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Gravity and Magnetic Exploration for Unconventional Oil and Gas Traps in Buried Volcanic Formations

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Abstract
This study considers the determination of the geometric shape of volcanic formations in geological sections of the Middle Kura Depression (MKD) in connection with the identification of hydrocarbon accumulations within them. Using gravity and magnetic exploration data, the distribution zones of volcanic formations were identified, and their depths of occurrence and thickness in the study area were determined. Given the presence of numerous oil and gas traps in igneous formations across many basins worldwide, the potential for unconventional volcano-tectonic traps in the MKD was investigated. The presence of a sedimentary complex beneath the volcanic strata in the region, which may contain oil and gas accumulations, is substantiated. A local distribution of volcanoes was revealed, and an uneven thickness distribution of volcanic rocks across the area was established. It was shown that the thickness of lava flows around the volcano's outlet channel is large (more than 2000 m) but decreases with distance to 400-500 m, at which point the full thickness of the volcanic formations can be uncovered.

Keywords
Volcanic trap, Unconventional trap, Oil and gas exploration, Hydrocarbon exploration, Gravity, Magnetic, Volcanic rock

1. Introduction

Unconventional oil, gas, and condensate deposits associated with volcanic formations have been explored and developed for many years in many oil and gas basins (OGBs) worldwide. These deposits are found in volcanic, intrusive, and metamorphic rocks. The first such oil and gas field was discovered in the United States in 1918 (the Hugoton Panhandle field) (Khalimov, 2012).

In subsequent years, more than 500 oil, gas and condensate fields were discovered in granitoids, serpentines, basalts and other igneous and metamorphic rocks in Central Europe, the Sahara-Libya, the Gulf Coast (USA), Kwanza-Cameroon (Africa), Maracaibo (Venezuela), on the shelf of Vietnam (Bach Ho-White Tiger, Rong-Dragon, Bavi fields), in Japan, in India (Bombay-Hai, Bapolla-Changpang fields) and other countries of the world (Panasenko, 1985; Koshlyak, 2002; Nguyen, et al. 2005; Khalimov, 2012; Ozdemir et al. 2021).

An analysis of literary data shows that hydrocarbon deposits associated with igneous and metamorphic rocks occur in traps and reservoirs of various shapes created by these rocks. For example, in the Sahara-Libyan, Reggan, Central European, and Sicilian oil and gas basins, numerous oil and gas fields have been discovered in traps shielded by intrusive rocks (Panasenko, 1985). Commercial oil at the Oymashy Field in Kazakhstan is associated with granite intrusions. In this field, non-conductive igneous bodies also act as covers on the oil-bearing granitoid masses, along with clay, argillite, and limestone-dolomite strata (Dosmukhambetov et al. 2011). Layered intrusions that formed a continuous fluid cover during the Triassic-Jurassic period on the Siberian platform created favorable conditions for hydrocarbon accumulation (e.g., the Sobinskoye Oil And Gas Condensate Field). In other cases, oil and gas deposits were discovered in the eroded upper part of the crystalline basement and in igneous rocks. For example, at the Bach Ho Field (White Tiger, Vietnam), oil was discovered in granites within the eroded crust of the crystalline basement (Khalimov, 2012; Glebova and Nguyen, 2014).

The first oilfields associated with volcanic and volcanosedimentary rocks in the Caucasus region were discovered in 1971 in the Muradkhanly Field (Azerbaijan) and in 1974 in Rustavi and Samgori (Georgia). Cretaceous effusive and partially intrusive formations were identified beneath a thick sedimentary complex in the Muradkhanly, Zardab, Sorsor, Jarly, and other fields (Azerbaijan). Eocene volcanosedimentary rocks were discovered by drilling in Western Azerbaijan and Eastern Georgia.

The presence of magmatic volcanism in the Middle Kura Depression was established through analysis of results from deep exploration wells drilled across various areas of the depression. The DW-1 superdeep well, drilled in the Saatly region of Azerbaijan, revealed that at a depth of 3,500 m, after a sedimentary (3,430 m thick) and volcanogenic-sedimentary (70 m thick) complex, the well encountered volcanic rocks. Further drilling to a depth of 8,324 m did not encounter these rocks, which consist of andesites, basalts, porphyrites, tuffaceous sandstones, tuffaceous andesites, and their varieties (Gadirov, 2024a).

Therefore, studying the oil and gas potential of the Middle Kura Depression's volcanic formations, even though they are not hydrocarbon producers but can create volcanic-tectonic traps in the region, is of great scientific and practical importance. Furthermore, the spatial distribution of these formations within the depression's geological cross-section is unclear, making their study highly relevant. Fig. 1 shows the location of the Middle Kura Depression in Azerbaijan.

This study considers the determination of the geometric shape of volcanic formations in geological sections of the Middle Kura Depression (MKD) in connection with the identification of hydrocarbon accumulations within them. Using gravity and magnetic exploration data, the distribution zones of volcanic formations were identified, and their depths of occurrence and thickness in the study area were determined.

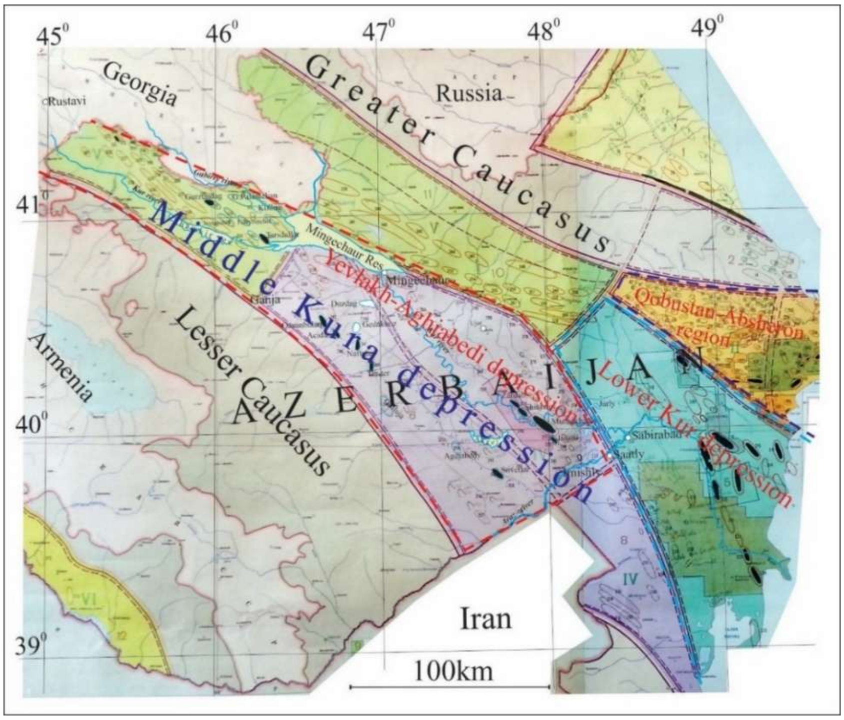

Fig. 1. The location of the Middle Kura Depression in Azerbaijan

2. Fluid Saturation of Volcanogenic Associations of the Middle Kura Depression

The Middle Kura Depression (MKD), encompassing a large portion of the Kura Intermontane Trough, has a complex, heterogeneous geological structure. The thickness of the sedimentary complex within the depression is estimated at 12-14 km. The surface of the Mesozoic complex, to which the identified structures are confined, lies at depths of 7-8 km in the axial zone of the Yevlakh-Agjabedi depression (the south-eastern part of the MKD), 3-4 km in the marginal zones of the depression, and 500-700 m in the Cis-Lesser Caucasus zone. Here, deep wells have uncovered deposits from the

Middle Jurassic (in the area of the Saatly ultra-deep well DW-1) to the Anthropogene, with individual stratigraphic units missing from the section.

Beginning in the late 1940s, exploratory wells identified an oil field (Gazanbulag) in various areas of the region, and commercial oil and gas potential was identified in certain areas (Dalimamedli, Ajidere, Tartar, Sovetlyar, Borsunlu, and others). The discovery of a new type of oil field in the volcanic and volcano-sedimentary formations of the Middle Kura Depression (the Muradkhanly, Zardab, Rustavi, Samgori, and other fields) prompted further detailed geophysical studies of the distribution of these formations and their hydrocarbon content. In these areas, wells identified Cretaceous effusive and partially intrusive formations beneath a thick sedimentary complex. Oil deposits here were confined to Upper Cretaceous effusive rocks, Eocene volcano-sedimentary and marl units, and, partially, Chokrak sandstones. At the Muradkhanly Field, oil was discovered in the windward part of effusive rocks, in depth range of about 0-50 m (for example, in wells 10, 19, 43, 45, 58, 64, 75, 211, etc.,) (Table 1).

Table 1. Oil potential of effusive rocks at the Muradkhanly Field

No. of well	Intervals of detection of effusive rocks (m)	Oil-bearing intervals (m)	Volume of oil (m^3/day)	Depth of the oil-bearing interval from the effusive surface (m)
3	3020 – 4106	3101 – 3144	52-86	81-124
5	3762 – 3800	3762 – 3794	30-40	0-32
10	3934 – 3995	3948 – 3995	72 – 140	14 – 61
19	4260 – 4400	4270 – 4290	2	10 – 30
42	3157 – 3257	3220 – 3230	5	63 – 73
43	3022 – 3092	3022 – 3030	80	0 – 8
45	3667 – 3882	3666 – 3700	10	0 – 33
58	2950 – 2978	2950 – 2978	400	0 – 28
64	2974 – 3027	2994 – 3027	216	20 – 53
66	2951 – 3000	2959 – 3000	2	8 – 49
70	3873 – 3975	3874 – 3975	45	1 – 102
75	3093 – 3112	3102 – 3112	100	9 – 19
81	4060 – 4163	4110 – 4152	180	50 – 92
211	3773 – 3823	3773 – 3823	270	0 – 50
213	3130 – 3357	3284 – 3296	2	154 – 166
237	4575-4740	4653-4715	11	78-140

Table 2. Drilling mud loss and fluid production in volcanic rocks in the southeastern part of the MKD

Fields, well No.	Depth of effusive rocks, m	Absorption			Fluid manifestations	
		Volume, m^3	Depth, m	Depth from the surface of the effusive, m	Depth, m	Type of fluid
Muradkhanly 3	3020	8 22 15	3280 3297 3970	260 277 950	3053 3297 3666 3750	water-gas-oil gas-oil gas-oil gas-oil
Muradkhanly 6	2950	25 65	3192 3827	242 877	3014	gas
Muradkhanly 7	3717	?	3718-3755	38	-	-
Muradkhanly 9	3510	30	3560	50	-	-
Muradkhanly 10	3934	50	3957	23	3957	qaz
Muradkhanly 18	3047	20	3195	148	3145 3162 3195	gas-oil gas-oil oil-water
Muradkhanly 20	3801	15	4030	229	4052	gas-water
Muradkhanly 5	3677	-	3774	97	drop of the drilling tool by 30 cm	
Muradkhanly 213	3130	-	3220-3230	100	sudden destruction, crumbling, and collapse of effusive rocks	
Jarly 6	3417 (K_1)	5	4554	137	-	-
Jarly 8	3686 (K_1)	7	4053-4098	367-412	4098	газ
Zardab 1	4364 (K_2)	5	4552	188	4463 4507	water-oil gas
Garadzhaly 2	3600 (K_2)	45	3982	382	-	-

At the specified field, oil was also produced from relatively deep layers of effusive rocks (approximately 50-150 m below the surface of the effusive rocks, for example, wells 3, 42, 70, 81, 213, 237). Some wells were characterized by high flow rates. In well No. 3, oil fountains were recorded at a depth of 81-124 m from the surface of effusive rocks, and in well No. 81 at a depth of 50-92 m, with a flow rate of 52-86 m^3/day and 180 m^3/day, respectively. In well No. 213, a small volume of oil (2 m^3) was obtained at a depth of 154-166 m from the surface of volcanic rocks (Table 1).

In addition, at great depths beneath the surface of the effusive rocks, absorption of drilling fluid and the presence of large amounts of water are observed, indicating the development of cracks, cavities, caverns, and pores in the deep layers of effusive rocks.

At the Muradkhanly Field, as well as at the Jarly and Zardab Areas, large volumes (15-65 m³) of drilling fluid were lost not only in the eroded surface of volcanic rocks, but also at depths of 877 and 950 m below the surface (in wells No. 6 and 3 of the Muradkhanly Site). In well No.8 on the Jarly Area, at a depth of 367-412 m from the surface of Lower Cretaceous effusive rocks, 7 m³ of drilling fluid was lost. In well No.2 (Garadzhaly Area), at a depth of 382 m from the surface of the effusive rocks, 45 m³ of drilling fluid was lost (Table 2).

At great depths beneath effusive rocks, oil and gas emissions are observed during drilling. In wells No. 3, 6, 18 (Muradkhanly Field), in well No. 1 (Zardab Field), in well No.8 (Jarly Field) at depths of 188-950 m, oil and gas shows were observed. In one case, in well 5 (Muradkhanly Field), the drilling tool sank by 30 cm; in well No. 213, sudden destruction, crumbling, and collapse of effusive rocks were observed, indicating a void within the magmatic bodies (Table 2).

Of particular interest is the aquifer capacity of effusive formations. Observations show that aquifers are present within effusive formations at very great depths. For example, in well No.6 (Muradkhanly Field), at a depth of 362-369 m from the effusive surface, water inflow reached 825 m³/day. In the Muradkhanly (well No.11), Sor-sor (well No.4), and Jarly (well No.1) Areas, at depths greater than 1,000 m from the surface, aquifers were identified within effusive formations, further demonstrating the presence of zones with enhanced reservoir properties within volcanic rocks, which may contain fluids of varying compositions (Table 3).

3. Display of Buried Volcanic Formations on Gravity-Magnetic Fields

Magmatic volcanism in the Middle Kura Depression continued into the Upper Cretaceous. It appears that the hypsometric level of the structures they formed is significantly higher than that of the crystalline basement (Gadirov, 2015a; Gadirov et al., 2016a). This makes it feasible to detect and study these structures and the associated unconventional oil and gas traps using geophysical methods. It should be noted that determining the distribution of volcanic rocks in the section, their geometric shape, depth, and thickness is a very complex task; nevertheless, it is of great importance for the study of unconventional traps. These and similar questions have been successfully addressed using gravimetric and magnetometric exploration based on the distribution of rock density and magnetic properties within the geological section (Gadirov, 1991; Gadirov, 2002; Gadirov, 2015a; Gadirov and Eppelbaum, 2012; Gadirov et al. 2016a).

Laboratory analyses of cores from the MKD boreholes indicate that the region's volcanic rocks are characterized by high density and magnetic susceptibility (Table 4).

Volcanic formations consisting of andesite, basalt, and porphyrites are characterized by high density (2580-2840 kg/m³) and magnetic susceptibility (1382-5752) 10^{-5} SI). The magnetic susceptibility of sedimentary rocks is significantly lower than that of effusive rocks, and within this basin in the Absheron-Upper Cretaceous sedimentary rocks varies in the range of (75-1130) 10^{-5} SI. The density of the Upper Cretaceous deposit's ranges from 200 to 500 kg/m³.

Studies have shown that effusive formations in the form of an anticlinal uplift with an amplitude of 400-500 m and a depth of 3 km can create a positive local anomaly of 0.5-2.0 mGal in the gravitational field and 15-20 nT in the geomagnetic field. Therefore, it is possible to register buried volcanic structures in a geological section using modern gravimetric and magnetometric instruments (Gadirov, 1991; Gadirov, 1994; Gadirov, 2002; Gadirov, 2013; Gadirov and Eppelbaum, 2012). However, in this case, it is imperative to adhere to the methodology of field work - the correct placement of observation profiles, the accuracy of surveying, the processing of field materials, the geological interpretation of gravity-magnetic anomalies, etc. (Gadirov, 2010).

Table 3. Water content of effusive rocks in the MKD areas

Fields, wells No.	Intervals of detection of effusive rocks, m	Water content intervals, m	Volume of water, m³/day	Depth of aquifer from effusive surface, m
Muradkhanly 6	2950-4900 (K_2)	3312-3319	825	362-369
Muradkhanly 223	3355-3481 (K_2)	3402-3472	432	47-117
Muradkhanly 11	3877-5202 (K_2) 5402-5500 (K_1)	4875-4930	6,2	998-1053
Sor-sor 3	3628-4700 (K_1)	4024-4095	62	396-467
Sor-sor 4	3230-4300 (K_1)	4123-4250 3680-3774	12 340	893-1020 450-554
Jarly 1	3636-4865 (K_1)	4490-4865	228	854-1229
Jarly 6	3417-4560 (K_1)	3854-3995	53	437-578
Jarly 8	3686-4470 (K_1)	4020-4150 3920-3996	100 750	334-464 234-310
Garadzhaly 2	3600-4210 (K_2)	3860-3890	192	260-290

It should be noted that the distribution characteristics of volcanic formations in many areas of the Middle Kura Depression were studied using magnetic surveys. Mesozoic tectonics were also clarified using a combination of gravimetric and seismic survey methods, the depth and thickness of effusive rocks were determined, their spatial position was established, and other issues were addressed. It was established that volcanic rocks within this depression are distributed in localized areas characterized by local magnetic anomalies (Gadirov, 1991; Gadirov, 2002; Gadirov, 2013).

In general, numerous studies have been conducted to trace deep faults in the upper crust, study the distribution of magnetically active masses, and determine other structural and tectonic features of the geological section based on the characteristics of geomagnetic field changes. Magnetic exploration data are used to determine the location, contours, extent, and size of uplifts of various structural and geological origins, as well as the material composition of the layers that make up the uplift, etc. It has been shown that zones with high magnetic field gradients occur at the edges of horst-anticlinal structures (Nikitsky and Glebovsky, 1990; Gadirov et al., 2018). Thus, it is crucial to find out which geological factors are responsible for the observed overall geomagnetic field.

An analysis of the vertical component (Z) of the geomagnetic field observed along regional profile No. 6, which intersects the Middle Kura Depression in a southwest-northeast direction and passes through the Gindark, Zardab and Sor-Sor regions and was conducted in 1965 using the correlation method of refracted waves (CMRW), shows that the geomagnetic field in the region consists of three main effects: the effects of the sedimentary complex, the effects of the masses between the crystalline basement and the Curie surfaces, and local magmatic volcanism. This result was obtained by calculating the geomagnetic effects of individual geological layers. It was established that the local magnetic anomalies observed in the Middle Kura Depression are associated with volcanic masses of high magnetic susceptibility that developed locally (Gadirov, 1991; Gadirov, 2002; Gadirov, 2024b).

Table 4. Physical properties of rocks composing the geological section in the MKD

Age	Lithology	Density, kg/m^3	Magnetic susceptibility, x 10^{-5} SI
Quaternary	Sandstones, sands, clays	2050	-
Upper Pliocene (Akchagyl)	Sandstones, sands, siltstones, limestones	2080-2180	75
Lower Pliocene (Productive strata)	Clays, sands, siltstones	2180-2290	75
Miocene	Clays, sandstones, marl, and dolomite interlayers	2210	103
Oligocene-Miocene (Maikop)	Calcareous clays	2300	138
Eocene	Calcareous clays, interlayers of limestone and dolomite	2340	377
Pliocene	Calcareous clays	2340	816
Upper Cretaceous	Limestones, interlayers of marl and dolomite	2580-2720	1130
	Andesites, basalts, porphyrites	2580-2840	1382-5752
Lower Cretaceous	Andesites, porphyrites, tuffaceous sandstones	2550-2700	1884

4. Methodology for Determining the Spatial Position of Buried Volcanic Formations

The discovery of new oil and gas fields in volcanic and volcano-sedimentary rocks of the Middle Kura Depression (Muradkhanly, Zardab, Alivand, Dalimammadli, Rustavi, Samgori, and others) has laid a solid foundation for studying the distribution zones of buried volcanic formations in this region. For this reason, it is extremely important to clarify the spatial position of these Mesozoic formations in the geological section. To detect volcanogenic formations buried beneath thick layers of sedimentary rocks, a rational combination of gravimetric and magnetometric studies was proposed. The basis for using the gravity-magnetic complex to address this geological problem lies in the high density of Upper Cretaceous rocks and the high magnetic susceptibility of volcanogenic formations in the Middle Kura Depression.

The methodology developed in this regard allows mapping the surface of Upper Cretaceous deposits, determining the depth of volcanic formations, and determining their spatial position based on the interpretation of high-precision gravity and magnetic data. In this case, the following sequential operations are proposed (Fig. 2):

- Determining the surface depth of Upper Cretaceous deposits, which are characterized by high excess density in the Middle Kura Depression (it should be noted that most volcanogenic formations in the region date back to the Cretaceous period);
- Preliminary determination of the depth of the upper part of the volcanogenic formations (some areas of this surface may disappear during subsequent refinements);
- Localization of the distribution zone of volcanogenic formations;
- Determining the spatial location of volcanogenic formations using the selection method.

The issue of determining the depth of the Upper Cretaceous sedimentary complex has been described in detail in the literature (Gadirov, 2010; Gadirov et al. 2016a; 2023). For this purpose, mathematical relationships were established between the depth values determined from numerous borehole data and seismic exploration of the Upper Cretaceous complex and the observed gravity values at these points, and corresponding formulas were derived (Gadirov, 2010; 2024b). The basis for using local anomalies to determine the spatial position of magnetically active masses is the idea that the local distribution of volcanic rocks in the Middle Kura Depression is reflected in the geomagnetic field as local anomalies (Gadirov, 1991).

And so, the spatial position of volcanogenic masses is determined by the method of selection in the zone of the selected local magnetic anomaly. In this case, the well-known palette of D. S. Mikov is used, and the form of the volcanogenic structure is selected until the magnetic anomaly generated by that shape coincides with the local magnetic anomaly selected from the observation curve.

5. Results and Discussion

5.1. Determining the Spatial Position of Volcanic Formations

Thus, the reservoir properties of effusive rocks in the Middle

Kura Depression can be linked to the development of cracks, caverns, and pores (cracks-cavity-porous reservoirs). The porosity of effusive rocks in this region has been shown to reach 9%. According to the literature, in many regions of the world, reservoirs in igneous and metamorphic rock deposits are characterized by cracks, voids, and pores formed by hydrothermal activity, secondary processes, and various erosions.

At this time, fractured granites, biotite granites occurring as sills and dikes, diabase intrusions, basalts, amphibolites, and gneisses form reservoirs capable of accumulating oil and gas (Koshlyak, 2002; Khalimov, 2012). On the other hand, igneous rocks can also act as a screen, covering sedimentary rocks (for example, deposits in Kazakhstan and Western Siberia).

In Azerbaijan, the search for unconventional oil and gas deposits associated with igneous associations and crystalline basement rocks is of great importance. The oil and gas potential of the crystalline basement in the intermontane Kura Basin has been comprehensively analyzed, drawing on international experience. It has been correctly demonstrated that the formation and distribution of hydrocarbons in the Earth's crust is global in nature from a geodynamic perspective, and the crystalline basement in Azerbaijan, as in other regions, should be considered promising for oil and gas (Narimanov, 2013).

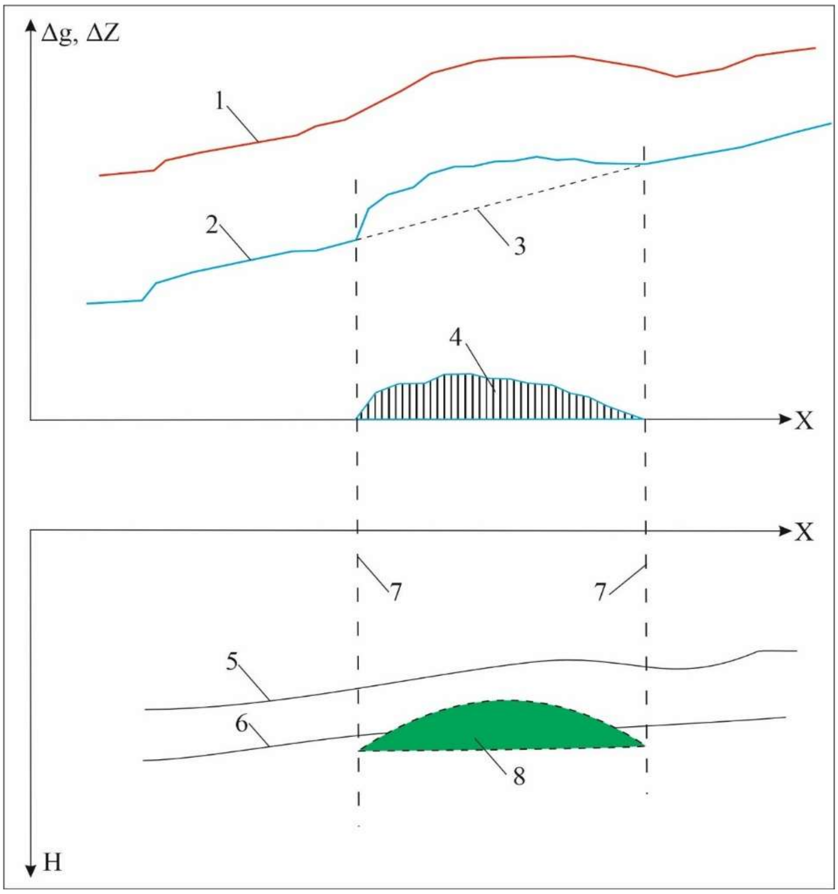

Fig. 2. Localization of the distribution zone of volcanogenic formations. 1 and 2- observed curves of the gravitational (Δg) and geomagnetic (ΔZ) fields, 3– regional background, 4- local maximum of the magnetic field, 5- surface of Upper Cretaceous deposits, 6- calculated depth of the surface of volcanic rocks, 7- lines drawn from the edges of the local magnetic maximum, limiting the distribution zone of volcanic rocks, 8- volcanic structure determined by the selection method

The depth of the crystalline basement in the intermontane Kura Depression is estimated at 6-7.5 km in the Goychay-Saatly uplift zone and 13-15 km in the central part of the Yevlakh-Aghjabedi trough. Volcanic edifices have been uncovered at shallower depths, for example, at 2950 m in the Muradkhanly Area.

Considering that magmatic volcanism in this region continued into the Upper Cretaceous, we see that the hypsometric level of the structures they formed is located several kilometers (3-7 km) above the basement. This makes it feasible to detect and study these structures and the associated unconventional oil and gas traps using geophysical methods and boreholes.

Therefore, determining the distribution of volcanic rocks in the section, their geometric shapes, depths, and formation thicknesses is of great importance for studying the formation of unconventional traps. Although volcanic rocks have been penetrated by deep wells in many areas of the Middle Kura Depression, the state of the lower boundary and the overall geometric shape of the section remain undetermined. These and similar questions have been investigated and explained in detail based on gravimetric and magnetometric exploration data (Gadirov, 1991; Gadirov, 2002; Gadirov, 2014; Gadirov, 2015a; Gadirov, 2015b).

Using data on gravitational and magnetic fields, applying the above-mentioned method, it was possible to construct geological sections in the SE and NW parts of the Yevlakh-Agjabedi trough (south-eastern part of the MKD), reflecting the depth, thickness, geometric shape, and location of the roots of volcanic formations on individual profiles (Figs. 2, 3 and 4).

Fig. 3 shows a profile through deep boreholes at the Muradkhanly field. As can be seen, the true portion of the effusive formations has been penetrated by some boreholes. The lower boundary and shape of this structure in a two-dimensional vertical section were determined from gravity and magnetic survey data acquired with the proposed method. The effusive formations have a root extending deep into the earth, cutting off the crystalline basement along which the igneous rock was extruded. Close to the magma outlet channel, the thickness of the effusive formations reaches several kilometers, decreasing to hundreds of meters with distance.

In the area of boreholes No. 203-209, the thickness of the effusive formations is 700-800 meters. It is assumed that these effusive formations cover the underlying sedimentary rocks of Lower Cretaceous and Jurassic age. If we consider that hydrocarbon migration originates from the central part of the Yevlakh-Agjabedi trough, then it can be assumed that volcanic formations can create non-traditional volcano-tectonic traps for oil and gas, acting as seals.

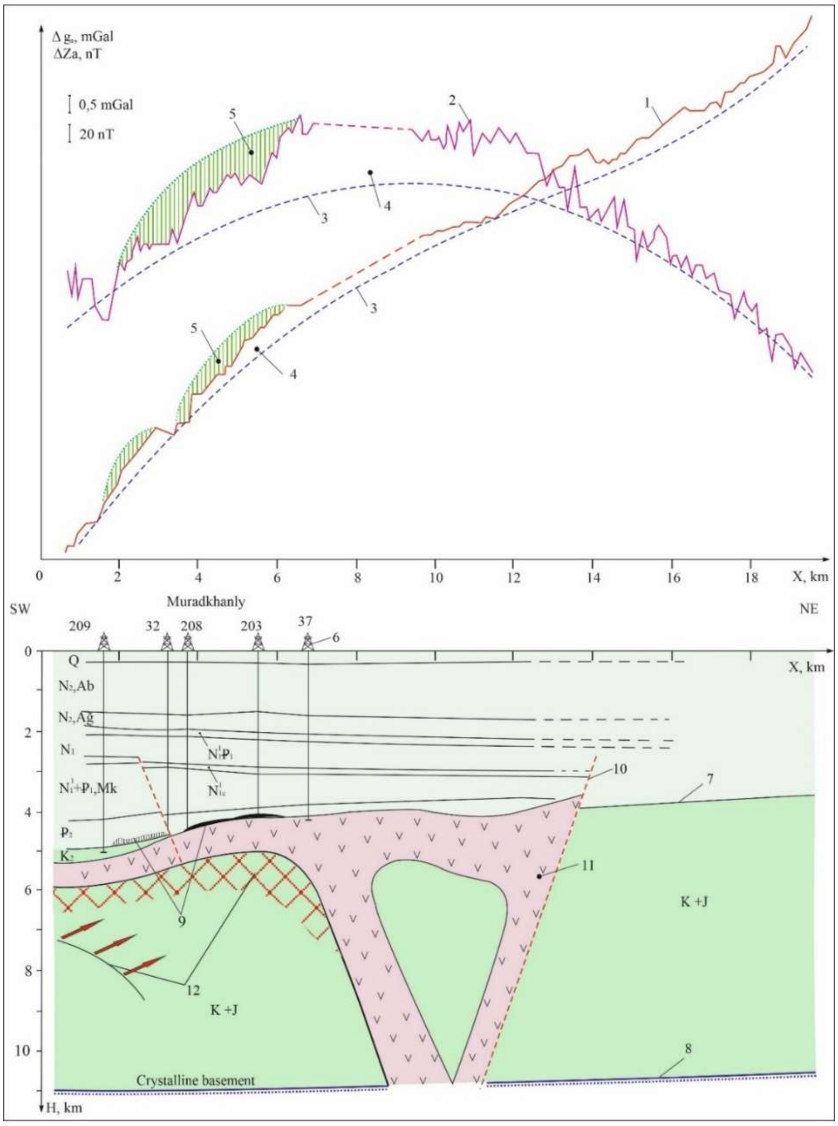

Fig. 3. Model of volcanogenic formations and possible zones of hydrocarbon accumulation based on gravimagnetic data (Muradkhanly Area, pr. 02). 1 and 2- observed gravity and magnetic fields; 3- regional background; 4- local maxima; 5- local minima associated with oil and gas; 6- exploration wells; 7 and 8- surface of Upper Cretaceous deposits and crystalline basement; 9- suspected and known oil fields; 10- fractures; 11- effusive rocks; 12- hydrocarbon migration directions and possible accumulation zones

As can be seen, well No. 208 and 203 penetrated an oil reservoir, above which local gravity-magnetic minima associated with oil and gas potential are identified. The amplitude of these minima reaches 0.6-0.8 mGal and 45-50 nT, respectively. Modeling studies of the Muradkhanly Area show that the calculated gravitational and magnetic effects of an oil reservoir with a thickness of 40-50 m, taking into account the effect of the subvertical zone, are 0.35 mGal and ≈37 nT, respectively (Gadirov and Eppelbaum, 2012; Gadirov et al., 2016b; 2018; 2022; 2023).

In Fig. 3, local gravitational and magnetic anomalies associated with oil and gas potential, identified from the observed field, are 0.6-0.8 mGal and 45-50 nT. As can be seen, the identified anomalies significantly exceed the calculated anomalies in the same field. It is assumed that this may be associated with hydrocarbons beneath effusive formations, which can generate additional gravity and magnetic anomalies.

A similar result was obtained on another profile passing through the Muradkhanly Area (Fig. 4). Three deep wells, No. 26, 16, and 65, were drilled in this part of the area. These wells encountered effusive formations at depths of 3,915 m, 3,320 m, and 3,135 m, respectively. Well No. 16 encountered the greatest thickness of volcanic rocks (574 m) and did not exit them. The constructed cross-section shows that the volcanic structure has nearly vertical roots beneath well No. 65. In the area of wells No. 16 and 26, the thickness of the volcanic rocks decreases to 800 m and 200 m, respectively.

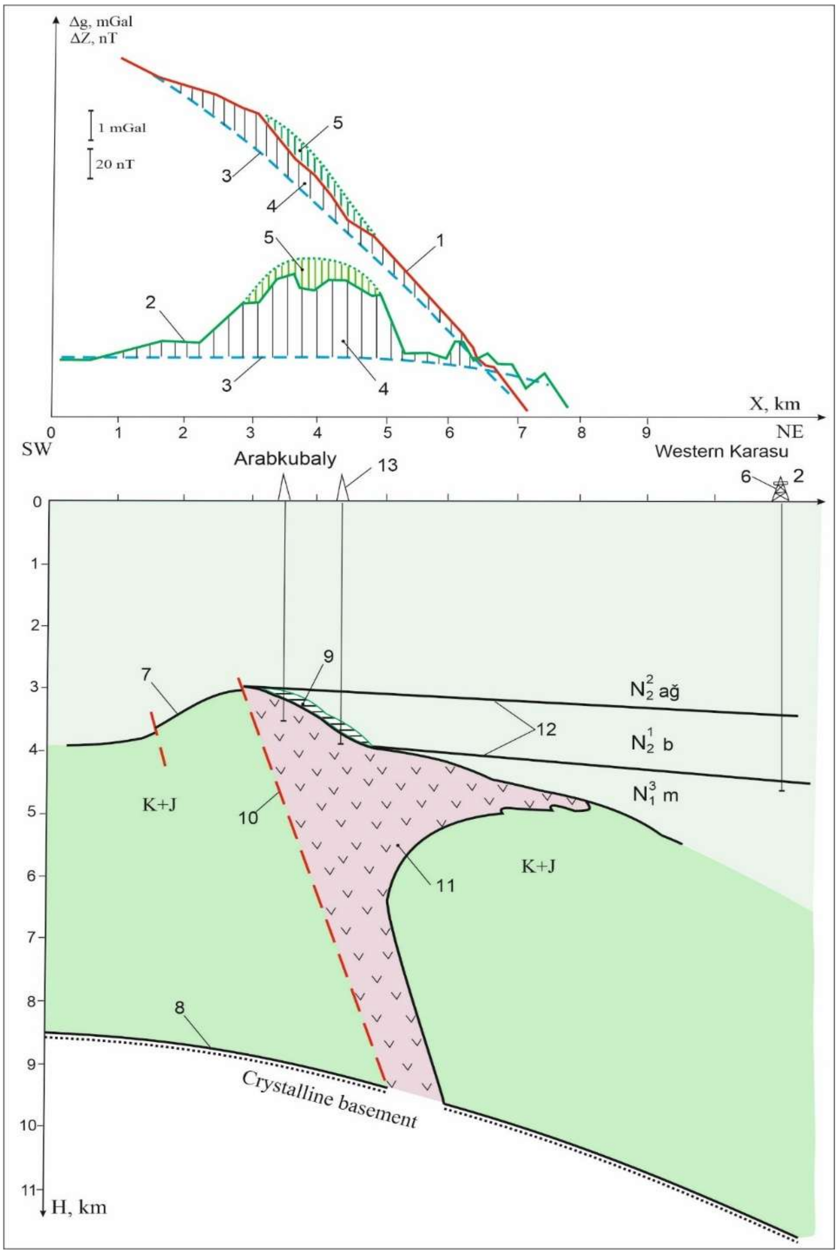

Fig. 5. Model of volcanogenic formations and possible zones of hydrocarbon accumulation based on gravimagnetometric data (Arabkubaly Area, pr. 14) Symbols see Fig. 3 and: 12- bottom and top of the productive layer (Balakhani Formation) according to seismic data; 13- proposed drilling wells

Observed gravity and magnetic fields reveal local anomalies with an intensity of 0.3-0.4 mGal and 20-30 nT, associated with oil and gas potential. Wells drilled here have not detected oil or gas in either sedimentary or effusive rocks. It is reasonable to assume that oil deposits could be expected beneath layers of volcanic rocks that act as seals, as in

Kazakhstan, Siberia, Central Europe, and other oil and gas basins worldwide. It is believed that if drilling of wells 26 and 16 had continued, the lower boundary of the effusive formations and the suspected oil deposit could have been discovered at a depth of 4,200-4,500 m (Fig. 4).

Fig. 5 shows the constructed geometric shape of volcanic formations in the geological cross-section of the Arabkubaly Area. In the southwest, it rests on a deep fault, while in the northeast, volcanic rocks extend for several kilometers, with increasing depth.

Based on data from deep well No. 2, West Karasu, the location of the productive strata (the Balakhani Formation-N_2^1), known for its oil and gas potential, was established. Seismic data also revealed a southwesterly upwelling of the Balakhani Formation. The constructed model shows that the Balakhani Formation rests against volcanic rocks. Local gravity (0.5-0.6 mGal) and magnetic (15-20 nT) anomalies, identified from the observed field and associated with oil and gas potential, are detected above the contact zone of sedimentary and volcanic rocks. This suggests that oil and gas deposits may accumulate on the surface of the volcanic body that contacts the Balakhani Formation. This suggests that an unconventional hydrocarbon trap, shielded by a volcanic formation, may be encountered in this area. Due to the lack of gravity-magnetic data within 3-4 km of the Arabkubaly Area in the north-east, it was difficult to assess the oil and gas potential of sedimentary deposits buried beneath the volcanic layer.

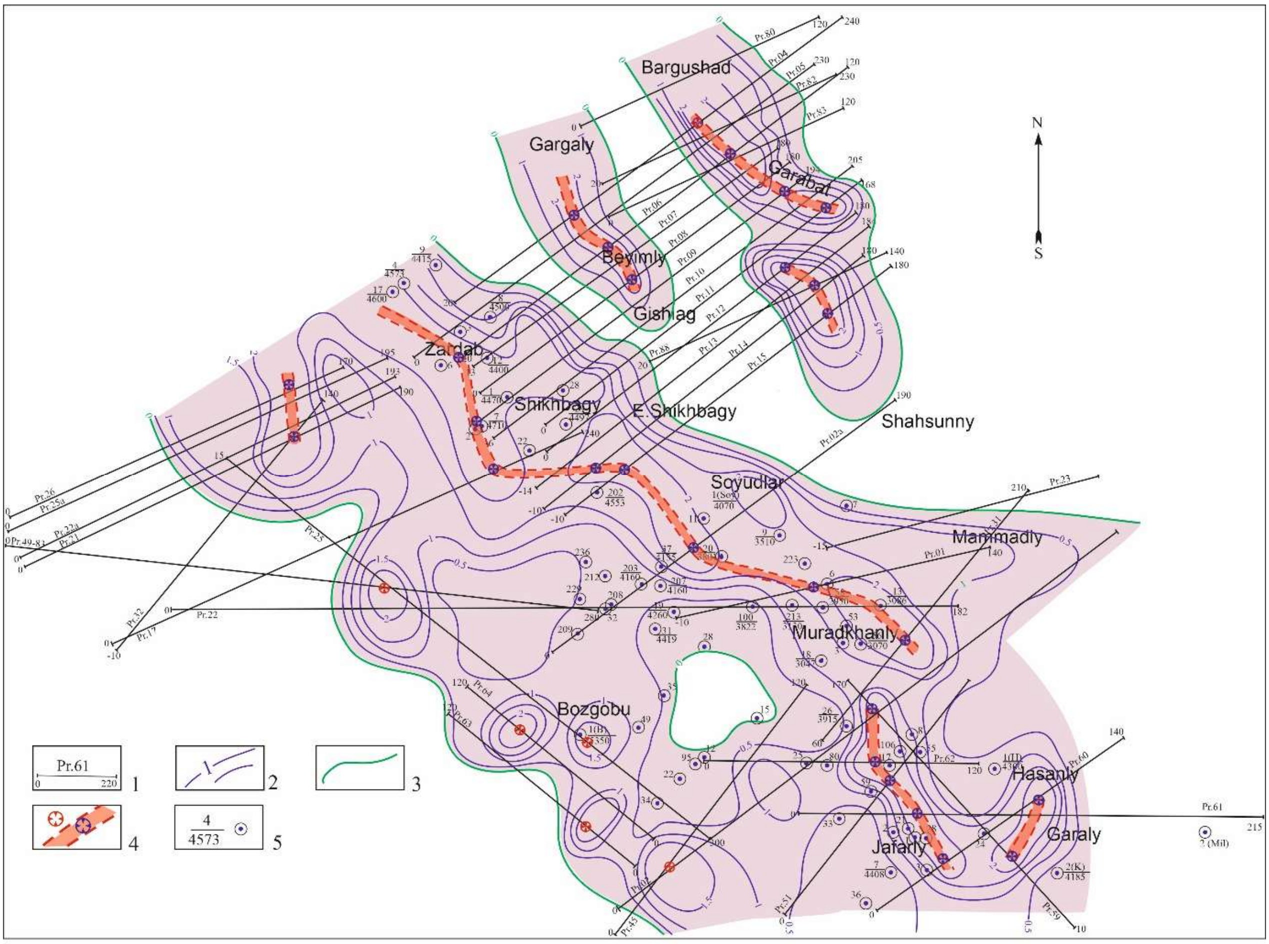

Fig. 6. Map of the thickness of volcanic formations (southeastern part of the Middle Kura Depression): 1-gravity-magnetic profiles; 2-isolines of equal thickness of volcanic rocks (in kilometers); 3-proposed boundary of volcanic rocks; 4-proposed deep faults and roots of volcanoes; 5-exploration well numbers and depth of volcanic rocks.

It should be noted that in 2006, seismic exploration work conducted in the Muradkhanly Region showed that a number of anomalies type deposit (ATD) were discovered at a depth of approximately 1000 m below the surface of the Mesozoic Complex, i.e., within the Cretaceous Complex (Novruzov and Gadirov, 1998). This once again indicates the possibility of discovering hydrocarbon deposits in deeper layers, including beneath volcanic formations. As can be seen from geological sections (Figs. 3, 4 and 5), the thickness of the lava flows around the probable channels of the eruption of the volcano is large (>2000 m) and decreases to 400-500 m as you move away from them. Such a distribution of effusive rocks in the geological section indicates that, in the Mesozoic era, a thick, organic-rich sedimentary layer accumulated within the depression, extending to the crystalline foundation.

At the same time, apparently, a complex of sedimentary rocks of great thickness accumulated under the lava flows formed by the volcano.

5.2. Construction of a Map of Thickness of Volcanic Formations

To create a map showing the distribution zones of volcanic formations, a map of gravity profile locations recorded in different years in the southeastern part of the Middle Kura Depression was first compiled. Data from 46 profiles covering the Muradkhanly, Bozqobu, Jafarly, Garaly, Zardab, Shikbagy, Gargaly, Kishlag, Garabat, and Shakhsunny Regions were used. The constructed depth sections reflecting the volcanic formations in these profiles were studied, and their thickness was determined.

Initially, a map of volcanic formation thickness was created on a computer using the Surfer program and then refined with deep-well data. This resulted in a map showing the distribution of volcanic formations in the SE part of the Middle Kura Depression and their estimated thickness in this area (Fig. 6).

The compiled diagram shows that in the Jafarly-Muradkhanly-Zardab Zone, volcanic masses develop in northwest-southeast-trending zones, whose lengths are several times their widths, and have variable thicknesses. The thickness of the volcanic formations around the magma-producing roots of the volcano is more than 2-3 km and decreases sharply (to 400-500 m) towards the edges. It is assumed that the volcanic complex southwest of the Muradkhanly-Zardab Zone, that is, towards the center of the depression, is not included in the geological cross-section at all.

Figs. 3, 4 and 5 show that the volcano's magma-erupting conduits are relatively narrow (≈1000-1500 m), and they are aligned in a northwest-southeast direction (Fig. 6). Based on this arrangement of the volcano's roots, it can be assumed that they are confined to deep fissures. This suggests that fissure-type volcanoes were prevalent in the region during that geological period. At that time, thick lava formations would be found around deep fissures, and with distance from the fissures, the thickness of the volcanic rocks gradually decreases.

It should be noted that during the distant geological period (the Mesozoic), fissure volcanoes were widespread and typically erupted gas-rich, fluid magmas. Indeed, deep wells have identified effusive rocks of basic and intermediate composition (basalts, basaltic porphyrites, andesites, andesitic porphyrites, and dacites) in the Jafarly-Muradkhanly-Zardab zone and the surrounding area.

The width of the volcanic rock distribution zone in the Jafarly-Muradkhanly-Zardab region is 9-10 km, whereas in the north, in the Gargaly-Beyimly-Gishlag and Bargushad-Karabat-Shahsunny regions, effusive rocks occur in bands approximately 3-4 km wide. However, deep wells have not been drilled in these areas, and the presence of volcanic rocks has not yet been proven.

It should be noted that no boreholes in the region have penetrated the full thickness of the volcanic rocks, which could provide valuable information for the volcanogenic formation thickness map. Drilling was halted after the boreholes had penetrated several hundred meters of volcanic rocks. This approach was developed after a number of initial boreholes had penetrated enormous thicknesses of volcanic rocks. For example, boreholes No. 3, 6, and 11 in the Muradkhanly Region penetrated 1-2 km of volcanic rocks but did not reach their full thickness. The volcanogenic formation thickness map shows that these boreholes were located near the volcano's magma-conducting roots.

Consequently, the exposed thickness of volcanic rocks here was very large. It is likely that the full thickness of volcanic formations can be exposed far from the volcano's roots, in the limbal areas, where the thickness reaches a minimum (Fig. 6).

Studies of volcanogenic structures and hydrocarbon traps associated with these formations in the Middle Kura Depression yielded the results presented below.

- The relatively narrow roots of volcanogenic formations in deep sections constructed on profiles and their orientation along a certain line in the plan gave grounds to assume that fissure-type volcanoes were developed in the Middle Kura Depression in a remote geological period (in the Mesozoic era).

- It was established that hydrocarbons formed in the Yevlakh-Agjabedi depression (the southeastern part of the Middle Kura Depression) could migrate to the slopes of the depression and accumulate here both in the upper part of volcanic formations, as well as in unconventional traps shielded by volcanic rocks beneath these formations.

6. Consolation

Based on the analysis of geological, lithological, geochemical, and thermal conditions of the Middle Kura Depression, it has been shown that during the Meso-Cenozoic period, this basin had favorable conditions for the formation of large volumes of hydrocarbons. The hydrocarbons formed at this time could migrate to the basin slopes and accumulate in traps associated with the sedimentary-volcanic complex. Thus:

– The study of the sedimentary rock complex underlying volcanic formations is of great interest from the point of view of oil and gas potential, and, given the possibility of the formation of unconventional traps here, shielded by volcanic rocks, the implementation of complex geophysical work is considered important.
– To detect oil and gas traps associated with volcanic formations, it is advisable to focus geophysical exploration work primarily on the marginal sections of the Yevlakh-Agjabedi trough (the southeastern part of the Middle Kura Depression).
– It is imperative to adhere to fieldwork methodology, including proper placement of observation profiles, survey accuracy, processing of field data, and geological interpretation of gravity and magnetic anomalies.

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