Sea-Floor Properties from the Inversion of 3D Multichannel Seismic Data: A Submarine Mud-Volcanic Flow in the Absheron Block, Offshore Azerbaijan

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***Abstract*-We have developed a 3-term liquid/solid, strong-contrast reflection equation and have used it, with an empirical V_P:reflectivity relation, to invert the sea-floor seismic reflection to determine V_P, V_S, and density. Applying this technique to pre-stack data from a Caspian-Sea 3D multichannel survey, we find that a submarine flow from the Absheron mud volcano, offshore Azerbaijan, has much higher seismic velocity and density than surrounding sea floor. We propose that this flow is enriched in high-density clasts of country rock – xenoliths – raised from depths of as much as ~9 km by the mud volcano. In contrast, onshore subaerial flows are predominantly low-density frothy gray clay. The 3D seismic data and gravity data further suggest that high-density, high-velocity regions near the mud volcano and buried up to 1000 m below the sea floor are stacked Pleistocene sea-floor mud-volcanic flows. These bodies appear to buttress slumping fault blocks.**

I. INTRODUCTION

The Absheron structure is a Plio-Pleistocene fold of Neogene clastic sediments in the southern Caspian Sea, 100 km southeast of Baku, Azerbaijan. Water depths over the structure (Fig. 1) range from 200-700 meters. To evaluate the

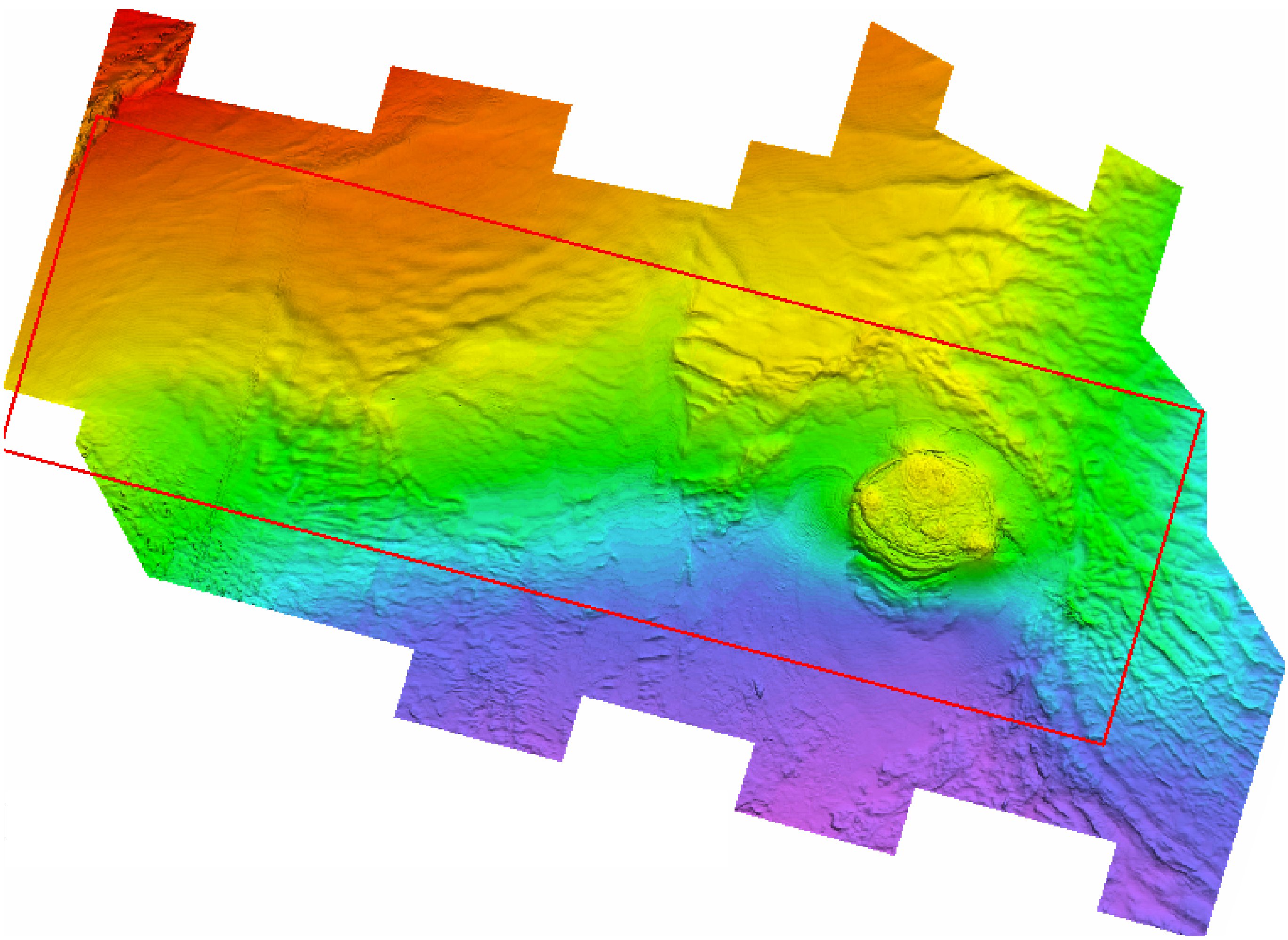

Fig. 1. Bathymetry of the Absheron block, with red (in the north) indicating 200 m below Caspian Sea level, purple (in the south) indicating 700 m, and artificial illumination from the north. The mud volcano in the east-central portion of the block is below about 440-460 m of water. The red box is approximately 10 x 40 km.

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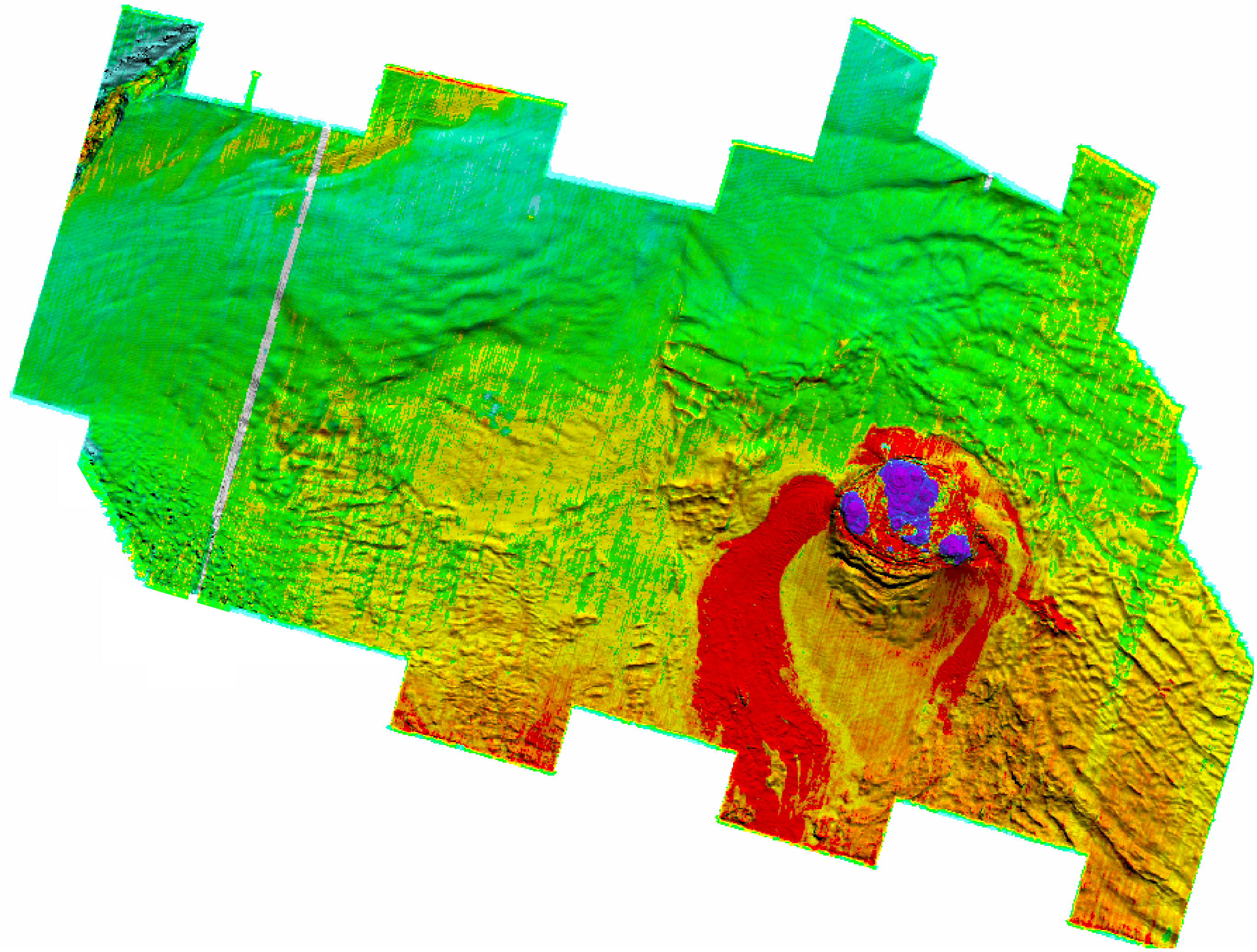

Fig. 2. Seismic amplitude of the sea-floor reflection. Red indicates high positive amplitude, green indicates low positive amplitude, and blue and purple indicate moderate and highly negative seismic amplitude.

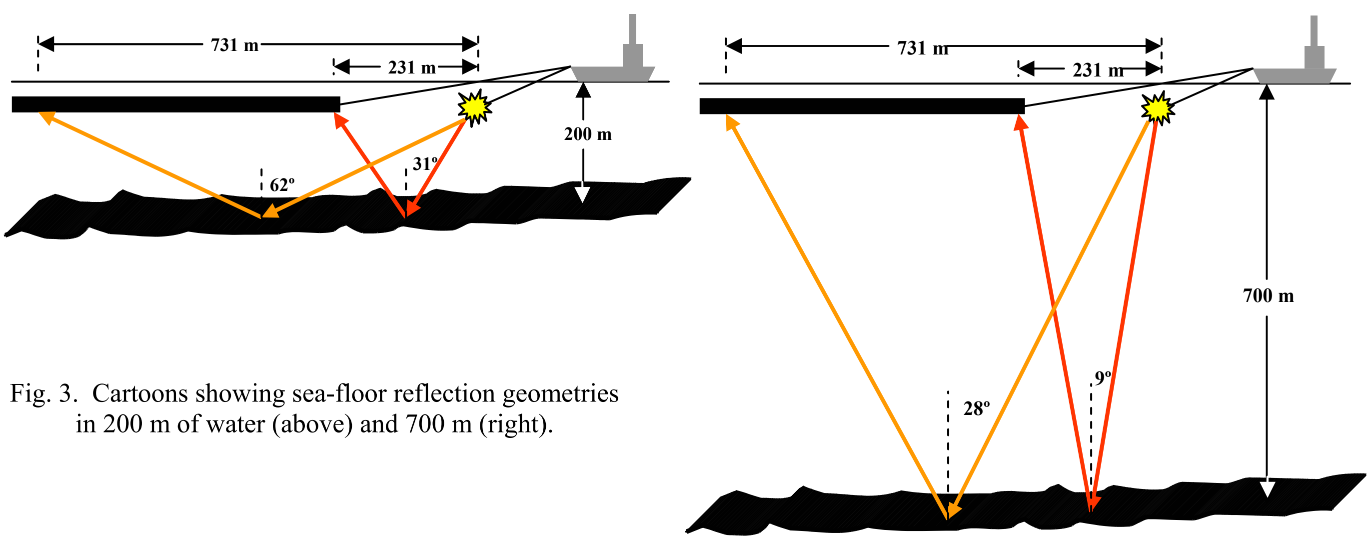

Fig. 3. Cartoons showing sea-floor reflection geometries in 200 m of water (above) and 700 m (right).

Absheron exploration area, Chevron and partners SOCAR and TotalFinaElf collected and processed a 3D multichannel seismic survey over a 650-km^2 area. While these data were gathered primarily to determine an optimum location to drill for hydrocarbons in deeply buried strata, they also were used in an initial evaluation of potential drilling hazards near the sea floor. One of these potential hazards is a large mud volcano. Paleontologic evaluations [1] of surface samples from this 4x5-km feature suggest that mud is erupting from at least 9 km below the sea floor. The 3D seismic data show that the mud volcano has been erupting since the early Pleistocene.

II. SEISMIC DATA PROCESSING AND INTERPRETATION

The 3D seismic data were collected by Caspian Geophysical during May and June 1998. In processing these data for the current study, we took care to preserve amplitudes of the sea-floor reflection, so common steps such as trace equalization and automatic gain control (AGC) were omitted from the processing flow. The sea floor was stacked 10-fold, with shot-receiver offsets ranging from 231-731 meters. Following a source-signature deconvolution, the data were phase-rotated so that the sea floor in deep water (roughly 500-700 m) was a zero-phased peak (shown in black). The data were placed into 12.5 x 37.5-m bins, interpolated to give final bins of 12.5 x 18.75 m, and 3D migrated. These data were loaded onto a Landmark workstation, taking care to not clip the sea-floor reflection.

The sea-floor reflection was interpreted using automatic-picking routines to pick the seismic peak over the majority of

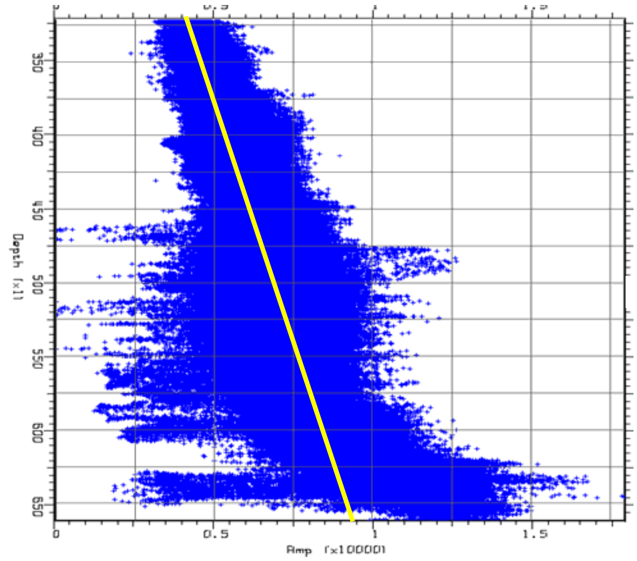

Fig. 4. Sea-floor amplitudes from the western half of the survey, plotted against depth. The least-squares line fit to these data was used to remove the north/south gradient from Fig. 2 to create Fig. 5.

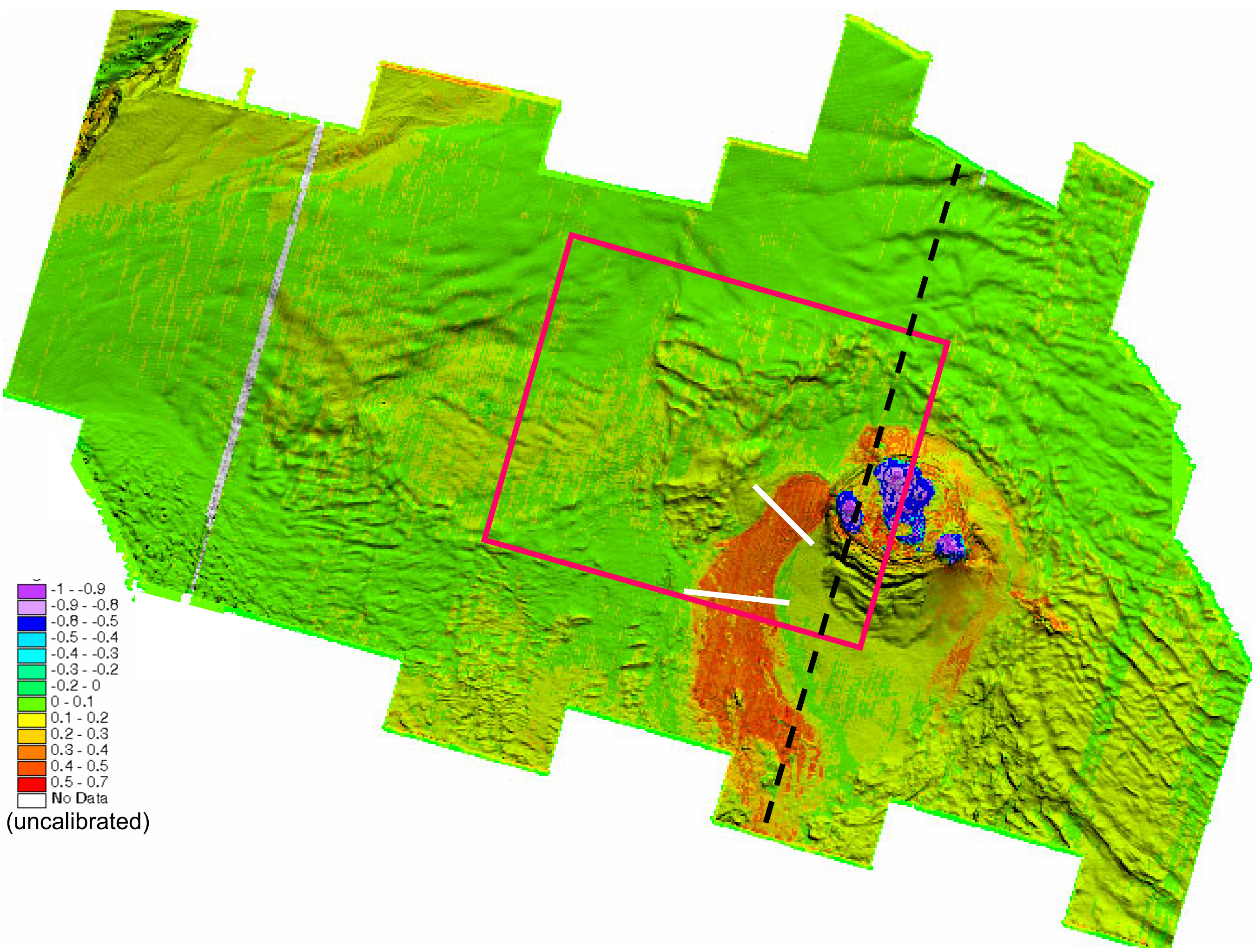

Fig. 5. The reflection coefficient (uncalibrated) of the sea floor over the Absheron prospect, calculated by removing a linear gradient (Fig. 4) from the amplitude of the sea-floor reflection (Fig. 2).

the survey. Over the mud volcano, however, the auto-picking was steered to pick the seismic trough where this appeared to be the first significant reflection. We interpret the areas with strong seismic troughs, which coincide with local topographic highs, to be highly gas-charged active eruptive centers.

The seismic amplitude of the sea-floor reflection is shown in Fig. 2. Note that, away from the mud volcano, there is a gradient across the area, with low amplitude (green) in the north (shallow water) and higher amplitude (red) in the south (deep water). This gradient appears to be an artifact of acquisition geometry, as shown in Fig. 3. In the northern part of the survey, the recorded rays reflect from the 200-m-deep sea floor at angles of 31° to 62°, and the beam-forming (downward focused) source and receiver arrays attenuate the signal before it is digitized. In contrast, the southern part of the survey, where the water is 700 m deep, the reflection angles are 9° to 28°, much nearer to vertical. The seismic amplitudes from the western half of the survey are plotted against depth in Fig. 4, as is a least-squares line fitting the data. This linear trend was removed from Fig. 2 to create Fig. 5, which approximates the uncalibrated reflection coefficient of the sea floor.

A major sea-floor feature in both Fig. 2 and Fig. 5 is a high-amplitude reflection (red) from a recent mud-volcanic flow. The uncalibrated reflection coefficient from this flow is about 0.5, compared to about 0.1 from adjacent sea floor. Seismic lines across this feature (Fig. 6) show that the flow eroded a channel up to 40 m deep, and that the top of the flow is currently about 2 m below the surrounding sea floor. The base of this channel is expected to be a seismic trough (red) if the contents of the channel are of higher acoustic impedance than the surrounding sediments.

In Fig. 7, we show the gradient of amplitude-*versus*-offset (AVO) for the sea-floor reflection in a 10x13-km subset of the 3D survey. Due to the high signal-to-noise ratio of the sea-floor reflection, the AVO gradient is much more coherent than is commonly seen in AVO gradients from within the sedimentary section. Note that the AVO gradient of the sea-floor reflection within the recent mud-volcanic flow is approximately –0.15, compared to approximately 0.00 in nearby areas and grading to –0.10 to the northwest.

At the sea floor, the Zoeppritz equation can be simplified because the upper medium (water) does not support shear waves. Following a change of variables and ignoring higher-

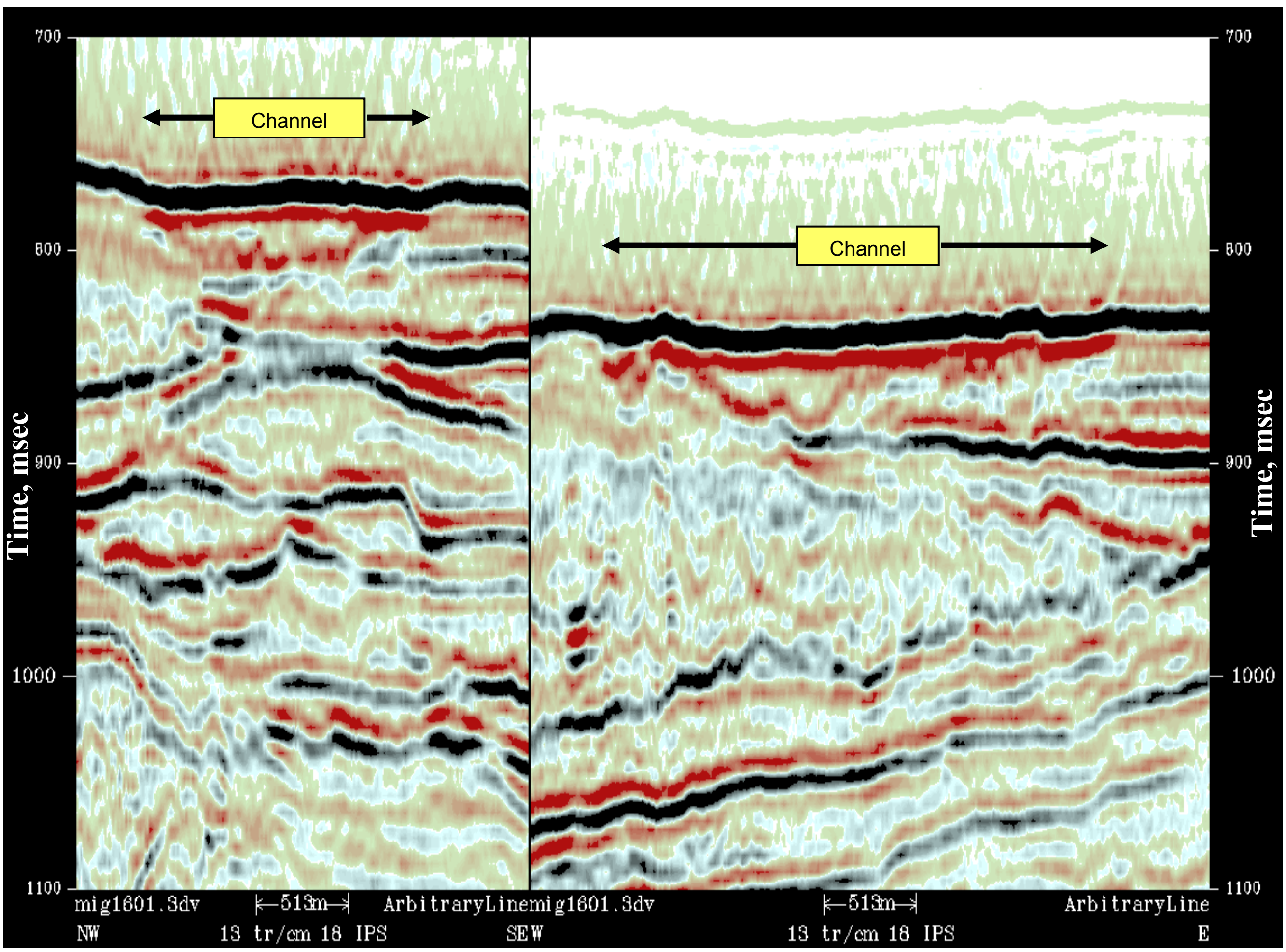

Fig. 6. Two seismic profiles across the high-amplitude mud-volcanic flow seen in Fig. 2 and Fig. 5. Line locations are shown as white lines in Fig. 5. Note the channel that has been cut approximately 40 m into surficial sediments; the base of the channel is a red reflection. Reflection amplitudes (Fig. 2) are measured from the black reflection at the sea floor.

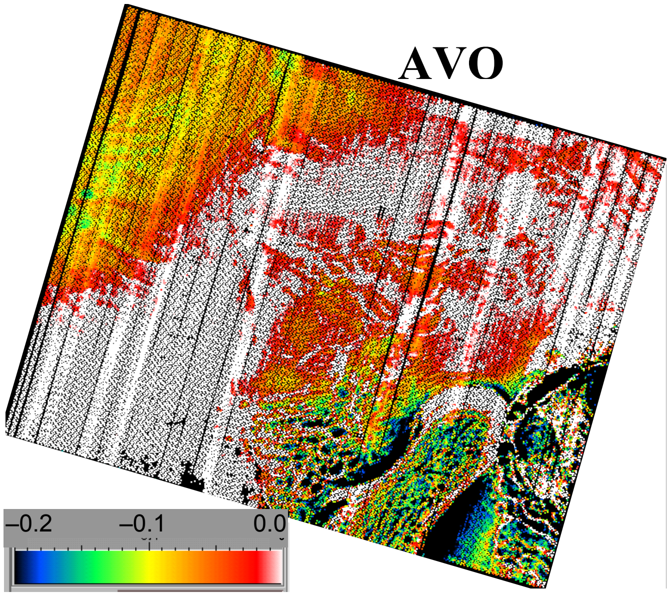

Fig. 7. AVO gradient in a 10x13-km portion of the 3D survey. Note the high negative gradient (green/blue/black) in the recent mud-volcano flow. The location of this map is shown on Fig. 5.

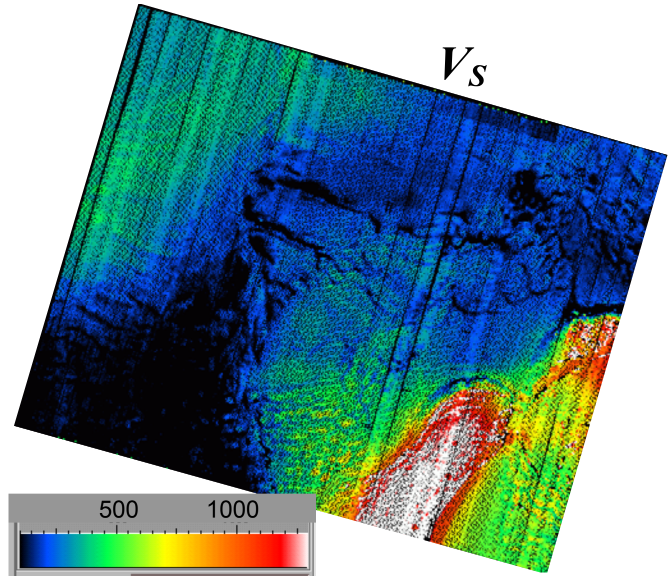

Fig. 9. Shear velocity (V_S) over the area shown in Fig. 7. Note the high velocity (1200-1300 m/s) in the mud-volcano flow, compared to 200-400 m/s over much of the area.

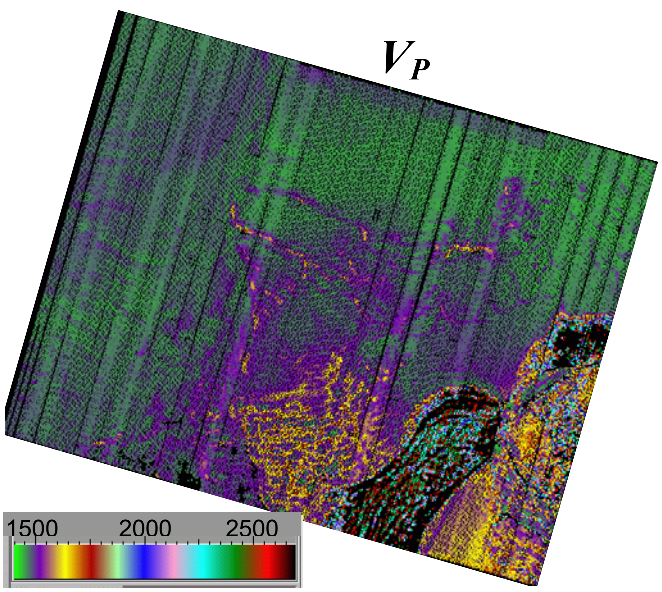

Fig. 8. Compressional velocity (V_P) over the area shown in Fig. 7. Note the high velocity (2300-2600 m/s) in the mud-volcano flow, compared to 1450-1600 m/s over much of the area.

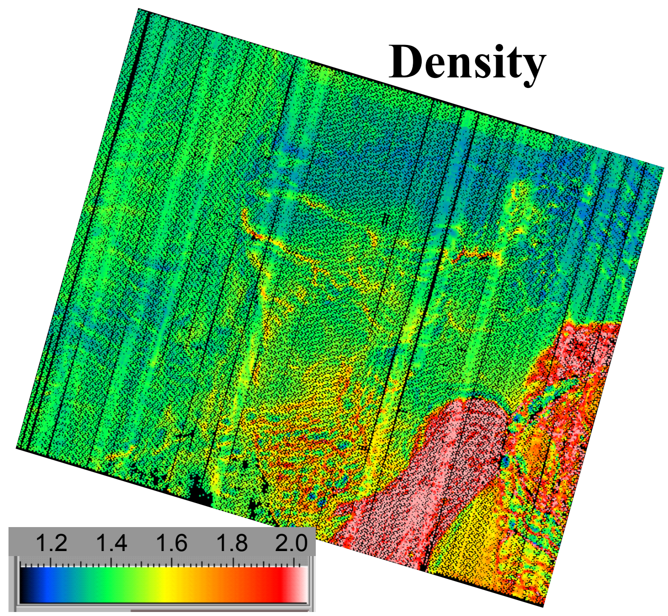

Fig. 10. Density (ρ) over the area shown in Fig. 7. Note the high density (1.9-2.0 g/cm^3) in the mud-volcano flow, compared to 1.3-1.5 g/cm^3 over much of the area.

order terms, in a derivation similar to that in [2], the equation reduces to the following:

$$A = R_0 - 2(V_{S2}/V_P)^2\sin^2\theta[1-(V_{S2}/V_P)\cos\theta] + {}^1/_2(\Delta V_P/V_P)\tan^2\theta, \qquad (1.1)$$

where

R_0 = vertical-incidence reflection coefficient

$$= {}^1/_2(\Delta V_P/V_P + \Delta\rho/\rho), \qquad (1.2)$$

$$V_P = {}^1/_2(V_{P1} + V_{P2}), \qquad (1.3)$$

$$\Delta V_P = V_{P2} - V_{P1}, \qquad (1.4)$$

$$\theta = {}^1/_2(\theta_1 + \theta_2), \qquad (1.5)$$

$$\rho = {}^1/_2(\rho_1 + \rho_2), \text{ and} \qquad (1.6)$$

$$\Delta\rho = \rho_2 - \rho_1. \qquad (1.7)$$

For the sea-floor reflection, V_{P1} is the velocity of Caspian Sea brackish water at the sea floor, estimated from STD measurements to be 1455 m/s, V_{S1} = 0, and ρ_1 = 1.01 g/cm^3. This leaves V_{P2}, V_{S2}, and ρ_2 as unknowns. As we lack sufficient data to solve for 3 unknowns, we have assumed that V_{P2} is related to the vertical-incidence reflection coefficient R_0 by the following empirical relation based on data in [3]:

$$^1/_2(\Delta V_P/V_P) = (0.87R_0 - 0.07)R_0\,, \tag{1.8}$$

for ΔV_P and V_P in m/s. Substituting (1.8) into (1.1), we can determine (V_{S2}/V_P) and R_0 from (1.1) using our pre-stack measurements of A as a function of θ. Substituting (1.8) into (1.2), we can determine ρ_2 from R_0. We can determine V_{P2} from (1.8) and V_{S2} from (V_{S2}/V_P). These quantities are estimated in the uppermost sediment, with a thickness of roughly one-quarter wavelength of the dominant seismic frequency, or about 7 meters for 50-Hz energy.

The mud-volcanic flow has considerably higher seismic velocity and density than the surrounding sea floor. Fig. 8 shows that V_P is about 2300-2600 m/s in the flow, compared with 1450-1600 m/s in nearby areas away from the mud volcano. V_S (Fig. 9) is about 1200-1300 m/s in the flow, compared with 200-400 m/s nearby. Density (Fig. 10) is about 1.9-2.0 g/cm^3 in the flow, compared with 1.3-1.5 g/cm^3 nearby.

III. COMPARISON WITH SUBAERIAL MUD-VOLCANIC FLOWS

The high density and velocity of the Absheron submarine mud-volcanic flow are in marked contrast to mud-volcanic flows seen onshore in Azerbaijan. These terrestrial flows are usually composed primarily of frothy gray clay, with the occasional (perhaps 1% by volume) clasts of denser rock brought up by the flow. The low density of the flows suggests that the mud volcanoes are driven by density contrast. Reference [4] and many other authors have proposed that overpressured shale, at depths of several km, is less dense than surrounding sands and silts, and is therefore gravitationally unstable. In this model, some perturbation, such as the thrust fault observed in the Absheron 3D seismic data at a depth of roughly 8-10 km, becomes a nucleation site for the less-dense shale to begin rising diapirically. By this model, the density difference drives the mud upward to within 1-2 km of the surface, and above this point, gas in the rising shale begins to come out of solution and expand, driving the mud to the surface. Many eruptions of Azeri mud volcanoes (for example, [5]) are accompanied by towers of flame as this natural gas burns.

While the model in [4] also should apply to submarine mud volcanoes, an important difference occurs at eruption sites on the sea floor. We propose that during submarine eruptions, the majority of the gray clay is carried by expanding gas into the water column and disperses over a wide area, so that the mud-volcanic flow is highly enriched in breccia clasts of country rock that have been carried up by the diapiric mud. To test this idea qualitatively, we sampled some breccia clasts from the Bozdag Kobu mud volcano,

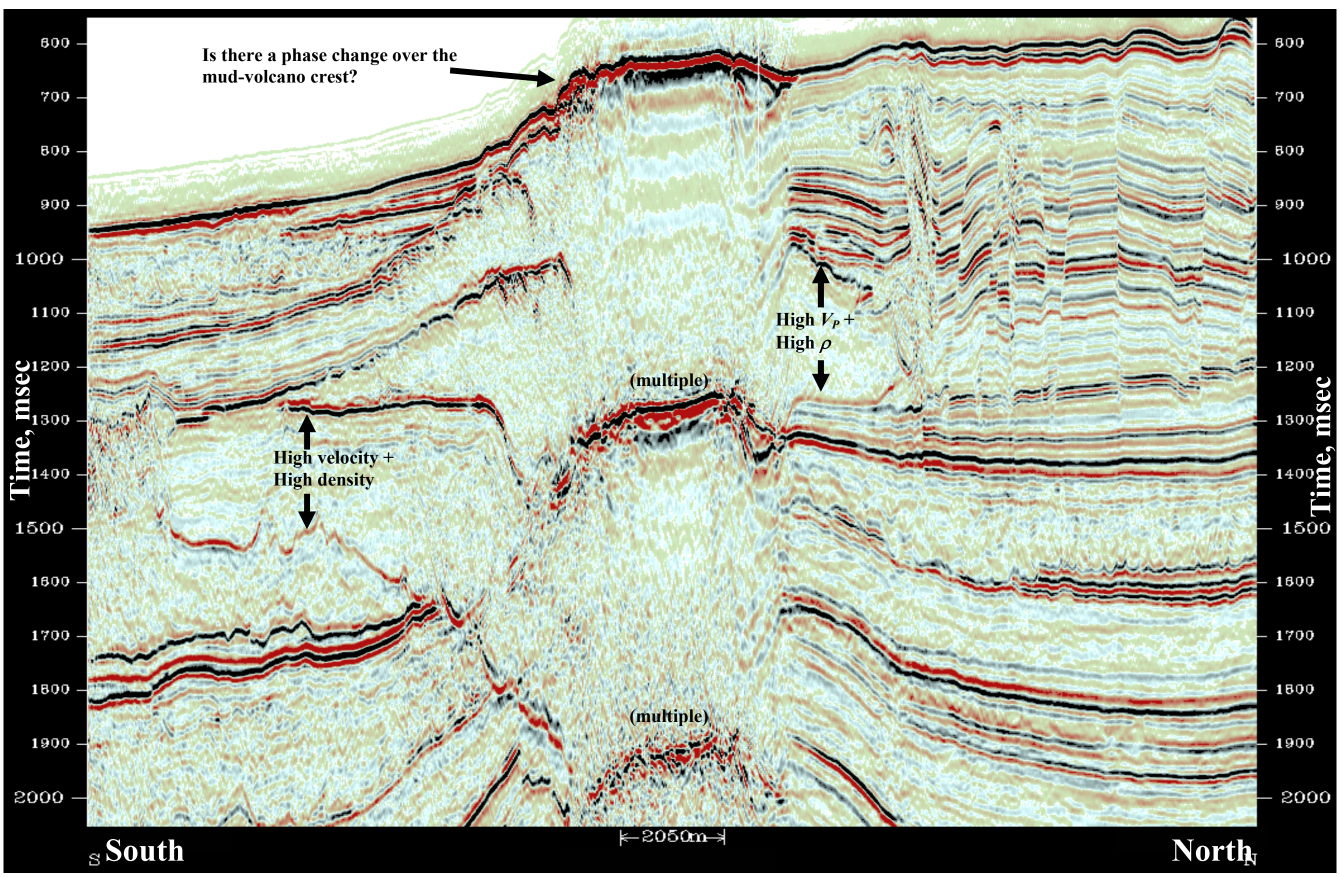

Fig. 11. Seismic profile (located at dashed black line in Fig. 5) from the Absheron 3D survey, showing chaotic regions with high V_P and high ρ. These regions are probably stacked Pleistocene sea-floor mud-volcanic flows that have later been buried. The right-hand region appears to buttress slump blocks in the upper right (north) quarter of the image.

about 10 km northwest of Baku, Azerbaijan [6]. Two of these clasts had bulk densities of 2.4 and 2.6 g/cm^3, so a mixture of similar clasts and mud could create a flow with an average density of 1.9-2.0 g/cm^3. Paleontologic dating of breccia from gravity cores atop the Absheron mud volcano [1] suggests that at least some of the breccia originated from Paleogene sediments, which in the Absheron area are buried to depths of approximately 9 km. This depth is an estimate for the source of over-pressured shale that drives the mud volcano.

IV. PLEISTOCENE MUD-VOLCANIC FLOWS

While processing and interpreting the Absheron 3D seismic data, we have observed regions up to 1000 m below the sea floor and near the mud volcano (Fig. 11) that have high seismic velocity (V_P) and tend to have chaotic or transparent seismic character. One initial model ([7]) proposed that high concentrations of gas hydrates, which are modeled to be stable in the area, were present in these areas and that their formation increased V_P. More recently, however, gravity data (Fig. 12 and Fig. 13) have shown that these high-V_P regions are also high-density regions, so that we now favor an alternate hypothesis that these are regions of stacked Pleistocene sea-floor mud-volcanic flows that have subsequently been buried. These dense regions appear to buttress down-slope movement of slump blocks riding on a sub-horizontal detachment seen about 1.3 seconds 2-way time in the right (north) half of Fig. 11. Also note in this figure that the right-most shallow fault has normal throw, as do several other faults (not shown) to the north of this. Closer to the mud volcano and the high-density body, in contrast, the throw on these faults is reverse, and beds appear to be thrust over the high-density body.

V. CONCLUSIONS

A 3-term liquid/solid, strong-contrast simplification of the Zoeppritz equation can be used to invert the sea-floor

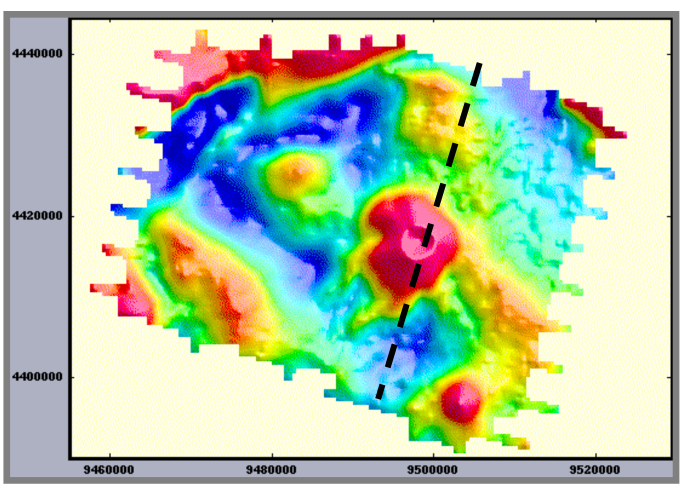

Fig. 12. Free-air residual gravity map of the Absheron structure. The mud volcano shows very high residual gravity (red), though the mud-volcano crest is a relative low. The dashed line is the location of Fig. 13.

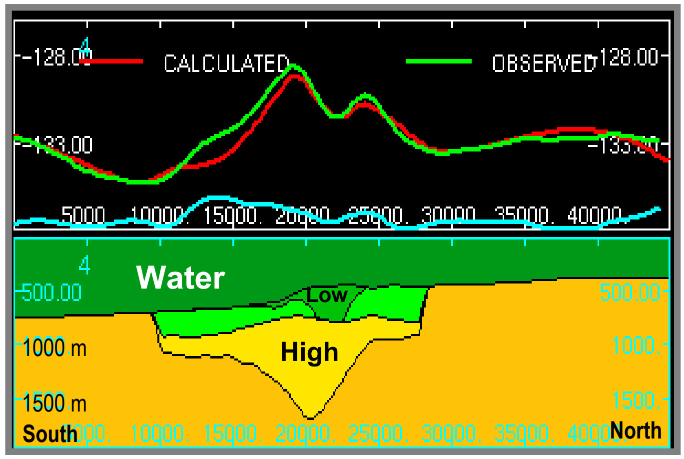

Fig. 13. South/north section through the Absheron mud volcano. The top portion shows the observed free-air residual gravity (green), modeled gravity (red), and difference (blue). The bottom portion shows the model, including water (dark green), low density (medium green), normal density (light green and orange), and high density (yellow). The high-density body correlates to the high-velocity, seismically-transparent zones in Fig. 11.

reflection to derive reasonable values for V_P, V_S, and density when used with an empirical V_P:reflectivity relation. From these values, we conclude that submarine mud-volcano flows, like those above the Absheron structure, offshore Azerbaijan, are enriched in high-density breccia clasts of country rock brought up from depths of as much as ~9 km by the mud volcano, and that the majority of low-density mud rises with accompanying gas into the water column and is dispersed over a wide area. We further conclude that high-density, high-velocity bodies buried up to several hundred meters beneath the flanks of the mud volcano are stacked Pleistocene sea-floor mud-volcanic flows.

Acknowledgments

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