Mud volcanoes and shear-wave imaging – an example 4C test line in the Caspian Sea

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Summary

The general description of a mud volcano is an injection or eruption of mud fluids from a highly pressurized zone to a shallower, lower-pressure zone or eruption to the surface. These features are often associated with gas and fluidized sediments forming complex structures. They are poorly resolved using conventional P-wave seismic imaging and they present a number of challenges for hydrocarbon exploration and development. The benefits from converted-wave methods include imaging through the gas, improved resolution, pore-pressure prediction, and better imaging of complex structures with wide-azimuth geometry.

Introduction

The mud volcanoes are not thought to be hydrocarbon reservoirs themselves, but they are associated with large structural traps and can cause significant problems for oil exploration in a number of areas around the world. Submarine mud volcanoes have been reported in many regions of the world including the Gulf of Mexico, the Mediterranean Sea, the Black Sea, the Caspian Sea, and around the Pacific Ocean (Milkov, 2000). There are several possible formation mechanisms that are linked to shale diapirism and fault movement, but there are many factors that influence their formation. Mud volcanoes that reach the surface can vary in size and features have been reported from a few meters to several kilometers across.

A short review of some of the suggested formation mechanisms for mud volcanoes will show why these can be complex features and why they are found distributed around the world. These complex structures are usually associated with poor seismic images, and their composition makes them difficult to characterize lithologically. Multicomponent seismic data has been proposed to help improve structural imaging and the characterization of sediments around mud volcanoes. This information will be of great value to guide exploration or production drilling near to these structures. The combination of conventional P-wave and converted-wave information recorded with multicomponent data will help in two different ways. First, the use of long offsets and wide azimuths from seabed systems can improve complex imaging and, second, the shear waves themselves are less sensitive to pore fluids, which means they can be used to improve characterization and imaging under gas zones.

During a conventional OBC seismic survey in the Caspian Sea, a small multicomponent test line was proposed to coincide with conventional data collected over a potential mud volcano feature. The conventional and multicomponent data were acquired at the end of 2000, and the processing is not completed at the time of submission of this abstract. However, the initial multicomponent processing results show that the method does have the potential to improve the imaging and understanding of these complex features.

Mud volcanoes

Mud volcanoes are generally associated with deep sediments that have undergone rapid deposition and subsidence. Milkov discusses the possible formation mechanisms and the relationship between mud volcanoes and shale diapirs (Milkov, 2000). He distinguishes between diapirs that have risen from depth due to density inversions and diapirs that have formed by injection along faults due to overpressure. He states that, as a rule, the former type does not reach the surface and the second type are more likely to erupt at the seabed or surface. Figure 1 shows possible paths for fluidized sediments to migrate to form mud volcanoes. They can be active or dormant, and may possibly have a cycle of repeated activity.

![Figure 1: Sketch showing possible mechanisms for mud volcano formation related to shale diapirs. The arrows indicate possible fluid migration paths. (From Milkov, 2000)](image)
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Milkov also reviewed existing research into the origins of mud volcanoes, and he presented a list of possible influences organised into four groups: geologic, tectonic, geochemical, and hydrogeological. A brief summary of these influences shows why they are complex and varied features.

- **Geologic**: thick sediments, presence of plastic shale layers, rock density inversion, and accumulation of gas in the deep subsurface.
- **Tectonic**: the rapid subsidence of sediments, occurrence of diapiric or anticlinal folds, faults, lateral tectonic compression, earthquakes, isostatic processes.
- **Geochemical**: petroleum generation in deep subsurface, clay dehydration.
- **Hydrogeological**: fluid flow along fractures.

Lebedev (1999) studied the mud volcanoes in the Caspian Sea and concluded that observed thermal anomalies associated with deep faults are the origin of the Caspian mud volcanoes, which are linear in form. The high thermal field causes the shale to become more plastic and the tectonic movement controls the diapirism development. There are a large number of features identified as active or dormant mud volcanoes in the Southern Caspian Sea, as shown in Figure 2.

**Benefits of shear-wave data**

There are many possible benefits from using marine seabed multicomponent data to image mud volcanoes. The seabed system will allow for acquisition with wide azimuth geometry to image complex structures. Also, long offsets and the asymmetry of the P-S paths can undershoot other problems. In comparison to P-waves, shear waves can have better vertical resolution in low-velocity layers due to the shorter wavelength, and they can image through gas zones because pore fluids do not affect them. The direct measurement of the Vp/Vs ratio from PP and PS TWT can be an indication of rock strength, and the different response of Vp and Vs to fluids and pore pressure can be used to discriminate between fluid and lithological effects and help identify over-pressured zones. Elevated pore pressure in some zones may be caused by fluids trapped during rapid burial or by sediments compacted during the burial process later being submitted to increased fluid pressure. These over-pressured zones may cause a number of problems for drilling, and, in the case of shallow, unconsolidated layers (possible shallow water flows or SWF’s), the only drilling option would be to avoid these layers. Using only P-waves, the same change in velocity could be caused by increased pressure or hydrocarbons, as shown in Figure 3. The overpressure can be estimated from the difference between the actual velocities and a background, or expected, velocity gradient.

Figure 2: A map of the southern Caspian Sea showing the size and number of identified mud volcano features (From Lebedev, 1999).

Figure 3: Graph showing modeled P and S velocities vs. depth. An increase in pore pressure cannot be distinguished from hydrocarbons using P velocities alone.
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Caspian 4C Test Line

During a conventional OBC seismic survey in the Caspian Sea, there was an opportunity to acquire a small amount of multicomponent data over a suspected mud volcano feature. There was only a small amount of recording equipment and limited shooting time available, but the test objective was only to show that the shear waves provided enough extra information to warrant a later, full-scale test. There were only 16 sensors recording 4-component data (using a telemetry system) and these were spaced at 300 m intervals along a 4.5 km receiver line. One shot line, 13.5 km long with a 25 m shot interval, was recorded parallel to the receiver line but offset 50 m from the receiver line. Seven orthogonal shot lines, 5 km long and 600 m apart, were also recorded. The water depth varied from 10-25 m. Figure 5 shows the good hydrophone data, but the geophones are noisy.

The initial stack of the P data shown in Figure 4 is overlaid with the stacking velocity function. Because of the low CMP fold in the shallow data, the P-wave stacking velocities are picked, using the structure, on each of the common receiver gathers. This stack is comparable to the initial 3D stack, and the picked velocities (Figure 4) show a very slow trend that corresponds to the expected effect of gas and unconsolidated sediments around the mud volcano. The P-wave refraction static model has also resolved possible shallow dip and depths outside the mud, but still ignores possible velocity inversions due to mud features that are seen at the seabed.

The horizontal components were orientated using direct arrival analysis, but the stacking velocity, binning gamma, and shear static are interrelated, and the low fold and large receiver spacing requires some non-standard solutions. The shear statics are not yet reliable and this work is continuing. Figure 6 shows the comparison of the initial PS and PP stacks with the same two events highlighted; the PS does show some signal where the PP data is weakest. Work is also continuing on shear-wave azimuthal analysis and refining the shear static, velocities, and binning.

Conclusion

Mud volcanoes are found in exploration areas all over the world, and they can be complex structures and difficult to characterize. We have discussed some of the potential problems for conventional seismic surveys and drilling, and shown how converted waves from multicomponent surveys can provide extra information. The initial results from the Caspian test line confirm that the converted waves do have potential to improve seismic images around the mud volcano and further work is expected to lead to some characterization of the lithology and a better understanding of these complex features.

References


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Figure 5: Common receiver gather for one location outside the mud volcano showing good P-component and noisy geophone data.

Figure 6: Initial comparison of PP and PS stacks (the PS time scale is compressed 2:1). Interpreted events have max fold 5 on PP and 3 on PS.