AAPG Annual Convention
Salt Lake City, Utah
May 11-14, 2003

Gravity Model of Mud Volcanoes

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Summary. Measurements have been made of gravitational field, geodetic uplift and thermal patterns in the general area of the Lokbatan mud volcano after its explosion on 25 October 2001, as well as in the crater itself. This massive compendium of information represents the first time such a detailed investigation has been possible of the deep structural effects of a mud volcano and also of the sources of mud and gas at outflow time. The data are integrated into a combined picture that shows the roots of both the mud outflow and of the gas causing the flaming eruption, are at several km depths into the sedimentary pile. The overall behavior is best served by a model in which a relatively thin jet of liquefied mud is extruded from depth due to action of the varying tectonic stresses in the region. The variation of Bouguer gravity across a profile including the Lokbatan mud volcano, and combined with the geodetic vertical motion immediately after and long after (10 months) the explosion, comfirms this basic model. The focusing of heat flux around the volcano prior to the explosion, and the thermal measurements made with time after the explosion both in the crater and also in the immediate vicinity of the Lokbatan volcano, are in accord with a thin hot jet model in which liquefied mud, with entrained gas from deeper in the sediments, rises through a neck region and, due to the Rayleigh-Bernard convective instability, produces a high temperature region.

Introduction. In the South Caspian Basin, the general region of onshore and offshore Azerbaijan is home to over 300 mud diapirs and/or mud volcanoes. These mud structures are associated with the production of copious oil and gas, and production wells are to be found on the flanks of many onshore mud diapirs. This association is no mere coincidence but is related to the dynamical development of mud diapirs and the generation, migration, and accumulation of hydrocarbons in the South Caspian Basin. Unfortunately, in spite of long-term complex studies of the Azerbaijan mud volcanoes, no special geophysical investigations have been undertaken. There are available only the results of geophysical studies obtained serendipitously while solving other oil field problems; these investigations are not enough to compile a mud volcano model nor to study the dynamics of its activity. Such a capability is possible only with special, very detailed geophysical and geodetic investigations.

This paper contains the results of such investigations carried out for the first time on volcanoes in the southwest Absheron region, viz. Lokbatan, Akhtarma-Puta and Gushkhana, all located within one single tectonic zone. The Lokbatan mud volcano was chosen because it is very active not only in comparison to other volcanoes in Azerbaijan but in respect also of all worldwide mud volcanoes. The last eruption occurred on October 25, 2001. The present studies were started immediately after that eruption.

Together with the gravimetric and geodetic studies observations were also conducted. Profiles in different directions were chosen to carry out gravimetric and geodetic measurements on areas of mud volcanoes. One profile, more extended than the others (11 km long), begins near a key gravity-geodetic point at Lokbatan and passes through a line joining the mud volcanoes Lokbatan – Akhtarma-Puta – Gushkhana. The distances between measurement points are never more than 250 m. More than quarter of all known mud volcanoes is concentrated in Azerbaijan within the SE ending of Great Caucasus. Areas around Azerbaijan mud volcanoes are reflected by minima of the Bouguer gravity field (from –120 to –40 mGal) (Kadirov, 2000).

Methods. *Gravity and Geodetic*. Measurements of gravity differences between points were undertaken by four gravimeters under a simple closed loop arrangement. The scale interval of the gravimeters was determined at different temperatures using a control instrument. When processing field measurements, corrections were made for relation of scale interval to temperature, for non-linearity of scale of a micrometer screw, and for lunar-solar attraction. The longitudes and latitudes of the measurement locations were determined with the help of GPS, and altitudes of the points with a level from the firm Carl Zeiss, Jena (the mean quadratic error on a 1 km traverse measured in both directions was 0.2 mm). For calculation of the Bouguer gravity anomaly, the altitude was read from the lowest level (at the Lokbatan reference point), and the interlayer density taken to be 1.82, 2.0, 2.3 g/cm3. Gravity modeling used a minimization condition on a multi-parameter functional describing the least squares difference between modeled and observed gravity fields and involving parameters of the initial structure model. The initial parameters of the model are modified such that the difference between observed and computed fields does not exceed 1mGal. Along the NE–SW profile gravity modeling was done to investigate the depth structure and tectonic evolution of the mud volcanoes.

Temperature Measurements. Measurements have been made at three sites within the Lokbatan crater at depths of 0.5m, 1.0m and 1.5m into the mud, using a thermistor thermocouple and a balancing Wheatstone Bridge, with resistance calibrated to true temperature in the laboratory to a precision of ± 0.01 °C using a mercury thermometer. The measurements continue at approximately 30-day intervals at the three crater sites (with exceptions for rainy periods when no traversal of the mud is possible or when flaming outbursts occur when the crater sites are not approachable). Similar temperature measurements, carried out earlier, have shown high temperature gradients in the crater area (Mukhtarov and Adigezalov, 1997).

Results of study. Along the profile Lokbatan – Akhtarma-Puta – Gushkhana, a chart of Bouguer gravity field anomalies is compiled for various values of intermediate stratum density (1.8; 2.0; 2.3 g/cm3). The results obtained show that in zones of mud volcano development (Lokbatan, Akhtarma-Puta, Gushkhana) there are local negative anomalies of -5, -3 and -2 mGal, respectively.

For gravity modeling, the observed gravity values and the geological/geophysical structure section along the NE-SW profile make up the initial reference information. The initial structure model along the profile was obtained using seismic data, well information, geological information, and the density-depth distribution of major rock units of the study area. The initial geologic-geophysical cross-section of the sedimentary cover along the profile is provided by seven contact boundaries: 1) boundary along the lower Akchagil (N_2^2); 2) apparent seismic horizon in the Productive Series (N_2^1); 3) boundary along the upper Kirmaki sandy suite (N_2^1); 4) boundary along the lower part of the Kirmaki suite (N_2^1); 5) boundary separating the upper-middle Miocene and lower Miocene-Oligocene series ($P_3 - N_1^1$); 6) boundary separating Oligocene- and Eocene-Paleocene series ($P_1 + P_2$); 7) boundary of the Mesozoic surface (Mz). The differential density contrasts across the seven contact boundaries (from shallow to deep) are 0.01; 0.04; 0.08; -0.2; 0.25; 0.15; and 0.3 g/cm^3, respectively. The gravity field calculated on the basis of the described model shows that there is a difference between observed and calculated fields in zones of mud volcanoes (Figure 1). When computing the gravity model, 10 iterations were first done on the selection of all boundary configurations. Then the selection on density was undertaken. The extra mass in zones of mud volcanoes in the initial model is compensated for by insertion of zones of deconsolidation and additional contact boundaries in these parts of the profile. The deconsolidation stretches to roughly 3 km depth. A contact boundary, representing the volcano neck (with a differential density -0.3 g/cm^3), is raised in these areas to depths of just 5 m below the surface.

The repeated geodetic leveling on the Lokbatan volcano shows that there are currently active geodynamic processes occurring there. During the period of 10.2001 through 10.2002, on the NE part of volcano (of length about 2 km), the contact boundary was as shallow as 60 cm (Figure 2).

Thermal information prior to the explosion of 25 October 2001 comes from production wells on the flanks of the Lokbatan mud volcano, indicating a strong focusing of heat flux centered on the Lokbatan volcano (Figure. 3) over a regional scale of kilometers (Sukharev et. al., 1969).

Three measurement locations within the crater and on the crater floor were marked with iron spikes for ease of relocation. At each location, the thermal resistance probe provides three equivalent temperature measurements at 1.5 m, 1.0 m, 0.5 m into the partially dried mud sediments. A discussion of the thermal information from these two sections has been given elsewhere (Mukhtarov et al., 2002).

The available thermal data are somewhat ambivalent in terms of either interpretation, suggesting that more detailed thermal measurements and other types of measurements are needed to help resolve the uncertainties (Lerche et al., 2002).A mud volcano provides a channel for heat advection from depth. A discussion of advection from such channels has been given elsewhere (Mukhtarov and Adigezalov,1997; Mukhtarov,2002).

Discussion. Paleogene - Miocene deposits spread throughout the subsidence zones of the SCB serve as an example of the interstitial plastic series. The viscosity (η) of such layers varies from 106 Pa s to 1015 Pa s; viscosity of the overlying and underlying formations is 5-6 orders of magnitude smaller. The density (ρ) of clays varies from 2.3 g/cm3 to 2.6 g/cm3. In the zones of regional deconsolidation the clayey series is least dense, up to 0.2 g/cm^3 less differentially. The less viscous Paleogene-Miocene series of the sedimentary complex has the following parameters: thermal expansion coefficient $\alpha = 10^{-5}$ K^{-1}; coefficient of thermal diffusivity $\chi = 5 \cdot 10^{-7}$ m^2/s; coefficient of thermal conductivity **k** =2W/(m. K). The thermal conductivity coefficients of sandstones and limestones are 5W/(m. K), respectively. For this reason, the Paleogene-Miocene deposits are heat insulators and, no doubt, they play an important role in the formation of the thermal field in the overlying layers.

According to the linear theory of stability, if the Rayleigh number is higher than a critical value $\mathbf{R_c}$, convection movement arises. The critical Rayleigh number for a horizontal layer with no-slip boundaries is $\mathbf{R_c}$=1300. But the actual Rayleigh number for the Paleocene-Miocene layer with thickness **d** = 5 km is

$$\mathbf{R} = \alpha\rho\mathbf{gqd}^4/(\chi\eta\mathbf{k}) = 3 \times 10^{-2} 10 \times 60 \times (5 \times 10^3)^4 \times 2.3 \times 10^3/(5 \times 10^{-2} \times 2 \times 10^{12}) \approx 10^4,$$

which is almost an order of magnitude higher than the critical value for the Paleogene-Miocene layer. For the viscous interstitial layer, the convection time is much less than the age of the Paleogene-Miocene complex. Hence, convection in this layer is stationary. After the establishment of convection, the temperature of the Paleogene-Miocene layer becomes stable as well. If the stresses created by the flow exceed the strength limit of the overlying rocks, then uplift occurs above the ascending flows (Trubitsyn et al., 1998). This Rayleigh-Bernard gravitational instability reflects one of the possible models of hydrocarbon migration in the Paleogene-Miocene series in the SCB (Kadirov and Kadyrov, 1990; Guliev and Kadirov, 2000). Transportation of hydrocarbons upward, together with the enclosing clayey plastic mass of the intermediate layer, under convective processes would appear to be a dominant mechanism of migration and accumulation in the upper parts of the series, with further breakthrough of the overlying permeable series. As the clay is raised, the lithostatic pressure lessens, with the result that hydrocarbon phase transitions will occur and hydrocarbons will be in free phase. It is quite possible that the interstitial layer is the main generator of most of the mud volcanoes in Azerbaijan (Guliev and Kadirov, 2000).

Conclusions. The results show that there are negative local gravity anomalies (-5, -3 and -2 mGal), respectively, in zones of mud volcanoes. The calculated field based on the model described shows that in zones of mud volcanoes there is a difference between observed and calculated fields. The extra mass in mud volcano zones is compensated for by introduction of decompaction zones and additional contact boundaries. From December, 2001 through June, 2002 the following sequence of events took place. The surface rises in and around the Lokbatan volcano. However, the amplitude of rise varies strongly along the structure. To the east, measured from the neck of the volcano, out to a distance of about 1km, the surface rise is 677 mm. A secondary maximum of 218 mm is observed on the western part to a distance of about 1000 m from the neck. The area of the crater also participates in the general rise, but lags appreciably behind the rise of the regional sites. Geodetic observations from December, 2001 through October 2002 show that, in the period June 2002 - October 2002, to the east away from the crater there is a relative lowering of the surface, while to the west and also in the crater structure, the surface shows a relative rise. Clearly, gas must still be upwelling from the Lokbatan volcano to feed the flame (currently around 0.5-1.0m high) over the last 11 months, so that the thermal regime cannot be one of simple cooling after a single flaming explosion. By mid-December (18 Dec 2001) the mud had cooled sufficiently that it was possible to complete the N-S thermal section. The crater measurements show elevated temperatures of 47ºC (0.5m), 53ºC (1m), and 58 ºC (1.5m) with a systematic cooling within about 100 m of the crater, indicating either thermal cooling of the ejected mud or rain enhanced cooling by infiltration. The background temperature of 35.3ºC had then been reached.

Acknowledgements. The authors gratefully thank the US CRDF for financial support under grant NG2-2285 that enabled this work to come to fruition.

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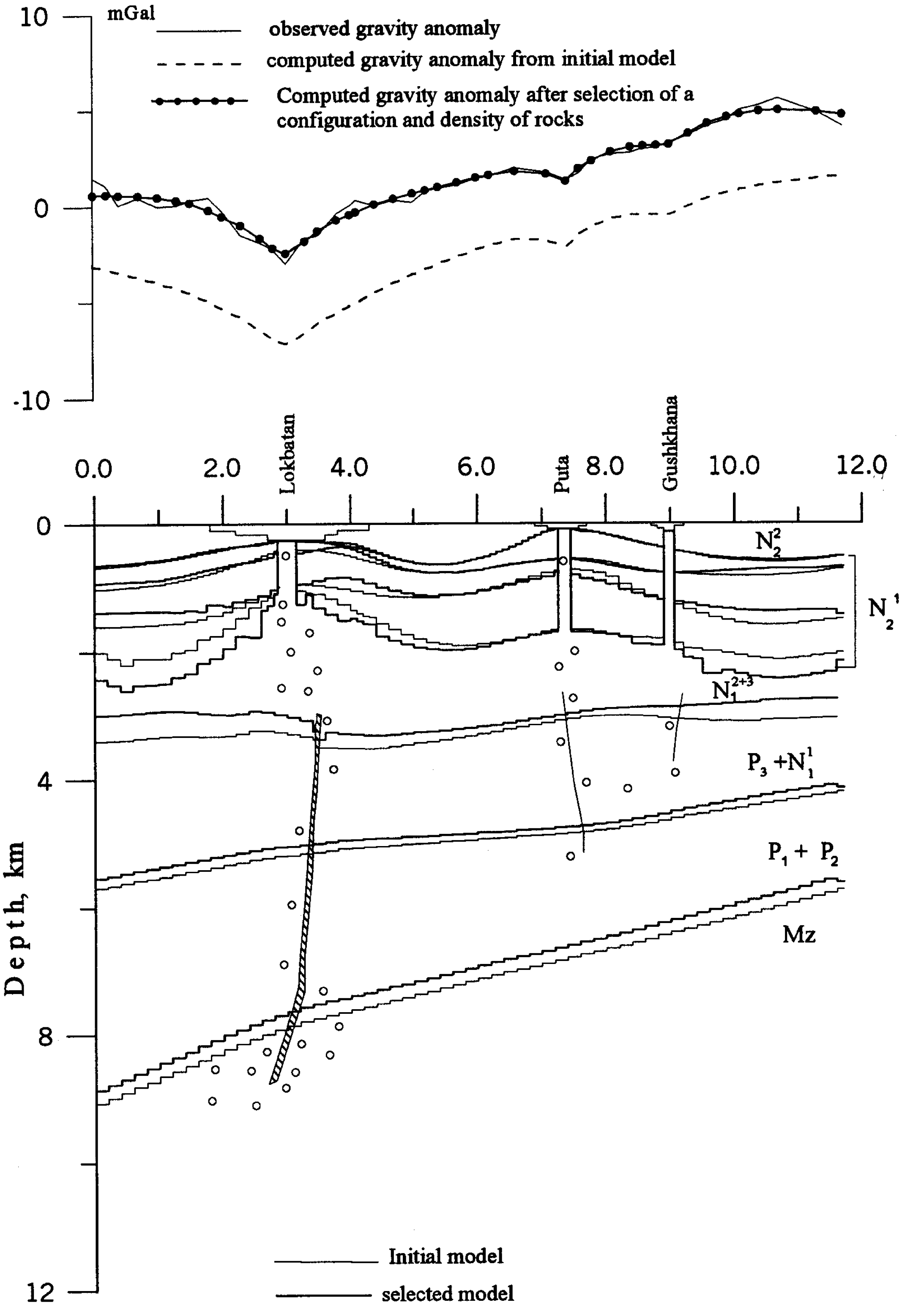

Figure 1. Gravity model of the Lokbatan - Puta-Akhtarma - Gushkhana profile.

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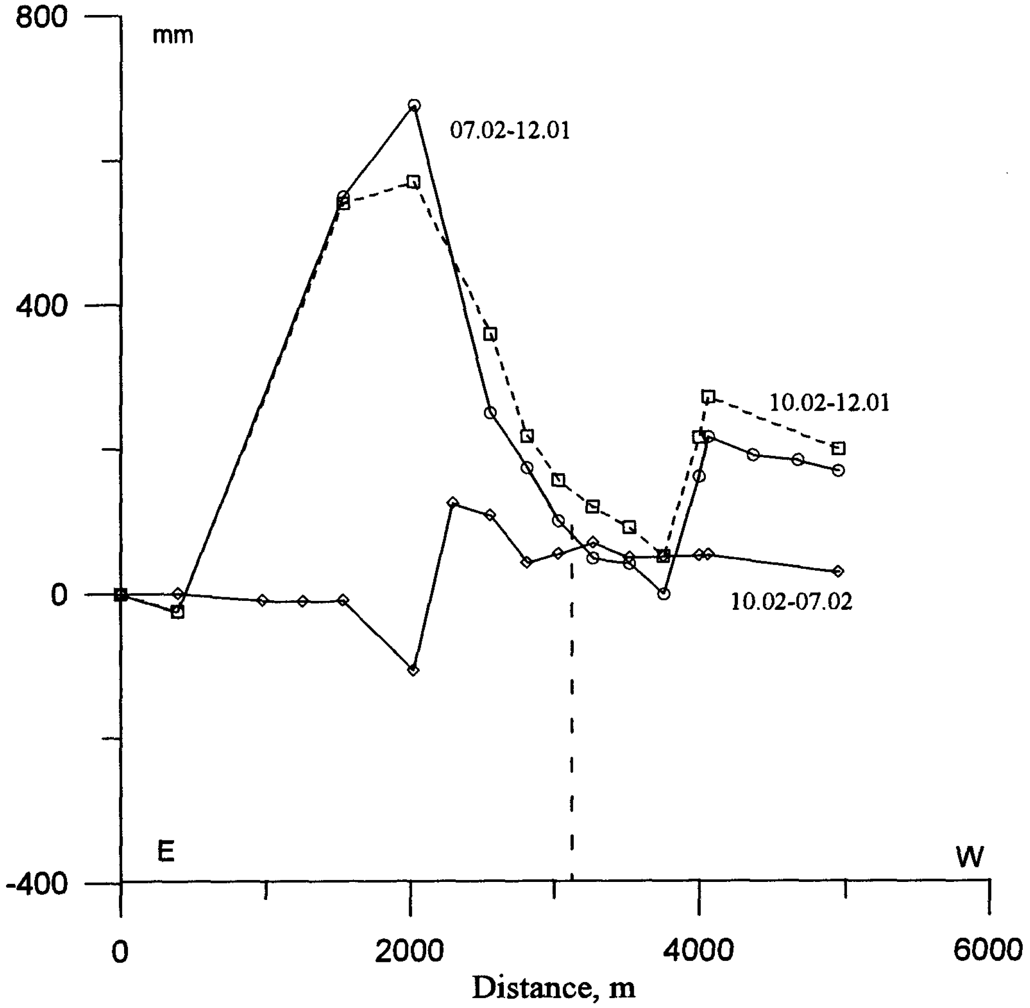

Figure 2. Vertical movement along profile crossing Lokbatan mud volcano.

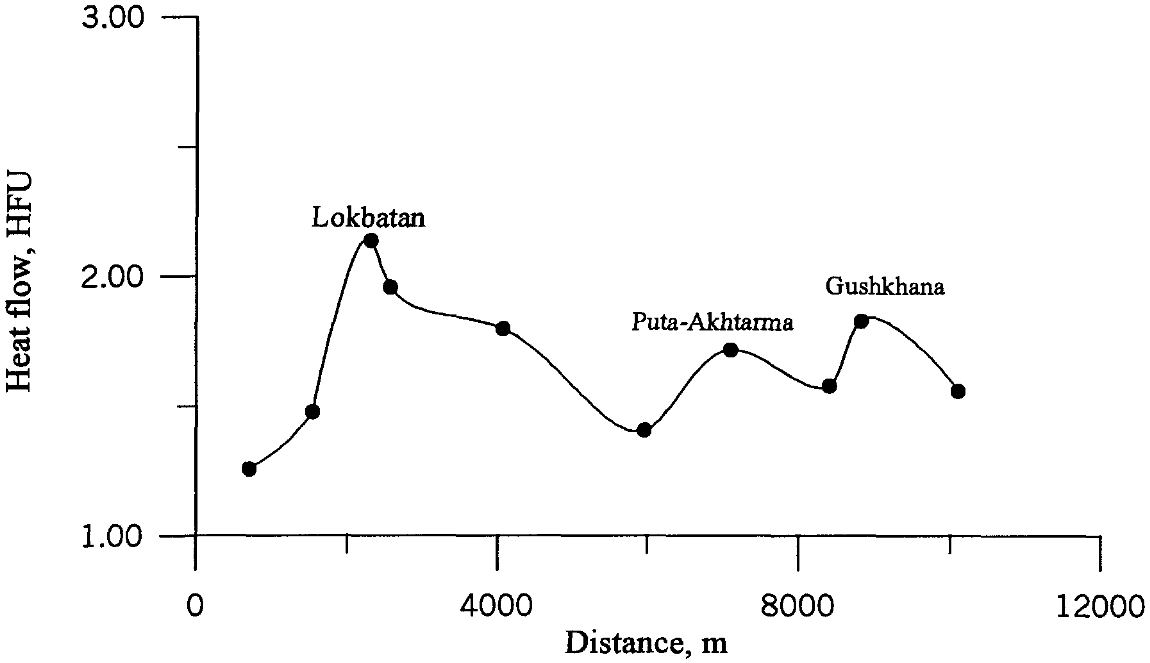

Figure 3. Heat flow distribution along Lokbatan - Puta-Akhtarma - Gushkhana profile.