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Seismic Investigations of a Geothermal Field in Southern Tuscany, Italy

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ABSTRACT

The Monte Amiata region in the Southern Tuscany, Central Italy, describes a volcanic complex with great significance in terms of the regional fresh water supply, mining and geothermal power generation. Mainly for the latter purpose, the volcanic area of Mt. Amiata has been the subject of extensive geological and geophysical research. The results from these studies have led to successful geothermal production in the Mt. Amiata region since the early 1960s. Today, the most important reservoirs in this area are the Bagnore and the Piancastagnaio fields which are both operated by Enel Green Power. In order to get a more detailed understanding of new and promising adjacent areas, five reflection seismic profiles were carried out. We have performed and tested different depth migration methods on those lines.

The vital point of depth migration algorithms is the accuracy of the velocity model that is used for the backpropagation of the seismic data. Therefore, we derived a suitable 1D starting model from nearby well logs and VSP measurements. In order to remove the large topography effects along the profiles, we then utilized first-arrival tomography for each seismic line. For the following processing we incorporated these 2D tomographic results into our starting model which compensates for static effects and improves the resolution in the near-surface area. The velocity models were then used in the application of Kirchhoff Prestack Depth Migration (KPSDM) to the seismic data for each profile, respectively.

Moreover, we applied a focusing depth migration method, Fresnel Volume Migration (FVM), which limits the migration aperture to the volume that physically contributes to a target reflection/diffraction. This methodology significantly improves the quality of the migrated image and therefore yields a better result than conventional KPSDM or time migration.

In comparison with time-domain imaging methods we conclude that depth migration generally provides an increased lateral resolution which is due to its flexibility with respect to lateral velocity heterogeneities in the near surface. This advantage particularly improves the imaging of fine-scale structures and geological faults.

In summary, the applied seismic techniques deliver a well-resolved image of the subsurface for a thorough characterization of the geothermal reservoir.

1. INTRODUCTION

The Mt. Amiata volcano-geothermal area is located in the Southern Tuscany, the hinterland of the Northern Apennines, Central Italy. The highly permeable volcanic rocks host an important aquifer which supplies fresh water for the entire region of Southern Tuscany. Moreover, the area has lately become important for its geothermal resources with heat flow up to 600 mW/m^2 which led to electric power generation since the 1960s (Batini et al., 2003) by Enel Green Power. Currently, the Piancastagnaio and Bagnore power plants, which are situated on the southern slope of Mt. Amiata, exhibit almost 70 MW of installed capacity.

For the purpose of geothermal exploration, data from seismic reflection profiles have been integrated with geological field work and borehole logs over the last decades in order to study the structural setting and to assess the hydraulic properties of this region (e.g. Brogi, 2008; Dini, 2010 and references therein). Currently, a joint research project focuses on the assessment of new potential geothermal reservoirs in the Mt. Amiata region by means of numerical simulation of flow and heat transport (Ebigbo et al. 2015). These computations demand a reasonable structural model (3D) of the reservoir as input for the simulation. For this purpose, we reprocess two existing reflection lines RA01 and RA02 that were obtained during the 1990s, together with new data from three recently acquired seismic profiles. Subsequently, we image the data by applying 3D prestack depth migration algorithms, namely the standard Kirchhoff prestack depth migration (KPSDM) and the more advanced Fresnel volume migration (FVM, see Buske et al., 2009). In this paper, we present our final images of line RA02 in comparison with previously published results (Brogi, 2006, 2008).

Past studies have exclusively used time migration methods for the preceding seismic interpretations of the area. Here, we utilize depth migration as it allows for an accurate 3D structural model with reliable depth information of the geologic layers. Obtaining such a model can be problematic when using time migration methodology in complex geologic environments. For this reason, we utilize depth-imaging methods in combination with an iterative velocity model building procedure.

The primary goal of this work is to further contribute to the understanding of the structural features of the Mt Amiata geothermal area and to estimate reliable depth information of the already imaged geologic layers.

2. GEOLOGICAL SETTING

The geologic and structural setting of the Mt. Amiata volcano-geothermal region has been the subject of integrated research for several years. A detailed description of the current state of knowledge can be found in Brogi (2008). Following the explanations of his work, the region of Mt. Amiata is mainly dominated by extensional structures that took place from Early Miocene to Quaternary and succeeded the original stacking of the Northern Apennines (Cretaceous to Early Miocene). Moreover, the extensional phase can be subdivided into three major phases: (a) the formation of boudinages (Middle to Late Miocene); (b) normal faulting and emplacement of a magmatic body in the middle to upper crust (Pliocene to Quaternary) and finally (c) the Mt. Amiata eruption (0.3 to 0.19 Ma).

The stratigraphic units of the Mt. Amiata region can be described as follows (from top to bottom; as displayed in Figure 1, following Dini et al., 2010):

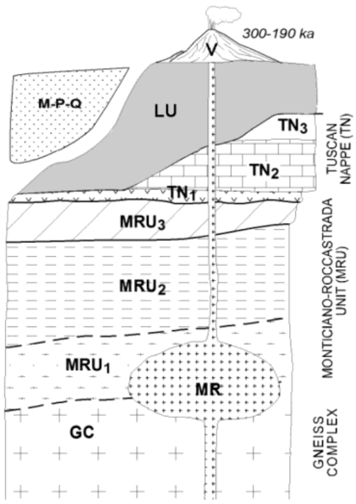

Figure 1: Stratigraphic units as they occur in the Mt. Amiata area (taken from Dini et al., 2010).

1. The volcanic complex (V) which is mainly represented by Mt. Amiata and has an estimated rock volume of 19 km^3 consists of dacitic, rhyodacitic and olivine-latitic rocks. It contains mafic enclaves which indicate mixing processes of anatectic and subcrustal magmas (Ferrari et al., 1996).

2. Neogene and Quaternary deposits (M-P-Q) consisting of continental and marine sediments. These fill in the tectonic depressions and Quaternary travertines.

3. The Ligurian Complex (LU) is composed of pelagic sediments which cover the remnants of the Jurassic ocean basement. During the Late Oligocene to Early Miocene they were thrust eastwards over the Tuscan Domain.

4. The Tuscan Nappe (TN) is made of three succeeding units which are (from bottom to top): evaporitic (Late Triassic, TN1), carbonate (Late Triassic to Early Cretaceous, TN2) and pelagic-tubiditic (Cretaceous to Early Miocene, TN3) rocks. After being detached from its substratum along the horizon of the Triassic evaporites, the Tuscan Nappe was thrust over the outer paleogeographical domains. This occurred during the contraction from the Late Oligocene to Early Miocene. The Triassic evaporite unit is also referred to as Burano Formation (Batini et al., 2003).

5. Below the Tuscan Nappe, the Tuscan Metamorphic Complex has only been encountered by deep boreholes (Elter and Pandeli, 1991). It is referred to as the Monticiano-Roccastrada Unit (MRU, Bertini et al., 1991), which has been drilled down to 4900 m. It consists of two groups of very low-grade metamorphic successions: (i) the Triassic Verrucano Group (MRU3), which is composed of metamorphosed continental pelites, sandstones and conglomerates; and (ii) the Palaeozoic group (MRU2) that consists of metamorphosed sandstones and graphitic phyllites (probably Carboniferous), possibly Devonian hematite-rich and chlorite phyllites, metamorphosed sandstones containing dolostone layers and fusulinid-bearing crystalline limestones and dolostones with intercalations of graphitic phyllite from Late Permian (Dini et al., 2010). The Palaeozoic Group belongs to the Farma Formation (Elter and Pandeli, 1991). Xenoliths in the Quaternary lavas documented the presence of the Micaschist Group (MRU1) and the deep Gneiss Complex (GC) as it is described in Van Bergen (1983).

6. Magmatic rocks (MR) have been investigated by gravity measurements (Bernabini et al., 1995) which determined the approximate location at 6 km depth.

Due to the extensional phase, the Tuscan Nappe can be represented by discontinuous geological bodies (extensional horses) that are also referred to as megaboudins. These structures are described in greater detail in Brogi (2004, 2006). In total, three megaboudins have been outlined (Figure 2). They are well constrained by boreholes and the interpretation of seismic lines. The megaboudins are laterally bounded by Low-Angle Normal Faults (LANFs). This faulting results in areas where the uppermost Ligurian Unit directly overlies the Late Triassic evaporites (Burano Fm.).

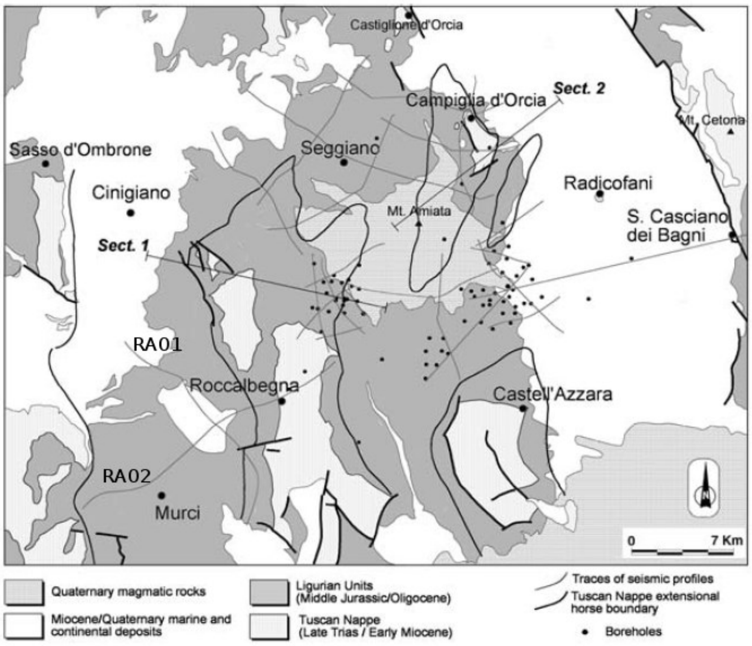

Figure 2: Geological map of the Monte Amiata area (modified from Brogi, 2008).

For the underlying study, the southern part of the Mt. Amiata area is of major concern (Figure 2). This area corresponds to the southern extension of the westernmost megaboudin, which is the biggest of the three outlined horses. It is over 12 km long, about 9-10 km wide and is composed of the Late Triassic to Early Miocene Tuscan Nappe succession. Partial outcrops occur at the surface near Mt. Amiata. The boudinage has been drilled by numerous deep boreholes in the vicinity of Mt. Amiata and the Bagnore geothermal field. Also, it has been imaged by the seismic profiles RA01 and RA02 in the eastern part of the investigation area.

3. PRECEDING SEISMIC LINE INTERPRETATIONS

The two reflection profiles RA01 and RA02 which were acquired during the 1990s cross the area of investigation in the southern part of the Mt. Amiata geothermal region as shown in Figure 2. Their interpretation is summarized in Brogi (2006). So far, these profiles have only been processed in the time domain. The geologic interpretation and depthing of the profiles was led by field and borehole data which mainly stem from the eastern part of the investigation area. As an example, the result of the seismic interpretation of the RA02 profile is shown in Figure 3. The unmigrated result already shows the extent of the geologic layers and also demonstrates the difficulties of the data from a seismic point of view. Looking from the southwestern end of the line, the boundary between the Ligurian Units (L) and the Triassic evaporite (TN1) is clearly indicated by a strong reflector demonstrating the significant seismic impedance contrast between the two different rocks units.

Towards the northeastern end of the profile, the boudinage structure becomes visible. Here, the Tuscan Nappe outcrops at the surface which is also referred to as the Roccalbegna Tuscan Nappe window. This structure is delineated by a southwest-dipping LANF which is challenging to be imaged precisely due to its steep dip. The successions of the individual Tuscan Nappe layers starting at the LANF only exhibit attenuated reflectivity which is ascribed to the gradual change of seismic velocity and density between the different Tuscan Units. Areas where the Ligurian Units overlie the carbonate rocks (TN2) also show low reflectivity.

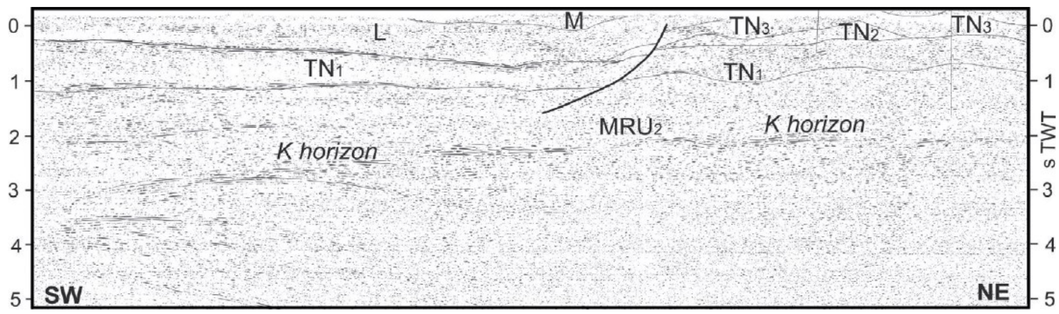

Figure 3: Interpretation of the final stack for line RA02 as it was obtained in a previous study (taken from Brogi, 2006).

According to geological information and well data the Triassic evaporite continuously overlies the Palaeozoic group of the metamorphic rocks (Farma Fm.). In this interpretation, the transition between these formations is evidenced by a second clear reflector in the southwestern portion of the line. However, beneath the Tuscan Nappe window this reflector also thins out. Within the Farma Formation a strong and continuous reflector represents the so-called K-horizon (Batini et al., 1978, 1985), which ranges between 1.9 and 2.1 s TWT and rapidly deepens in the western part down to about 3.5 s. Its origin, however, has not been fully understood, yet. According to the current interpretation, the K-horizon marks the upper boundary of the brittle/ductile transition zone (Cameli et al., 1998 and references therein). The nature of its high reflectivity is assumed to be over-pressured fluids.

The goal of depth-migrating these profiles is to enhance the quality and lateral resolution of the seismic reflectors and to obtain more reliable depth information.

4. VELOCITY MODEL BUILDING

The first step in our depth imaging procedure is to derive a suitable velocity model. The depth migration methods we use require an accurate but smoothly varying model. The heterogeneities must be comparable in size to the seismic wavelength in order to ensure a stable calculation (e.g. Jones, 2010). For this reason, we applied a two-stage methodology for velocity model building. First, we utilized first arrival tomography in order to obtain a detailed model of the near surface (down to about 500 m below topography). Next, we performed an iterative layer stripping procedure adjusting the velocities above picked migrated horizons. We started with the first geologic layer below the tomographic model and subsequently went down estimating velocities for the deeper structures. The model that we obtained as the final result of this process is displayed in Figure 4.

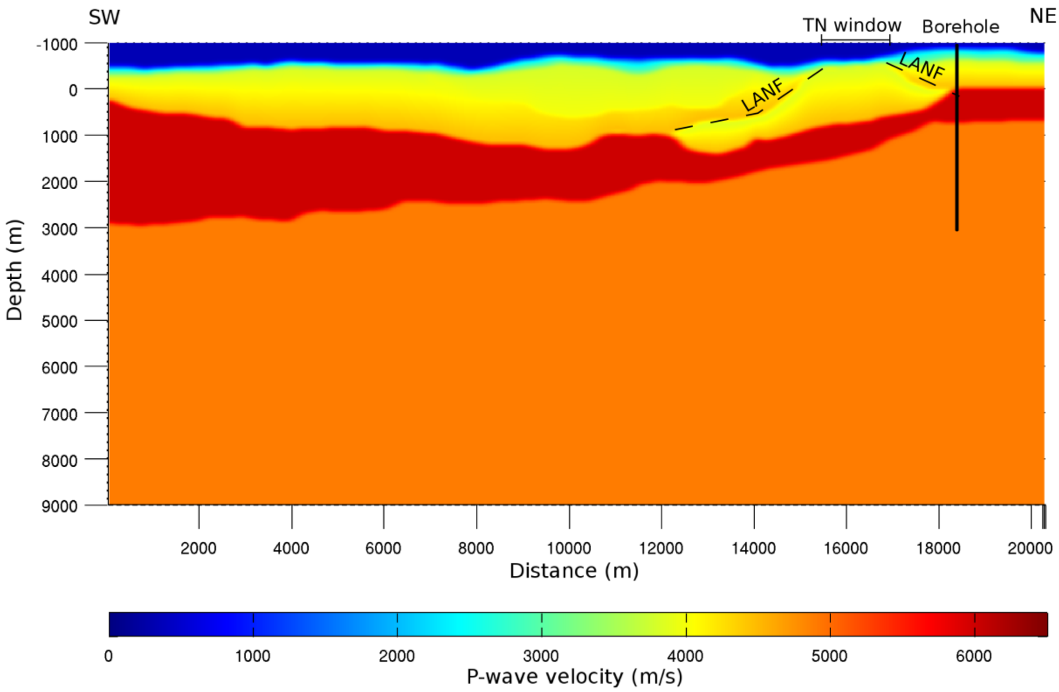

Figure 4: Velocity model that was used for depth migrations of line RA02.

The northeastern part of the model is additionally constrained by data from surface geology and VSP. The borehole location for the vertical seismic survey is also displayed in Figure 4. The model reflects the expected velocity changes. Below the tomographic model, the Ligurian Units are represented by velocities around 4000 m/s. In southwestern part of the model they directly overlie the Triassic evaporites (Burano Fm.) whereas in northeastern part the TN1 and TN2 units are interposed between the Ligurian and the Burano. This full Tuscan Nappe sequence (Tuscan Nappe window) outcrops at the surface and is constrained by two LANFs. The resulting megaboudin can be clearly identified within the model. On the contrary, the velocity contrast itself from the Ligurian over the full Tuscan Nappe sequence is rather gradual. Hence, these units are not distinguishable from each other in the velocity model.

5. DEPTH MIGRATION RESULTS AND NEW INTERPRETATION

Using the velocity model described above, we carried out our prestack depth migration analysis. For this purpose, we first computed the corresponding traveltime tables utilizing the finite difference method of Podvin and Lecomte (1991). In that way, the migration algorithm is more robust with respect to rapid velocity changes. Subsequently, the pre-computed traveltimes were passed to our migrations in order to obtain the images below. Initially, we carried out KPSDM, which performs quickly and therefore is the method of choice for velocity analysis and depth model building. The final result is shown in Figure 5.

The KPSDM result shows the important reflectors of the reservoir. The contrast between the Ligurian and the Triassic evaporites (Burano Fm.) in the southwestern part of the model is marked by a strong reflector at approximately 1 km depth. The second reflector between 2 and 3 km could represent the boundary between the Burano and Farma Fms. An alternative interpretation is a repeated Burano-Farma Fms. sequence that would be particularly supported by further weaker reflective areas between 4 and 5 km depth. These repeated formations can possibly be ascribed to stacking. The strong reflector starts at about 3 km depth at the southwestern margin and meets the reflector above at about 12 km distance. This junction of the two reflectors meets the LANF that delineates the Tuscan Nappe window. Unfortunately, both reflectors almost vanish within the megaboudin. This is a characteristic feature that is also observed in the old interpretation of the seismic line (Figure 3) and which is ascribed to the gradual change of the rock properties from the Ligurian Units through the Tuscan Nappe sequence.

At the northeastern end of the Tuscan Nappe window, the upper reflector appears again. Its depth corresponds well with log data from the nearby borehole that is marked in Figures 4-6. However, the second reflector separating the Burano and Farma Fms. or its stacking cannot be detected.

Below these two reflectors, the K-horizon is also clearly visible within the metamorphic rocks. Its shape indicates an updoming structure which dips rapidly to the southwest. Here, a large vertical offset within the reflector can be observed which spans almost 2 km.

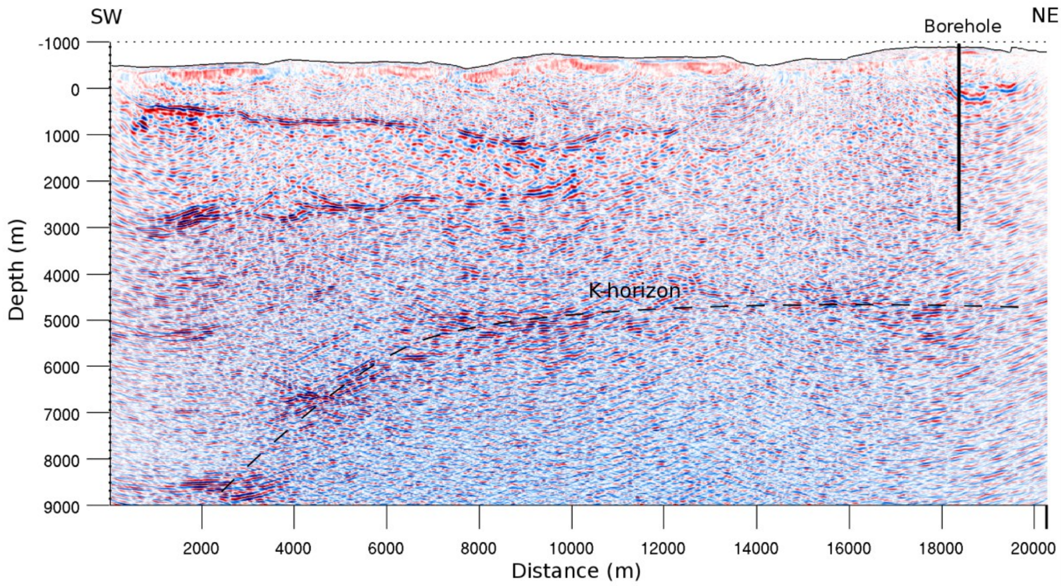

Figure 5: KPSDM result of profile RA02 using the velocity model show in Figure 4.

Above the K-horizon other reflective structures can be observed within the Farma Fm. However, they are not well-defined and hardly stand out from the background noise. This is largely due to the manually defined migration aperture of KPSDM and can be overcome by utilizing the FVM (Figure 6).

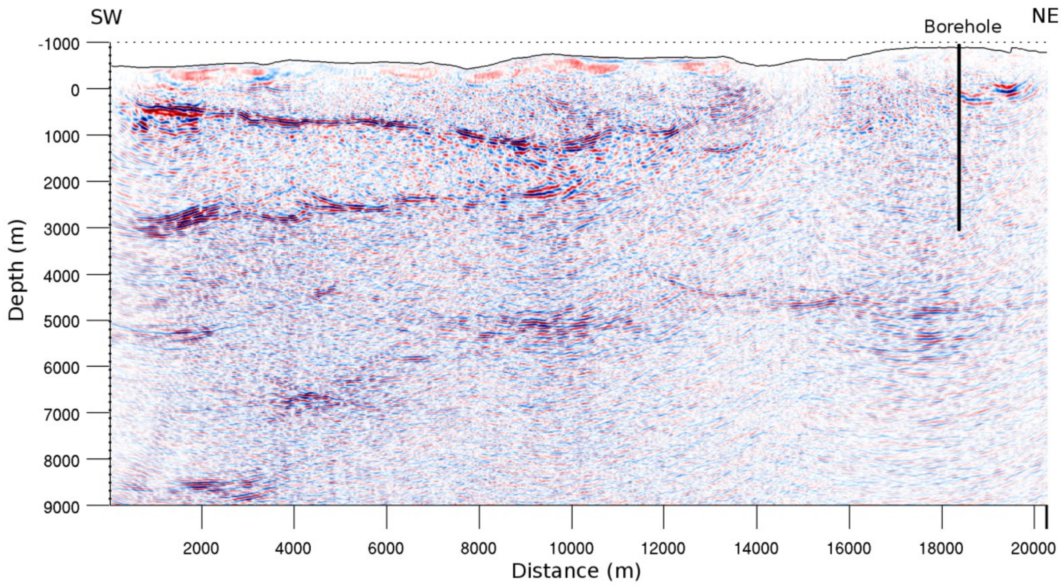

Figure 6: FVM result of profile RA02 using the velocity model shown in Figure 4.

Comparing the two results, it is obvious that FVM significantly enhances the image's quality by eliminating the majority of unphysically migrated seismic energy. As a consequence, the reflectors stand out clearly from the background which is particularly true down to the bottom of the Burano Fm. In the deeper parts of the model which belong to the Farma Fm., FVM still improves the migrated image. However, this does not always highlight the reflective features as well as in the upper layers.

One open question which still needs to be addressed is the investigation of velocity variations below the Triassic evaporite layer. So far, we use a homogeneous layer to represent the Farma Fm. in our depth migrations. The adjustment of the migration velocities is more complicated throughout this region since the reflective features are more diffuse and might not be associated with a lithologic boundary (especially the K-horizon). Migration velocity analysis generally uses the coherency of migrated reflectors as a measure for the accuracy of the current model. Diffuse reflectors introduce ambiguity into this process and hence complicate the model building for the deeper areas in the reservoir.

6. CONCLUSION

Prestack depth migration methods have proven to be useful for investigation in this complex geologic environment. Combined with iterative velocity model building, these methods provide increased lateral resolution and more reliable depth information than depth-converted images obtained from standard time-domain processing. The application of FVM significantly reduces migration noise and therefore enhances the quality of the final image. In this way, geologic reflections can be better distinguished from artifacts introduced by a manually defined migration aperture.

Considering the RA02 profile, the main geologic horizons are imaged by the depth migrations. The upper geologic layers in the depth-migrated images reflect accurate spatial dips of the lithologic horizons and geologic faults, particularly for the southwestern part of the profile. The imaging of horizons within the Tuscan Nappe window still remains challenging due to the low impedance contrast between the different rock units.

In the deeper layers of the reservoir, the K-horizon is well-imaged. Throughout the Farma Fm. several other reflective areas can be observed. In order to improve their spatial appearance and to characterize their nature, further analysis is required to recover possible velocity variations within the metamorphic rocks.

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