SEISMIC REFLECTION IN THE BOLSENA LAKE : A CONTRIBUTION TO THE KNOWLEDGE OF A CALDERA CONTROLLED GEOTHERMAL SYSTEM

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1. FOREWORD

Within the "Energetics II Special Project", a Geothermal Energy Subproject sponsored by National Research Council, ISMES S.p.A. carried out a geophysical investigation in the Bolsena lake (Central Italy), during july 1988. The project included a high resolution seismic reflection survey and a magnetic survey, and was followed by a preliminary interpretation of the data.
Recently, new volcanological and geothermal studies carried out by University of Pisa and National Power Electric Company (ENEL) brought to the definition of a new stratigraphic scheme based on surface and boreholes data, and to the outlining of the presence and role of a complex calderic structure in the area. These new results provided additional information for the interpretation of the seismic data.

2. EVOLUTION OF THE VULSINI VOLCANIC DISTRICT

The Vulsini Volcanic District represents the northernmost occurrence of the Pleistocene volcanism of the Roman Magmatic Province. In the Vulsini, the volcanism began around 600 ka and continued until 150 ka ago, with the early activation of the Bolsena Complex (in the eastern sector) followed by the Montefiascone and Latera ones (Barberi et al., 1992). A strong influence of the regional tectonics can be recognized both in the start of the Bolsena activity (related to an extensional, N-S trending structure whose expression can be found in the Pleistocene Marta basin) and in the later activation of the Latera Complex, near the margins of a NNW-SSE trending extensional structure, dating back to around 300 ka and bordering the western margin of the Odinano plateau (Barberi et al., 1993).

2.1 The Bolsena Volcanic Complex (BVC)

The geological and structural setting of the BVC is connected to the presence of a very wide caldera (circa 13 x 15 km), which developed during the first volcanic phases of the Complex, and was frequently reactivated (Nappi et al., 1991; Cioni, 1993). The BVC products are represented by thick successions of tephra deposits and lava bodies, with interlayerings of some widespread ignimbrite sheets; in these sequences some primary lithostratigraphic units have been singled out, each representing a well-defined eruptive phase and somewhere separated by surfaces of primary unconformity.
The main eruptive phases of the BVC can be summarized in the following stratigraphic scheme:
Basal Pyroclastic Activity, represented by some pumice fall deposits dating back to 590 ka, and followed by a hiatus in the activity of about 100 ka; the deposits of this phase are confined to a few outcrops in the peripheral sectors of the BVC, and cannot be identified in the drilling logs;
Bolsena Caldera Lower Sequence (BCLS); its deposition began around 490 ka with a paroxistic ignimbritic activity ("Nenfro" Ignimbrite) leading to the first important collapse of the Bolsena caldera. The BCLS comprises the main portion of the Bolsena products, represented by pyroclastics (from strombolian lapilli beds to thick plinian and ignimbritic layers) and lava flows related to central and fissural peri and intra-calderic vents. The end of the sequence is marked by the emplacement, around 350 ka, of very peculiar latitic and trachytic products outcropping around the north-eastern sector of the Bolsena Lake and recognized in some boreholes. During the emission of the very large volumes of the BCLS (estimated in about 150 km^3 by Cioni, 1993), the caldera probably underwent a strong incremental growth.
Bolsena Caldera Middle Sequence (BCMS) represents an important eruptive phase mainly characterized by trachyphonolitic lava domes, cumulodomes and lava flows. These products crop out in the north-eastern sector of the Bolsena caldera and are crossed by several drillings all around the Bolsena lake (even in its southern and western sector), so suggesting their importance in the evolution of the complex. They also mark a sharp unconformity, related to the following emission of the Orvieto-Bagnoregio Ignimbrite (OBI) and syneruptive caldera collapse. The interpretation of borehole stratigraphy and seismic reflection data suggests that the top of the widespread trachyphonolitic lavic products can be generally related to the lower horizon detected by the seismic analysis ("G" horizon, see below). Similarly to the outcropping sequences, in the lake area this horizon is dissected by some normal faults, with a total displacement of several hundred meters.
Bolsena Caldera Upper Sequence (BCUS) is characterized by lava flows mainly related to peri and intracalderic vents and scoria cones, spanning an activity interval from 300 to around 240 ka BP. In this period several plinian and subplinian eruptions were issued from vents probably located inside the Bolsena Lake. Martana and Bisantina islands grew in this period, together with other sublacustrine vents. In the outcropping successions of the northern sector, and in the lake (as deduced from the seismic data), the first ignimbritic sheets of Latera Complex are interlayered with the BCUS and with lacustrine sediments; these deposits were successively uplifted before the emplacement of the final Latera products. In the south-eastem sector, the BCUS is topped by the final products of the Montefiascone Complex.

3. HIGH RESOLUTION REFLECTION SEISMIC SURVEY

The technique of multichannel seismic reflection has been used. It consists of receiving several times and with different paths the reflected energy from a single out-going pulse. Sound returns from buried reflecting elements lying beneath the receiver line (hydrophones) (fig.1).
A motor boat (M/B Vulcano) of approximately 10 meters length was employed, allowing work even in quite shallow water (approx. 3 meters). Energy was provided by an Airgun with a 40 cu. inch volume camera, releasing compressed air, with pressure of 120 atm., every 10 m.
The receivers were composed of 24 groups of hydrophones placed in a polyurethan tube (streamer), suitably balanced in order to operate at a 2 m depth from the lake surface. The streamer was towed by the motor boat, thus allowing a continuos survey across the lake.
Twelve seismic lines have been recorded (about 90 Km total length): three of them with a NW-SE direction, eight with a SW-NE direction and one with a N-S direction (Figs. 2, 3, 4).

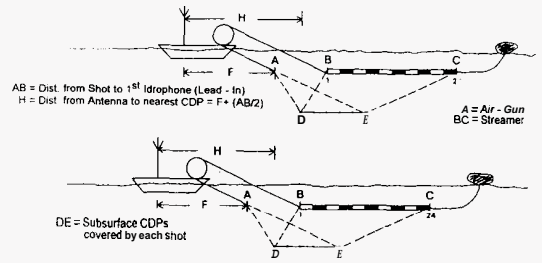

Fig. 1 ***Aquisition tecnique***

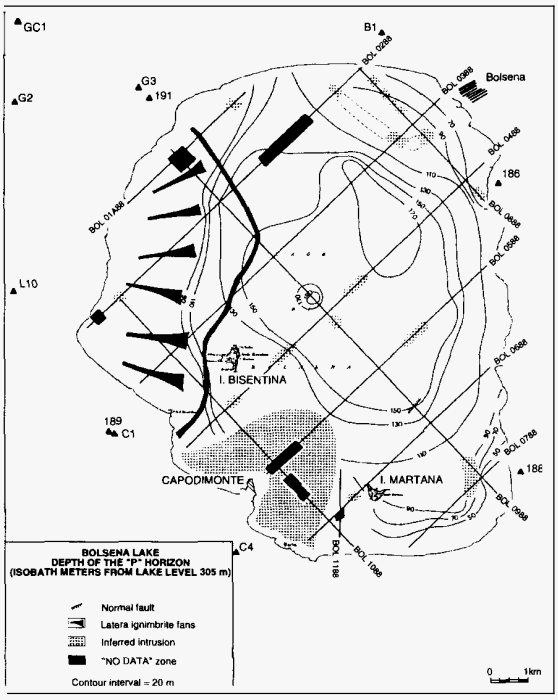

Fig. 2 "P" horizon depth map

4 SEISMOSTRATIGRAPHIC INTERPRETATION

Since this study represented the first seismic reflection survey carried out on the Bolsena lake, no previous data were available to infer acquisition parameters and equipment calibration.
Information about geology underlying the bottom of the lake is scarce and avalaible interpretations are based on previous magnetic, geoelectric and gravimetric surveys.
The interpretation of the final seismic data pointed out two main horizons called "P" (Pink) and "G" (Green), areas of probable feeder systems, volcanic conduits and dykes (stippled areas on maps of fig. **4),** faults and areas of diffuse brittle tectonics related to the calderic structures.
Figures *5, 7* and 9 show final stacks of lines BOL-04, BOL-08 and BOL-09. On lines BOL-04 and BOL-08 special processing analysis were performed (Reflection Strength Attribute) to detect the probable occurrence of volcanic intrusions (fig. *6,* 8).
In figures **2** and *3* a depth contour of the "P" and "G" horizons is shown. The trasformation of the seismic two way times into depths has been carried out by means of the stack velocities, properly corrected.
Figure 4 shows the isopach value of the volcanic sequence included between "P / G" horizons.

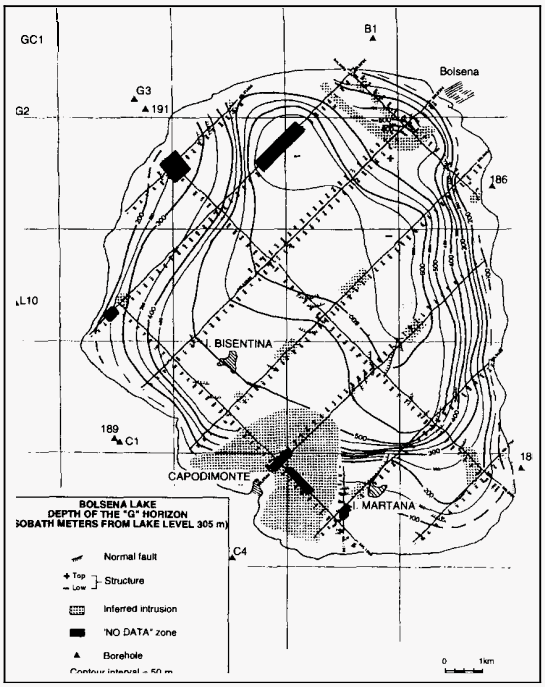

Fig. 3 "G" horizon depth map

4.1 "P" horizon

The "P" horizon represents the base of the upper sediments deposited in the lake, with a thickness ranging from some tens of meters along the edge of the lake to about 50-60 m in the central area. This layer has been defined according to the seismic facies; it represents the deposit of a uniform, sub-horizontal sedimentation throughout the whole surveyed area, not presenting any peculiar sedimentary structure or sudden changes of the seismic facies.
Only few tectonic structures affect these top sediments.
A special situation is noted along the north-westem area, where the recent sediments are laterally in contact with the oldest ones (Latera ignimbritic flow units) through a marked unconformity (Fig. 9). Unfortunately, this unconformity is not traceable on the eastern side because of the water bottom multiples occurring at the same time of the "seismic signal".
This formation could be ascribed to a lacustrine formation deposited since the very final phases of the eruptive activity of the area.
Figure *2* shows the map of the depth (isobath) of the the "pink" limit.

4.2 "G" horizon

The "G" layer is the base of the volcanic pile underlying the "P" horizon. The deepest point of this horizon (Fig. 3) lies at about *700* ms in two way time (about *670* m) from the lake surface *(305* m m.s.l.).
Because of its strong seismic response, this layer is often visible and represents the bottom of a thickness of sediments with a peculiar seismic facies. It consists of quite compact stratified deposits showing contact surfaces with a winding and sometimes very irregular trend. Sidewards, the stratification is often discontinuos with frequent thickness variations.
The contacts among the strata are very disturbed by several diffractions, probably produced by fractured and rough surfaces with sudden lithological variations. Sometimes it is possible to note some dome structures, included among subparallel levels, probably related to effusive phenomena.
In the area facing the village of Bolsena, the "G" horizon sinks very rapidly in SW direction and it is interrupted by **a** sharp and widespread dislocation, probably intruded by magmatic material (Fig. *5).* The horizon presents a marked anticlinal folding trend, that becomes almost horizontal in the central area of the lake. The "G" horizon is often crossed by subvertical bodies of magmatic (diapiric ?) origin, particularly in the SW area. In this area (centered around Capodimonte) the seismic reflection response seems to indicate the presence of a high concentration of fractures and related volcanic phenomena. Generally, no great downthrows are recognizable through the "G" horizon. The overlying sediments appear sometimes to assume a quite "plastic" behaviour, mostly indicating no rigid collapse phenomena.

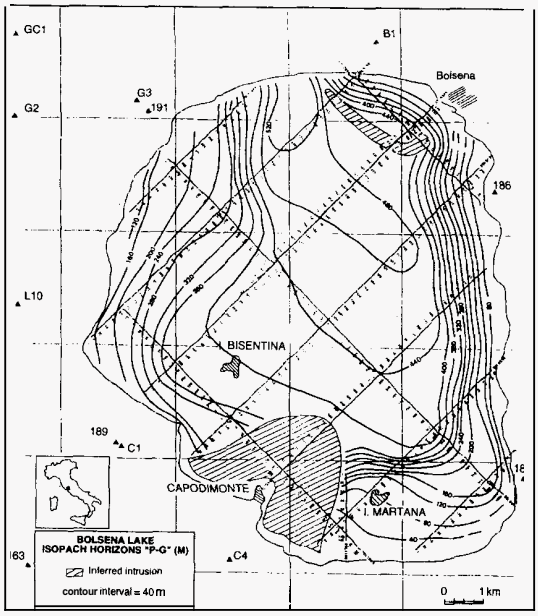

Fig. 4 "P/G" isopach map

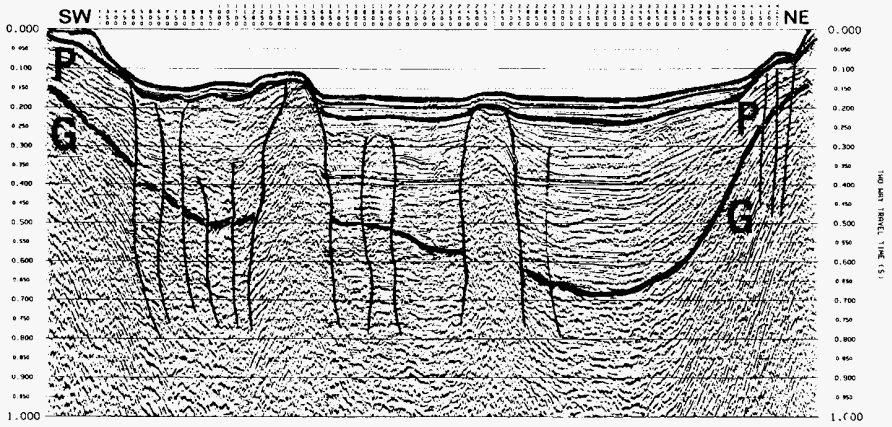

Fig. 5 Line BOL 04-88

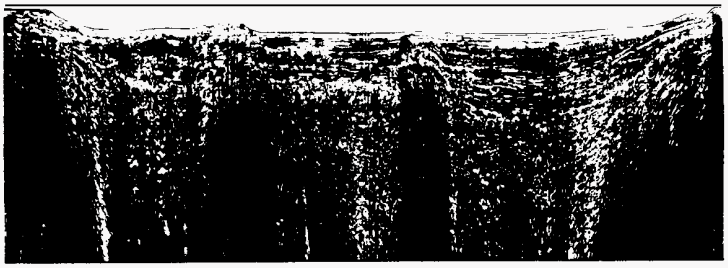

Fig. 6 Line BOL 04-88: rejection strength

4.3 Isobath and isopach maps

Figure 2 shows the depth map of the "P" horizon, in which it is possible to note an increase of the depth towards the central area of the lake.

On the western side, the "P" horizon shows a moderate increase in depth towards the distal zone. This is probably due to the presence of the old Latera ignimbrite flows that are recognizable, under the "P" horizon, through a marked unconformity (lines BOL-01, BOL-02, BOL-03, and Fig 9, line BOL-09).

On the eastern area of the lake the "P" horizon draws a trends very similar to the morphological situation of the lake.

The isobath map of the "G" horizon (Fig. 3) shows a different structural behaviour between the eastern and the western side of the lake. In the western area, the increase of "G" depth has a moderate gradient, reaching maximum values within 5-6 km from the lake shore.

On the contrary, in the eastern area the increase of depth is very rapid, reaching the maximum values in 2-3 kilometers from the lake edges. This is probably due to a combination of volcanic and tectonic phenomena, explained in more detail in the following section.

The maximun depth (670 m) of the "green" horizon is reached in the northeastern area of the lake.

The isopach map (fig.4) of the volcanic sediments included between the "**P**" and *"**G**"* horizons shows a pseudo-elliptical area, located in the central zone of the lake, with maximun thickness of about 440-480 meters. The maximun value is located in the north area *(520* m).

5. GEOLOGICAL INTERPRETATION

The seismostratigraphic units shown by the seimic survey seem to be related to the eruptive phases post-350 ka, our interpretation beeing strictly constrained by the stratigraphy of several peri-lacustrine geothermal boreholes. In this view, the older units do not provide a clear seismic signal. Seismic data show the occurrence of several horizons identifying deposits with peculiar seismic facies; the lowermost horizon ("G") has an important displacement (at least *650* m from the lake surface) in the central part of the lake, and shows a very rapid ascent toward the lake margins.

When compared to the stratigraphic logs of the perilacustrine drillings, the depth of the "G" horizon seems to be consistent with the top of the mainly lavic portion of the BCMS, immediately preceeding the paroxistic emission of the Orvieto-Bagnoregio Ignimbrite. In this view, the "G" horizon represents an unconformity linked to the last major collapse of the structure connected with the OBI emission. The strong seismic evidence of the "G" horizon can be related to the sharp lithologic contrast between the mainly lavic units of the BCMS and the overlaying pyroclastics (OBI) or lavic and pyroclastics units (BCUS). The possibility that the "G" horizon represents the basal surface of the volcanic cover can be absolutely ruled out on the basis of the drilling data.

The"G" horizon shows its greater displacement in the central area of the lake (Fig. 10); the connection between this central zone and the shoreline of the lake is achieved by a narrow area with a steep gradient of the *"**G**"* horizon, especially clear in the eastern sector. In

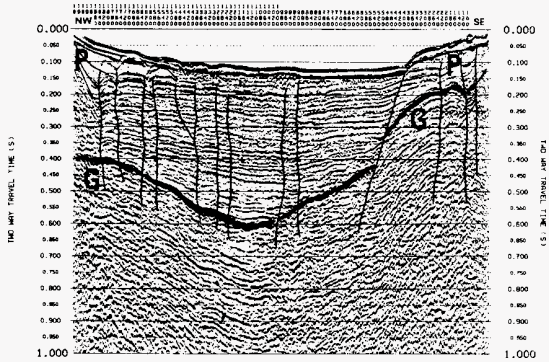

Fig. 7 Line BOL 08-88

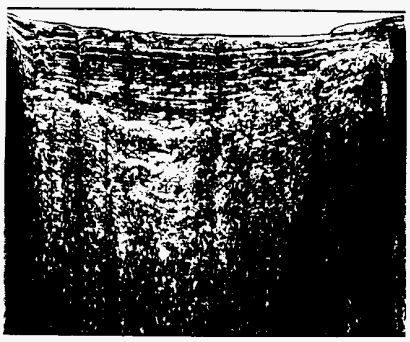

Fig. 8 Line BOL 08-88: reflection strength

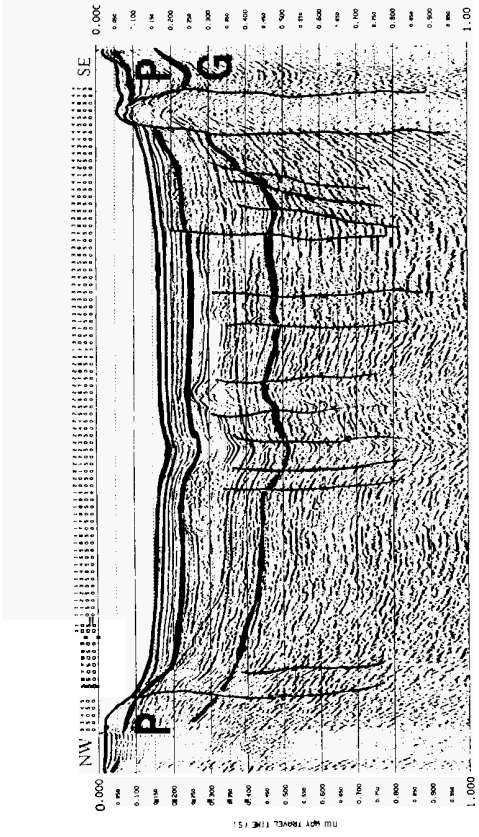

Fig. 9 Line Bol 09-88

this area, where the lavic trachyphonolitic units of BCMS crop out near the shoreline, the "G" horizon shows an anticlinal trend (Figg. 5 to 9); we think that this geometry could reflect the geometry of a narrow step fault (master and associated antithetic faults) displacing this horizon more than 700 meters, similarly to the pericalderic structural arrangement. The deformative style of the overlaying sediments suggests a long term displacement (incremental growth) of the caldera following the mantling of the pyroclastic and epiclastic deposits over the step fault. In the outcropping sequences around the village of Bolsena a further step fault displacement of at least 300 meters affects these trachyphonolitic lavic units. While in the eastern sector the area of strong vertical displacement begins very close to the shoreline, in the northern area it is located in a more landward position (Fig. 10). This evidence, and the shape of the isobathes of the "G" horizon, indicate that the calderic area does not

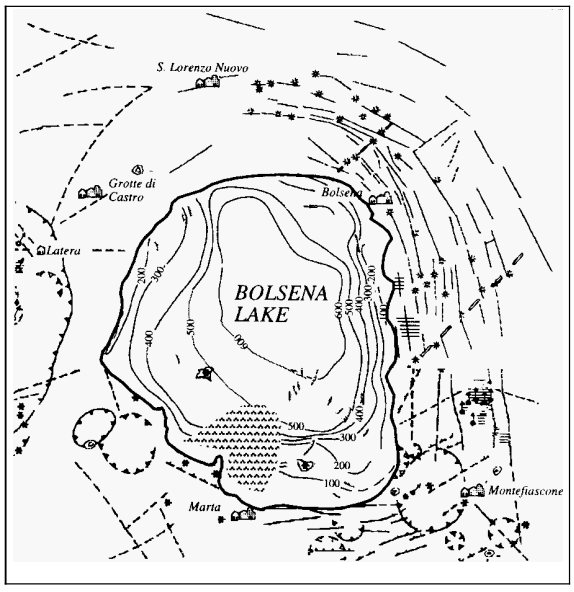

***Fig. 10 Structural sketch of the Vulsini Volcanic District: the lines inside the lake represents the depth of the "G" horizon Structural setting from Cioni** (1993)*

exactly correspond to the present lake, and its sector of greater collapse can be placed in the northern half of the structure. Moreover, this sector shows strong evidences of a late resurgence, post-OBI lacustrine sediments cropping out up to 150 meters higher than the present lake level, probably due to the reactivation of the shallow plumbing systems and to isostatic compensation.

On the contrary, in the western area of the lake the geometry of the "G" horizon seems to be different, its vertical displacement beeing distributed on a wider, brittle deformed belt (Fig. 10).

The seismic data reveal a great thickness of the post-OBI caldera products (Fig. 4); as suggested by their strongly homogeneous seismic facies, at least 1/3 of the products overlaying the "G" horizon in the central area could correspond to the syn-caldera infilling of the OBI flow units. If it was the case, the role of the OBI in the reactivation of the preexisting caldera should be completely revisited.

In this view, the great thickness of "P-G" products inside the lake (Fig. 4) has to be ascribed to the interlayering, above the OBI flow units, of the BCUS volcanics with the main ignimbritic deposits from Latera Complex and with lacustrine sediments. The caldera infilling is particularly clear in the western area of the lake (Fig. 9), where we can observe a prograding sedimentary fan formed by the Latera ignimbrites: this sedimentary wedge is interlayered with lacustrine sediments and with the last products of the Bolsena activity, issued from vents in the northern, reactivated and uplifted, sector. A clear lacustrine sedimentation can be identified in the upper portion of the seismostratigraphic sequence (above the "P" horizon), reaching at least 60 meters in the central area of the lake. These lacustrine sediments appear rarely deformed by sub-volcanic, dome-like structures or interrupted by faults or volcanic vents, so placing the start of their sedimentation in the very final phases of the volcanic activity.

We conclude that the interpretation of the last stages of the Bolsena caldera evolution can be improved in the light of the seismostratigraphic and drillings data; the last important volcanotectonic event coincides with the last major unconformity ("G" horizon), the caldera depression beeing partially infilled by syn-caldera products and by the deposits of the following activity. The brittle deformation continued incrementally, displacing the upper products and, somewhere, the lacustrine sediments of only a few meters.

6. METHODOLOGICAL CONCLUDING REMARKS

In the geothermal exploration of the Monti Vulsini area, ENEL carried out some seismic reflection profiles on land aimed to investigate the deep geometry of the pre-volcanic basement. The seismic response was poor, due to the presence of the unhomogeneous and thick volcanic cover. Aimed at the reconstruction of the structural setting of a geothermal area in a volcanic region, ISMES S.p.A. experimented the application of high resolution seismics of an area with a water cover in a region where land reflection seismic gave always poor results. The presence of a water body can indeed improve the transmission of high frequency seismic signals, allowing to acquire useful material for the study of the geothermal areas surrounding the Bolsena Lake. Recently, an ENEL - ISMES agreement brought to the reprocessing and reinterpretation of the seismic data recorded in the lake.

New stratigraphic and structural insights on the Bolsena Caldera were deduced; the main seismostratigraphic units are related to the outcropping successions and tied to the boreholes stratigraphy; a step fault geometry strongly controls the subsidence of the central blocks of the caldera, in agreement with the structural style of the main outcropping caldera faults. The reinterpretation of the whole seismic survey will permit to trace the shape of the caldera and the geometry of its main blocks, allowing the reconstruction of the evolution of a very complex volcanic area. From a technical perspective, the seismic survey in the lake revealed a sharp improvement of the seismic response due to the presence of water, representing a very homogeneous "first layer" (i.e.: no problem of static corrections). On the other hand, being this survey the first seismic reflection test in the Bolsena Lake, the type of instruments used (boot, cable length, and seismic energy) did not allowed a very deep penetration. It follows that the deepest structures of the carbonatic formations individuated all around the lake by the geothermal wells and geophysical investigations could be defined by a new lake seismic survey, planned to investigate at greater depth. Considering that volcanic lakes are quite common in geothermal regions, their surrounding areas could be investigated by means of such a tecnique adopting an energization/recording system with a water/land configuration.

This metodology may be considered similar to that applied in shallow water oil research, apart from different geological conditions and cost/benefit considerations.

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