Near-Surface Characterization for Seismic Exploration Based on Gravity and Resistivity Data*

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Abstract

No doubt there is continuous progress in the methodology of exploration seismic surveys. However, especially on land, seismic data processing is still facing difficulties in near surface detailed characterization that is affecting the seismic resolution on the whole. If the static corrections and subsurface velocity model are not accurate, not only fine deep details, but the complete section quality is deteriorated by a certain level. It is evident that application of supporting geophysical techniques may be crucial in certain geological environments.

Detailed and micro-gravity, as well as resistivity (multi-electrode tomography, vertical electrical sounding or electromagnetic methods) can assist in improving the near-surface characterization. Numerous structural or petrophysical features can be distinguished by these techniques. Gravity may indicate e.g. karst, voids, faults, reefs, and buried channels, provided sufficient density contrast.

Resistivity is strong in horizontal layers, like weathered layers, or water-saturated levels, as well as vertical boundaries definition, provided resistivity contrast. Even if the interpretation is not perfect due to ambiguity, these features, or at least respective anomalies of density or resistivity enable adjusting of the seismic velocity model and improving statics.

The examples from real surveys in big fields in the Middle East demonstrate the integration of gravity and resistivity data with seismic processing. Substantial improvement of static corrections and consequently the clear shape of horizons in seismic sections are shown in Figure 4. As well, lateral changes in a gravity map served as a basis for adjusting 3D velocity model for detailed seismic exploration in an already developed field Figure 5. A major fault was sharply defined by both gravity and resistivity where no such clear picture was provided by seismic alone. These examples justify application of detailed gravity and resistivity surveying alongside with high resolution 2D-3D seismic.

Introduction

It is evident from many seismic surveys that good knowledge of the near-subsurface layer geometry and physical properties is crucial for achieving amplitudes stability and correct event locations. There are numerous sources of heterogeneity in the near subsurface. Among them, the most important are variable thickness and properties of the weathered zone, complex topography, karst, collapses, small structures and faults, lateral changes of physical properties, reefs, volcanics, buried channels, etc. They all can cause erroneous calculation of static corrections and deteriorate the quality of a seismic section.

Among the non-seismic geophysical techniques, gravity and geoelectrics are the most suitable for near-surface characterization. As well, under suitable geological conditions, GPR (ground penetrating radar) may also help with very shallow sections of the first tens of metres. Any detected heterogeneity could be used for adjusting the near-surface velocity model and improving the static corrections.

Recently, detailed gravity and resistivity surveys have been increasingly used as supporting techniques for high resolution seismic exploration. We may refer, for example, to Colombo et al. (2008, 2010), who presented on various examples the improvement of seismic sections after adjusting the velocity model according to gravity data, improving the near-surface resolution after TDEM (time-domain electromagnetic) was used to define dunes bottom surface in the Rub Al-Khali desert (Figure 3), or using gravity modeling for joint inversion of seismic data. Similarly, Seeni et al. (2014) and Setiyono et al. (2014) showed such improvement in of 3D seismic data in the Dukhan Field in Qatar (Figure 5).

Data Acquisition and Processing Quality

I had a chance to join some projects where detailed gravity data were acquired, as an “academic eye”. It was clear that quality control (QC) was needed right from the beginning, as contractors sometimes use new operators of geophysical instruments selected from local or other labour forces. Therefore, the intensive training is a must to ensure the proper procedures would be followed. Besides careful reading of the gravimeter, there are a number of tricks to teach and assure, like good correspondence of exact position of gravity readings at each station with GNSS (Global Navigation Satellite System) observation of co-ordinates. However, usually the critical issue is the local terrain corrections estimates, which is quite a big pain of most gravity surveys, as a detailed DEM (Digital Elevation Model) is usually not available. All this may not matter that much in semi-regional (scouting) surveys with station separation of 500-2000 m, but it is substantial in detailed or micro-gravity projects with stations spacing equal or less than 250 m.

To some extent, this is also valid for resistivity surveying where the lines have to be planned according to local artificial networks, like electricity, pipelines, etc. As well, good coupling of electrodes is crucial for a successful survey, especially in desert conditions like in the Middle East. In some cases the time-domain electromagnetics together with detailed gravity can be successfully applied, e.g. for the determination of the surface relief under continuous dune cover in the deserts like the Rub Al-Khali Desert in Saudi Arabia, Oman, Yemen and UAE.

Gravimetric Characterization of Subsurface

Micro-gravity can detect most of the above mentioned geological anomalous phenomena, provided there is sufficient density contrast, which is similar to its application in geoengineering (Mrlina, 2002, 2011; Issawy et al., 2010). Even quite thick (up to 100 m) layers of subsurface clay overlying hard bedrock (limestone) can be modeled to obtain the relief of the contact, as demonstrated by Lamontagne et al. (2011).

It is well known that gravity data cannot provide unique solutions, however geometry of the source can be well estimated from the wavelength and edge gradients of a gravity anomaly. Even if the gravity data only indicates sections of density deficit (or surplus) without any exact interpretation, it is profitable to consider it in the building of near subsurface velocity models. Similarly, Seeni et al. (2014) and Setiyono et al. (2014) showed such improvement in 3D seismic data in the Dukhan Field in Qatar.

Karst represents very disturbing and actually hazardous geological conditions not only for seismic surveys, but also for drilling. From the beginning of the karst process, aggressive waters disintegrate the rock massif in tiny fractures and gives origin to density decreases. The process can consequently develop a small void to a large underground dome system (cave). A micro-gravity survey can locate such zones and give an idea on mass (block density) deficit which consequently develops the decrease of seismic velocity. In Figure 1 I present a simple example of the gravity effect of a huge cave in Qatar. Such caves are common in Saudi Arabia and Oman as well.

Part of the range of subsurface features detectable by detailed gravity or micro-gravity surveying is presented in Figure 2. Two wellbores, UH1 and UH2, are assumed to limit the gravity profile in the distance of 1000 m (in reality the wellbore distances are usually greater). Another assumption is that the wellbores (100 m deep) do not encounter the anomalous geological features located between them. Respective gravity signals are shown in the upper part of Figure 2.

Case 1 shows a fault in between the wellbores with a shift of a carbonate layer, here with a positive density difference +0.10 g/cm^3 to clastics. Despite the weak amplitude of the gravity response (about -0.100 mGal) it still can be recognized with a good detailed gravity survey (blue line); especially around the fault the gravity gradient can be detected in the data.

Case 2 represents a laterally limited zone of strong deep weathering of the subsurface layer down to 20-30 m due to whatever geological reason, producing a negative density contrast, e.g. -0.10 g/cm^3. The gravity signal has very similar parameters as in the Case 1.

The Case 3 describes the effect of karst in the 50-m thick layer. As mentioned above, karst may develop from carbonate formation fracturing and water erosion into big void/cave similar to the one in Figure 1. Here we consider the fracturing and the existence of small voids that altogether cause the decrease of density by -0.10 g/cm^3 in relatively short section of a line (200 m). The signal is stronger than in the previous cases, up to -0.150 mGal, and also the gradients at the body edges are very clear.

Case 4 is a tentative model of a channel filled by clastics with the same negative density difference as in the Case 2 and Case 3. The gravity response is almost -0.300 mGal. The amplitude would decrease with increasing depth of the model body, therefore a feasibility study should be performed to evaluate the depth vs. size of such a channel to stay detectable.

The improvement of a seismic section after including gravity data into the processing procedures is demonstrated by significant changes in horizons smoothness and sharpness without too many spikes as in Figure 4.

Importance of Petrophysics

The analysis of detailed gravity data should be supported by petrophysical investigation. Rock samples from surface outcrops or well cores can be analyzed in the laboratory for dry, wet and grain density, and porosity. The data help not only to demonstrate the surface (and near-surface) rock density variations, but also assist to more accurately process gravity data in which the density of the upper-most rock formation plays an important role for achieving correct amplitudes of gravity anomalies. Gardner's Law of the density-velocity relation (Gardner et al., 1974) may be used to estimate what can be the impact of anomalous density of a geological formation or object on seismic velocity value to be used in the velocity model.

A specific issue is the property of sand in desert areas, very frequent in exploration regions. In a laboratory I studied sand samples collected from the Rub Al-Khali Desert in Saudi Arabia using a special procedure in order to obtain similar sand property as on-site on a dune. Actually, the results were different from expectation, with density well below 1.80 g/cm^3. These unpublished density data were used by Colombo et al. (2008) who proved that the dune property is also crucial for seismic processing (see Figure 4).

Resistivity – Boundaries Detection

Geoelectrical methods are used to define both horizontal and sub-vertical boundaries of formations with different resistivity. There are significant differences in resistivity of sedimentary rocks: clay and shale exhibit very low values of 1-100 Ωm, sandstone 100 to 1000 Ωm, and compact limestone as high as 100 kΩm. Various multi-electrode tomographic techniques, as well as electromagnetic, have been developed, while the traditional vertical electrical sounding (VES) is still effectively used (Setiyono et al., 2014). The resistivity section may provide clear distinction on a contact of different formations, even if there is no striking difference in the seismic section. As mentioned earlier, the dune bottom is one of the targets; the dry sand of the dune has high resistivity, contrary to sedimentary formations with fractured and weathered surfaces comprising humidity or water (see Figure 3).

Contrary to gravity, there may be difficulties in performing resistivity surveys in industrial areas (e.g. in developed fields) where surface or buried pipes and cables, as well as other industrial facilities, may significantly complicate the survey logistics and deteriorate the quality of data.

Integration of Seismic with Gravity and Resistivity

Near-surface heterogeneity and sparse distribution of wellbores justify the application of gravity and resistivity surveys on high-resolution seismic projects. They enable improving the characterisation of the LVL (low velocity layer) for layer-stripping. VES (vertical electrical sounding) defines semi-horizontal horizons and supports the interpretation of gravity data. Then both datasets can be integrated into the seismic section and distinguish some structures or faults that may not be visible in the time-slice. The joint inversion of seismic-gravity-resistivity data can improve not only near-surface, but actually the whole seismic section

This is nicely demonstrated in Figure 5. The VES data clearly define different subsurface layers. On the left side of the section there is a very sharp and sudden change in both resistivity and gravity, interpreted as a major fault within the area under study (yellow dashed sub-vertical line). This fault was not impressive in the seismic data alone. As well, very distinct gravity anomalies affected the construction of seismic processing models.

Conclusions

The given examples demonstrate how efficient gravity and resistivity surveys can be in locations of heterogeneous zones of near-surface formations. They include the bottom of dune surfaces in large deserts like the Rub Al-Khali Desert in the Middle East, volcanics, overthrusts, carbonate inter-layers, various paleo-structures, as well as karst features.

Various geological phenomena and processes which affect and change the density and/or resistivity will have impact on seismic velocity. Therefore, the non-seismic techniques may significantly support the definition of the near-surface velocity model and static corrections. Consequently, seismic processing and imaging can provide improved resolution and more accurate images. Moreover, gravity is an especially very low-cost method compared to seismic.

The data can be important also for onshore drilling sites investigation where the hazard is coming mainly from karstic features that may cause drilling rig damage. Again, this may often be a case in the Rub Al-Khali Desert in Saudi Arabia and deserts in adjacent countries.

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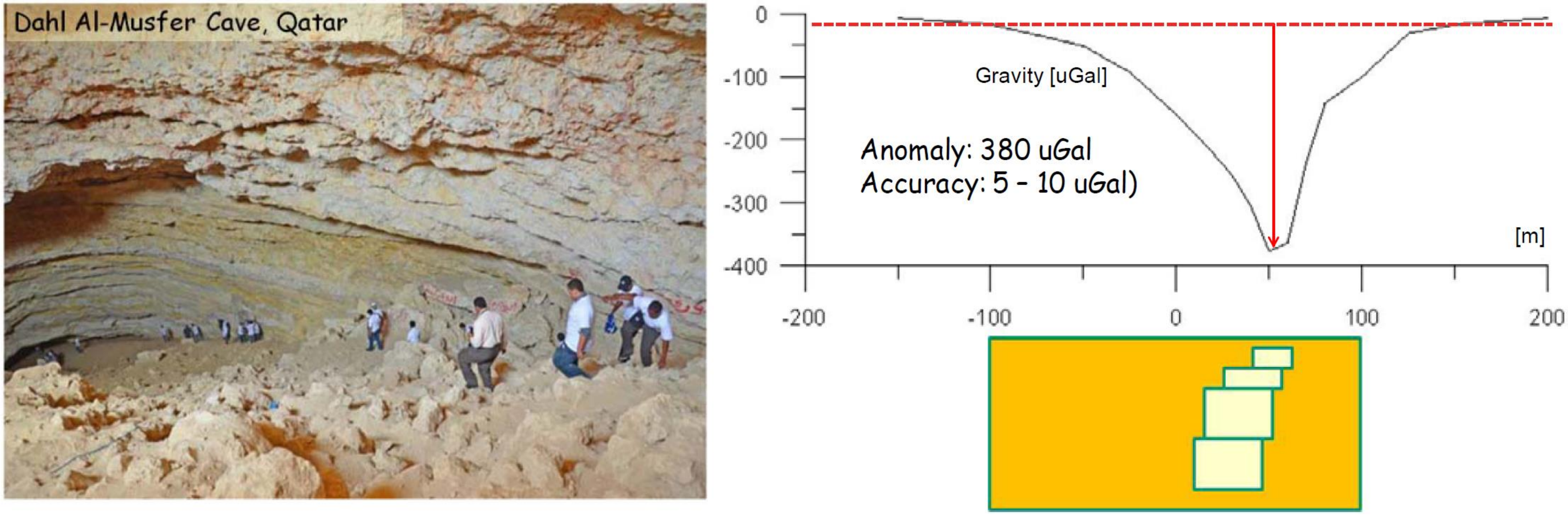

Figure 1. One of the critical phenomenon affecting static corrections is karst. For example, in the Middle East there are many karst areas with enormous caves, as this one in Qatar. Caves are a traditional target of microgravity surveys. A simple scheme demonstrates how clear and strong the gravity signal of such geological feature can be; moreover, even a rock mass just disintegrated by tiny fractures with aggressive groundwater can produce detectable density contrast to homogeneous bedrock.

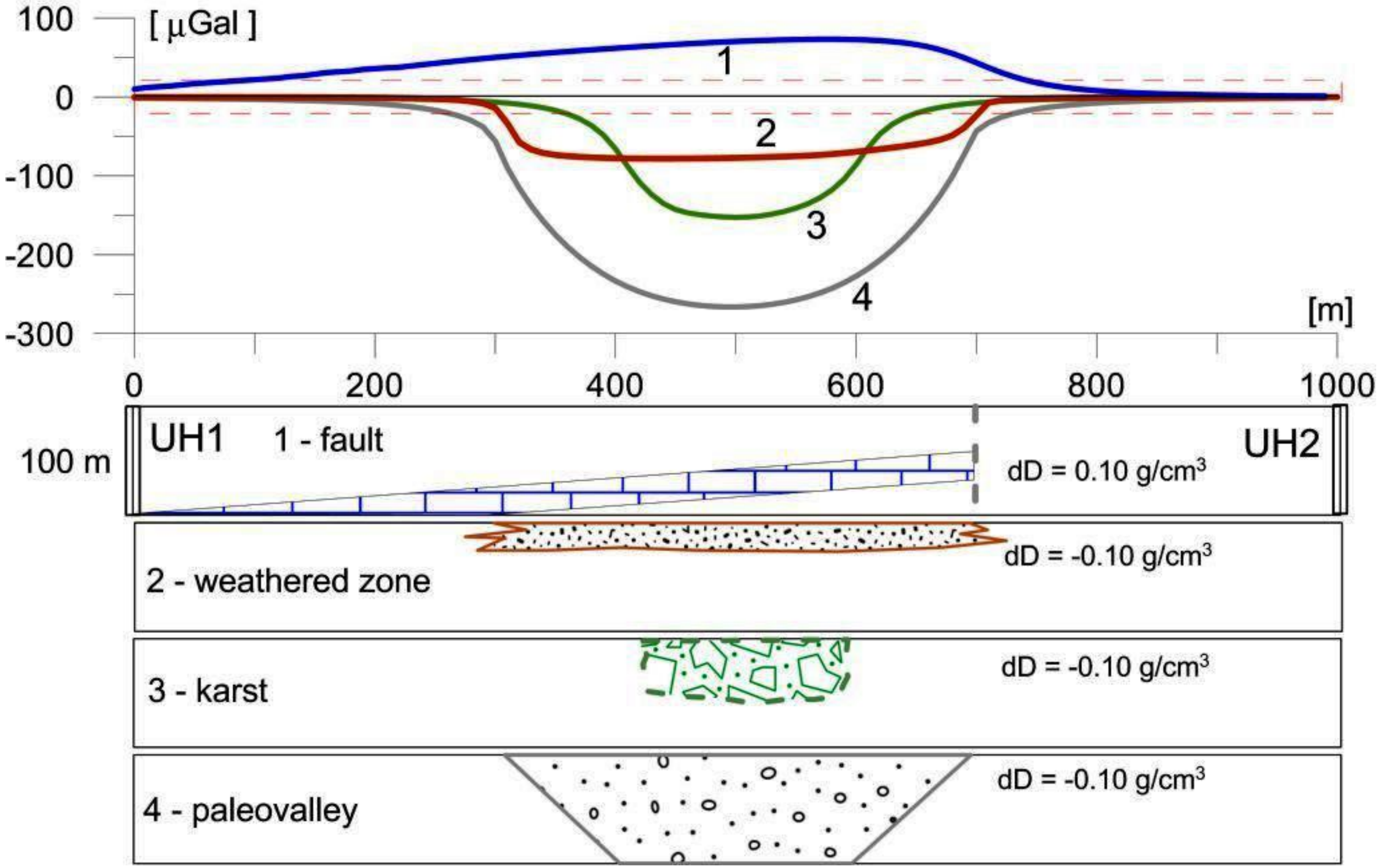

Figure 2. Four types of subsurface heterogeneity that produce significant density contrast to country rock; the features can occur easily between two wellbores and a seismic processor may have no idea on their presence. Relevant gravity anomalies are shown above; from their shape and amplitude the geometry of the source can be estimated, despite known ambiguity of gravity data. Even if the estimate is not perfect, it indicates the extent of heterogeneity to be considered during processing seismic data. Density contrast +0.10 g/cm3 is used in case 1 (faulted carbonate layer), and -0.10 g/cm3 in cases 2 to 4. The limits of gravity data accuracy of (e.g.) ±0.020 mGal are shown as dashed lines.

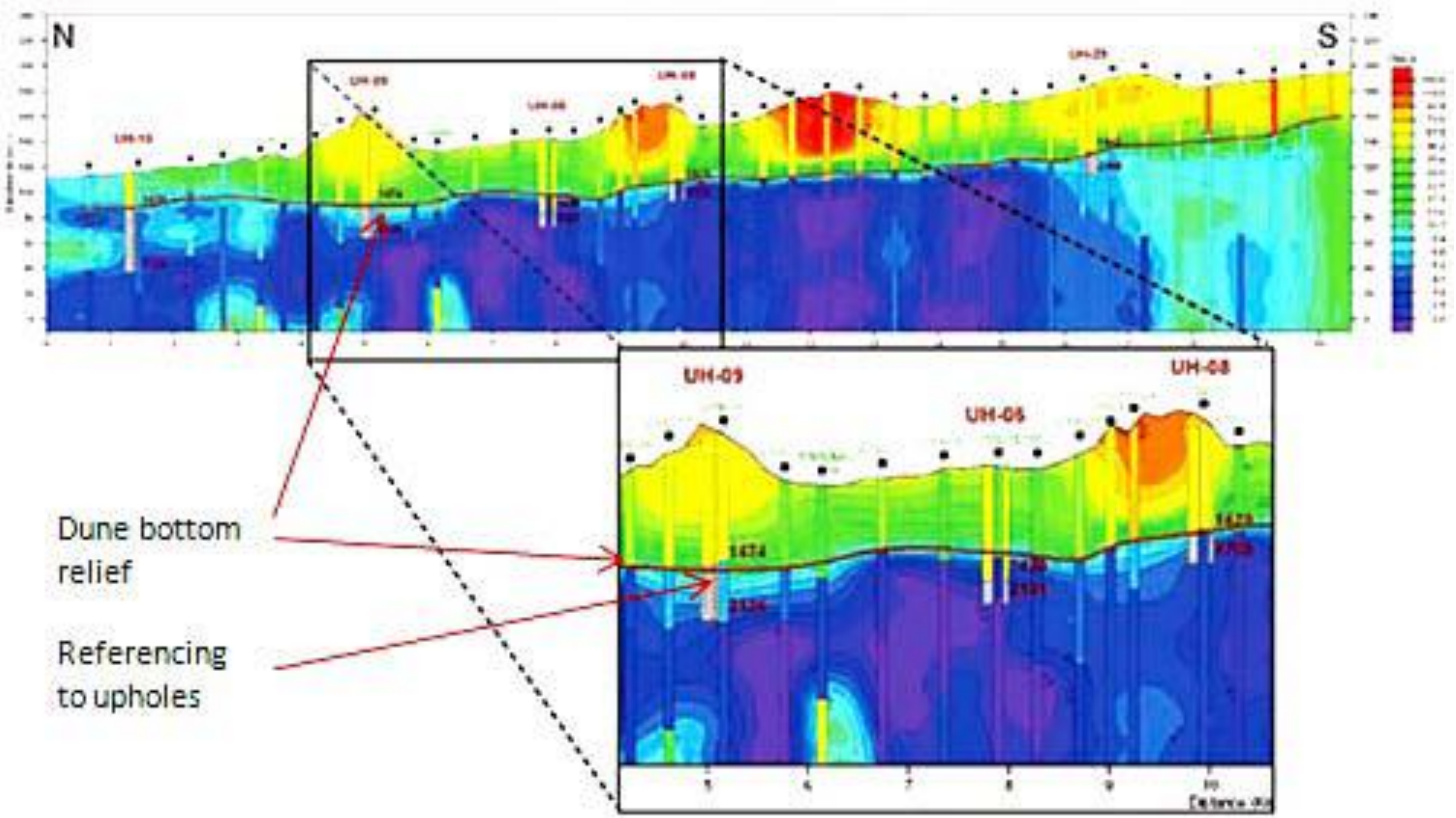

Figure 3. TDEM (time-domain electromagnetic) resistivity line observed in desert conditions with dunes. The lithologic data from numerous wellbores served well for TDEM results calibration. The bottom surface of the dunes seem to be well defined as an almost straight line with only very gentle topography variations (adapted after Colombo et al., 2008).

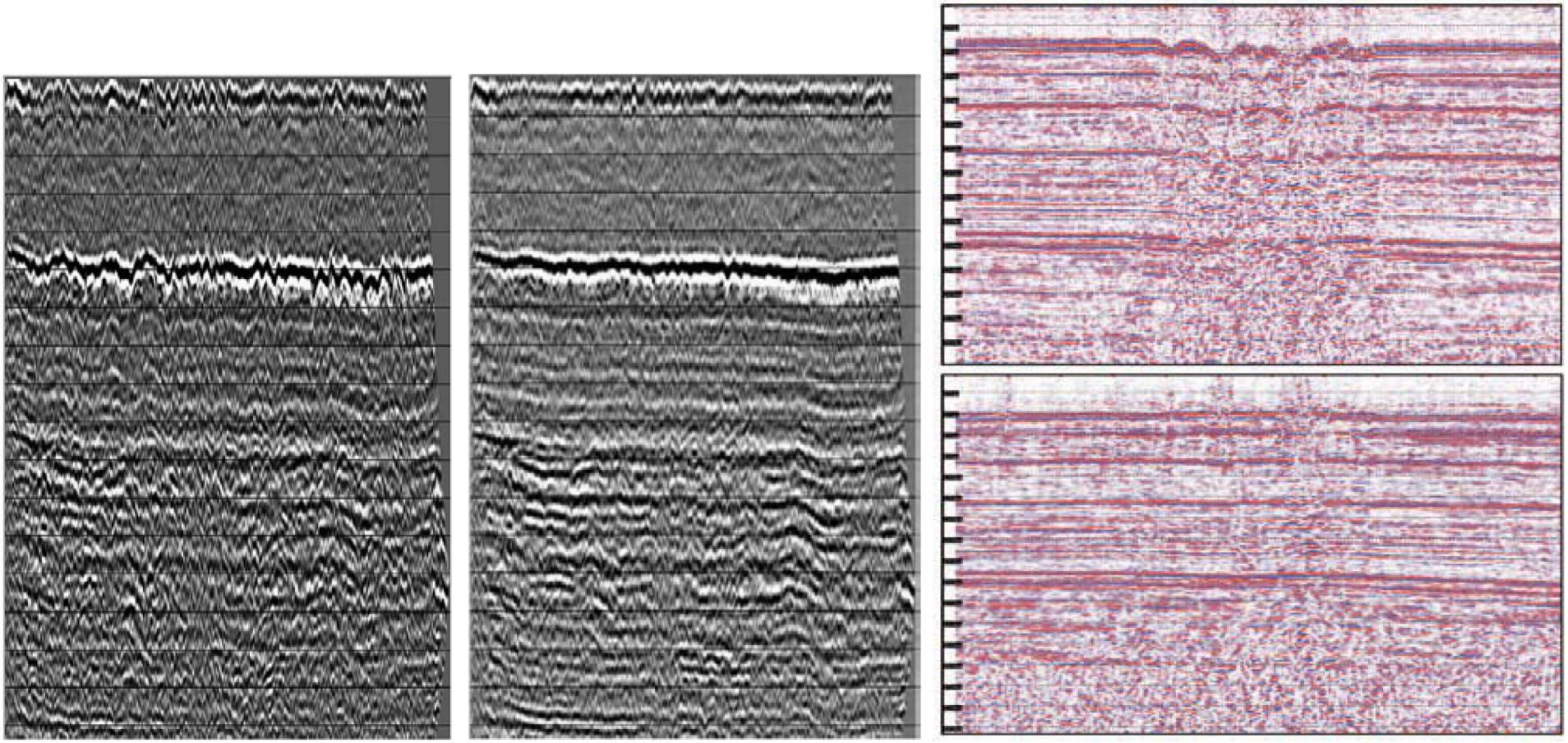

Figure 4. Two examples of the impact of gravity data application in static correction processing (after Colombo et al., 2008-left, 2010-right). The dune density was considered, too, as mentioned in text.

1) Constant replacement velocity applied – black-white figure left side, colored figure right top.

2) Gravity data were used for improving the near-surface velocity model; the horizons quality change is obvious - black-white figure right side, colored figure right bottom.

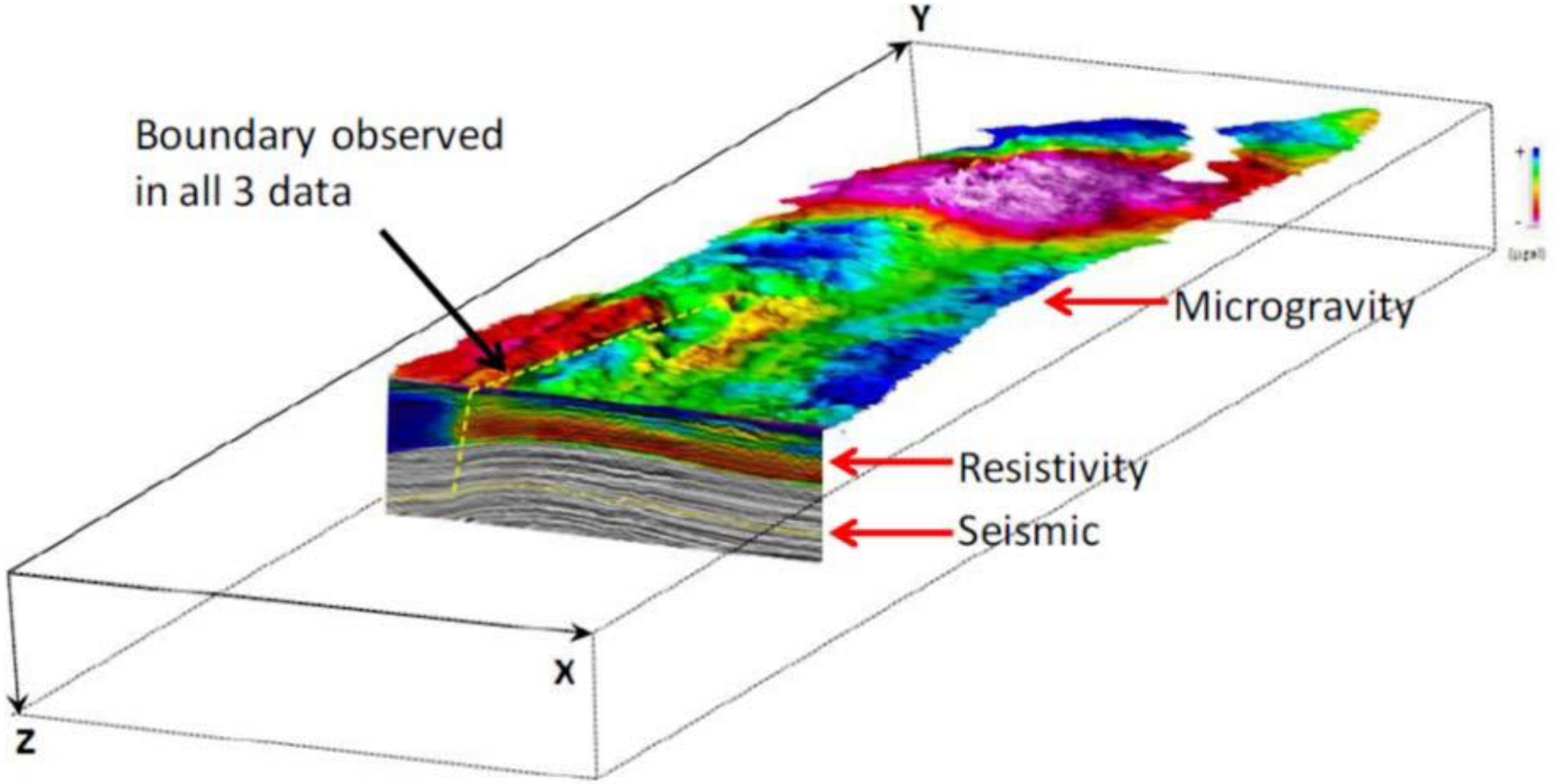

Figure 5. Example of composite integration of seismic with detailed gravity and vertical electrical sounding data, Dukhan, Qatar (adapted after Seeni et al., 2014). Contrary to seismic, both other techniques identified an important vertical geological boundary very clearly, see the left corner of the section. Dense gravity coverage provided a high frequency spatial gravity image reflecting near-surface distribution of density used for improving near-surface seismic velocity model.