Dating the varnishes of active Petousi-Souli fault zone (Northwestern Greece) using Portable XRF

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In this paper, the dating of Petousi-Souli fault zone (PSFZ) is being studied through a chemical analysis of the rock varnishes which identified in the outer fault surface. Several attempts have been made to identify the ages of geological and tectonic phenomena that develop on the surface of the earth. Other times using absolute dating methods, such as Radiocarbon dating (^{14}C) and Luminescence dating, and others through the use of more qualitative analyzes which, although they lag behind in accuracy, outweigh the speed at which the result is obtained. Such a method is the dating from the observations and the chemical analysis of rock varnishes.

Methods

The methodology applied to determine the ages of Petousi-Souli fault zone is based on the chemical analysis of rock varnishes with the methods from Dorn (1983; Eq. 1) and the calibration of Nobbs and Dorn (1988; Eq. 2):

$$R_C = (Ca^{2+} + K^{+}) / Ti^{4+} \qquad (1)$$

where, Ca^{2+}: is the percentage concentration of Calcium (%), K^{+}: is the percentage concentration of Potassium (%), and Ti^{4+}: is the percentage concentration of Titanium (%).

$$T = e^{\frac{16.218 - R_C}{1.137}} \qquad (2)$$

where, T: is time and R_C: is the cation-ratio, resulting from above equation (2).

It is a method that has been applied in many areas of the world and especially in petroglyphs, using either a Scanning Electron Microscope or Portable X-Ray Fluorescence. More specifically, in this study the chemical analysis was applied using the EDX POCKET III P730 - QUALITEST XRF mobile spectrometer.

Study Area

As the study area determined the PSFZ, which located on the central part of northwestern Greece (Fig. 1A). The PSFZ features one of its largest tectonic structures, of a total length of approximately 36.5 km, generally trending E-W, with a southern inclination. The Petousi-Souli fault zone constitutes the largest fault zone of northwestern Greece, while forming at the same time a natural boundary between its northern and southern part.

It is classified as active because of its intense morphology and the impressive surface trace consisting of well-preserved fault surfaces which has deep and well-marked striations and canellures (Fig. 1B and C).

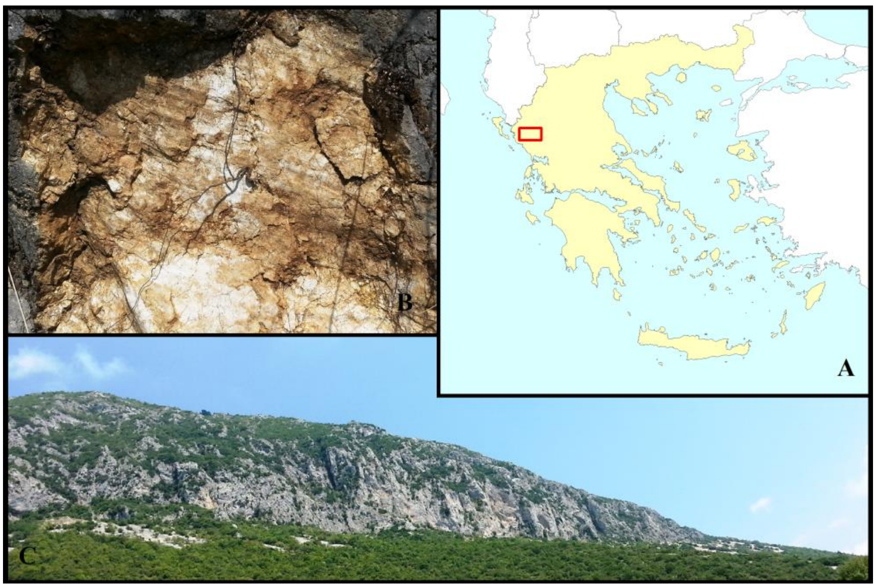

Figure 1. (A) Study area and (B and C) field photographs of the PSFZ surfaces in the area of Souli.

This tectonic structure has caused the displacement of pre-existing structures, such as the synclines and anticlines formed during the Alpine fold, as well as recent Quaternary deposits (Ntokos, 2017a, 2018a). It has affected the morphology and relief of a large area, while a typical example of the displacements it has caused can be found in the syncline structure of Voutsaras, which is transversely intersected in the middle, by the Petousi-Souli fault. The Voutsaras syncline seems to present a displacement in the order of 2 km to the east, while the displacements of the geological boundaries, along the length of the fault's trace, often exceed 4 km.

The western and eastern ends of the Petousi-Souli strike-slip active fault feature a series of minor normal and strike-slip active faults, running in a parallel direction to the orientation of the fault, whose high concentration is similar to an enechelon layout, which is typically observed in strike-slip zones. Observations show that this tectonic structure fans out into numerous smaller branches, typical in cases on strike-slip faults (imbricate fans). Since these faults are consistently oriented from E-W to NE-SW (right stepping faults) they may well constitute Riedel faults, which have impacted the sedimentary nappe and which are associated with a large-scale sinistral movement of the bedrock.

The impact and the tectonic regime, which created the Petousi-Souli strike-slip fault, has left its imprint throughout the area, where many minor faults, trending E-W were observed, as well as other faults, which are affected by the same regime that caused the rupture of the main fault, albeit developing in a different direction. A number of surfaces were detected; the nature however of the geological materials at their contact did not enable the identification of kinematic evidence, since their surfaces and tectonic striations have largely disintegrated due to erosion.

Results

Due to its well-preserved fault surfaces and the limited erosion effect, this tectonic structure is indicated to apply the R_C method. Specifically, by fieldwork, rock varnishes were found both in the Petousi-Souli segment, Agia Maura segment and in Saloniki ones. According to the methodology, calcium, titanium, and potassium cations were analyzed, and their concentration was determined in percentages at 21 sites. From these measurements using the Dorn's equation (1; 1983), the R_C ratio takes values between 2.1 and 110.1 corresponding to ages from 10.000 to 3.8 Ma years ago (Table 1).

Table 1. Distribution of the R_C ratio by fault and the varnish age based on the Nobbs and Dorn (1988).

Fault	**R_C**	**Dating**
Petousi-Souli	2.4 - 110.1	10,000 - 2.2 Ma
Agia Mavra	2.2 - 62.6	220,000 - 3 Ma
Saloniki	2.1 - 13.3	10,000 - 3.8 Ma

Discussion - Conclusions

Tectonic and geological observations made in the field, geomorphological features (Ntokos, 2018a), paleomagnetic data (Kissel *et al.*, 1985), paleoseismological data (Boccaletti *et al.*, 1997), and recent microseismicity records (Pavlides, Caputo, Zouros, Mountrakis and Boccaletti (1992), Tselentis *et al.*, 2006) all indicate recent fault activity. According to Boccaletti *et al.* (1997), over the last 30,000 years, at least three tectonic paleo-events are particularly associated with the Petousi-Souli Fault. Initial fault activation, based on recent tectonic geomorphological data on the evolution of northwestern Greece (Ntokos (2018a), dates to between the Miocene and Pliocene, which is similar to the rock varnish ages.

In addition, it is worth mentioning that in the Petousi-Souli Fault the dating of the rock varnishes gave better results compared to other areas, e.g. Arkitsa (Ntokos, 2019) and Epirus, Greece (Ntokos, 2018), where the same method was applied to faults due to the well-preserved fault surface, verifying the application of the method to tectonic structures.

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