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TUSNAD-BAI - A GEOTHERMAL SYSTEM ASSOCIATED WITH THE MOST RECENT VOLCANIC ERUPTION IN ROMANIA

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ABSTRACT

Carbon dating (^{14}C) ages ranging between 10,700 and >42,650 years BP have been reported by various investigators for organic matter (charcoal fragments included in a pumice flow deposit; paleosoil underlying the pumice deposit) from Ciomadul volcano, next to Tusnad-Bai. This is the most recent volcanic eruption in Romania documented to date, and it implies the existence of a still active magma chamber, with which a high temperature (>225°C) geothermal system might be associated. The most significant hydrothermal activity in the area consists of a lineament of springs that discharge about 5 kg/s (aggegate flow rate) of sodium chloride thermal water which is CO_2 rich, relatively low in TDS (1.5-4.5 g/l), and has a maximum temperature of 23°C. The Na-K geothermometer indicates that the spring waters could have originated from a hot (≈300°C) reservoir of thermal fluid. At the same time, the K-Mg geothermometer points out that chemical re-equilibration becomes more advanced further south. Actual outflow temperatures of the springs and their TDS contents accordingly decrease southward. Next to the thermal springs a well has been drilled to a total depth of 1120 m. During tests it discharged 4 kg/s of sodium-bicarbonate, thermal water, with 12.5-13 g/l TDS, at a temperature of 63°C. The Na-K geothermometer indicated that, compared to the springs, the water discharged by the well originated in a reservoir separate from and cooler than (at ≈180°C) the reservoir which conceptually feeds the aforementioned thermal springs. The poorer results of the well (compared to the geothermometer indications of the springs), also suggest that the area of surface hydrothermal manifestations at Tusnad-Bai represents only a lateral, shallow outflow from a more distant and deeper, hot geothermal system (possibly located several kilometers to the north). In similarly mountainous areas, such settings have been previously recognized world-wide. Thermal gradients recorded in shallow (<50 m deep) boreholes provide additional evidence for the inferred setting: the 250°C/km contour extends northward from the surface discharges, over lava domes which are significantly less permeable than the pyroclastics from which the thermal springs emerge. Such a high thermal gradient recorded on a virtually impervious formation also suggests that a lateral, southward directed outflow probably occurs beneath that lava dome.

1. INTRODUCTION

Most countries in continental Europe display virtually no traces of recent volcanic activity (Italy is the outstanding exception). After 1990, evidence of late Quaternary eruptions has been, however, identified also for Ciomadul volcano, in the South Harghita mountains, in Romania. The long known hydrothermal surface manifestations situated nearby provide, under this new perspective, indications of a geothermal system possibly related to a still cooling pluton.

Consequently, an assessment procedure specifically devised for geothermal resources associated with active volcanic areas (Hochstein, 1990) was adopted. Intensive use was made of the Na-K-Mg geothermometry (Giggenbach, 1986, 1988), corroborated with former investigation results.

2. STUDY AREA

2.1. Volcanologic setting

The East Carpathian mountains include a Neogene-Quaternary volcanic arc, related to a complex collisional pattern between the Eurasian and the African plates. The volcanic history lasted ca 9.5 Ma, with the oldest activity occurring in the northern parts, and the youngest at the southern chain terminus (Szakacs and Seghedi, 1995). Strong seismic activity suggests that the final stage of an active, intraplate subduction of the lithosphere could still be in progress in the southern section of the ridge (Kiratzi, 1993). The probable location of the subducting slab, as indicated by the seismological models, is overlain by the volcanic structures of the South Harghita mountains.

No volcanic event has been recorded historically in this area. Yet the assumption of South Harghita volcanoes being rather young was for a long time supported by a few obvious facts (Radulescu *et al.*, 1981):

- the fresh-looking morphology of the Sfanta Ana crater, in Ciomadul massif;
- vents releasing dry CO_2 and hot sulfur gases, most probably of magmatic origin.

More recently, a deep gas contribution of about 50% from the mantle was suggested by high $^3He/^4He$ ratios (up to 4.61 R/R_A, with R=measured value and R_A=air value, 1.39×10^{-6}) recorded in CO_2 rich gases close to Sfanta Ana crater lake (Abbado *et al.*,1998).

Currently available data indicate that the youngest eruption of Sfanta Ana crater is constrained by a ^{14}C age of 10,700 years, obtained on a charcoal piece engulfed in a pyroclastic flow deposit (Juvigne *et al.*, 1994), and a ^{14}C age of >42,650 years obtained on a paleosoil underlying the pumice fall deposit (Moriya *et al.*, 1996). This is the most recent volcanic eruption in the Carpathians and in the whole of Eastern Europe.

2.2 Surface manifestations

The existence of a deep geothermal reservoir was suggested in the first place by several warm springs (15-23^{o}C) at Tusnad-Bai. Springs emerge from a pyroclastic dacite formation at the bottom of Ciomadul volcano (Fig. 1) and discharge 8-10 kg/s aggegate flow rate of sodium chloride, CO_2 rich, relatively low TDS (1.5-4.5 g/l), near neutral pH water (***, 1961, Pricajan, 1972, Peter, 1984).

Shallow (<50 m deep) thermal gradient holes completed in this area (Radulescu *et al.*, 1981) outlined two maxima of 250-400^{o}C/km (Fig. 1). For the most part, the maxima correspond to the emergence area of the previously mentioned springs. As a result, it was formerly assumed that the only origin of the recorded anomalous thermal gradients was vertical upflow along fractures.

2.3 Possible reservoir rocks

The best reservoir properties have been assessed to be those of the *pyroclastic* rocks from which the thermal springs at Tusnad-Bai emerge (Radulescu *et al.*, 1981, Peter, 1984). Pyroclastics form the main, twin cratered cone of Ciomadul (Szakacs and Seghedi, 1995), a massif that occupies mainly the eastern bank of the Olt river, although it extends also to the west of the stream valley, where it is in contact with the adjoining Pilisca massif (Fig. 1). In spite of this large extent, there is so far no evidence of pyroclastics being buried to any significant depth. Hence, they can not be considered as hosts of a deep geothermal reservoir in this area.

Dacitic (and occasionally andesitic) *massive volcanics* occur as lava flows and parasitic summit and flank lava domes, superimposed on the Ciomadul pyroclastic cone, as well as a steep sided lava dome complex forming the upper structure of the Pilisca massif (Pecskay *et al.*, 1992). Beneath the latter massif, lava is liable to occur at greater depths (Fig. 3); still its permeability is ranked as rather poor and restricted to fractures and alteration zones (Radulescu *et al.*, 1981, Peter, 1984).

The volcanic structure of Ciomadul, and to some extent also those of Pilisca, are directly underlain (Szakacs and Seghedi, 1986) by a basement consisting of the folded Cretaceous *flysch* series of the East Carpathians (Fig.3). Similarly to the lava flows and domes, flysch formations are virtually impervious, with feeble water flows occurring only along fractures. It has been inferred (Peter, 1984) that a common sandstone sequence, the "Bodoc flysch", outcropping to the east of the prospect area and displaying better reservoir properties, might also exist at depth at Tusnad-Bai.

Beneath the flysch basement, several wells drilled in Tusnad-Bai next to the Olt streambed (Fig. 3), intercepted a *volcanic intrusion* at 400 - 700 m below the ground surface, (Radulescu *et al.*, 1981, Peter, 1984). The petrochemical character of the intrusion is similar to that of constituents in the Ciomadul volcanic structure. None of the wells entirely traversed the intrusion, which was thus proven to exceed 400 m in apparent thickness. Poor to moderate productivity was recorded during well tests (see 2.4 below).

2.4 Deep drilling

In the late seventies, a deep drilling program targeted the two previously mentioned thermal anomalies (Fig. 1) associated with the warm springs at Tusnad-Bai (Radulescu *et al.*, 1981, Peter, 1984). The drilling showed that the shallow high thermal gradients (250-400^{o}C/km) sharply decrease with depth to moderately above-normal values (40-70^{o}C/km), to virtually an isothermal profile.

The highest downhole temperature, 78^{o}C, was recorded at the bottom (1140 m) of well 320. During tests, the well discharged 4 kg/s of sodium bicarbonate, 12.5-13 g/l TDS, nearly neutral (pH values of 7.2-7.5), 63^{o}C water. The reservoir rock was the volcanic intrusion intercepted beneath the folded flysch basement (Fig. 3). Thermal alteration products (mainly calcite, and sporadically quartz, kaolinite, chalcopyrite and pyrite) occur inside the reservoir formation.

The other well, 322, of 750 m total depth, had poorer results in terms of both its maximum bottomhole temperature (54^{o}C), and output (46^{o}C well head temperature, recorded during a 2 kg/s swabbing discharge test).

3. Na-K-Mg GEOTHERMOMETRY

Empirical geothermometry performed on thermal water samples from Tusnad-Bai (Craciun and Bandrabur, 1993) provided ambiguous results.

Compared to empirically calibrated geothermometers, procedures based on theoretical thermodynamic considerations may take into account a wide range of processes that affect a geothermal solution during ascent. Such an investigation tool, to provide additional hints on the "thermal history" of the fluid, was devised through the combination of the Na-K and K-Mg geothermometers (Giggenbach, 1986, 1988).

3.1 Basic principles of the method

It has been frequently observed that for the same sample, each of the two (Na-K and K-Mg) geothermometers indicated significantly different apparent temperatures of equilibration. The explanation is that the K-Mg reaction responds much faster to a change in temperature and, therefore, estimates cooler temperature than does the Na-K reaction.

The method uses a triangular diagram (fig. 2), with the Na-K isotherms converging to the K (bottom right) corner, while the K-Mg isotherms converge to the Na (top) corner. Fluids sampled directly from a deep reservoir (through well bores) plot close to the "full equilibrium line". Conversely, when fluids of the same reservoir are sampled from surface springs, they plot virtually on the same Na-K isotherm as the "deep" samples, yet severely shifted to "cooler" K-Mg isotherms. Hence, the shift in K-Mg temperature is likely to be a function of the time taken by the water to rise from its deep reservoir to the surface.

The application of the Na-K-Mg geothermometer is rather straightforward, being, however, subject to a series of restrictions:

1. it is valid only for near-neutral chloride-bicarbonate waters, but not for acid sulfate, or chloride sulfate waters;
2. data points that plot close to the far-from-equilibrium Mg-corner (in the area marked "immature waters") are liable to have undergone admixing usually with low temperature, high

magnesium, bicarbonate waters; in this case application of both Na-K and K-Mg geothermometers becomes doubtful and great care should be taken in interpreting the suggested temperatures.

3.2 Results obtained in Tusnad-Bai area

The combined Na-K-Mg geothermometer method has been applied to water samples collected (***, 1961, Peter, 1984, Craciun and Bandrabur, 1993) from the thermal springs lineament Ileana - Ana - Apor - Mikes and from the deep wells 320 and 322. As previously mentioned (2.2 above), the sampled waters are neutral, of sodium chloride (occasionally sodium bicarbonate) type, and as a result they comply with requirement 1, above. On the other hand only the samples from well 320 fall within the "partial equilibrium" domain, and hence are fully appropriate for the analysis provided by the Na-K-Mg geothermometer. In the case of the other samples, that fall within the “immature waters” diagram area, additional evidence was brought forward in order to corroborate the proposed interpretation.

An obvious feature on the diagram is that, although the sampling sites are concentrated on a quite restricted area (especially the warm springs and the well 320), the data points plot on two distinct Na-K isotherms: approximately 180°C for the well data points, and 300°C for the springs. This setting suggests that the springs on one hand, and the deep wells on the other, are supplied by two distinct deep reservoirs, of highly contrasting temperatures.

Another striking characteristic is that the sequence of the diagram data points, when considered with respect to their deviation from the "full equilibrium" line, is somehow analogous to the succession of the sampling sites.

- in the case of the wells, a shift to "cooler" K-Mg temperatures takes place from south to the north (i.e. from well 320 to well 322);
- in the case of the springs, if Ana and Ileana are taken as the origin, there is a definite shift to "cooler" K-Mg temperatures southwards (i.e. towards the Apor and Mikes springs). Other warm springs (not plotted on the diagram) shift even further towards low K-Mg temperatures.

4. DISCUSSION

The present analysis, based primarily on the Na-K-Mg geothermometry corroborated with past results, provides additional information on the geothermal prospect at Tusnad-Bai in two respects: its location (Fig. 1,3) and thermal condition.

4.1 Location of the deep geothermal reservoirs.

The Na-K-Mg geothermometer results clearly indicate that the water discharged by the warm springs at Tusnad-Bai *does not originate* in the aquifer below, intercepted by the deep wells 320 and 322 drilled near the springs. Under these circumstances, it is of interest to track the origin of the fluids in the warm springs on one hand, and of those in the deep wells on the other.

The apparent cooling indicated by the K-Mg temperatures between well 320 and well 322 suggests that the 180^{o}C deep reservoir which supplies the aquifer tapped by those two wells is situated somewhere southward of well 320. Currently there seems to be no further way to locate it more precisely.

As for the warm springs, the apparent cooling recorded by the K-Mg temperatures, corroborated with the coherent decrease of the outflow temperatures and TDS values which is recorded southwards (Pricajan, 1972), suggests that their source reservoir is located to the north. This interpretation is also supported by the shallow thermal gradients reported in Radulescu *et al.*, 1981: the 250^{o}C/km contour extends also northward from the surface discharges (Fig. 1), over lava domes of the Pilisca massif, which are significantly less permeable than the pyroclastics from which the thermal springs emerge. Such a high thermal gradient recorded in a virtually impervious formation clearly suggests that a lateral, southward directed outflow probably occurs beneath the lava dome of Pilisca.

There seems to be a similarity between the described setting (Fig. 3), and the conceptual models of either intermediate or high temperature systems occurring beneath a mountain, as illustrated by Hochstein, 1990. According to this author's scheme, warm, near neutral NaCl type springs, like the ones at Tusnad-Bai, form outflow discharges which are generally located several kilometers away from a main geothermal reservoir. In many geothermal projects conducted worldwide, such outflow structures have been misinterpreted as primary reservoirs and deep wells have been unsuccessfully drilled in their close proximity. This seems to have also happened in the Tusnad-Bai area, hence it appears reasonable to shift future exploration for geothermal resources further to the north, on the northeastern slopes of Pilisca massif.

There is also an indirect element in support of such an approach: the youngest volcanic activity documented so far, in the Ciomadul massif, is a biotite amphibole dacite (Szakacs and Seghedi, 1986); the upper structure of the adjoining Pilisca massif consists of lava domes that have a similar petrochemical composition, suggesting that volcanic activity simultaneous to that of Ciomadul might have developed here too (Pecskay *et al.*, 1992). Consequently, there is no evidence to contradict the assumption that a magma chamber supplied both the lava domes of the Pilisca upper structure and the Ciomadul pyroclastic cone. Such a magma chamber, and implicitly the associated deep geothermal reservoir, could be located beneath Pilisca mountain, on the western bank of the River Olt.

4.2 Temperature of the deep geothermal reservoir

K-Mg temperatures and natural heat discharge values are the main criteria proposed by Hochstein (1990) for assessing geothermal systems with respect to their temperatures. Possible evidence in support of either an intermediate (125-225^{o}C), or high (>225^{o}C) temperature system iassociated with the warm springs at Tusnad-Bai is discussed below.

Intermediate temperature system

The highest K-Mg geothermometer temperature (~125^{o}C), indicated by the Ana spring, falls in the lower bound of the intermediate temperature domain.

The total heat naturally discharged by the currently known springs in Tusnad-Bai (cf. 2.2 above), realisticaly amounts to about 0.5

MW_t (by adopting the local annual average temperature value of 6°C, indicated by Craciun and Bandrabur, 1993). This heat discharge value is very low, even for intermediate temperature systems (that according to Hochstein, 1990, should discharge between 3-30 MW_t). Additional, concealed thermal water outflows might, however, occur under the streambed of the Olt river, which in the considered area has a minimum discharge of about 2 m^3/s.

High temperature system

Since over only a few hundred meters between the Ana and Ileana, Apor and Mikes springs, the K-Mg temperatures exhibit a progressive "cooling" of about 50°C (Fig. 2), an analogous K-Mg temperatures "heating" could be inferred from Ana and Ileana spring "upstream", toward the deep reservoir. On the other hand, in order to have a natural discharge of at least 30 MW_t (the lower bound of high temperature systems, according to Hochstein, 1990) the previously inferred concealed outflow into the Olt river streambed must be really significant (e.g. a heating of at least 4°C should be recorded under minimum discharge conditions).

5. CONCLUSIONS

The possible existence of a geothermal system associated with the young volcanic activity in the South Harghita mountains was considered in the light of recent advances in chemical geothermometry and assessment principles of geothermal systems.

The analysis indicates that an intermediate or high temperature deep reservoir could occur a few kilometers away (probably to the north) from the surface manifestations at Tusnad-Bai. The thermal springs at Tusnad-Bai appear to be a lateral outflow of this deep reservoir, while currently existing well bores discharge water from a much cooler reservoir, completely separate.

Further information on the geothermal potential of the deep reservoir inferred to exist north of Tusnad-Bai may be readily obtained by detailed discharge, temperature and chemistry surveys of the Olt river in the considered area. On the other hand, a more precise delineation of the reservoir requires detailed exploration studies (electrical resistivity, shallow thermal gradient holes, deep drilling).

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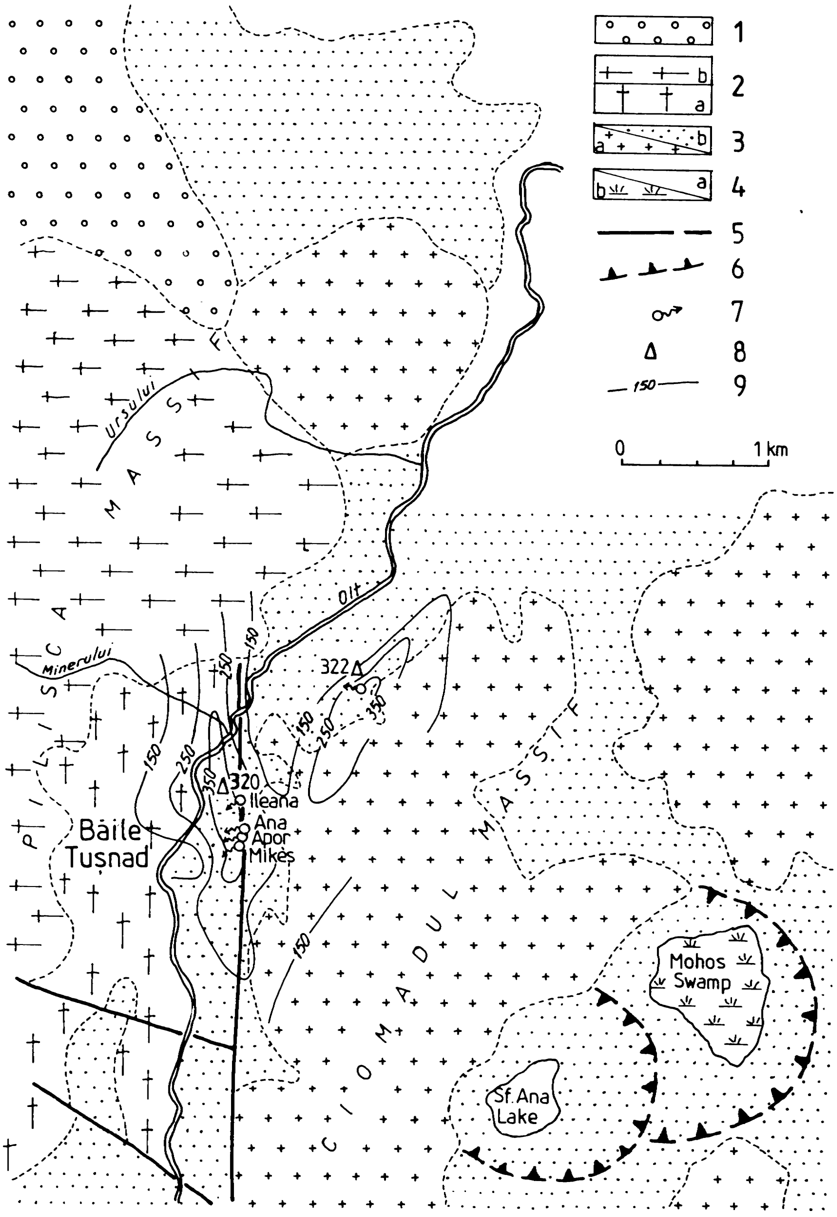

Figure 1. Volcanological and hydrothermal setting in Baile Tusnad area (geology after Pecskay *et al.*, 1992; shallow thermal gradient contours after Radulescu *et al.*, 1981). 1 - Volcaniclastics (the so-called volcanic-sedimentary formation); 2 - Pilisca volcanic structure: a-lava flows; b-lava domes; 3 - Ciomadul volcanic structure: a-lava flows and domes; b-pyroclastics; 4 - Quaternary: a-alluvium; b-swamp; 5 - Fault; 6 - Remnant of crater rim; 7 - Thermal spring; 8 - Geothermal well; 9 - Shallow thermal gradient (^{o}C/km).

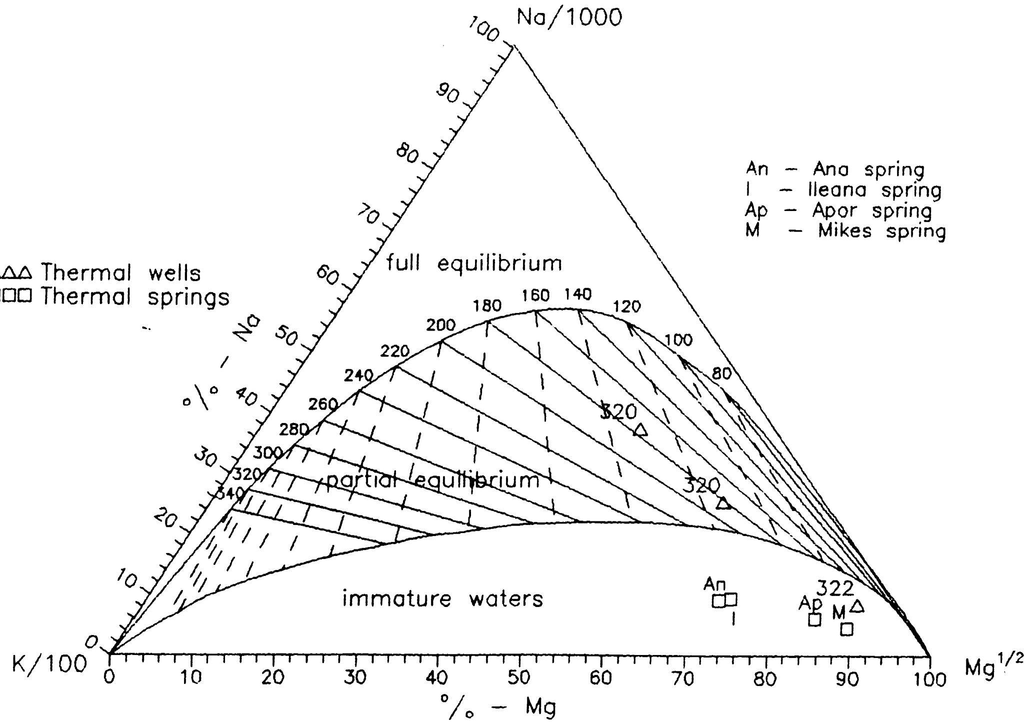

Figure 2. Relative Na, K, Mg contents of geothermal waters in the Baile Tusnad area (diagram for evaluation of water rock equilibration temperatures, according to Giggenbach, 1986).

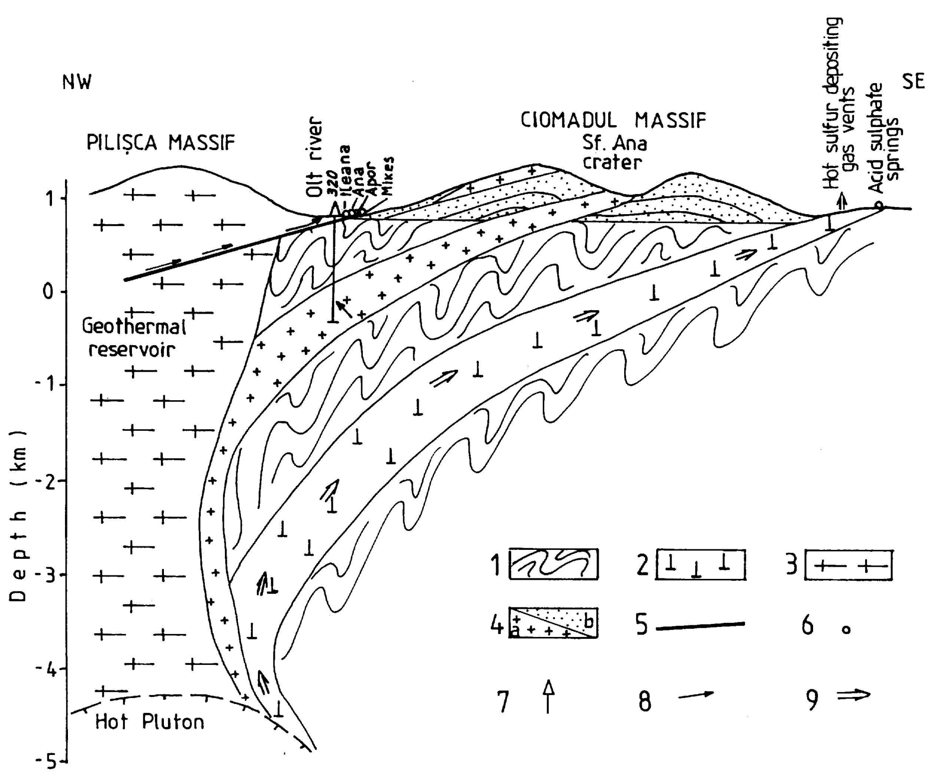

Figure 3. Schematic hypothetical cross-section of the volcanic and geothermal structures. 1 - Cretaceous flysch; 2 - Calc-alkaline extrusive dome; 3 - Lava dome of Pilisca volcanic structure; 4 - Ciomadul volcanic structure: a-lava flows and domes; b-pyroclastics; 5 - Fault; 6 - Thermal spring; 7 - Geothermal well; 8 - Geothermal water inflow; 9 - H_2S flows.