Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Structural Modelling of Mouil Graben, Sabalan Geothermal Field, NW Iran

Mahnaz Rezaeian, Mohsen Elyasi, Mohammad Faridi, Isa Karami and Hasan Moghimi

Institute for advanced studies in basic sciences (IASBS), Zanjan, Iran.

m.rezaeian@iasbs.ac.ir

Keywords: Sabalan volcano, Maximum horizontal stress, Temporal pattern, Multi-inversion of fault kinematic data.

ABSTRACT

The Plio-Quaternary strata-volcano of Sabalan in Arabian-Eurasian collision zone, shows a meaningful structural control on the configuration of the geothermal field in the area. In NW of the volcanic cone, the location of highly potential geothermal field in Mouil graben is bounded by first order longitudinal Mouil and Dizu oblique normal faults. The area has been investigated structurally through a detail field observation in order to extract the maximum horizontal stress orientation and corresponding volcanic structure. Temporal pattern of maximum horizontal stress orientation in the time of eruption and after that correlate with structural evolution of the volcanic cone. By applying multi-inversion method, we show that magma ascending induced a major radial pressure distributed around the injection axis and caused formation of syn-eruption structures. The trace of radial pressure has been tracked in Sabalan by the inversion analysis of faults geometry data in those reverse faults are the most important product of this phenomena. The analyses correspond to an estimated stress ratio of n =0.9 where sigma3 stress axis is vertical. The normal faults those formed in the same stress field have caused subsidence in the caldera area. Radial extension with estimated stress ratio of n =0.1 where sigma1 stress axis is vertical. Post-eruption stress regime, in last 149 ka, has been identified in kinematic analysis of the structural data. There is a good correlation between the current stress regime in NW Iran and the results in which dominant stress regime is strike slip with stress ratio of n=0.5 where sigma2 stress axis is vertical. An anticlockwise rotation is tentatively implied from syn- to post-eruption maximum horizontal stress orientation in last 4.5 MY.

1. INTRODUCTION

The orientation of maximum horizontal stress tends to be the first priority in geothermal exploration, because it is a primary control on subsurface fluid flow in geothermal reservoirs (Tingay et al., 2005). The post-collisional Sabalan volcano is located in NW Iran where a strike slip stress regime is presented by a NW-SE maximum horizontal stress orientation (Heidbach et al., 2016; Fig. 1). Located in NW Sabalan, the Mouil graben, is the most important geothermal prospect which channelizes heated groundwater downstream the graben where a main cluster of hot springs is emerging in the Sabalan (Rezaei et al., 2019). The graben is bounded by normal dextral faults of Mouil and Dizu (Fig. 2b).

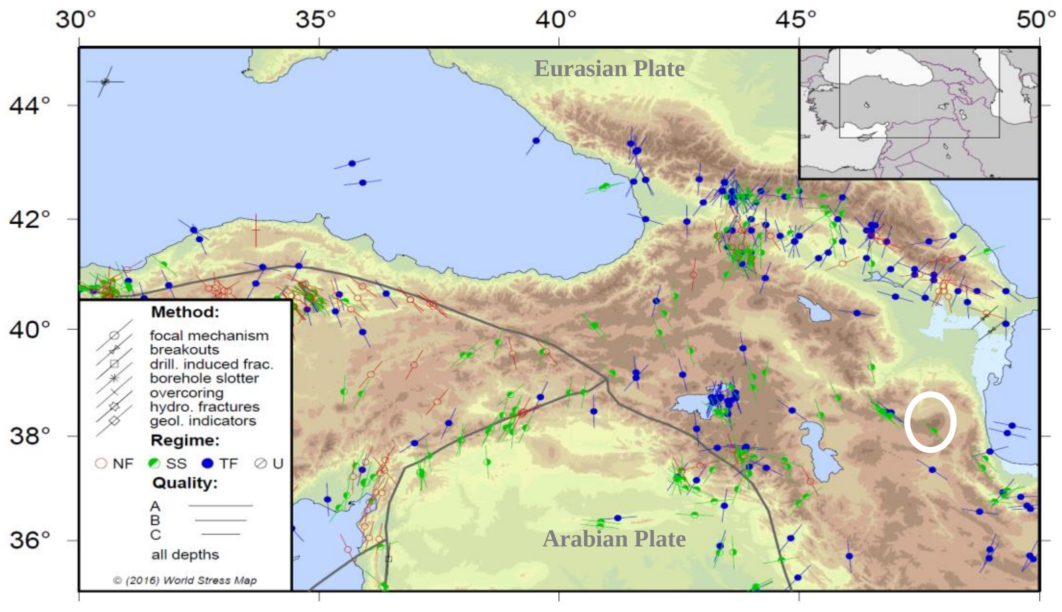

Figure 1: Map of current orientation of maximum horizontal stress in NW part of Arabian-Eurasian collision zone, including NW Iran, East Turkey and South Caucasus, adopted from world stress map (Heidbach et al., 2016). Sabalan volcano located in the white circle. The stress regime has been classified by red, green and blue symbols for normal, strike slip and thrust faulting. A dominant strike slip tectonic regime is evident in the study area; it persists toward eastern part. A NW-SE direction of maximum horizontal stress is evident.

2. METHODOLOGY AND DATA ANALYSIS

Investigating geothermal prospects, it is significantly important to produce fault kinematic data besides orientation of extensional fractures. The main approach includes introducing orientation of maximum horizontal stress and consequently detect the structural barriers and conduits those affect subsurface fluid flows. In this study we collected structural data including joint and faults by remote sensing and dense field measurements. Statistical analysis of extensional fractures along with the multiple inversion analysis of faults kinematic data (Yamaji, 2011; Yamaji, 2016) resulted in emerging a better understanding of geothermal field prospects and developments in the area. Statistical analysis of >3000 extensional fractures in Sabalan shows two pattern of radial and circular depends on spatial distribution of measurement station. However, frequency of the fractures strike azimuth indicates a meaningful dominant NW-SE trend which is correlated with the current orientation of maximum horizontal stress. It also means that NW-SE Mouil graben has been optimally directed to transfer subsurface hydrothermal fluid from highly elevated Kasra Mount in the SE to downstream in NW (Fig. 2a). Given detailed structural surveys along the Mouil and Dizu oblique faults, we detected 700-900 meter dextral displacement along strike and 400 meter vertical throw. The right lateral component in the shear zone facilitated the subsurface fluid flows through the shear zone and emerging the most important cluster of hot springs of the area in the graben (Fig. 2a).

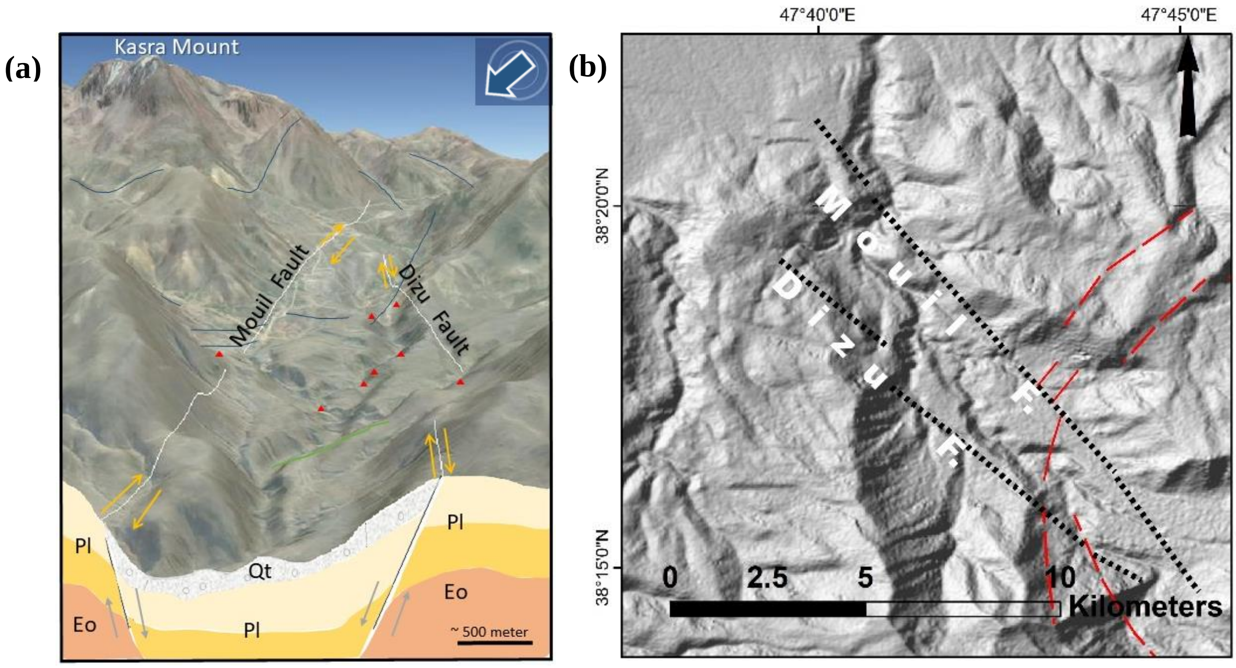

Figure 2: (a) Left map- A 3D structural reconstruction for Mouil graben. Google earth image overlaid by a relief map extracted from Sasplanet (vertical exaggeration 2:1). Caldera ring fault system, oblique slip faults of Dizu-Mouil and a main reverse fault are delineated by deep blue, white and green lines, respectively. Red triangles represent major hot springs. Kasra Mount (4505m) located in Mouil graben upstream. (b) Right map-The longitudinal first order structures in the study area that overlays on the DEM. NW-SE trending of oblique (normal dextral) faults of Mouil and Dizu are shown by dotted pattern. Normal ring faults of caldera are presented in red.

Inflation - deflation of magma chamber and consequent radial compression around an axial intrusion has been recorded using geodetic and seismic deformation data, in active Etna volcano (Patanè et al., 2003), however, validation the geological evidence by structural data is rare. Here, by measuring 112 main fault plane across the Sabalan cone, it was doable to record structural evidence of inflation and deflation of the Sabalan magma chamber during injection and evacuation. Temporal pattern of maximum horizontal stress has been detected using multi-inversion method (Yamaji, 2011) of fault slip data. The analyses indicate that a major cluster of longitudinal faults those are active in the current stress field are classified as dextral and sinistral oblique slip faults trending NW-SE and N-S, respectively (Fig. 3c). Moreover, there is a cluster of normal and reverse faults which correlates with a different stress field than today. The orientation of maximum horizontal stress in related to the early stage of Sabalan volcano activity in Pliocene and has been estimated to be NE-SW. Using further evidence an anticlockwise rotation in the stress field is deduced that corresponds well to the other studies in the Arabian-Eurasian collision zone (e.g. Berberian, 1976; Jentzer et al., 2017). Magmatic chamber inflation-deflation and cyclic resurgence are considered to be the main magmatic engine for constructing a volcanic cone that is reflected in the fault system arrangement (Walter and Troll, 2001). To justify the geological condition in that normal and reverse faults formed simultaneously in a single stress field, the geological events during construction of the cone of Sabalan volcano is investigated. Neo- and Paleo-Sabalan were constructed in last 4.5-0.15 My (Ghalamghash et al., 2016) during multi injection and evacuation of magma chamber. Inversion analysis of fault slip data is to decipher the arrangement of normal and reverse faults related to the volcanic construction (Fig. 3a and b). The normal and reverse faults belong to a single stress field. The reverse faults formed during radial compression which was induced by magma injection following the inflation. The NE-SW orientation of maximum horizontal stress in a compressional regime is shown where principle stress axis of sigma3 is vertical, stress ratio= 0.9 and misfit angle for 32 percent of the data is estimated <30 degree (Fig. 3a). The normal faults formed during radial extension which was induced by magma evacuation following the deflation. The NE-SW orientation of maximum horizontal stress in an extensional regime is shown where principle stress axis of sigma1 is vertical, stress ratio= 0.1 and misfit angle for 28 percent of the data is estimated <30 degree (Fig. 3b). After volcanic activity diminished, the oblique dextral and sinistral faults formed in last 150 ka. The NW-SE orientation of maximum horizontal stress in a strike slip regime is shown where principle stress axis of sigma2 is vertical, stress ratio= 0.5 and misfit angle for 40 percent of the data is estimated <30 degree (Fig. 3c).

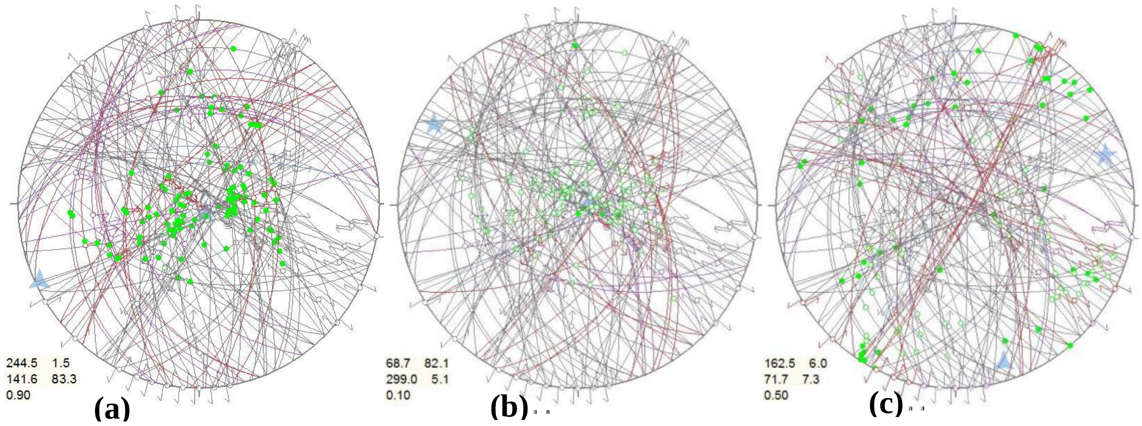

Figure 3: Lower hemisphere, equal area projection of 112 fault slip data which was analyzed by using multiple inversion method (Yamaji, 2011). Presentation of three stress states from left to right a) radial compression with a vertical sigma3 stress axis and stress ratio n=0.9; b) radial extension with a vertical sigma1 stress axis and stress ratio n=0.1; c) strike slip with a vertical sigma2 stress axis and stress ratio n=0.5. The strike azimuth and dip for the maximum (blue triangle-sigma1), minimum (blue star-sigma3) principle stress axes and stress ratio are displayed in the left hand side of each stereogram. Estimated misfit angle is considered <30 degree for the representative clusters of slip data (red and purple fault plane) corresponds with 32 (a), 28 (b) and 40 (c) percent of the data set.

3. CONCLUSION

The multi-inversion of fault kinematic data reveals temporal changes in the maximum horizontal stress orientation in last 4.5 MY. An anticlockwise rotation in the orientation is deduced. A NE-SW trend is shown for the orientation of maximum horizontal stress during syn-eruption period, when multiple inflation-deflation resulted in constructing Sabalan cone. That affected the faults mechanism and arrangement. During inflation, the magma ascended and its injection induced an axial compression resulted in reverse fault formation. Subsequent deflation of the magma chamber generated normal faults that presented by an axial extension has been shown in inversion analysis. The orientation of maximum horizontal stress during post-eruption period, in last 149 ka, correlated with the current stress regime.

REFERENCES

Berberian, M.: The 1962 earthquake and earlier deformations along the Ipak earthquake fault, *Geol. Surv. Iran,* **39**, (1976), 419-427.

Jentzer, M., Fournier, M., Agard, P., Omrani, J., Khatib, M., and Hubert Whitechurch, H.: Neogene to Present paleostress field in Eastern Iran (Sistan belt) and implications for regional geodynamics. *Tectonics*, **36**, (2017), 321-339.

Ghalamghash, J., Mousavi, S. Z., Hassanzadeh, J., and A. K. Schmitt.: Geology, zircon geochronology, and petrogenesis of Sabalan volcano (northwestern Iran), *Journal of Volcanology and Geothermal Research*, **327**, (2016), 192-207.

Heidbach, O., Rajabi, M., Reiter, K., and Ziegler, M.O.: World Stress Map 2016. GFZ Data Services, http:// doi.org/10.5880/WSM.2016.002, (2016).

Patanè, D., De Gori, P., Chiarabba, C., and Bonaccorso, A.: Magma ascent and the pressurization of Mount Etna's volcanic system, *Science*, **299**, (2003), 2061-2063.

Rezaei, A., Rezaeian, M., and Porkhial, S.: The hydrogeochemistry and geothermometry of the thermal waters in the Mouil Graben, Sabalan volcano, NW Iran, *Geothermics,* **78**, (2019), 9-27.

Tingay, M., Müller, B., Reinecker, J., Heidbach, O.: Understanding tectonic stress in the oil patch, The World Stress Map Project. - *The Leading Edge*, ***24***, (2005), 12, pp. 1276—1282.

Walter, T. R. and Troll V.R.: Formation of caldera periphery faults: an experimental study, *Bulletin of Volcanology,* **63**, (2001), 191.

Yamaji, A., Sato, K., and Otsubo, M.: Multiple inverse method software package. *User's guide,* (2011), 1-37.

Yamaji A.: GArcmB program package, (2016).