# Relative Location of a Microearthquake Cluster at the Larderello Geothermal Field

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## Introduction

On March 20, 1993, seismometers connected to the Larderello seismic network began recording a series of microearthquakes near the Larderello geothermal field in western Tuscany, Italy. Ente Nazionale per L'Energia Elettrica of Italy (ENEL) produced the initial estimates of the hypocentral locations and origin times of the events (Figure 1; ENEL, 1993). The Earth Resources Laboratory (ERL) at the Massachusetts Institute of Technology (MIT) extended the analysis of this cluster in order to accomplish three objectives: (1) to more precisely determine the hypocentral locations using relative event location techniques such that the cluster geometry and overall location might suggest the geologic conditions and structures causing the cluster, (2) to determine focal mechanisms for a portion of the earthquakes to supplement the information from the locations, and (3) to interpret the results from 1 and 2 in light of available geologic and geophysical data.

Relative event location techniques improve upon traditional methods of event location by placing additional constraints on the hypocenters of multiple events in a cluster. The constraints take the form of differential arrival times between pairs of events, and they supplement the usual P and S arrival times picked for each event individually. The incorporation of these additional constraints is suggested by the similarity of waveforms between related evrnts. The fundamental premise is that events with idrntical waveforms must be co-located (or very nearly so) (Geller and Mueller, 1980; Poupinet *et al.*, 1984; Thorbjarnardottir and Pechmann, 1987; Pechmann and Thorbjarnardottir, 1990: Deichmann and Garcia-Fernandez, 1992). We can use this similarity to improve the estimates of event source parameters (i.e. hypocenter coordinates and origin times) if we can identify and compensate for events whose waveforms are dissimilar. To do this we must first consider the cause of waveform variations.

Fremont and Malone (1987) state that variations in waveforms can be attributed to four main causes; fluctuations in the source time functions, changes in focal mechanisms, changes in the properties of the media, and changes in hypocentral location. In order to use waveform similarity to improve the locations, the method of differential travel times requires that the set of seismic events to be located are related to each other in both spatial and temporal aspects. Placing this constraint on the events controls, to a degree, one of the possible sources of waveform variation, specifically variations introduced by changes in the media properties. This is reasonable because if the temporal distribution of events is small, we can assume that the properties of the media have riot changed significantly, and if the spatial distribution is also small then the changes in the travel times introduced by variations in velocity structure is minimized as well (Fremont and Malone, 1987).

The second possible cause of waveform variation that can be determined, if not controlled, is the focal mechanisms of the events. Fremont and Malone (1987) suggest that variations in focal mechanisms usually affects the waveform shape more than the arrival times of the P and S waves and therefore, do not, constitute as strong a constraint as those imposed by the spatial and temporal correlations. In our study, we will show that the focal mechanisms for the Larderello cluster exhibit a high degree of similarity and therefore, no degradation of the waveform is expected from this variation source.

If the events in the cluster exhibit similar waveforms, then we can use cross-correlation techniques to determine the degree of similarity between them, and then either eliminate outliers completely or weight them appropriately in the relative location inversion. By identifying and controlling variations from other sources, we maximize the likelihood that any remaining variations are attributable only to changes in hypocenter coordinates.

Interest in the occurrence of events showing identical or nearly identical waveforms has increased in recent years as high precision location techniques are developed. Multiple events with a strong similarity in waveform have been classified into "families" or termed doublets, triplets or multiplets according to the number of similar events observed (Geller and Mueller, 1980; Frankel, 1982; Poupinet *et al.*, 1984; Fremont and Malone, 1987). An earthquake cluster exhibiting these characteristics is an excellent candidate for relocation using differential arrival time techniques

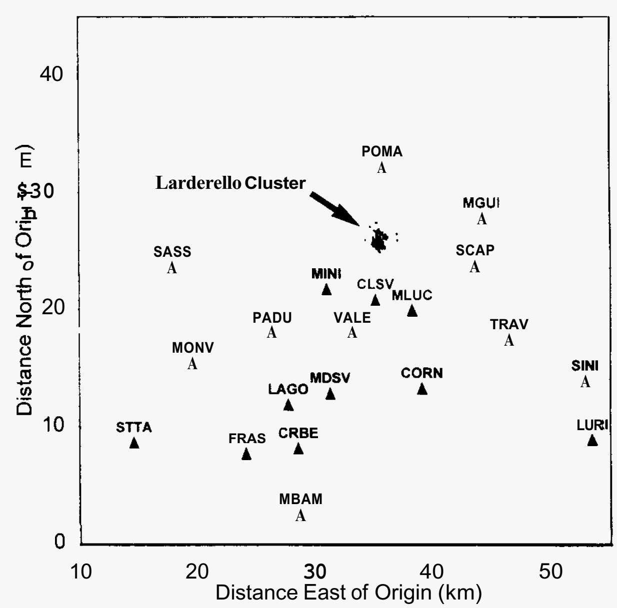


Figure 1: The Larderello seismic network (triangles) and the locatioii of the 1993 earthquake cluster as determined by ENEL. The coordinate system origin is located at Latitude 43°N2'35", Longitude 10°E29'58".

# Methods

## Relative Event Location Using Differential Arrival Times

Our event relocation method fits the hypocenters and origin times of a set of eveiits in a cluster simultaneously to a set of absolute and differential arrival time data observed at various stations. 'The absolute arrival time for an event e, station s and wave type $w$ (P or S) is modeled as

$$T_{esw} = t_e + F(x_e, x_s, u_w) + n_{esw}. \quad (1)$$

Here, $x_e$ is the hypocentral coordinate vector and $t_e$ the origin time of the event. The function $F$ gives the theoretical travel-time between $x_e$ and the station location $x_s$ through an assumed slowness model $u_w$. $n_{esw}$ denotes the observational error in $T_{esw}$. Differential arrival times between a "slave" event $e$ and "master" event $r$ are modeled as

$$\Delta T_{resw} = t_e - t_r + F(x_e, x_s, u_w) - F(x_r, x_s, u_w) + n_{resw}. \quad (2)$$

Note that the observational error in a differential time is not a difference between absolute arrival time errors, because we assume that $\Delta T_{resw}$ has been measured independently of $T_{esw}$ and $T_{rsw}$. An additional source of error occurs in both absolute and differential times when the slowness models $u_w$ are not known exactly, e.g., a 1-D approximate model is often assumed. Such "modeling errors" affect primarily absolute times and tend to cancel in differential times between closely spaced events. We solve equations (1) arid (2) for the $x_e$ and $t_e$, using available $(e, s, w)$ and $(r, e, s, w)$ combinations, by minimizing the errors $n_{esw}$ arid $n_{resw}$ in a least squares sense (Rodi *et al.*, 1993).

The differential arrival time between a slave and master event. for a given station and phase (P or S), is measured by calculating the cross-correlation function between the seismograms from the two events, appropriately windowed to include the phase of interest. Let $x(t)$ and $y(t)$ denote two such seismograms. Their cross-covariance function is defined as

$$S_{xy}(t) = \int x(t')y(t'+t)\,dt' \quad (3)$$

and their cross-correlation function as

$$C_{xy}(t) = \frac{S_{xy}(t)}{\sqrt{S_{xx}(0)S_{yy}(0)}} \quad (4)$$

The peak value of $C_{xy}(t)$ measures the degree of similarity between the two seismograms. To the extent the similarity is high the time lag between the seismograms can be estimated as the time of the maximum peak of $C_{xy}(t)$. This time lag adjusted for window start times, is an estimate of the differential arrival time between the master and slave events.

Figure 2 shows an example of seismograms used in this study, indicating P and S arrivals. Figures **3** and **4** give an example of the cross correlation method applied to S waves.

## Determination of Focal Mechanisms

Focal mechanisms were determined using a computer algorithm developed by Stewart Guinn and L.T. Long (1977). This algorithm uses forward modeling to predict the polarity, or "sense," of the P wave first motions observed at a set of seismic stations. Valid solutions include all focal plane orientations that produce a match between the predicted first motions and the observed ones. In order to accomodate the potential for incorrect first motion determinations in the input data, the user may relax the fit criteria by allowing a set number of predictions to be inconsistent with the observations (Hermann, 1975; Guinn and Long, 1977).

The predicted first motions are modeled by assuming a point dislocation source on a fault plane with a given strike, dip and rake. The modeling is implemented using the well known fact, that two seismic events with different dislocation sources will produce identical first motion patterns (at a given set of recording stations) if the sources lie on orthogonal fault planes and have orthogonal slip vectors. These two sources are represented by the same hypothetical stress tensor whose principal axes are oriented 45 degrees to each of the fault planes. Therefore, the search for valid planes is parameterized in terms of these principal stress axes, i.e. the compressional, tensional, and null axis ("P","T", and "B",respectively). Consequently, for each orientation of the stress axes, the algorithm calculates the two fault planes and slip directions that correspond to the focal mechanism solution. The final output consists of the azimuth and plunge of each axis and the strike, dip and rake for each plane that produces a match to the observations (Guinn and Long, 1977).

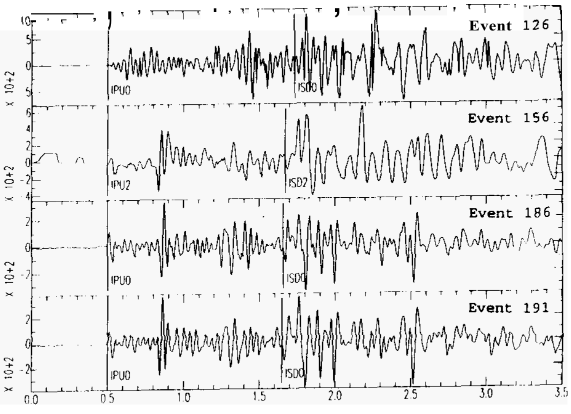


Figure 2: Seismograms for four master events recorded at station POMA.

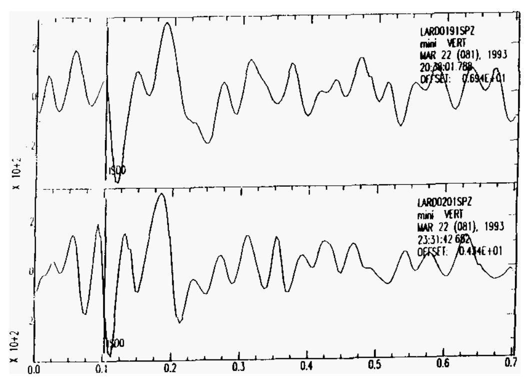


Figure 3: S wave windows for a master and slave event pair recorded at station MINI.

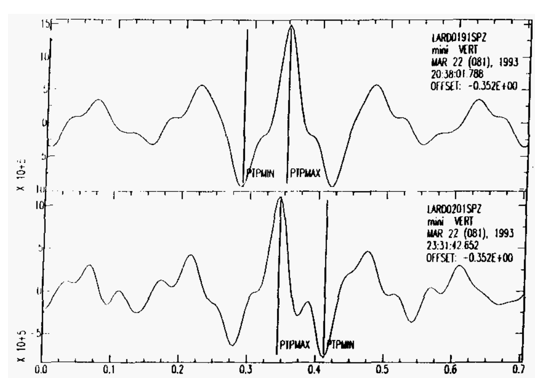


Figure 4: Auto- and cross-covariances of S wave windows for the master slave pair shown in Figure **3.**

# Results

## Hypocenter Relocation

The 1993 Larderello microearthquake cluster is an appropriate choice for the application of multiple event relocation using differential arrival times because it meets the similarity criteria discussed earlier. The cluster occurred in a spatially restricted zone near the northern boundary of the Larderello geothermal region. An evaluation of the waveforms indicated a high degree of similarity, suggesting that the true locations are closely located (Figure 2). Temporally, the cluster occurred over the course of a few days, with origin time intervals ranging from minutes to hours. The waveform similarity suggests that the events can be classified into multiplets, which supports the use of cross-correlation techniques.

The cluster was recorded by the Larderello seismic network which is a local array of thirty-one short period seismometers (Figure 1). ENEL provided MIT with seismic records of 200 events recorded by twenty-one of the thirty-one stations. Nineteen of these stations were equipped with seismometers that recorded the vertical component of ground motion only. The remaining two stations recorded all three components, i.e. north, east and vertical.

Eighty-six events from the Larderello cluster were analyzed in three phases beginning with the determination of the absolute and differential times, followed by inversion for event source parameters (i.e. hypocentral locations and origin times), and finally calculation of focal mechanisms. The 86 events were divided into four subsets of consecutive events. Differential times were determined for each event in a subset by referencing one of two master events from that subset. The masters were chosen to represent typical waveform types from two multiplets observed in the seismograms. Usually, a slave event would exhibit higher correlation with one or the other masters and subsequently, the differential times derived from this pair would be used in the relocation inversion. Event pairs with correlation coefficients below 0.58 were rejected from the data set. Figure 2 presents seismograms for four of the eight master events. These masters produced the highest correlations.

The results of the relocation confirmed the absolute location of the cluster as determined by ENEL (Figure 1). However, the relative locations of the events, when taken in smaller subsets, revealed spatial trends not immediately evident in the full set of locations. Figures 5, 6, and 7 present the epicentral relocations for three of the subsets. The events presented here represent the highest quality solutions from which all outliers have been removed. The semi-major axis of the 90 percent confidence regions for these epicenters range from 171 meters to 586 meters. The relocated depth estimates range from **4.5** to 5.5 kilometers with uncertainties of 156 meters to 801 meters. Figure 8 presents the original epicentral locations for the same events presented in Figure 5.

## Focal Mechanisms

Focal mechanisms were determined for 17 events in the Larderello microearthquake cluster using first motion P wave data. The clarity of the P wave arrivals was excellent at most stations and no problems were encountered discerning the sense of the motion (Figure 2). Focal mechanisms were calculated using a search increment of 10 degrees, as recommended by Guinn and Long (1977), and the number of inconsistent first motions was limited to one or zero. Events for which focal mechanisms could be determined were recorded by between **13** and 16 stations, generally including CLSV, CORN, CRBE, FRAS, FROS, LAGO, LURI, MRAM, MDSV, MGUI, MINI, MONV, POMA, SCAP, TRAV, VALE, and MLUC (Figure 1).

The fault plane solutions for the 17 events exhibited little variation and all indicated reverse faulting with varying degrees of strike-slip. Figure 9 presents the results of four representative mechanisms as determined from the 17 events.

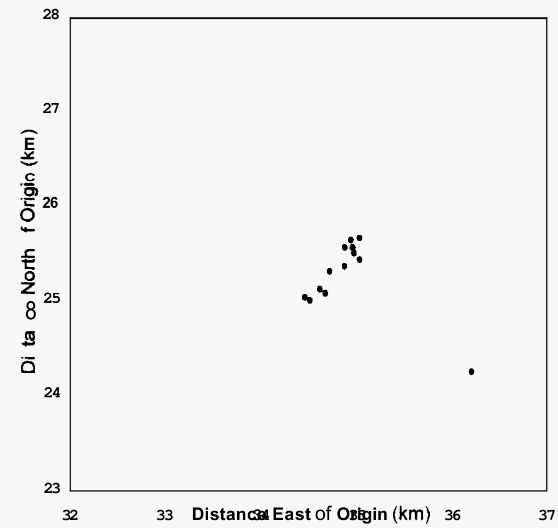


Figure 5: Map view of a subset of the microearthquakes from the March 1993 Larderello earthquake cluster as relocated by MIT (Events 188–218).

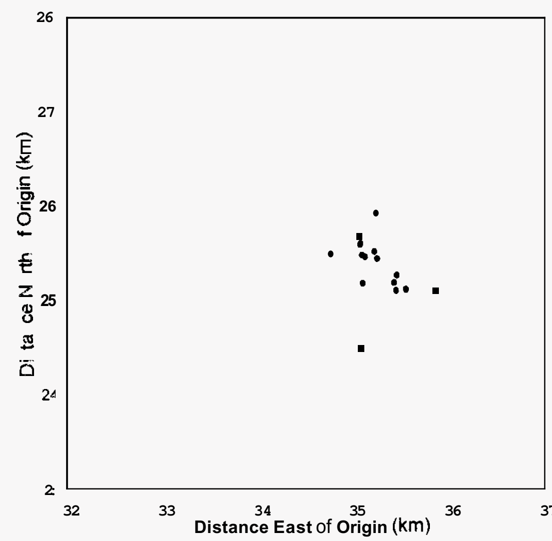


Figure 6: Map view of a subset of the microearthquakes from the March 1993 Larderello earthquake cluster as relocated by MIT (Events 157–187).

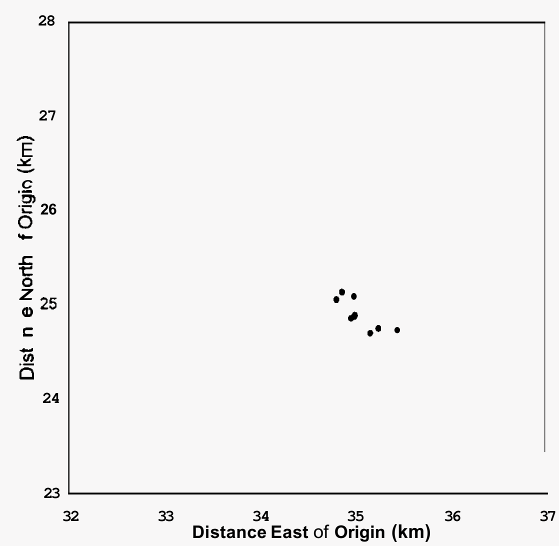


Figure 7: Map view of a subset of the microearthquakes from the March 1993 Larderello earthquake cluster as relocated by MIT (Events 116–140).

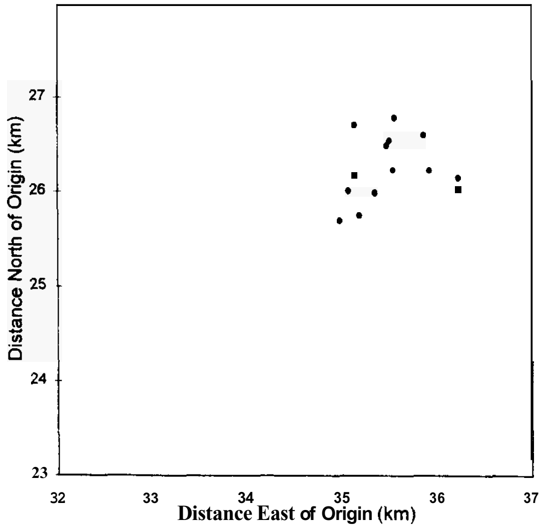


Figure 8: Map view of a subset of the microearthquakes from the March 1993 Larderello earthquake cluster as originally located by ENEL (Evrnts 188 218).

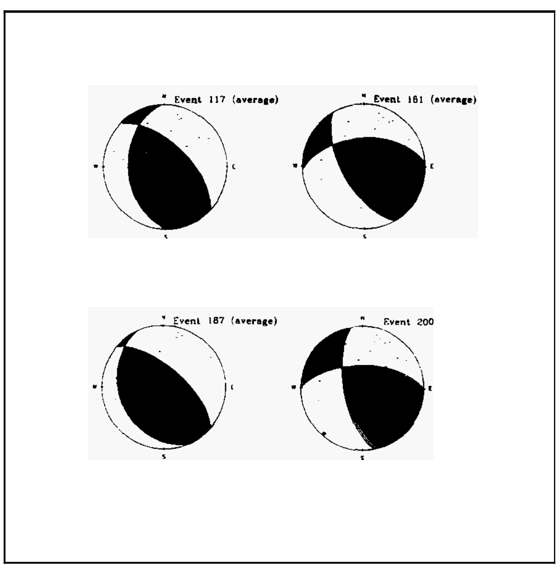


Figure 9: Focal mechanisms for four events. These examples are representative of the range of solutions found for seventeen events from the March 1993 Larderello cluster.

## Discussion

The Tuscany region of Italy is associated with the Tyrrhenian-Apennine orogenic system which trends NW-SE through the Italian peiiinsula. Structures within this region reflect at least three separate phases of tectonic disturbances, which are recognized by remnant features in both the sedimentary formations and in some of the basement units (Carmignani and Kligfield, 1990; Cameli *et al.*, 1993).

The first disturbance, an Eocene-Oligocene phase of compression? is referred to by Carmignani and Kligfield (1990) as the D1 phase and is represented by structural features created during the initial collision of the Corsica-Sardinia microplate with thr Adriatic microplate. The D1 phase created nappe structurrs by displacing preexisting sedimentary formations along detachment horizons (Carmignani and Kligfield, 1990). The sedimentary formations involved in the nappe building are identified as the Liguride complex and the Tuscan Nappe. These two units are overlain by Neogene sediments (Cameli *et al.*, 1993: Block. 1991; Batini *et al.*, 1985a). The Tuscan nappe is underlain or replaced by the Monteciano-Roccastrada unit and a pre-Alpine gneiss complex. Metamorphism affecting this unit predates the D1 disturbance and included the formation of northeast-southwest trending fractures (Batini *et al.*, 1985a; Cameli *et al.*. 1993; Carmignani and Kligfirld, 1990; Block, 1991j.

The D1 compressional stress that lead to the displacement of the Liguride and Tuscan sedimentary sequences onto the core complex was followed in the late Tortonian (Miocene) by a period of post collisional extension (referred to by Carmignani and Kligfield as the D2 deformation). Effects of the D2 deformation on the upper crust can be seen in the northwest-southeast trendiiig extensional normal faults. Vertical displacement along these fractures created Horst-Graben structures into which sediments deposited during the Miocene and Pliocene (Neogene sediments) (Cameli *et al.*, 1993; Carmignani and Kligfield, 1990).

The third episode of tectonic disturbance includes Pliocene and later age magrriatism and volcanics (Puxeddu, 1984). This magmatism is thought to be responsible for the formation of the Quaternary volcanics located in Tuscany as well as numerous granitic intrusions ernplaced throughout the geothermal regions.

Batiui *et al.*(1985b) identified several seismically reflective horizons which correlate well with the Liguride, Tuscan, and "Basement" units. In addition, another reflector, known as the "K" horizon. has been identified below these. It is regionally extensive, covering large areas in southern Tuscany and varies in depth from as shallow as 2.8 km in the southern Larderello geothermal field to greater than 9 km near Montalcinello (20 km cast) and other locations (Cameli *et al.*, 1993; ENEL, 1988). Although its exact nature has not been clearly established, several possibilities have been proposed including that the "K" horizon represents a zone of fluid-filled fractures or that it represents a rheological houndary between brittle and ductile crust (Batini *et al.*. 1985b; Cameli, 1993).

The Larderello geothermal field is a vapor dominated, hydrothermal type field producing steam primarily from zones associated with anhydrites at the base of the Tuscan nappe (Puxeddu *et al.*, 1977). The geothermal source at Larderello is thought to be a granitic type intrusion at depths ranging from 6 to 40 km (Batini *et al.*, 1985a; Block, 1991).

Two geologic structures which might be seismically active are located near the 1993 Larderello earthquake cluster; specifically, the NW-SE trending. high angle, normal faults and the seismic "K" horizon which is located between **4.4**and 5 km depth in this area (ENEL, 1988). The relocated epicenters of some of the earthquakes are shown in Figures 10 and 11 along with the locations of the faults and "K" horizon contours. These relocations indicate spatial distributions with strong linear trends. These trends agree in direction with the northwest-southeast trending D2 faults and the northeast-southwest pre-Alpine faults. The orientation of the slip plane from the focal mechanisms also strongly suggests ari association between the events and **the** northern-most high angle fault. The relocations for events 116 through 187 (Figures 6 and 7) show the direction trend of iiorthwest-southeast, suggesting that the predominant association is with the D2 Tortonian faults. The relocations indicating the northeast-southwest trend were derived from events which occurred later in the cluster (Figure 5). Additional relocations of events after number 218 may clarify whether a temporal evolution of the spatial distribution occurred in the Larderello cluster.

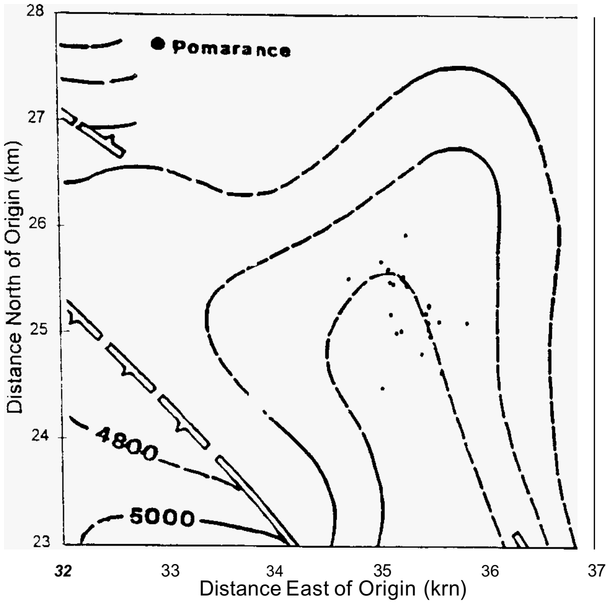


Figure 11: Epicentral relocations of events 188-218 in the March 1993 Larderello microearthquake cluster. Also shown are the locations of the high angle normal faults and the depth contours of the seismic "K" horizon.

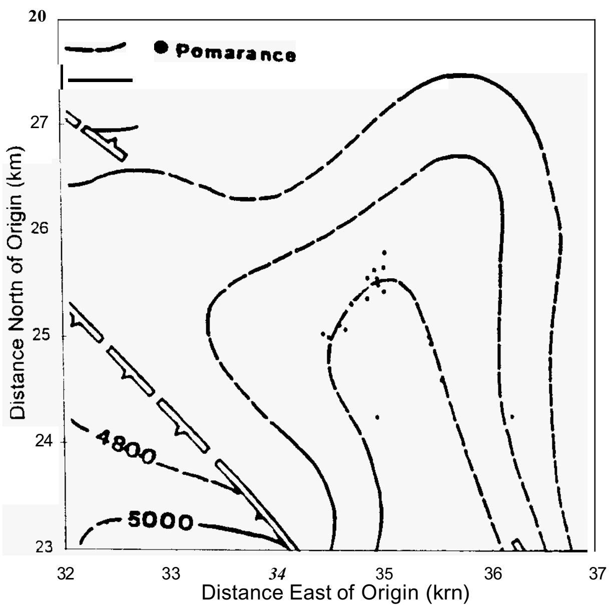


Figure 10: Epicentral relocations of events 157-187 in the March 1993 Larderello microearthquake cluster. Also shown are the locations of the high angle normal faults and the depth contours of the seismic "ti" horizon.

## Conclusions

The results of the relocation of the March 1993 Larderello microearthquake cluster place the events near the northern boundary of the vapor-dominated geothermal reservoir. Spatial distributions of the relocated hypocenters suggest a strong association with northwest-southeast trending Tortonian age faults and northeast-southwest trending pre-Alpine faults in the gneissic basement units. In addition. these events occurred between 4.5 and 5.5 kilometers in depth near a seismic reflector referred to as the "ti" horizon, which is thought to represent a zone of fluid filled fractures. This suggests a possible interaction between the pre-existing structures and the hydrologic conditions at the site which might be clarified by additional hypocenter relocation.


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