticlinal subsurface structures. Others, predominantly in the southern region, occur on the flanks of the anticlines or in the syncline. This does not preclude that these present day structures are not associated with paleostructures. Further studies are necessary to address this association. Studies on mud volcanoes onshore as well as numerous 3D surface extractions of the sea floor around mud volcanoes (Dimitrov, 2002; Fowler, Mildenhall, & Zalova, 2000; Graue, 2000; Guliyev & Feizullayev, 1995; Hovland, Hill, & Stokes, 1997) show that the body of a mud volcano may consist of many morphological features (gryphones, salsas, domes). These elements can occur on the volcanic plateau itself or can be attached to it within some proximity. Therefore, the feature that is interpreted as a separate mud volcano might be a part of one volcanic system. The seismic coverage is too coarse to distinguish between these relatively small features.

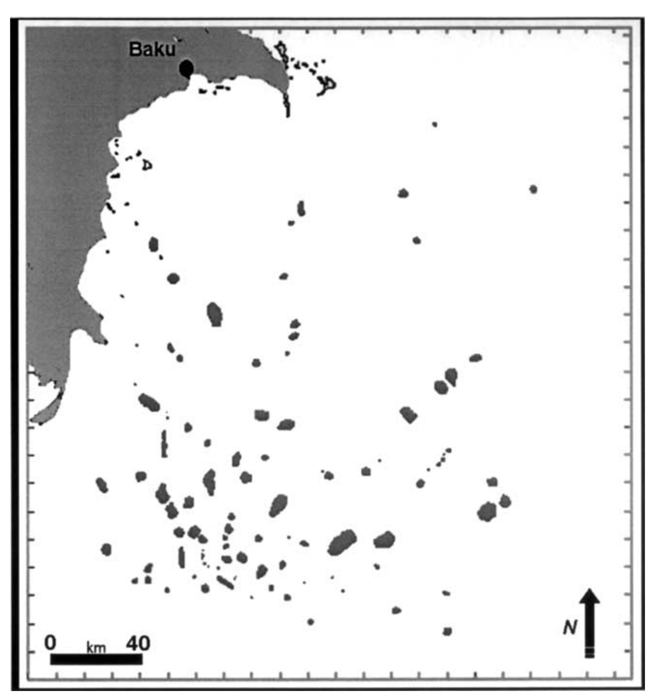

Fig. 3. Areal distribution of the mud volcanoes within the area of study.

3.2. Size and shape

Studies of onshore mud volcanoes in Azerbaijan indicate that their height and areal extent depends on the physical properties of the material that had been erupted (Guliyev & Feizullayev, 1995; Jakubov et al., 1971; Planke, Svensen, Hovland, Banks, & Jamtveit, 2003). Lerche and Bagirov (1999) describe different variables of mud volcanoes (length, width, area, and diameter) observed onshore Azerbaijan and note that mud volcano flow is different on land surfaces than on the sea floor. In offshore conditions, turbidity flows associated with the mud volume release may decrease the length of the mud flow. The low viscosity of mud flows in marine conditions compared with those on land would make the distance covered by a marine mud flow greater. However, the areal extension of the mud volcanoes both onshore and offshore depends on the local morphology and on the angle of the slope.

The height and areal extent of mud volcanoes are plotted in Fig. 4. Eighty percent of all mud volcanoes we observed are less than 240–270 m in height and 25 km^2 in areal extent. There are, however, instances of mud volcanoes with great areal extent and very low relief as well as of small mud volcanoes with significant elevation. The mud volcanoes

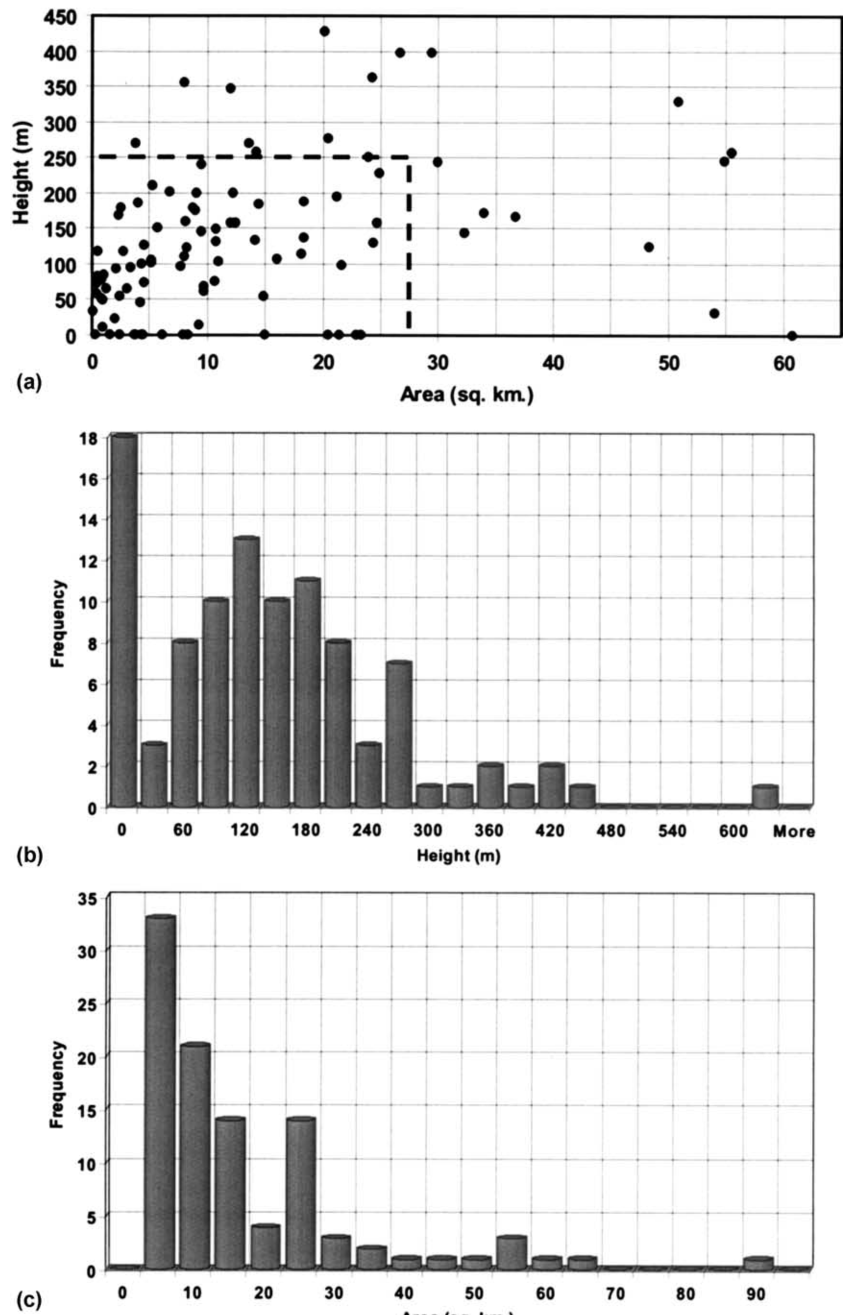

Fig. 4. (a) Plot of the area versus height of the mud volcanoes, (b) height and (c) area distribution from the obtained data population.

with the greater relief tend to be concentrated in the south-west. Those with low relief and great areal extent are concentrated in the north-east.

The shape of the mud volcanoes can be classified as convex, concave, flat or buried as observed on seismic reflection profiles (Fig. 5). Most of the analyzed mud volcanoes create convex (~46%) and flat-topped features (~33%) on the seafloor (Fig. 5). Others form concave and buried types—11 and 10%, respectively. They are scattered mainly chaotically without visible trends. There tends to be a concentration of convex and buried mud volcanoes in the south, and concave and flat features in the north and northeast. However, there is no regularity in distribution of these different types of mud volcanoes (Fig. 6).

3.3. Mud volcano activity over time

The presence of mud flows from the mud volcanoes are identified and the time of their activity determined. Core and log analysis from the different wells allowed assigning time to mapped reflectors. These reflectors represent the base of Sabunchi—Upper Surakhany time (4.33 MY), Uppermost Surakhany (3.5 MY), Lower Akchagyl (3.4 MY), Middle

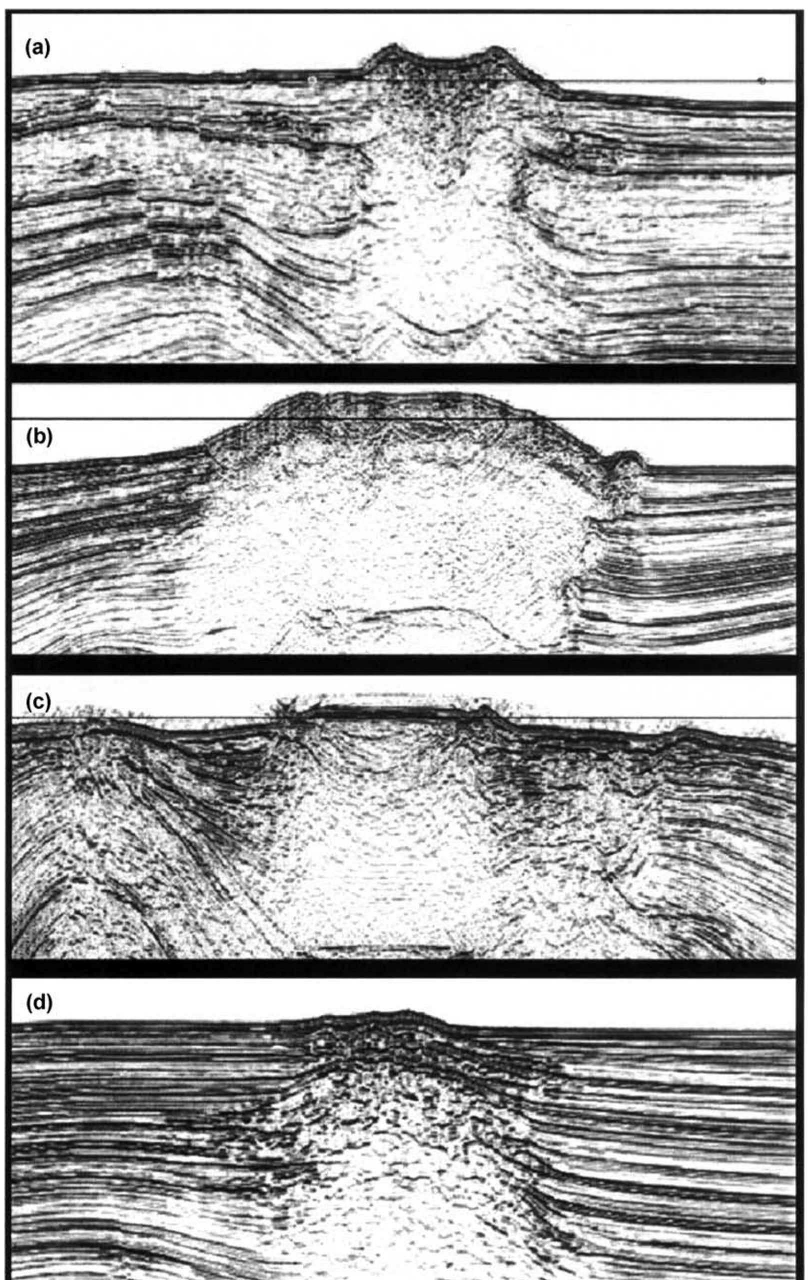

Fig. 5. Types of mud volcanoes based on the shape and appearance on the seismic line. (a) Concave; (b) convex; (c) flat; (d) buried.

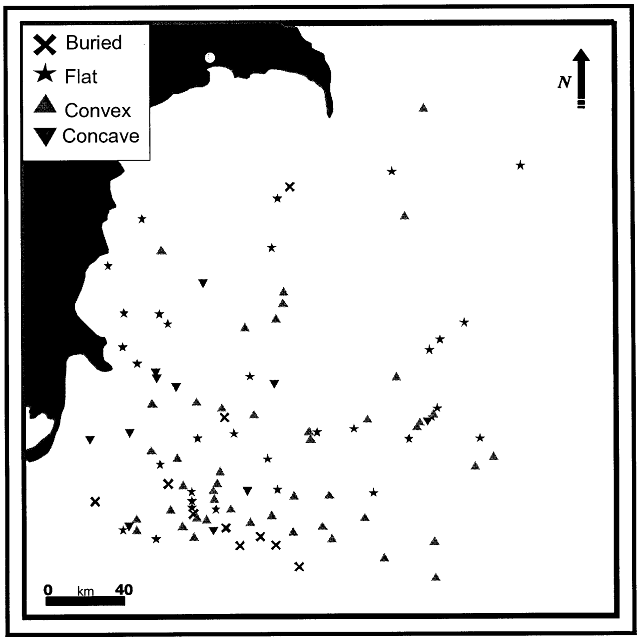

Fig. 6. Areal distribution of the mud volcanoes of different shapes.

Akchagyl (2.8 MY), Upper Akchagyl (2.3 MY), Lower Apsheron (1.8 MY), Upper Apsheron (1.3 MY), Lower Quaternary (0.75 MY), Middle Quaternary (0.63 MY), Upper Quaternary (0.3 MY). It is important to recognize that the absolute ages for the stratigraphic zones are estimated and are not very well constrained. A simple procedure is followed in order to relate the paleo flows to the relative time intervals (Fig. 7). All lines that define the studied mud volcano are inspected in order to determine the existence of paleo flows. Once these features are outlined, their relevance to the particular time interval is defined. If the mud flow occurs between the mapped horizons, the time of the lower horizon is assigned to it. Analysis of paleo flows reveal cyclicity in mud volcano development. Fig. 8 represents mud volcano activity through time captured in a cumulative curve of activity of the analyzed mud volcanoes from Lower Pliocene time through upper Pleistocene.

The Surakhany–Sabunchi time (4.33 MY) is considered here to be the beginning of the mud volcano activity in the offshore South Caspian Basin. As shown in the activity chart (Fig. 7), there are several cycles of mud volcano development. Each cycle consists of the period of increasing activity, of the period of stable activity and of the period of general quiescence followed by the beginning of the next cycle. In order to observe the evolution of mud volcano development in offshore Azerbaijan, a series of maps that reveal the activity in different time periods are created (Fig. 9).

During Sabunchi–Surakhany time (4.33 MY) mud volcano development initiated. There is only one mud volcano that has certain activity within this region of the South Caspian. This volcano developed in a syncline zone. Two other locations, one in the south and another one in the north, may have also been active during this period of time.

The uppermost Surakhany time (3.5 MY) is recognized as the beginning of the first cycle of mud volcano activity within the South Caspian Basin. The distribution of active mud volcanoes has a similar appearance to the Sabunchi–Surakhany time, except that one of the mud volcanoes in the south became active.

By the Upper Akchagyl time (2.3 MY), the area evolves into an intense stage and there are more volcanoes in the south that initiate their activity. The central part of the area also underwent mud volcano development, while the northern part was still without evidence of mud volcano activity.

The upper Apsheron time period (1.3 MY) shows progressive spreading of the mud volcano activity from south to north. Along with many other mud volcanoes that developed in the south, the northern part also substantially evolves during this stage. It is important to notice that some of the previously active mud volcanoes actually ceased development and became dormant.

The Lower Quaternary time period (0.75 MY) is manifested by further intensification of the mud volcano development process. Along with the mud volcanoes in the north and in the central part of the region, there are more volcanoes in the south that became active.

Finally, by the Upper Quaternary time period (0.3 MY), most of the region is involved in mud volcanic activity. However, some mud volcanoes in the south-west region which started activity during the Lower Akchagyl period have become inactive.

4. Discussion

Mud volcanism is a widespread phenomenon occurring in many regions that have similar geological settings. Mud volcanoes predominantly develop at convergent plate margins, where high volume of the sediments is subjected to great lateral and vertical stresses. The actual number of features, as well as the amount of material involved in mud volcanism, is much greater in offshore areas than onshore (Dimitrov, 2002).

Extensive studies of onshore mud volcanoes in Azerbaijan commencing with Goubkin (1934) concluded that mud volcanism in this area is a manifestation of mud diapiric processes. This basic concept has also been accepted by Guliyev and Feizullayev (1995), Jakubov et al. (1971), and Kalinko (1964) who conclude that many mud volcanoes develop on the crest of the diapirs. However, there are many examples where mud volcanoes are not connected with diapirs (Dimitrov, 2002). In this case, a type of mud extrusive feature called, a *diatreme* (Brown, 1990) that evolves from the violent eruption of overpressured mud, cross-cutting the overlying strata in a fashion similar to

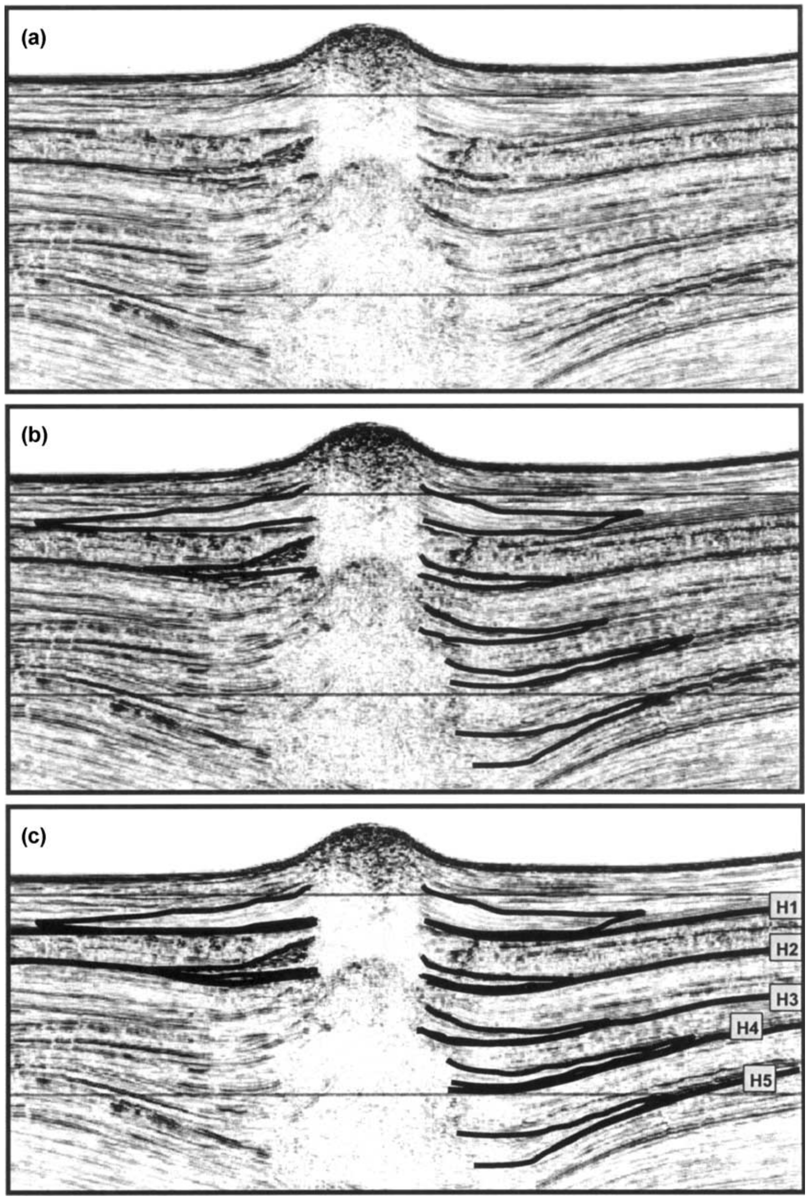

Fig. 7. Scheme for identifying time of mud flows. (a) Seismic line without interpretation, (b) same seismic line with identified mud flow features and (c) mapped reflectors. The time of the first from the top flow is H1 time, second is H2 time, etc.

a dyke (Kopf, 2002). Mud diapirs and diatremes are distinguished based on the mechanical stress and the mud intrusions that they originate from.

Seismic data acquired across the mud volcanoes offshore Azerbaijan show enormous parabolic, diaper-like zones of signal distortion. From a conventional point of view on mud volcanism in Azerbaijan, a seemingly obvious conclusion is that diapirs compose the core of mud volcanoes (Guliyev & Feizullayev, 1995; Jakubov et al., 1971). The recent models suggest that mud diapirs were initiated during the deposition of the Lower Productive Series in Late Miocene time and underwent repeated intermittent inflation (Cooper, 2001). Such a model would require thinning of the syndepositional sedimentary series across the rising high. In this study, we carefully examined the strata attached to the discontinuous zone of weak reflections. However, syndepositional thinning was not detected. The majority of mud volcanoes are related to the regional deep fault systems along with shallower listric and normal faults. Such a setting suggests that mud volcanoes in this area form due to instantaneous events of pressure release through diatremes.

The stratigraphic section of the South Caspian Basin consists of a high percentage of the fine-grained matrix (Fig. 2). Sand successions are highly interbedded by shales and silts. Moreover, sediments that are brought by the Kura river have poor reservoir quality due to high content of a silt material. It has been proposed that mud volcanism in Azerbaijan is related only to the Maykop plastic shale succession (Guliyev & Feizullayev, 1995; Jakubov et al., 1971), a theory confirmed by the analyses of rocks sampled

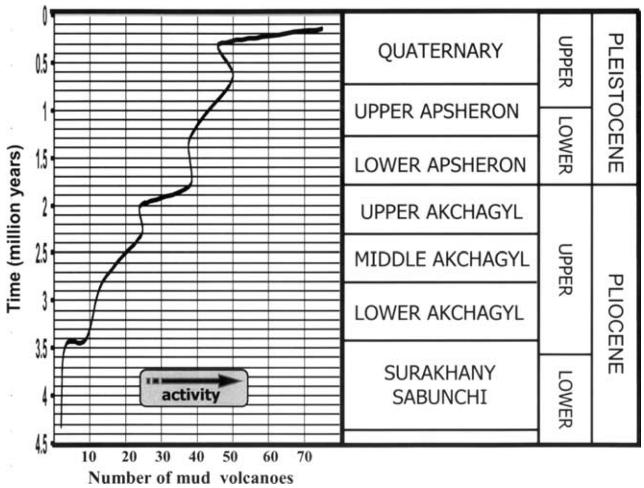

Fig. 8. Cumulative chart of mud volcano activity from Lower Pliocene to Quaternary.

around onshore mud volcanoes. However, in the offshore the Maykop lies at depths of about 12 km (Cooper, 2001). It would then require extremely high pressures for mud volcanoes to overcome the overburden and instantaneously break through to the surface. One possibility is that due to the shaly nature of the stratigraphic section, the mud volcano activity may not always be related to the Maykop shale succession. If this possibility exists then mud volcanism may occur from a shallower stratigraphic zone that can accommodate and store the great pressure and have sufficient plasticity to be transported to the surface. However, further studies are necessary to verify whether the Maykop is the only source for mud volcanism.

Compressional settings are also important in mud volcano formation and development. We noted earlier that the mud volcanoes tended to be distributed on anticlinal subsurface structures suggesting therefore that their origin is due to structural growth. The appearance of mud volcanoes on the flanks of the structures is usually associated with faults that detach subsurface structure. Such observations may reveal violent escape of the fluidized and highly overpressured material through the faults and cause of seal failures. Consequently, the question arises whether the mud volcanoes are triggered by the activity of these faults, or conversely whether there is any connection at all. Graue (2000) in his work on mud volcanoes of Nigeria suggests that sudden pressure release associated with eruption will cause trembling of undercompacted shale at the root and that the liquefied and gasified mud subsequently flows up the event. This model proposes that eruption triggers spontaneous activity along the listric faults.

4.1. Timing of mud volcano activity

Studies offshore Azerbaijan (‘Shah Deniz’ structure; Fowler et al., 2000) show that mud volcanism commenced after the onset of structural growth at the beginning of Akchagyl time. Since the Middle Pliocene time at about 4–5 MY ago sedimentation rate in South Caspian Basin substantially increased and reached turbidite values (Lerche et al., 1997). Approximately 2 MY ago the Azerbaijan part of the South Caspian Basin had undergone the next pulse of rapid sediment load. When these sedimentation rates are compared with the timing of activity of mud volcanoes it becomes apparent that the first pulse of mud volcano activity in the Uppermost Surakhany offsets the major pulse of sediment load. The later event of an increase in sediment supply also coincides with the peak of mud volcano activity in Upper Akhagyl time. We emphasize once again that the absolute ages for the stratigraphy are poorly constrained.

Lerche and Bagirov (1999) and Lerche et al. (1997) analyzed the data from 18 offshore wells and concludes that the major episode of hydrocarbon generation, migration and accumulation of excessive pressure within the South Caspian Basin occurred between 3 and 1 MY with the emphasis to the interval of 1.8 MY. This coincides with the major increase in activity of mud volcanoes with a large increase around Upper Akchagyl (1.8 MY).

The cyclicity of mud volcano evolution in the South Caspian Basin by itself is very important aspect of mud volcano development. Based on several studies on mud volcanoes in Trinidad and Nigeria, in addition to the studies of mud flows at the Shah Deniz structure, it is possible to differentiate three stages of mud volcano development (Barboza & Boettcher, 2000; Boettcher, Jackson, Neal, & Quinn, 2000; Fowler et al., 2000; Graue, 2000).

Stage 1 Eruption. Hydraulic failure of strata within the overpressured stratigraphic section.
Stage 2 Depletion. Migration of gas, oil and water to the surface from cracks, mud flow and adjacent porous strata.
Stage 3 Quiescence and build-up. Accumulation of primary and/or secondary overpressure.

These stages may reflect the development of the mud volcanoes in the South Caspian. Each cycle shown in Fig. 8 clearly distinguished the periods of maximum activity, depletion and quiescence. Therefore, the general pattern of development of the mud volcanoes observed globally is influenced by similar factors of the seal failure, gas supply and pressure build-up.

4.2. Morphology

There are many terms that describe the shape and seize of mud volcanoes (Cooper, 2001; Dimitrov, 2002; Graue, 2000; Guliyev & Feizullayev, 1995; Hovland et al., 1997; Kopf, 2002). Some terms are referred to as mud cones, mud pies, domes and craters. The distinctive type of mud volcano with a negative surface expression is called a mud pool, when extruded material is so fluidized and gassy that it collapses into the crater and fills the depression. Simple

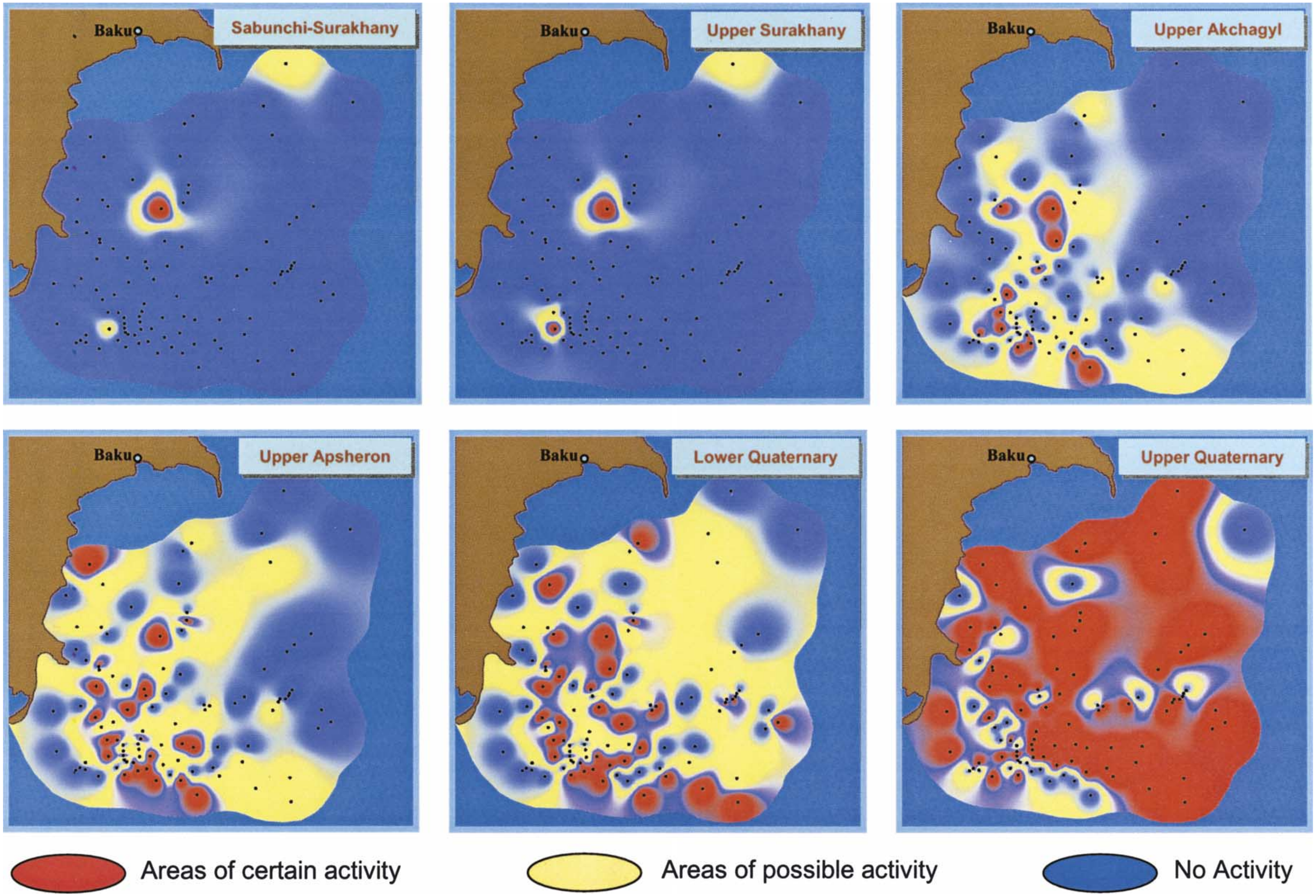

Fig. 9. Maps of mud volcano development from Sabunchi–Surakhany to Upper Quaternary.

rules appear to apply to the formation of different shapes of the mud volcanoes. The higher the pore-fluid pressure, the more violent the eruption; the more frequent the activity, the larger the structure; the lower the viscosity, the larger and flatter the body. Mud with low porosities form mud domes or ridges, more consistent mud with intermediate fluid content can give rise to mud volcanoes with large diameters and elevation above the sea floor, and high porosity mud creates mud pies with great areal extent. Summarizing the general knowledge of mud volcano geometry, it is possible to conclude that the size of mud volcano is mainly a function of the size of the conduit and the driving force of the mud volcanism in the area. Large features are generally thought to have a wide conduit and efficient trigger at depth (Kopf, 2002). In addition, the consistency of the mud is suggested to be the controlling parameter for the height of the mud volcano. Analog modeling of mud volcanism in the laboratory has yielded flat mud pies for wide feeders and cones for narrowing feeders when using the same material (Lance et al., 1998).

The different morphology of the mud volcanoes may also be related to the different stages in their development. At the first stage of the mud volcano evolution one can expect a product of violent eruption manifesting itself by creating a large crater and a huge amount of mud and parts of rocks deposited on the sides. Then during the time of fluid migration the crater can be filled by the mud, or in the case of more dense material, it could form a dome-like feature. Later stages of quiescence may result in subsidence of the feature and formation of a very low dome that would eventually merge with the surrounding plane. However, this does not mean that this process is controlling the geometry of the mud volcanoes. It may have a relationship with the general and widely accepted point of view, described above, such as a relationship with the density of material and frequency of eruptions (Cooper, 2001; Dimitrov, 2002; Graue, 2000; Guliyev & Feizullayev, 1995; Kopf, 2002).

5. Conclusions

The following are the major conclusions drawn from this study:

1. 99 Mud volcanoes have been recognized. Seventy percent of mud volcanoes are situated above anticlines that are complicated by faults. The remaining 25% develop on the flanks of anticlines or on the synclines. These are clustered in the south.
2. Four types of mud volcanoes were recognized based on the shape of the morphological features on the sea floor: concave, convex, flat and buried. There is no relationship between the mud volcano parameters such as size, shape areal extent, etc. and their distribution. Differences in morphology may be due to the relationship between driving force (pressure) and material supply, width of conduit or could represent different stages in mud volcano evolution.
3. Cyclicity in offshore mud volcano development was revealed, with their beginning in Lower Pliocene (Sabunchi–Surakhany time) and with the greatest activity during Upper Pleistocene (Upper Apsheron–Quaternary time). The cycles of mud volcano activity in the South Caspian Basin coincides with the time of high sedimentation rate, a regional contraction episode, and major stage for hydrocarbon generation.
4. Mud volcanism in the offshore region of the South Caspian Basin is associated with high fluid pressure gradients (diatremes) in the subsurface and not with diapirism as observed onshore.
5. Mud volcano activity offshore may not always be related to the Maykop shale succession as believed to occur onshore but may occurs at younger stratigraphic sections.

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