Mud volcanism of the northwestern Caucasus and the oil and gas prospects

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[1] In this paper, an effort is made to consider mud volcanism of northwestern Caucasus from the most complete data including data on the abutting seas water areas and available data on ancient mud volcanoes. A number of new mud volcanoes are described in the mountainous area of the Caucasus and in the Black Sea area. New mud volcano provinces, the Caucasus province and the Eastern Black Sea (Tuapse) province are separated. Most likely mechanisms of clayey diapir formation (clayey diapirism) are discussed. Some steps are made to estimate the role of mud volcanoes and clayey-diapir formations as one of the features of oil and gas presence. *INDEX TERMS:* 1033 Geochemistry: Intra-plate processes; 1719 History of Geophysics: Hydrology; 3022 Marine Geology and Geophysics: Marine sediments: processes and transport; *KEYWORDS:* mud volcanism, clayey-diapir formation, sedimentation, Black Sea.

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Introduction

[2] One of the most widely known manifestations of recent tectonic activity in the northwestern Caucasus is mud volcanism, which is a function of active development of deep gravitation (clayey diapir) folds in the orogenic foreland. This paper makes an effort to consider mud volcanism of northwestern Caucasus with the use of data as complete as possible from the authors' viewpoint including data on the water areas of adjacent seas and available data on ancient mud volcanoes. Some steps are made to estimate the role of mud volcanoes and clayey diapir formations as one of the features of oil and gas existence.

Mud Volcanism as One of the Manifestations of Deformation Process

[3] The occurrence of clayey diapirism apparently results from external causes, such as the form of occurrence of clayey formation body producing diapirs and the development of structure formation processes in the adjacent areas. The triggering effect of regional strain state fluctuations is markedly shown by the example of Golubitskiy volcano eruption accompanied by the earthquake intensity of 3 in Temryuk in the summer of 1988. This eruption resulted in the decrease of mud volcanic activity in Kerch–Taman region and the general reduction of the carbon dioxide and methane ratio, which only began to increase a year after the eruption [*Yurovskii and Valter,* 1991]. Mud cone gases studied in Kerch Peninsula (Nasyrskiy volcano, Bulganakskoye cone hill field, Kerch cone hill) strongly suggest the single reaction of the total body of diapir-forming Maikopian series to the local close discharge in Golubitskiy mud volcano source. Data of hydrogeodeformation observations in Krasnodarskiy Krai corroborate this conclusion as well. Thus strong compression of sedimentary bed rocks in western Ciscaucasia, which was manifested by a sharp rise of underground water, was noted before the above-mentioned eruption of Golubitskiy volcano [*Sheremet'yev et al.,* 1996]. Abrupt change in hydrogeodeformation field also preceded Golubitskiy volcano eruption in 1994. Similar reaction to seismic events in Anatolia was noted in the variation field of gas index in Anatolia (the abovementioned carbon dioxide – methane ratio) for mud volcanoes of Kerch Peninsula [*Yurovskiy,* 1997].

[4] These facts testify to the reaction of the total diapir-forming Maicopian complex of Kerch–Taman depression as a single body to external effects. Stress in the rock bed is realized by injection of low-viscous clayey mass into relatively more competent overlying beds (viscous inversion [*Pil'chin,* 1985]). Such realization of the process of clayey diapir formations and consequently of mud volcanoes is apparently characteristic of many areas of their manifestations.

[5] This view point appears to be justified and in our opinion is more preferable than complicated and not convincing

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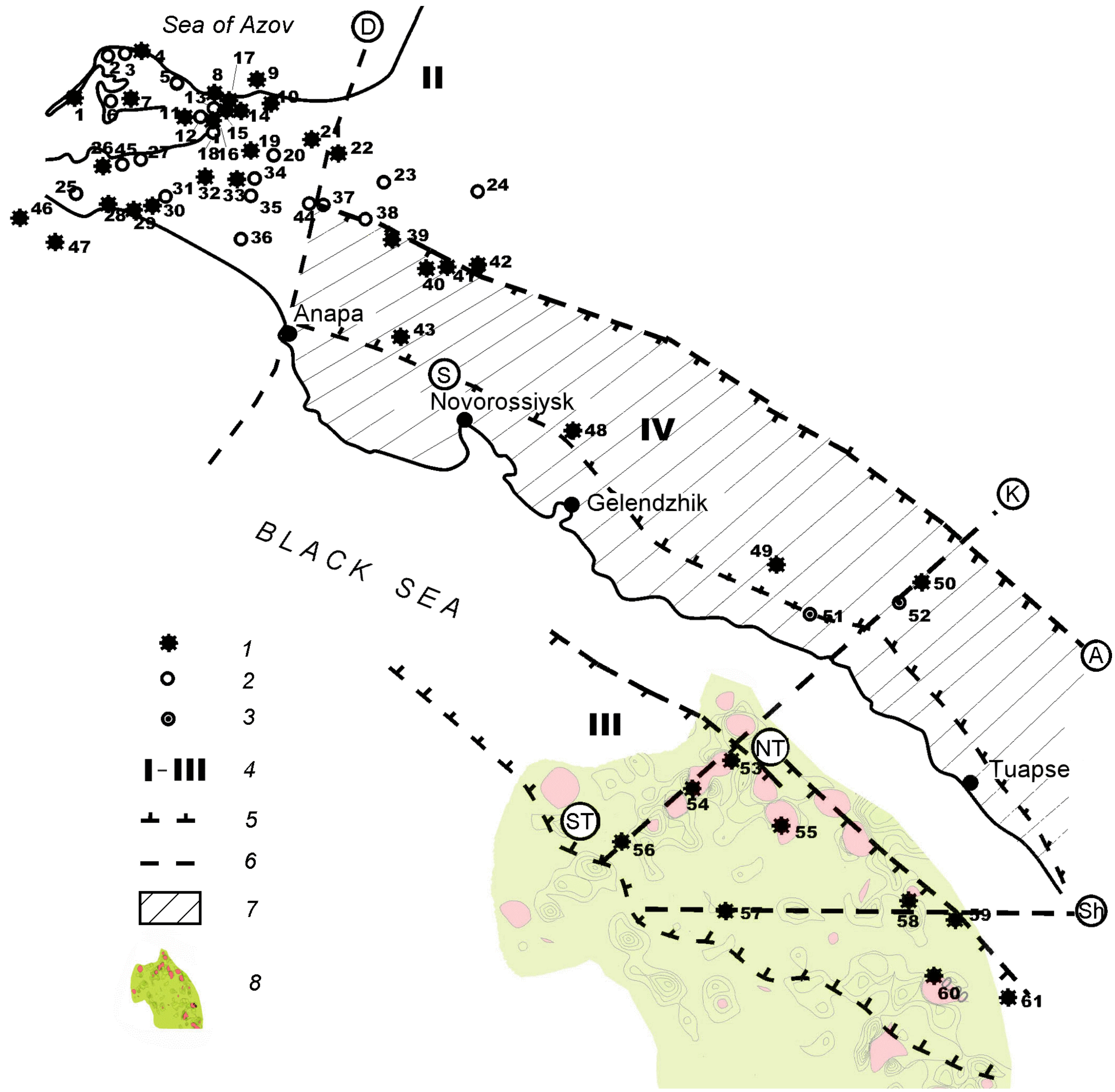

Figure 1. Map of northwestern Caucasus mud volcano location. 1 – active mud volcanoes; 2 – passive mud volcanoes (stabilized); 3 – paleo volcanoes; 4 – mud volcano provinces: I – Kerch–Taman, II – Indol–Kuban, III – Eastern Black Sea (Tuapse), IV – Caucasus; 5 – longitudinal (Caucasus general strike) faults: A – Akhtyrskiy, S – Semigorskiy, NT – Northern Tuapse, ST – South Tuapse; 6 – non-Caucasus extension and other faults cutting the Caucasus extension: D – Dzhiginskiy, K – Krasnodarskiy, Sh – Shepsinskiy; 7 – mountain structure of Northwestern Caucasus; 8 – deformation anomalies of the Miocene complex in Tuapse depression (deformation areas with negative distortion, areas of Miocene complex discontinuities coinciding with Maikopian diapirs bodies are shown in pink color; lettuce-green color indicates the zone of Miocene complex dilatancy or positive distortions). Mud volcanoes: 1 – Blevaka; 2 – Akhilleon; 3 – Cape Kamennogo; 4 – Peklo Azovskoye; 5 – Kuchugury; 6 – Mt. Gorelaya; 7 – Mt. Fontalovskaya; 8 – Mt. Sinyaya Balka; 9 – Temryukskiy marine; 10 – Golubitskiy; 11 – Western Tsimbaly; 12 – Eastern Tsimbaly; 13 – Northern Akhtanizovskiy; 14 – Mt. Sopka; 15 – Akhtanizovskiy; 16 – Shopurskiy; 17 – Sennoy; 18 – Borisoglebskiy; 19 – Northern Neftyanoy; 20 – Dubovy Rynok; 21 – Mt. Miska; 22 – Mt. Gnilaya; 23 – Kurchanskiy; 24 – Anastasievsko-Troitskiy; 25 – Kostenkova Mogila; 26 – Mt. Karabetova; 27 – Mt. Chirkova; 28 – Peklo Chernomorskoye; 29 – Bugazskiy; 30 – Mt. Polivadina; 31 – Northern Kiziltashskiy; 32 – Vyshesteblievskiy; 33 – Southern Neftyanoy; 34 – Kamyshevatskiy;

mechanisms explaining clayey diapir occurrence and mud volcanism, which results from diapirism, either at the expense of hydrothermal air lift [*Kityk and Plotnikov,* 1977] or as a result of density inversion at the expense of montmorillonite transformation to illite [*Meisner and Tugolesov,* 1997].

Mud Volcanism of Northwest Caucasus

[6] Mud volcano activity is abundant in northwestern Caucasus. Its active manifestations in Taman and in the lowland of Kuban (Indol–Kuban deprsession) have been known since the old times. In the last few decades, marine geological and geophysical research established a number of mud volcanoes in the sea area of the region (the Azov Sea, Kerch–Taman shelf, Tuapse depression of the Black Sea); a number of mud volcano formations both ancient and active now were established in the mountainous area of northwestern Caucasus mountain-building area. Such situation (Figure 1) makes the understanding of mud volcanism considerably more difficult and at the same time enriches our ideas of this phenomenon. Considerable heterogeneity is apparent of recorded mud volcanic formations in both conditions of forming clayey diapir deep gravitation folding and the type of major mud-forming (diapir-forming) complex. In this case, the tectonic control of observed variability is evident, which manifests itself among other things in the difference of the geological structure of clayey diapir bodies initiating mud volcanism. This fact allows the authors to approach the problem of mud volcanism zoning in the northwestern border of Great Caucasus mountain-building area and to separate four mud volcano provinces[1]: 1. Kerch–Taman, 2. Indol–Kuban, 3. Tuapse, 4. Caucasus. Further we will consider the features of mud volcano formations in each of the separated provinces.

Kerch–Taman Mud Volcano Province

[7] Kerch–Taman mud volcano province (Figure 1) is located in the orogenic depression of the same name that separates the Crimea and the Caucasus. This province is one of the most extensively studied areas as far as various manifestations of mud volcanism are concerned and is practically a model area to work out various mechanisms of their formation.

[8] At present Kerch–Taman depression is an area with the greatest abundance of mud volcanoes in the northern Black Sea coastal region. All known forms of mud volcano manifestations are found there: continental and marine, buried and exposed, extinct and active. Mud volcanoes and diapirs are grouped in anticline zones forming extended lines of ranges running to the Black Sea water. It is interesting to note that those anticline zones with general subparallel extension are abruptly cut by faults locating the borders of Kerch–Taman depression and specifically submeridional Dzhiginskiy fault. Diapir-forming complex in Kerch–Taman mud volcano province is a 3–4-km thick rock bed of Maikopian clays, which form mud volcano constructions and accumulate considerable amounts of coniform hill breccia. Diapir bodies forming a number of extended anticline zones close to parallel are linear clayey walls with symmetrical axes that, in structural geology terms, form in fact the injection filling of the system of extended syngenetic faults combined in an echelon-like manner, which are apparently separations as far as kinematics is concerned. Paragenesis of such ruptures (diapir walls – anticline zones) embraces the total Kerch–Taman province and is sharply limited by its borders. This fact is remarkable and apparently reflects features of late orogenic deformation of the thick body of Maikopian clays of the depression under consideration. The specified characteristics of the clayey–diapir formations mentioned above suggest shear stress distribution in lateral plane with respect to the complex being deformed. This assumption is to the point if we take into consideration echelon-like framing of the clayey Maikopian body of Kerch–Taman depression with the rigid blocks of the northern Taman spur in the northwest and Anapa spur in the southeast, which may produce shearing stress. This is corroborated by data on seismogenic ruptures orientation in the region in the upper area of the earth's crust [*Pustovitenko and Kapitanova,* 1997] with account for the directions of their cutting open. The general character of the structural relations described above allows us to define them as pronounced of Ridel paragenesis and to treat the system of clayey–diapir walls of Maikopian bed of Kerch–Taman depression as a wide zone of left lateral shift deformations.

[9] Considering the above-said it is reasonable to conclude that the total bed of Maikopian clays of Kerch–Taman depression reacts as a single whole to the applied force and the stress field formed by it, which caused the start of the processes of clayey diapirism and finally the appearance and development of mud volcanism. Volcanoes were most active in the Chokrakian, the Sarmatian, and the Kimmerian [*Shardanov et al.,* 1962]. It is interesting to note that in the history of northwestern Caucasus and adjacent Ciscaucasia, these periods were associated with maximum manifestations of planation processes [*Viginskiy,* 1986] that completed tec-

[1] In this case, the term "province" is not taxonomical because the hierarchy system of the elements of mud volcano activity zonation apparently awaits elaboration in the future.

35 – Belyy Khutor; 36 – Blagoveshchenskiy; 37 – Raznokol'skiy; 38 – Ust'-Chekupskiy; 39 – Shugo; 40 – Gladkovskiy; 41 – Semenovskiy; 42 – Kievskiy; 43 – Semigorskiy; 44 – Dzhiginskiy, 45 – Mt. Komendantsksya; 46 – Besymyanny-1; 47 – Bezymyanny-2; 48 – Manzhosova; 49 – Khomyakova; 50 – Poleshchuka; 51 – Beregovoy; 52 – Pereval'ny; 53 – St. Petra; 54 – St. Mikhaila; 55 – St. Leonida; 56 – St. Anny; 57 – St. Voskreseniya; 58 – St. Tat'yany; 59 – St. Natal'i; 60 – St. Vitaliya; 61 – Velesovoy Padi.

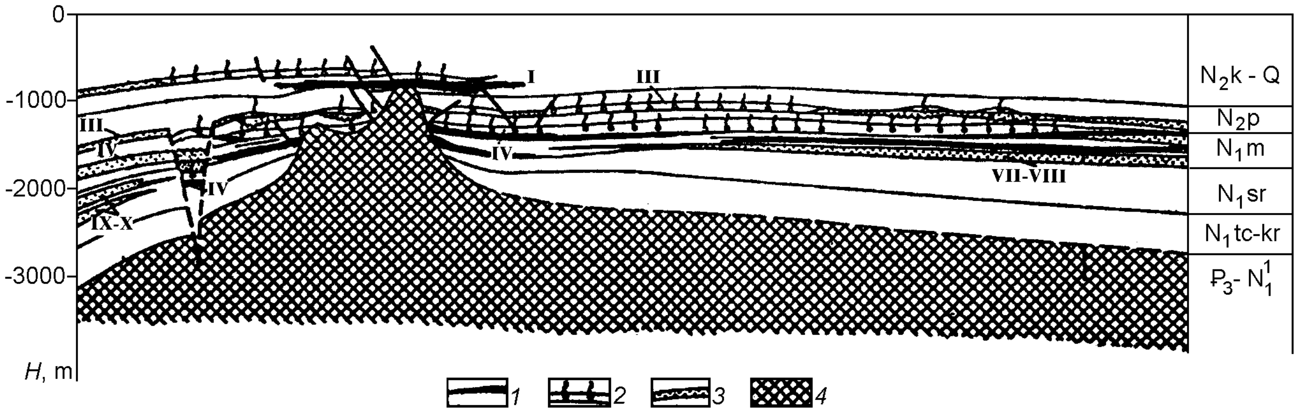

Figure 2. Generalized geological section of oil and gas deposits confined to mud volcanoes and clayey diapirs (from *Burshtar* [1966] with modifications) (deposits Anastasievsko-Troitskoye, Kurganskoye, Zaporozhskoye, Severo-Neftyanoye and others)

tonic cycles and immediately preceded the abrupt activation of tectonic movements in the Caucasian orogen. In this context, we may assume that mud volcano processes are of cyclic character owing to tectonic settings in the province under consideration. In this case the modern stage of mud volcano activation apparently started in the Kimmerian, which approximately corresponds to the age of Taman Peninsular [*Viginskiy,* 1997b].

[10] Oil and gas deposits located in Miocenic sediments are associated with clayey diapir structures of Taman Peninsula. Producing horizons are found in areas: Borisoglebskaya, Zaporozhskaya, Blagoveshchenskaya, Dzhiginskaya, Zapadno-Akhtanizovskaya, Severo-Neftanaya, Strelchanskaya, Belyi Khutor, Kapustina Balka and others. Mud volcanoes are located at some of the anticlines noted above.

[11] In the past in a number of mud volcanoes of Taman, repeated explosive-type eruptions were noted and here the high activity was most commonly observed in the last few decades. They are mud volcanoes Akhtanizovskiy, Mt. Karabetova, Shugo, Gladkovskiy, Mt. Gnilaya, Mt. Borisa and Gleba and sea volcanoes Golubitskiy, Temriukskiy and others, in the latter two volcanoes outbursts were noted that resulted in island formations in the sea. Earlier the outbursts were commonly accompanied by the release of explosive gases, probably hydrocarbon (hill Gorelaya). Among other things this phenomenon marks the activation of hydrocarbon generating processes in the eruptive deformation of Maikopian sediments saturated with organic matter. Such development is emphasized by the structural position of known deposits, which at least characterizes their Post-Kimmerian formation and, in our standpoint, accounts to a large extent for their location features.

Indol–Kuban Mud Volcano Province

[12] Indol–Kuban province boundaries (Figure 1) are determined by the location of orogenic (Post-Eocene) depression of the same name extending from the Indol river mouth (Crimea Peninsula) and encompassing the Azov Sea southern area approximately to the junction of the Laba River, which is the left-side tributary of the Kuban River. In this paper we only discuss the eastern part of the depression (within western Kuban area).

[13] The axial part of the depression approximately coincides with the course of the Kuban riverbed. Approximately in the axial plane of the depression, Anastasievsko-Krasnodar anticline zone is located, which is a long clayey–diapir wall locally echelon-like, locally broken and locally crowned with mud volcanic formations (Kurchanskiy and Anastasievsko–Troitskiy). Other manifestations of mud volcanism are only recorded in this province in the southern area along Akhtyrskiy reverse fault and are characterized by distinct features of gravitational northern vergence [*Burshtar et al.,* 1969].

[14] Generally Indol–Kuban province is characterized by significantly less abundant and much less pronounced manifestations of mud volcanism as compared to Kerch–Taman province discussed above. Three mud volcanoes are located at Anastasievsko–Krasnodar anticline zone and six mud volcanoes are situated at the folds of southern side of western Kuban depression (Figure 1). These mud volcano formations are associated with the development of clayey diapirism in the trough, which is apparently of arch origin [*Burshtar et al.,* 1969; *Grachev,* 1998] and in the axial part is probably caused by gravitational pressure of Maikopian clayey mass at the walls of the depression. This assumption is corroborated by the abundance of pillow-form clayey cryptodiapiroids in the northern gentle slope of western Kuban depression [*Viginskiy and Gromin,* 1995]. In this case, a feature of intradepression clayey diapirism is its apparent linear confinement to the zones of large deep faults: Akhtyrskiy, Timashevskiy (pillow-form cryptodiapir) and assumed Zapadnokubanskiy fault, which may be intruded by hyperbasite [*Viginskiy et al.,* 1988], that is positive linear magnetic anomaly. This fact can serve as a basis for the assumption of the triggering role of dislocations with a break in continuity in complexes underlying the diapir-forming layer.

[15] Oil and gas presence is a feature of practically all

clayey-diapir formations in Indo–Kuban province (western Kuban depression). Diapir bodies are channels evidently still functioning, which bring hydrocarbons to deposits the location of which depends on traps position (Figure 2). In this case, mud volcanism is not a limiting factor in spite of the evident unloading channel. This fact may be caused by anomalous high pressure in the vents of volcanoes that significantly exceeds rock pressure in deposits. There is no denial that mud breccia plays a preserving role as regards the broken reservoir in the dying zones of vents.

[16] Especially interesting is oil and gas presence in the deposits overlying Maikopian deposits of cryptodiapiroid deformations band of the western Kuban depression northern side. Hydrocarbons are confined there to the Middle Miocene (gas condensate) and Upper Miocene–Lower Pliocene complexes (gas in Meotian-Pontian). In both cases, there is reason to assume a Maikopian source of hydrocarbon migration to deposits. The paths of such migration could have been subvertical faults, which, as a rule, reach the upper horizons of the sedimentary cover as fissuring or thinning zones [*Viginskiy and Gromin,* 1995].

[17] A significant feature of clayey-diapir formations of the province under discussion as well as of Kerch–Taman province is their active development at the recent stage. This is supported by both manifestations of mud volcanism and pronounced cryptodiapir folds in the topography (with marked weak capability of rocks composing them to stand denudation). In some cases, when we deal with cryptodiapiroid, we can easily reveal modern activity from Holocene sediments facial replacement. Activity of this kind as well as the empiric relation between maximum hydrocarbon resources in deposits and immediate contact of the latter with Maikopian core of the diapir tearing them (mud volcano vent) or wide development of tearing channels running from the core to the deposit suggest processes of recent oil and gas formation. Considerations of this kind are also supported by cases common in the last few years of flows from abandoned boreholes of the exhausted area of Kiev–Raznokolskaya band of deposits (locally after a rest period of 30–50 years).

Tuapse Mud Volcano Province

[18] Tuapse mud volcano province is located in the water area of the Black Sea long southern slope of northwestern Caucasus within Maikopian depression of the same name. It begins in the east near Gagry and Sochi cities and ends in the west in the area of Anapa city. The province is totally located in the Black Sea water area and is confined to the above-mentioned depression. The depression was separated by D. A. Tugolesov [*Tugolesov et al.,* 1984] for the major part from Maikopian sediments. The thickness of Maikopian sediments in the depression locally reaches 5 km. From Eocene top, Tuapse depression has asymmetric structure with a steep northern slope (dip may be up to 40°) and a very gentle southern slope. Its width is approximately 50 km and its length along Caucasian shore makes 250 km.

[19] Maikopian beds are overlapped with a cover of Miocene–Quarternary sediments. In modern time owing to the Black Sea deep basin, Tuapse depression is drawn into the zone of progressive downwarping of the basin and is broken up as a preorogenic depression. Considerable deformation of Maikopian orogenic complex and post-orogenic sedimentary complexes of Tuapse depression [*Viginskiy,* 1997a; *Viginskiy et al.,* 1997] is apparently caused by the structural position of the sedimentary body under the studiy on the slope of the Black Sea abyssal basin, which is being formed, and by Maikopian plastic clayey bed sliding to the basin center [*Viginskiy et al.,* 1997]. The more active process went on from the beginning of the neotectonic stage when Tuapse depression was drawn into the process of the Black Sea basin formation and reformed in the deep-sea basin conditions causing active subsidence of the Black Sea basin floor.

[20] Morphologically folds in which sediments overlying Eocene sediments are crumpled are of diapir appearance and are commonly overturned and thrust over southwards; they are of considerable length by the long axis (tens of kilometers with the average width of less than 5 km) coinciding with the depression extension; the amplitude is up to 1 km. Folded zones for the major part are subparallel [*Meisner and Tugolesov,* 1997; *Viginskiy,* 1997a]. Features like those corroborate the gravitation nature of folding. Especially high degree of deformation of sediments overlying Eocene sediments is noted in the central part of Tuapse depression (Krasnodar city meridian locality). In this zone, a series of pronounced structural lines marked by formations were established from seismic survey that the authors interpreted as mud volcanoes (Figures 1 and 3). The craters of some of them have the diameter of 6–7 km and in this case the tongues (cryptodiapir linearized injections) may form structures of a diameter of up to 20 km (St. Anny volcano) [*Viginskiy et al.,* 1997].

[21] The assumed mud volcanoes are characterized by anomalous seismicity record in the form of a hill of chaotic reflections at a conventional boundary from where the inphase state regular axes stop to be traced (Figure 3). Such form of record was identified with clayey diapir with sufficient reliability; forms like this are revealed in the northern half of the profiles up to the structure line limiting the prevalence of intensive deformations of sediments overlying Eocene bed. As for seismic horizon “B” (Sarmatian sediments top), these forms are either enveloped in it or underlain it, locally they tear off the horizon and are traced to the floor surface. In the latter case they were interpreted as mud volcanoes. Nine exposures of the floor in the surface were recorded (Figure 1). Most northern mapped mud volcanoes are located at the sea floor depths of 1800–1900 m and northern volcanoes are at the depth of 1200–1400 m. Apical parts of clayey diapirs are revealed at depths ranging from 1500 m to 2800 m.

[22] Morphologically the assumed mud volcanoes are objects weakly manifested in the topography and characterized with exposures on the sea floor surface of head parts of Maikopian clayey diapirs. A likely explanation of missing cones of breccia in the relief is in the undersea position of assumed mud volcanoes, which provide high mobility of erupted mass apparently forming extensive mantle-form “covers” characterized by a random-layer pattern of seismic record similar to a record pattern typical of submarine landslides. The form of diaper-forming complex injection, that is Maikopian diapir body can vary from classical channel-like

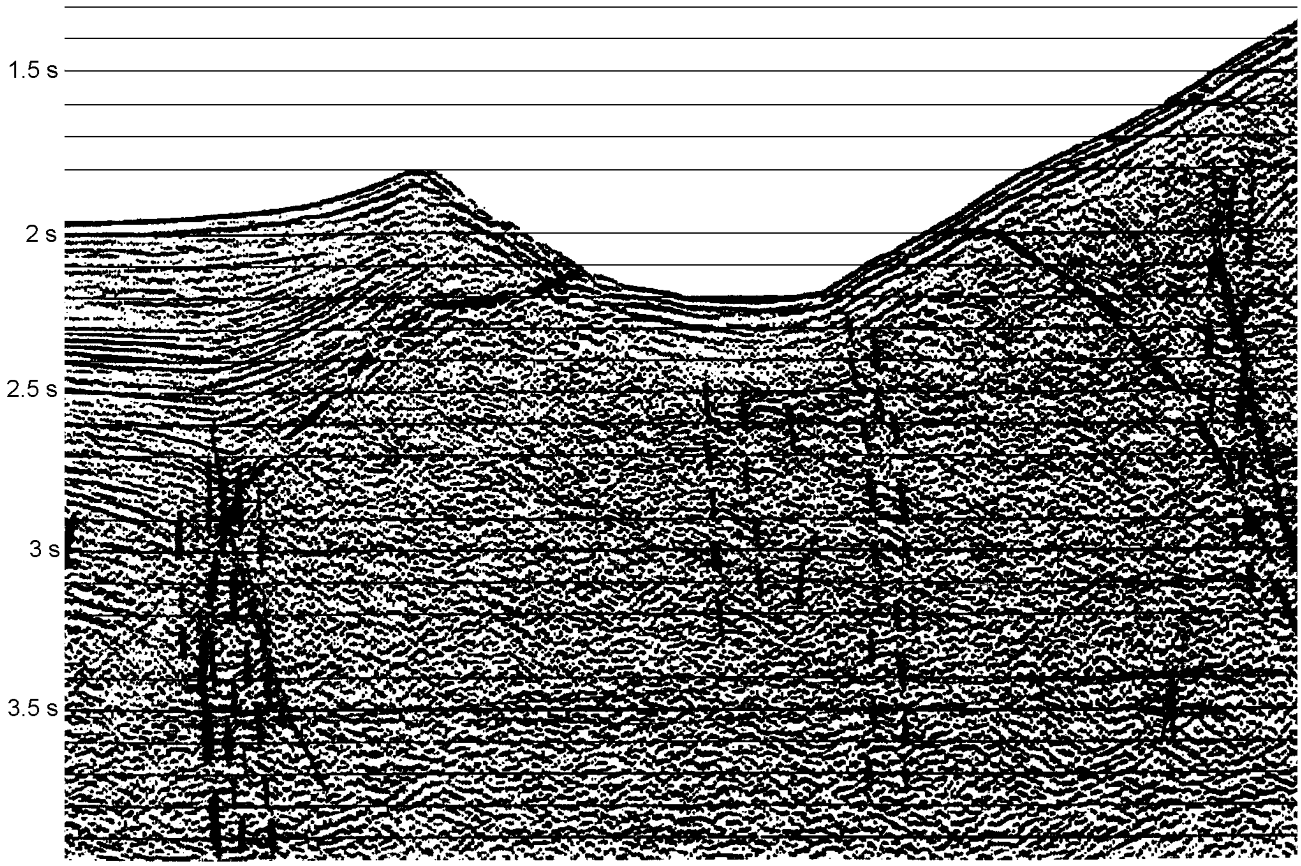

Figure 3. Fragment of time seismic section across mud volcano Sv. Tat'yany (graphic interpretation by V. I. Efimov).

form to mushroom-shaped form fixing the break through of the extended head part of Maikopian "scales" forming upthrust hanging sides on the sides thrusted under gravitational folds.

[23] It is interesting to note that in spite of the fact that mapped mud volcanoes are located at pronounced clayey diapir walls extended for tens of kilometers (gravitational "scales"), as it was mentioned above, they are spatially organized in line structures with orientation different from diapir ridges extension (Figure 1). In the western part of the depression, a line of northeastern strike is pronounced, which apparently fixes the marine continuation of Krasnodar fault transverse to western Caucasus fault. The heat flow contrasting anomaly, which did not receive any explanation until recently coincides with this line [*Grachev,* 1998; *Viginskiy,* 1997]. In the northern area of Tuapse depression, the assumed mud volcano formations evidently retain the linearity caused by the structural plan of gravitational diapir folding. One more structural line cutting the strike of Tuapse depression is formed by volcanoes St. Voskreseniya, St. Vitalia and Velesova Pad' (Figure 1). It is characteristic that on its continuation on land (northwestern Caucasus) it is located at structural forms testifying to active shifts on it. Earlier this fact allowed the authors [*Viginskiy et al.,* 1998] to separate active neotectonic Shepsinskiy fault (Figure 1).

[24] Thus in this case as well as in the mud volcano provinces described above, faults in the bed underlying the major diapir-forming complex to a large extent have the role of controlling mud volcano activity. At the same time a characteristic feature of Tuapse province is the discordance of the disjunctive structure of the base under diapirs and the inner structure of complexes dislocated by clayey diapirism processes. This fact emphasizes secondary tectonic origin [*Shults,* 1979] of clayey diapirism and correspondingly mud volcanism of Tuapse depression. Evidently tectonogenic air lift does not take place in this case and therefore its manifestations seem doubtful in other situations either.

[25] We can estimate the role of Tuapse province mud volcanism in oil and gas geology only from general considerations. As it is known the prevailing part of mud volcanism manifestations is genetically associated with structures bearing oil and gas. Similarly to mud volcano provinces described above, possible manifestations of mud volcanism of Tuapse depression initiated by Maikopian clayey diapirism suggest that the water area under investigation is favorable for searching for considerable hydrocarbon deposits. The more so, that there are good foundations for such statements [*Meisner et al.,* 1996; *Viginskiy et al.,* 1997]. At the same time areas of wide-spread direct manifestations of mud volcanism are less interesting because the conditions of con-

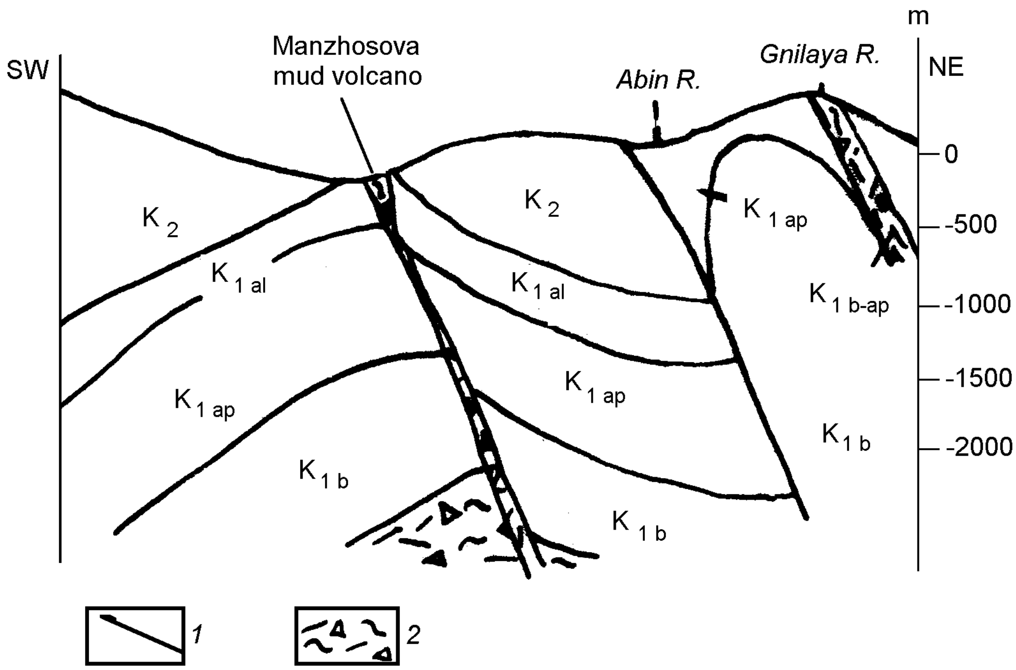

Figure 4. Geological section across Manzhosova mud volcano. 1 – geological boundaries; 2 – unconsolidated clayey matter with limestone fragments.

servation are partially upset. Besides as the research in the conditions of deformation of Tuapse depression complexes overlying Eocene complex showed [*Viginskiy et al.,* 1999] the development of mud volcanoes activity is related to the active change of volumes with sedimentary base deformation (Figure 1). In this connection, most favorable conditions of elite oil and gas presence are found in beds that show deformation that is uniform (without volume variation) or close to it. Such areas are located out of the zones of mud volcanism intense manifestations or are close to them.

The Caucasus Mud Volcano Province

[26] This mud volcano province is separated for the first time in this paper as well as Tuapse province. A number of active and paleo mud volcanoes are established in it (Figure 1). The previous studies of them are not sufficient. Nevertheless we can make some general comments.

[27] Mud volcanoes of the Caucasus province are revealed in the band where Lower Cretaceous and Jurassic sediments for the major part clayey are abundant. All of them are confined to faults on conjugation with anticline faults. The latter are complicated by regional faults of the general extension of the Caucasus. It can be seen most evidently from the example of Semigorskaya anticline zone, which is apparently of diapir origin, confined to a fault of the same name; four of six mud volcanoes of the province known at present (Semigorskiy, Manzhosova, Khomiakova, Beregovoy) are located on the fault at its considerable length.

[28] Mud volcano manifestations are for the major part small cone-form structures of a height of up to 1.0–1.5 m. The diameter of the largest gryphon in Shapsugskaya village (mud volcano Manzhosova) reaches 3.5 m. Mud cone sediments make breccia of clays of black color with fragments of sandstones and siderite exposed in steep slopes of the ravine pattern in the area of the volcano. Mud cone breccia apparently dates back to the Jurassic–Lower Cretaceous (the mud-forming complex is Jurassic–Lower Cretaceous flysch).

[29] The gryphons of volcanoes active now are confined to the fields of abundant Cretaceous sediments strongly dislocated consolidated and commonly argillized (Figure 4). It is interesting to note that springs outlets immediately close to the gryphons (volcano Manzhosova) are strongly mineralized and the mud (diluted mud cone sediments) is often used by local population for medical purposes.

[30] Ancient mud volcanoes occupy a special place in the row of mud volcano manifestations noted above. Their mud cone sediments underwent metosomatic reworking in Late Alpine activation phases of tectonic movements and hydrothermal activity. Old mud volcano structures were revealed in northwestern Caucasus in the period of geological prospecting for mercury in 1959–1960 (K. V. Platonov, A. V. Netreba). It is those structures that Perevalnoe deposit and Beregovoe show of ore are confined to (Figures 1 and 6). They are supposed to be associated with pipe-shape bodies in old volcanoes vents [*Fedorchuk,* 1983]. Thus Perevalnoe deposit is presented (Figures 5 and 6) by a single ore body of isometric form in the bed of Early Cretaceous clays and sandstone. Mud cone breccia sediments composed of subrounded fragments of different size of both enclosing rocks and more ancient sediments of the Cretaceous and Jurassic are subject to mineralization. This fact allows dating back the mud-forming complex within the Caucasus

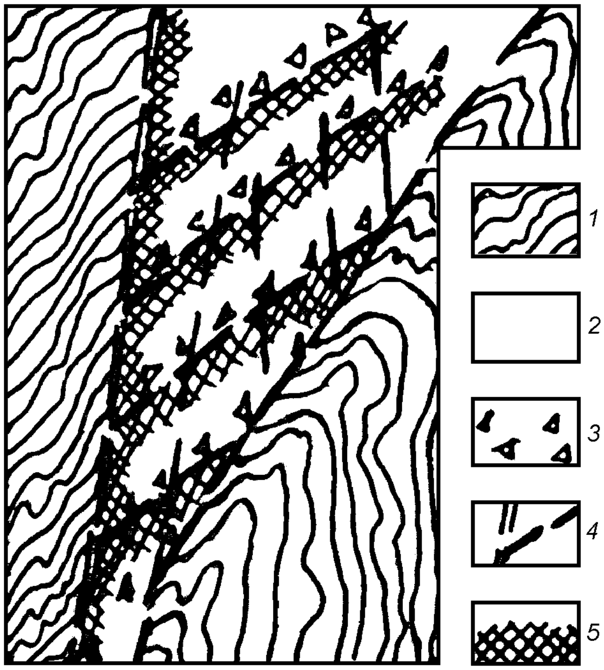

Figure 5. Basic chart of ore deposits confined to paleo mud volcanoes and clayey diapirs (after *Fedorchuk* [1983], with modifications) 1 – sandy clayey sediment of the Jurassic–Cretaceous; 2 – conglomerate breccia filling the vent of mud (paleo) volcano; 3 – jointing and breccia formation zones; 4 – deep fault with fissures locating ore (local screens); 5 – rich nests of ore (Deposit Pereval'noye, ore show Beregovoye).

mud volcano province. The breccia cement is carbonaceous–clayey and worn. Cinnabar commonly in unbroken nests and dickite stand out in cementing mass. It is a characteristic feature that rich ores are confined to local screens that is worn planes of gently sloping fissures conjugated with steeply dipping faults. Note that with depth, funnel-shaped ore bodies are thinned out though breccia with characteristic local impregnation of cinnabar and pyrite is also traced at great depths.

[31] The studies of the mud volcanoes structure of the Caucasus province allow us to conclude that they are formed of Jurassic–Lower Cretaceous clayey stocks and are evidently the result of compression thick Jurassic–Lower Cretaceous clayey (terrigenous flysch) beds, which may develop "in passing the chord" as a result of isostatic floating of the orogene construction of northwestern Caucasus (by the type of F. V. Meinesz tectogene).

[32] It is interesting to note that active mud volcanoes in the province are characterized by noticeable manifestations of increased concentrations of such useful components as mercury and hydrocarbons. Thus anomalous cinnabar ore manifestations accompanied by increased bitumoid content (Voskhod and Aprelskoye) are associated with mud volcano Manzhosova; mud volcano Poleshchuka controls similar ore shows of Adova Shchel. This is not surprising that mercury and hydrocarbon in combination occur in anomalous concentrations in mud volcano activation zones in the Caucasus mud volcano province. Similar facts are noted in Kerch–Taman and Indol–Kuban provinces (mud volcanoes Borisoglebskiy and Shugo respectively). This stable bimodal mineragenetic combination (with different weight ratios of useful components) in mud volcanism zones suggests its paragenetic dependence. These paragenetic correlations are apparently associated with deformation processes activation up to maximum level with forming mud volcanic structures and reflect miragenetic zonality manifestations in the lateral distribution of useful minerals [*Viginskiy et al.,* 1997]. In this case, typically metallogenetic zones of meganticlinorium, which in fact are areas of erosional truncation, are followed by areas of bitumen manifestations commonly enriched with vanadium, nickel, cobalt and others [*Kandaurov,* 1995].

Figure 6. A photograph of Mt. Pereval'naya paleo mud volcano (photo by A. T. Poleshchuk).

Discussion of Results and Conclusions

[33] The material given in this paper supporting the concept of secondary tectonic origin or mud volcanism and clayey diapirism often causing it at the same time testifies to the diversity of concrete deformation mechanisms of diapir-forming complexes. Nevertheless the conditions that determine mud volcanism development against the background of diapir-form dislocations going on in one way of another can be definitely defined. For the most part they are as follows:

- Thick diapir-forming rock complexes weakly competent (of low viscosity) in stress state (Maikopian or Jurassic–Lower Cretaceous beds);
- Dislocations with a break in continuity active in the recent time underlying diapir-forming sediments not always corresponding to diapir ridge extension and to a large extent providing decreased strength characteristics of overlying sedimentary bodies (for example in the influence band of deep Timashevskiy fault–gravitational step–in sedimentary cover. Increased

dislocation is manifested as systems of echelon dislocations with a break in continuity in Jurassic and Middle Miocenic complexes;

- Layer fluids softening clayey rocks of which mud cone breccia is formed.

[34] The latter cause sources of considerable size with anomalously high pore (rock) pressure (AHPP) in deformed clay beds. There are a lot of hypothesis accounting for the formation of this kind of areas. Without going into consideration of them we can only note that in all cases stress concentration in AHPP sources is doubtless and stress tensor has a distinct deviation constituent in the lateral plane. Taking into consideration that the zones of AHPP development generally coincide with diapir formation areas it is reasonable to associate the formation of such zones with the development of clayey diapirism processes compensating for stress tensor ellipsoidal character. This indicates the formation of high potential energy in the interior, which is capable of causing mud volcano activity under certain conditions. In this case AHPP values (P_p/P_{hydr}) as a rule reach 1.8–2.0.

[35] Lateral stress development in clays results in the fact that fluids contained in them are under geostatic pressure (or higher pressure) and flow to areas of lower pressure. Approximately since the Meotian, such areas unloading plastic clayey bed from excess fluids have been diapir cores and mud volcanoes associated with them genetically. In doing so hydrocarbons breaking through mud volcanoes or open diapirs up to the surface with water or in free phase disperse in the atmosphere or in water. If diapir core is overlapped (sealed) and is in contact with reservoirs of good permeability with relatively low rock pressure it is reasonable to expect that water and hydrocarbon excess in clays will drain to the reservoirs through the core. In this case potential energy in the diapir core area discharges ("goes down") into permeable layers and mud volcano eruption is not formed. If permeable layers are local and are only found in the zone close to diapir or are strongly argillized, then in the geological time, the rock energy pulse discharge will result in the formation of anomalous high rock pressure in the layers, which will form prerequisite conditions of mud volcano eruptions.

[36] The role should be noted especially of mud volcano formations in the process of oil and gas deposits formation. Besides evident concepts of conducting role of mud volcano vent zones and the formation of perivolcanic hydrocarbon deposits through it, the generation function of diapir crumpling zones and especially of mud volcano foci seems to be significant. The more so, that in our case diapir forming complexes including the Maikopian in all the depressions described above and the Jurassic–Lower Cretaceous undoubtedly fall with generating complexes, being saturated with organic matter. In this context, the concept of mineragenetic paragenesis "hydrocarbon–cinnabar (mercury)" proposed in the aforesaid is of great interest. Considering the problem from this viewpoint allows us to assume a certain general mechanism of formation of useful mineral deposits seemingly differing in their origin.

[37] In this case, it seem evident that echelon movement of the sediment litification front and facial zones consolidation in linearly extended blocks makes natural physical and geochemical barriers on which combined solutions seep with the formation of stratiform and a peculiar kind of telethermal deposits and of ore show of mercury, copper, molybdenum, gold, platinum, and other elements as well as of hydrocarbon deposits screened tectonically or by injections. Immediately in the areas of mud volcano development and adjacent oil and gas deposits, iodine, bromine, mercury, vanadium and other chemical elements are revealed. Apparently in all these cases, "barrier effect" appears where geodynamic activity conditions the borders of clayey diapirism and mud volcanism manifestations; in the clayey mass, the matter becomes differentiated into more fluid and less fluid components; the formed areas and zones of concentrations of one or other component in their turn make filtering or absorbing barriers. Thus it appears that very important regularities of chemical elements redistribution and the formation of a peculiar kind of mineragenetic zonality may be associated with clayey diapirism and mud volcanism manifestations including their manifestations in the previous epochs. The conclusive solution of this problem will certainly be found in the future. At the same time setting up the problem is undoubtedly timely especially in the light of certain vagueness in concepts on conditions of oil and gas formation and in a broader sense of minerageny.

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