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Geological Interpretation of Geothermal Manifestations in the East of Morocco

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ABSTRACT

For most developing countries, using renewable energy sources is always conditioned by government's fear and reluctance towards the high cost and the complexity of technology needed. One of the greatest problems to face, once decided to get into the eco-friendly source, is the variability of energy potential in the globe generally and the region specifically. Morocco as a developing country and one of the most stable states in Africa in terms of politics and infrastructures has done a huge effort to surpass its energy deficit by launching a very large-scale integrated program for producing electricity using clean sources. The country's project aims to save 15% of energy consumption by the year of 2030.

Over the last few years, a huge interest to evaluate the feasibility of geothermal energy production in Morocco has been done. Thus, several studies were done and are still going to make this green energy useful in many ways and orientate the country towards its development.

This contribution examines the relationship between the geothermal potential of the Northeastern part of Morocco (highlighted by the presence of several geothermal manifestations) and the recent volcanism activity (Plio-quaternary) observed within the same area.

1. INTRODUCTION

The geology of the Northeastern part of Morocco has been the focus many studies and research during the last decade by both academic and investing sectors, and that was because of its geographical key position. The abundance of hot springs in this area led scientists to investigate the geothermal potential within the region (e.g., Benaabidate 1994, Zarhloule 1994, Rimi et al. 1998, 2008, 2010, 2012, Rimi,1999, 2000, 2001, 2005, El Morabiti, 2000, Zarhloule et al., 1998, 1999, 2001, 2005, 2007, 2010, Barkaoui et al., 2013a, 2013b, 2014, 2015 and Correia et al., 2017). Although the academic research was progressing, the state actions towards this clean resource have not been launched until recently. Today, the National Office of Hydrocarbons and Mines is leading the prospection of geothermal potential in this region and also in the southern part of Morocco.

Previous studies have shown that the geothermal gradient in the Eastern Rif (Northeast of Morocco) has an average of geothermal gradient of about 126 ºC/km at depths greater than 300 m (Zarhloule et al., 2010, Barkaoui et al., 2013a, Correia et al., 2017 and references therein). This hot fluid activity is mainly originated from a deep circulation with regard to a system of basement active faults, individuating horsts and grabens, in a recent volcanic area (Zarhloule, 1999).

2. GEOLOGICAL SETTING

The Rif mountain in the North of Morocco belongs to the peri-Mediterranean Alpine belts, which extend along the North of Africa (together with Tell and Kabylia) and continues eastward to Sicily and Calabria in southern Italy (Figure 1).

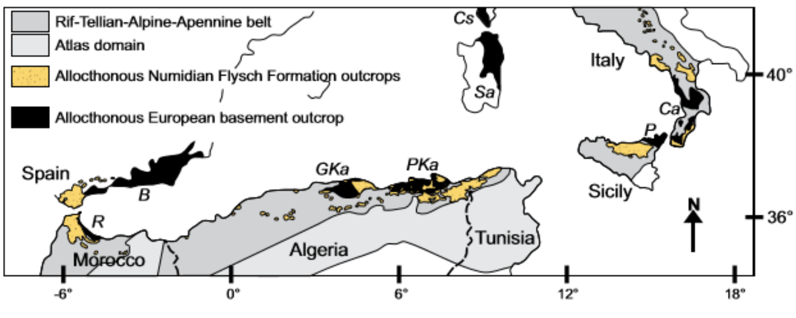

Figure 1: Western Mediterranean map showing the extension of Alpine belt (B=Betic, R=Rif, GKa=Grand Kabylie, PKa=Petit Kabylie, P=Peloritani, Ca=Calabrian) (modified by Thomas, 2011)

Three main structural-paleogeographic domains are defined in the Rif belt, from the North to the South: Internal zones, Flysch Zones and External Zones. Each domain is divided itself to several sub-domains. The superposition of several tectonic, compressive and extensional phases of Alpine age formed a morpho-structural zone from both Atlas and Rif domains during the late Cretaceous.

Recent magmatic activity has started during the Langhian with a calc-alkaline metaluminous to peraluminous granitoids and associated andesites/ dacites in Central and Eastern Algeria. The same magmatic activity has started later (Serravallian) in Oranie, Tunisia and Western Morocco, followed by the alkali basalts dated essentially for Plio-Quaternary. This diference in timing between Central and Eastern Algeria and the Oranie, Tunisia and Western Morocco was explained by Piqué et al., 1998 by the presence of a tectonic indenter where Algeria behaved as an indenter during the NS compression while Oranie and Morocco have experienced lateral escape along NE-SW transcurrent faults and Eastern Tunisia along NW-SE. This theory is consistent with the results of the geophysical study realised by Carminati et al., (1998).

PETROLOGY

Recent volcanic activity in Morocco has been extensively studied (e.g. Fuster, 1955; Hernandez, 1983; El bakkali, 1995; El bakkali et al., 1998; El azzouzi et al., 1999; Maury et al., 2000; Duggen et al., 2002, 2003, 2004 & 2005). The main volcanic outcrops are:

Guilliz massif located in the Northern border of the sedimentary basin of Guercif (Figure 2), described in details by Hernandez (1983): the most presented types are Absarokites (SiO_2<52%), Shoshonites (52%<SiO_2<58%), Latites (58%<SiO_2<63%), and Trachytes (63%<SiO_2) with the presence of enclaves of hawaiite composition.

Ras Tarf and **Gourougou** magmatim (Figure 2) is related to two episodes: the first was more volumetric and occurred during Early Tortonian to Late Messinian and the last took place afterwards (Plio-quaternary) according to El azzouzi et al. (1999).

Oujda magmatism (Figure 2) is represented by basalt lava flows, basanites, hawaiites and Mugearites as the main volcanic rocks forming stromboli structures set up in a small graben oriented SSW-NNE (El azzouzi et al., 1999).

Based on the magmatic (petrography and Geochemical) criteria and age, two main groups were identified:

- A Neogene shoshonitic, High-K Calc-alkaline and Calc-alkaline (s.s.) volcanism (Miocene, 13.5 Ma).
- A Mio-Plio-Quaternary alkalin volcanism (5.6-0,65 Ma)

The ***first group*** includes:

- High-Na Calc-alkaline series: covering the andesitic rocks of Ras Tarf. According to the petrographic study, the Miocene Calc-alkaline lava in Ras Tarf is particularly silica-oversaturated and displays La/Nb ratios>2, with a magmatic affinity of subduction zone (El bakkali et al., 1998, El azzouzi et al., 1999 and Rkha chaham et al., 2003)
- Rhyolites of Tres Forcas
- Shoshonitic series: covering the basalts, Trachytes and Rhyolites of Gourougou
- High-K Calc-alkaline series: Identified essentially in Guilliz and have a higher content of Fe than in Gourougou (Hernandez, 1983).

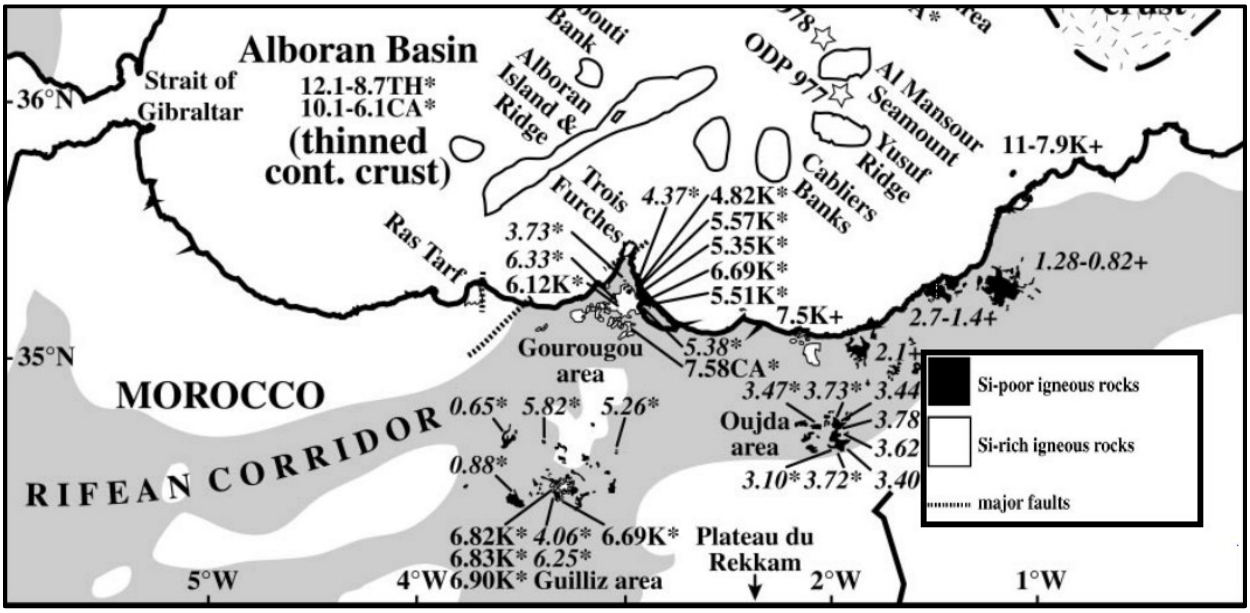

Figure 2: Map of the westernmost Mediterranean showing the location of Middle Miocene to Pleistocene post-collisional igneous rocks in the Alboran Basin and the continental margin of Northwestern Africa (in Duggen et al., 2005)

Alkali basalts, basanites, hawaïtes and nephelinites form the ***second group***. Having a geochemical fingerprint comparable to the intra-oceanic basalts suggesting the contribution of the ''so-called'' Moroccan Hot Line (Missenard et al., 2006).
These Plio-quaternary basalts include:

- Alkali basalts of Gourougou, Guilliz, Oujda and few other outcrops in the NE of Morocco (Jeremine and Marcais, 1962 & Hernandez, 1983).

GEOCHEMISTRY

The magmatic evolution of the Alboran Basin area is then marked by firstly a calc-alkaline volcanism (12 to 5 Ma) in Ras Tarf and Gourougou, then transitional (7.9 to 2.2 Ma) in Gourougou and Guilliz and finally alkaline (6.4 Ma to 0.6 Ma).

Table 1 shows how the geochemistry and isotopes compositions support this evolution from Neogene to Quaternary volcanism in this part of Morocco, a progressive passage from Calc-alkaline with a high **$^{87}Sr/^{86}Sr$** (0.7058 to 0.7088) to transitional (0.7046 to 0.7078) and then Alkaline with a lower **$^{87}Sr/^{86}Sr$** (0.7039 to 0.7031) (El Bakkali et al., 1998 & El Azzouzi et al., 1999).

Other studies on geochemistry of these magmatic rocks involving major (TiO_2 , Al_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, H_2O, CO_2) and trace elements (Li, V, Cr, Co, Ni , Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd) geochemistry have identified strong affinities to volcanic rocks generated in subduction zones, comparable to those the eastern central Alboran Sea in both, age and chemical composition (e.g. Hoernle et al., 1999 and Duggen et al., 2005).

A large sheet-like region of upwelling sublithospheric mantle domain extending beneath Western Europe, the Western Mediterranean and the Eastern Atlantic margins was suggested by tomographic and geochemical results (Maury et al., 2000).

Table 1: Summary of the magmatic and chronological features of the Northeast of Morocco with the range of available K-Ar (Hernandez et Bellon, 1985, Andries et al., 1989; El bakkali et al., 1998; El azzouzi et al., 1999), Ar-Ar (Duggen et al., 2005) ages and Sr–Nd ratios (Hernandez et Bellon, 1985 & El azzouzi et al., 1999).

		$^{87}Sr/^{86}Sr$	**$^{143}Nd/^{144}Nd$**	**Age (K/Ar)**	**Age (40Ar/39Ar)**
Oujda	Alkali basalts	0.7037-0.7039	0.5127-0.5128	1.5-5.6 Ma (Andries et al., 1989 & El azzouzi et al., 1999)	——
Gourougou and TresForcas	Shoshonitic andesites & Calcalkaline	0.7058-0.7087	0.5123-0.5124	5.4-6.6 Ma (El bakkali et al., 1998)	——
	Transitional shoshonitic andesites	0.7046-0.7078	0.5124-0.5126	6.5-7.8 Ma (Hernandez et Bellon, 1985)	7.58 to 4.8 Ma (Duggen et al., 2005)
	Alkali basalts	0.7049	0.5128	2.6 Ma (El azzouzi et al., 1999)	6.3 and 4.8 Ma (Duggen et al., 2005)
Guilliz	Transional Alkaline basalts	0.7063	0.5125	2.2 Ma (El azzouzi et al., 1999)	——
	Alkaline basalts	0.7031-0.7036	0.5125-0.5129 (Hernandez et Bellon, 1985)	1.7 to 8 Ma (Hernandez et Bellon, 1985 & El azzouzi et al., 1999)	0.65 Ma and 0.88 Ma (Duggen et al., 2005)
Ras Tarf	High-K Andesites	0.7088	0.5123	12.1-13.1 Ma (Hernandez et Bellon, 1985, El bakkali et al., 1998 & El azzouzi et al., 1999)	——

STRUCTURES

Middle to Late Miocene igneous rocks are considered as a part of the Alboran Basin (Duggen et al., 2004) and coastal stratovolcanic complexes are bordered by major strike-slip faults in both sides of Gibraltar arc (Cabo de Gata and Aguilas block in southern Spain and Ras Tarf and Tres Forcas in northern Morocco).

Volcanic outcrops in Guilliz are aligned in two main directions N40-45° and N135-140° (El Azzouzi et al., 1999) and structures were mainly controlled by normal faults and senester strike slip fault during the synmetamorphic thrust (e.g. South of Nekor fault) (Andrieux, 1971; Frizon de Lamotte, 1985, El Azzab et al., 1997).

Three major directions in the region of Al Hoceima were identified through satellite images analysis and Focal mechanism of major earthquakes: NS to NNE-SSW, NE-SW and NNW-SSE to NW-SE (Van Der Woerd et al., 2014 & Mahsani & Ait brahim, 2018).

Whereas magmatic activity at the Miocene–Pliocene limit has proceeded in Morocco along a SW–NE lineament oblique to the Mediterranean Margin (Maury et al., 2000).

Table 2 shows that structural manifestations in the Northeast of Morocco are the result of a polyphased tectonic during the Plio-Quaternary:

- Starting with a large period of distension oriented NE-SW from the Tortonian to the Pliocene followed by a compressive episode, oriented NS during late Tortonian.
- Then, a compressive period, during the upper Pliocene and the early Quaternary, well visible in the Northern border of Gharb and Guercif basins.
- Finally, an extensive period in Quaternary, marked by the most recent features, where the subsidence is well-conserved (Tesson et Guensous, 1989).

Table 2: Structural evolution of Neogene post nappe basins of Eastern Rif (Tesson et Guensous, 1989 & Gullemin et Houzay, 1982)

	Neotectonic behavior			Major Volcanic Episodes	
AGE	WESTERN RIF	EASTERN RIF	ATLASIC FORLAND (Guercif)		
1 Ma Quaternary	Extension	Extension	Extension	Alkali volcanism Gourougou Guercif Middle Atlas	1 Ma 1.2
2 to 3 Ma	Compression	Compression	Compression		
Pliocene				Calc-alkaline volcanism Gourougou Guilliz	
5 Ma	Extension	Extension	Extension		4.6 5.3
Messinian					6.5 7.4 7.5
8 to 9 Ma					7.9 8.1
Tortonian		Compression Extension		Rhyolitic volcanism (Tres forcas) Andesitic volcanism (Ras Tarf)	9.6 15.7

GEOTHERMAL POTENTIAL

A very high heat flow density and temperatures as high as 93°C at 650 m (Figure 4) depth were measured in the Northeast of Morocco (Barkaoui et al., 2015 & Correia et al., 2017) where the crust is thinned to 15–20 km (Figure 3) (Polyak et al., 1996 & El Azzab et al., 1997).

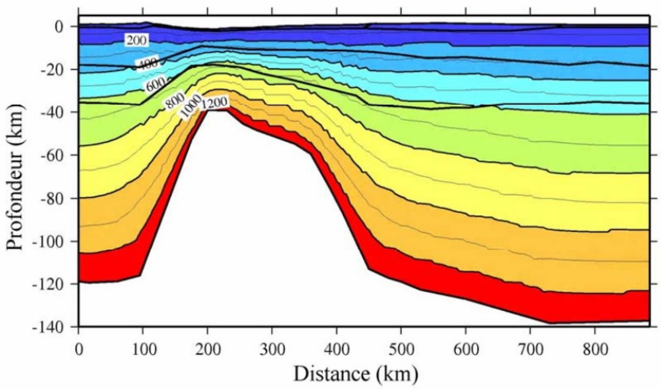

Figure 3: Temperature distribution model in a NS profile (3°W, 36° N --->3°W, 28°N ; Melilla region) (Rimi et al., 2008)

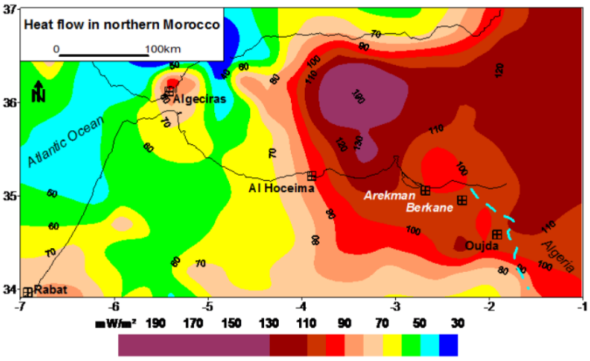

Figure 4: Detail of the heat flow density map for the northern part of Morocco (Correia et al., 2017)

According to Zarhloule (1999), the hot temperature and the artesian rise of most of the thermal springs in Northeastern Morocco originate from deep circulation in relation to a system of basement active faults, individuating horsts and grabens, in a recent volcanic area (Rimi et al., 2010). Hot water is tapped essentially in the most important aquifer, formed by Liassic carbonates with a thickness up to 500 m (Zarhloule 1999). The highest geothermal anomaly is located in Arekman (Figure 5), mainly formed by Rhyolitic and Andesitic series (Rimi et al., 1998, Rimi et al., 1999 and Barkaoui et al., 2014).

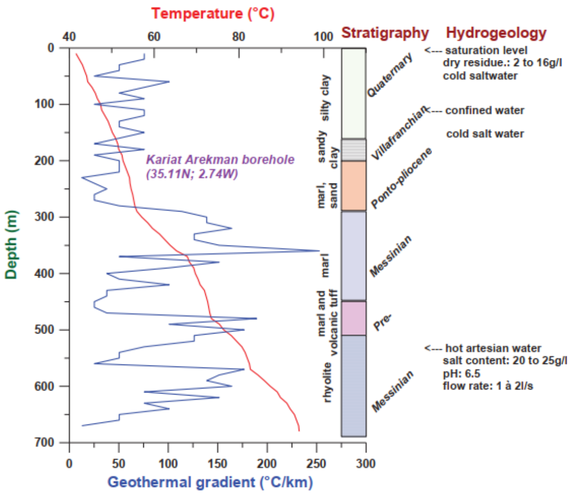

Figure 5: Kariat Arekman borehole. *Temperature (Red line); Geothermal Gradient (Blue line)* (Zarhloule et al., 2007)

CONCLUSION

This paper aims to highlight the importance of identifying the relationship between the geothermal potential of the eastern Rif and the recent volcanic activity reported there.

The three following axis will be studied during the next years:

- El bakkali et al., 1995 have suggested the presence of a Caldera (Oumassine basin) with a Messinian age, close to Gourougou outcrop based on Stratigraphic and structural arguments. This suggestion has to be verified, if possible, to find if it is related somehow to the geothermal activity nearby (Kariat Arekman);
- Polyak et al., 1996 & El azzab et al., 1997 have found very high magnetic anomalies in the eastern Rif, this could be because of the high percentage of Fe in the magma, a gravimetric survey has to be carried out to compare and identify the hot source;
- Despite the reservoir being studied and considered as Liassic Carbonates, many other studies have to be completed to be able to come up with a model that explains the geothermal activity and its origin, taking into consideration the fault's directions and different structures involved in the process.

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