European Geothermal Congress 2016
Strasbourg, France, 19-24 Sept 2016

A model of permeability and porosity in the different type of basement of the Upper Rhine Graben inferred from outcropping analogues rocks.

Lionel Bertrand[1], Yves Géraud[1], Marc Diraison[2], Pierre-Clément Damy[3].

[1] GeoRessources, Lorraine University, 2 rue du Doyen Marcel Roubault, TSA 70605, 54518 Vandoeuvre-les-Nancy

[2] IPG, Strasbourg University, 1 rue Blessig - F-67084 Strasbourg cedex

[3]Fonroche Géothermie, 2 av. Pierre Angot 64053 Pau Cedex 9

lionel.bertrand@univ-lorraine.fr

Keywords: basement reservoirs, weathering, porosity, permeability, fault zone.

ABSTRACT

To reach to suitable temperature for electricity production with geothermal fluids in non-volcanic areas, many EGS projects are bought to target the basement rocks of continental rifts as the Upper Rhine Graben. Unconfortunately these basements and their reservoir properties are not well known and investigations from the surface cannot currently detect important parameters like the basement lithology or faults barrier/conduit behaviour. This study proposes an analysis of the reservoir properties of outcropping analogues of different basement rocks of the URG in order to characterize their reservoir potential. Thus, different petrophysical measurements have been performed on "fresh", meteoric weathered or weathered in damaged zones and fault cores samples for the different lithologies outcropping in the Northern Vosges Mountains. These analysis allow the classification of the basement's reservoirs in different groups: from the most interesting with a high potential of development, characterized by high matrix permeability and porosity due to weathering to the low matrix porosity reservoir rock but high permeability in the fault zones.

1. INTRODUCTION

In non-volcanic areas, to reach at temperatures suitable for electricity production (≈200°C) with geothermal fluids, the reservoir's targeted is commonly at more than 4 km depth. In consequence, the reservoir rock is in general the basement of the sedimentary basins, composed of magmatic and metamorphic rocks.

In this kind of rocks, the matrix permeability and porosity are low, except for the fault zones or for the weathered top of the basement at the interface with the sedimentary infilling (*Dewandel et al 2006, Faulkner et al 2010*). Indeed, in theses areas, the alteration du to hydrothermal flows in the faults or meteoric weathering of the basement during palaeo-exhumation can significantly enhance the reservoir properties.

Unfortunately, no geophysical prospection is currently available for the determination if a fault expresses an altered layer enough developed to make them suitable for a geothermal reservoir. Thus, the aim of this study is to use outcropping analogue of the buried basement of the Upper Rhine graben in France. In this graben, the detected positive thermal anomalies led to the development of several deep geothermal projects. Petrophysical analysis of the different basement' facies will be performed in order to determine the potential of alteration and development of subsequent reservoirs of the rocks in depth.

2. GEOLOGICAL AND STRUCTURAL CONTEXTS

The Upper Rhine Graben is a part of the West European rift system that is the subject of several deep geothermal projects in order to produce electricity and heat energy. The basement rock of this graben is linked to the hercynian orogeny and is covered by the Permian to Jurassic pre-rifting sediments. These rocks are outcropping at the shoulders of the graben, in the Vosges and the Black Forest mountains and are the result of the stuck of different plates that moved together during the hercynian orogeny (*Autran and Cogné 1980, Bard et al. 1980, Paris and Robardet, 1990, Van der Voo, 1993, Cocks, 2000, Franke, 2000, Robardet, 2003, Von Raumer et al. 2003, Lardeaux et al. 2014, Schulmann et al. 2014).* In the Vosges Mountains, the Southern Vosges represents the orogenic metamorphic root, within the moldanubian crust (Fig. 1a). Separated by the Lalaye-Lubine fault zone (LLFZ), the Northern Vosges are composed of the termination of the Teplà-Barrandian plate and the Saxothuringian plate intruded by magmatic bodies of Champ-du-Feu massif that is defined as "Mid-german-crystaline ridge" (*Tabaud et al 2014*). In light of the varied lithologies that compose the Northern Vosges, their continuity as the basement of the URG as investigated using geophysical data (*Edel and Schulmann 2009*), this area is the focus of the study.

The Teplà-barrandian plate is represented in the Northern Vosges by the Cambrian to Ordovician southern schists, derived from shallow marine sediments in a platform environment (*Skrzypek et al 2014 & ref cited*) (*Fig. 1b*). The Saxothuringian plate at the North is composed of a volcano-sedimentary unit with varied lithologies from conglomerates, schists to recifal carbonates (The Bruche unit) with a main identified volcanic event (the Rabodeau-Schirmeck unit), all metamophized in Barrovian conditions. Intruded between the two metamorphic massifs, the "Champ-du-Feu" massif is composed of 3 magmatic suites (*Altherr et al 2000, Elsass 2008, Tabaud 2012*). First, calco-alcalin magmatism emplaced in ENE-WSW bends, from the oldest (334±5 Ma for the "Bande Mediane") "Southern unit" composed of two successions of varied rock types like micrograbbros, diorites, andesites, and granodiorite bends; to the slightly younger Northern granites (319±3 Ma for the Belmont granite). The second is a shoshonitic suite with circular-shaped plutons that intruded the first suite, like the Natzwiller, Senones or Andlau granites. Finally, a peraluminous suite mainly represented by the Kagenfels granite that crosscut the magmatic "bends", and several minor plutons.

3. METHODOLOGY

The aim of the study was to sample all different lithologies in the focussed area in the different compartment of the fault zones, i.e. from the fresh sample to the more and more fractured and weathered ones in the damaged zone to the completely weathered rocks in the fault core or meteoric-weathered horizons.

On these samples, different petrophysical measurements, including thin sections observations, have been performed in order to characterize the evolution of the reservoir properties of the different lithologies. On 2.5mm diameter cores, the porosity has been measured with saturation by water following the RILEM standard, (*essai n°I 1978*). For some specific and representative samples, a mercury injection test (MIP) has been performed, allowing the observation of the pore size distribution. The density of the mineral assemblage has been estimated with a Helium pycnometre AccuPycII 1340 from micrometrics®. Finally, the matrix permeability has been measured with the "steady state flow method" (*Rosener, 2007*). On surface polished parallelograms, the thermal conductivity has been measured using the " Thermal conductivity scanner" device (*Popov et al 1983, Popov et al 1985, Popov et al 1999)* and also the P-waves velocity using the "Pundit-Lab" device by Proceeq©. These two properties have been characterized in three directions, in order to take account the anisotropy than can be created by the microfracture network in the samples.

4. RESULTS

For better understanding, the results of the petrophysical measurements have been grouped in different lithology classes:

- The metamorphic southern schists and northern Bruche and Rabodeau-schirmeck units.
- The granites of the three successive magmatic suites.
- The "southern unit" of the Champ-du-Fe massif.

4.1 Porosity, density and permeability

For the different facies sampled for the Rabodeau-Schirmeck and the southern schists, no porosity >2% is recorded (*Fig. 2a*). Only the Bruche unit, with the specific facies of the grauwackes (Moyenmoutier and Fouday) shows a significant enhancement of matrix porosity until 7.5%. There is a unique linear relation between the porosity and the apparent density on all samples, except for 4 grauwackes that show a different linear trend. This change in trend is due to a specific fault zone area (*see section 5*). Despite these linear relations, the mineral phase density expresses the high variability of the mineral assemblages, with a wide range between 2.65 and 2.85. The volcanic breccia with 15% porosity is an exception; indeed, it is a weathered sample at the interface between the Triassic cover and the Rabodeau-Schirmeck unit.

The granitic samples show almost the same linear diminution of the apparent density with the augmentation of the porosity (*Fig. 2b*). There is no clear distinction between the northern granites, the latter circular shaped plutons of the peraluminous fini-hercynian bodies. The apparent density for the less porous samples is around 2.65 that correspond to the mediane of the measured mineral phase density. In a petrophysical view, the mineralogy of the different granites is therefore almost the same. The maximum measured porosity is around 8.9%, but the most weathered samples that could not be measured with the water saturation show porosities until 15% in the mercury injection tests (*Fig. 2d*).

For the southern unit, the Hohwald granodiorite shows a linear relation between the apparent density and the porosity (*black line*), and there is another one for the other facies (*blue line, Fig. 2c*). Only the granodiorite shows a significant porosity enhancement, the other facies sampled never exceed 3% porosity and are mostly clustered around 0.7%. Moreover, the mineral phase density shows a clear distinction between the granodiorite and the other facies that have a high variability of mineralogical facies. Thus, in the Southern unit, we have to consider two subgroup: the granodiorites that have a "granitic like" petrophysical characteristics and the other facies with "metarmorphic units like" characteristics.

Mercury injection is the most relevant in the granitic samples (*Fig. 2d*). For the whole sampled set, the injections show an evolution of the pore size threshold from the less to most porous and weathered samples. In all samples, there is a dominant size between 0.3 and 0.6 µm that becomes most important as the total porosity increases (*1*). For porosity higher than 8%, with samples kept in an arenitic horizon or in altered fault core, a new threshold family is created around 30 µm (*2*).

The permeability measurements need to be completed, but they show that the main samples, including those with porosity until 5%, have matrix permeability around 10^{-3} – 10^{-5} mD (*Fig. 2e*). Only one sample of weathered granodiorite shows a high permeability until 100 mD as this porosity is not significantly higher.

4.2 Thermal conductivity (CT)

For the metamorphic rocks, the thermal conductivity is highly variable in the grauwackes, between 2.20 and 4,90 $W.m.^{-1}.K.^{-1}$. This variability is mainly explained by the presence of coarse-grained quartz beddings in some samples that enhance the conductivity. For the southern schists and the Rabodeau Schirmeck massif, the conductivity is between 2.58 and 3.31 $W.m.^{-1}.K.^{-1}$. The granites' CR values are between 1.71 and 2.72 $W.m.^{-1}.K.^{-1}$ and for the southern unit between 1.98 and 2.72 $W.m.^{-1}.K.^{-1}$. For the most weathered samples, the P-waves velocity could not been measured and they are therefore not represented in the graphs, but they show thermal conductivities weaker (1.83 $W.m.^{-1}.K.^{-1}$ for the Hohwald granodiorite and 1.61 $W.m.^{-1}.K.^{-1}$ for the Senone granite).

4.3 P-waves velocities (Vp)

With the exception of the volcanic breccias, the P-waves velocities vary between 3000 and 6000 $m.s^{-1}$ for the metamorphic samples. This variability is even more pronounced for the granitic samples, but less important for the southern units.

The P-waves velocities and thermal conductivity are linked both on the porosity and the mineralogic composition. In the granitic case, the density measurement shows that there is a light mineral phase density variation, but a high link between the apparent density and the porosity evolution. The CT-VP linear trend is therefore almost controlled by the porosity variation and poorly by the mineralogy. For the metamorphic units and in a lesser extent the southern unit, we observe the effect of both the porosity and the mineralogy.

5. DICUSSION

From a general point of view, all non-weathered samples have a porosity of less than 2%. This porosity is due to the pervasive weathering of primary minerals of the granites, whether the biotite and amphibole or the K feldspar and plagioclase (*Fig. 4a*). The permeability of these samples is also always low, between 10^{-3} and 10^{-5} mD.

For the granites and granodiorites samples, further weathering can subsequently enhance the porosity. The study of the thin sections of these samples shows that this evolution is due mostly to a more important weathering of the ferromagnetic, feldspar and plagioclase minerals (*Fig. 4b*). In these samples, the cracks linked to the brittle deformation in the area are sparse. Starting from a porosity value of 4-5% the cracks density increases whether in the damaged zones or in the weathered samples (*Fig. 4c*). The sampled fault cores are those with the most important alteration, with a total loss of the granitic texture (*Fig. 4d*). It is not the case for the most weathered samples outside the fault zones, i.e. the arenitic samples with the porosity that can reach to more than 13.50% (Hg injection), as the fault cores can reach to the same order of porosity values (12.6%). In these two kinds of samples, we notice the development of porosity with a larger thresholds (between 10 and 100 µm) that is no longer visible in the other samples. We therefore infer that this threshold is the marker of the open cracks, as the thinner threshold (between 0.5 and 1 µm) are linked to the minerals weathering that is enhanced as the porosity increase. The highest permeability measured for the altered samples is for the granodiorite with about ten mD.

The variation of the thermal conductivity, the P-waves velocities and the apparent density follow also a coherent trend with the evolution of the alteration (*Fig. 4*).

The Bande-Mediane, diorites and most of the metamorphic rocks have porosity less than 2%. These rocks were never found as altered in fault cores or in weathered horizons. Only the Moyenmoutier fault zone, that crosses the Moyenmoutier grauwackes, shows authentic fault zone architecture with a highly altered fault core and damage zone structure (*Fig. 5*). In the damage zone, the porosity is globally less important that far from the core, and therefore with higher thermal conductivity and P-waves velocity. The study of the thin-sections show that the microcracks density is not significantly higher in the damaged zone that in the protolith, as the macrofracture density is higher on the outcrop. However, the microcracks in the damaged zone are sealed with oxyds and quartz precipitation (*Fig. 5*), as the granular porosity between the quartz grains around the cracks is filled with oxyds too. Thus, in the case of these grauwackes, we have an example of a sealed fault zone, where the fault core is acting as a barrier with the secondary precipitation that plugs the fractures in the near damage zone. Samples of outcrop 24 shows higher porosity in the same rock facies but are taken close to the Permian cover. The weathering at the basement/cover interface seems therefore to development a more important porosity that the fault zones where the precipitated secondary minerals have seal the pores.

All theses observations allow the proposition of modele of “reservoir quality” of the basement in the studied area (*Tab. 1*).

Table 1: Synthetic table of matrice porosity and permeability model for the different lithologies of the Northern Vosges in the different structural position.

Units	Φ fresh (%)	Φ DZ (%)	Φ FC (%)	K fresh (mD)	K DZ (mD)
Granites and granodior-ites	1-2	2-4	<13.5	10^{-3} – 10^{-5}	10^{2} – 10^{-2}
Metam. with sediment-ary origin	1-2	2-6	1-4	10^{-3} – 10^{-5}	10^{-1} – 10^{-2}
Metam. with volcanic origin	1-2	1-2	1-2	10^{-3} – 10^{-5}	10^{-3} – 10^{-5}
Bande-mediane and diorites	1-2	1-2	1-2	10^{-3} – 10^{-5}	10^{-3} – 10^{-5}

In the granites and granodiorites bodies, the rocks show a progressive evolution of the weathering, and therefore of the petrophysic properties from the protolith to the fault cores. In fact, the alteration due to paleofluids circulation in the fault produces a subsequent mineral degradation that enhance the matrix porosity and in consequence the diminution of the thermal conductivity and P-waves velocities. Although the permeability measurements need to be completed for the most weathered samples, the matrix permeability shows also a substantial enhancement. Moreover, the most altered samples both in the meteoritic-weathered horizons and in the fault core show almost the same altered level. At the opposite, the metamorphic units never show an important alteration with a development of matrix porosity, excepted in the Moyenmoutier fault zone. Even in this case, the matrix porosity in the fault core and damaged zone is not enhanced and is on the contrary reduced by the secondary mineralization.

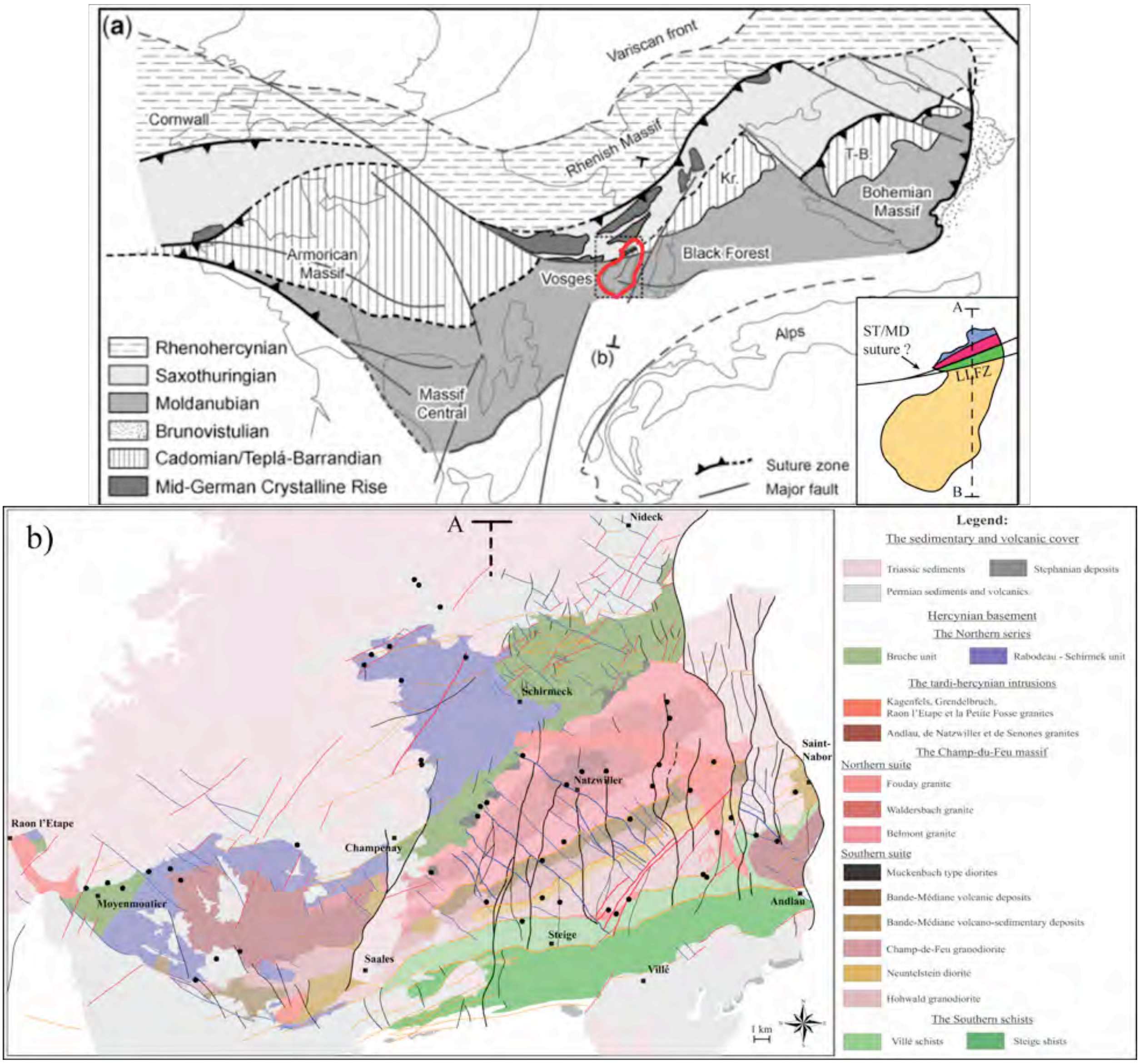

Figure 1: a) Map of the lithotectonic domains of the Hercynian orogeny in Europe modified by Skrzypek et al 2014 after Edel and Schulmann 2009, b) Map of the studied area with the faults and sampling points.

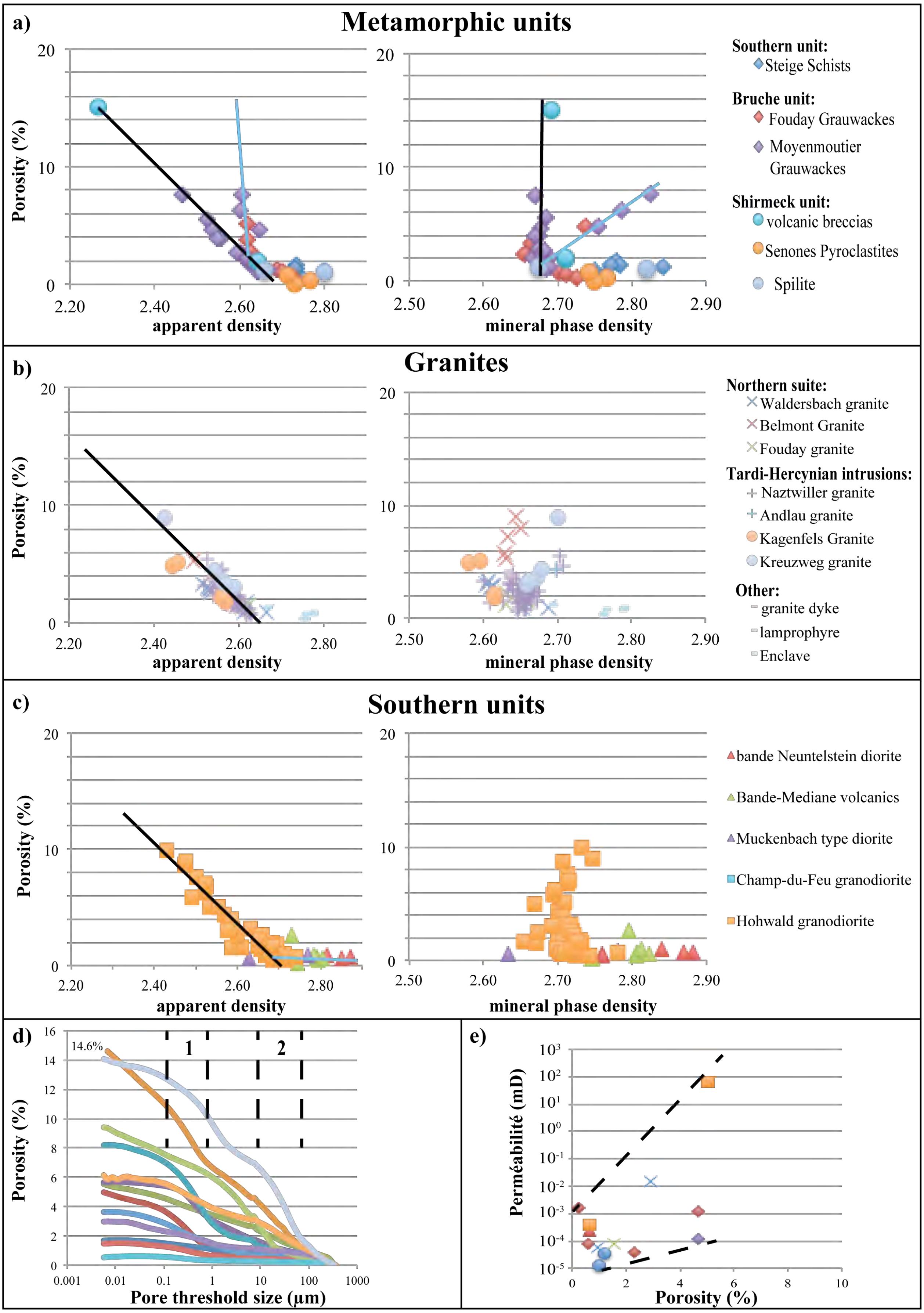

Figure 2: Porosity against apparent density and mineral phase density for a) The metamorphic samples, b) the granites samples, c) the "southern units" sample. d) Porosity against pore threshold size for granitic samples measured with Mercury injection, e) Permeability against porosity.

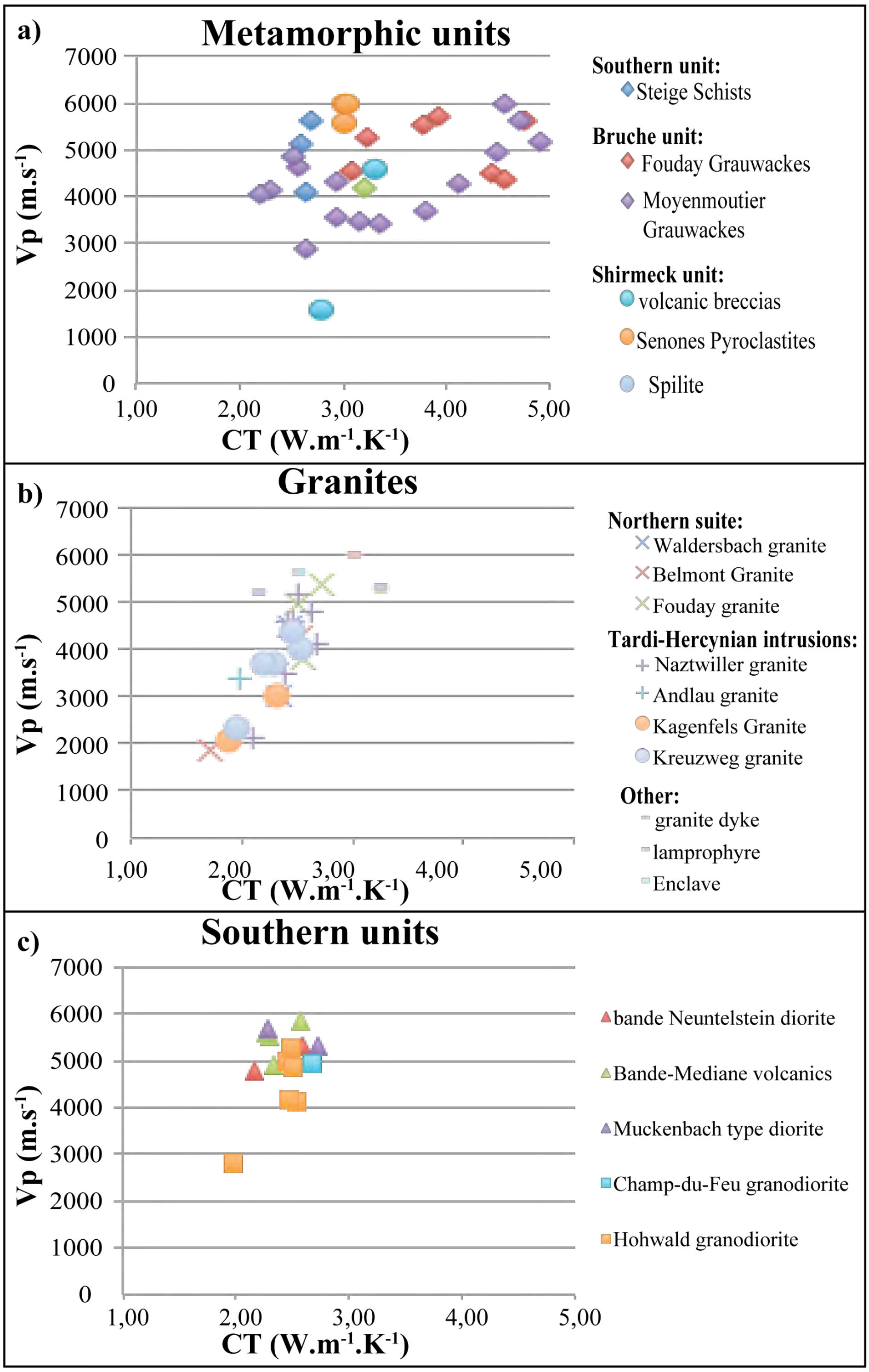

Figure 3: P-waves velocity against Thermal conductivity for a) The metamorphic samples, b) the granites samples, c) the "southern units" sample.

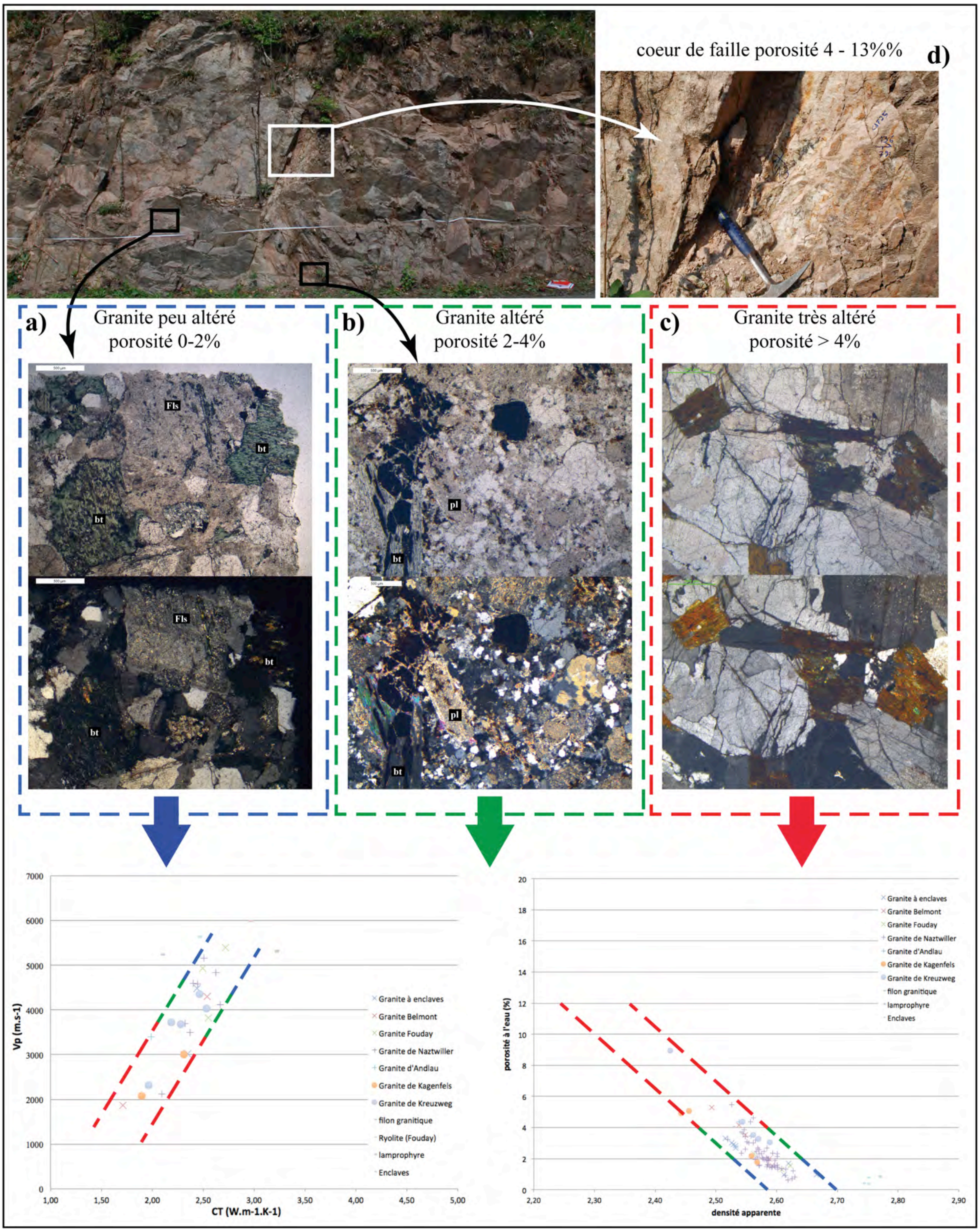

Figure 4: Synthesis of the relation between the structural position, their weathering degree and the petrophysical measurements of the granites and granodiorites samples.

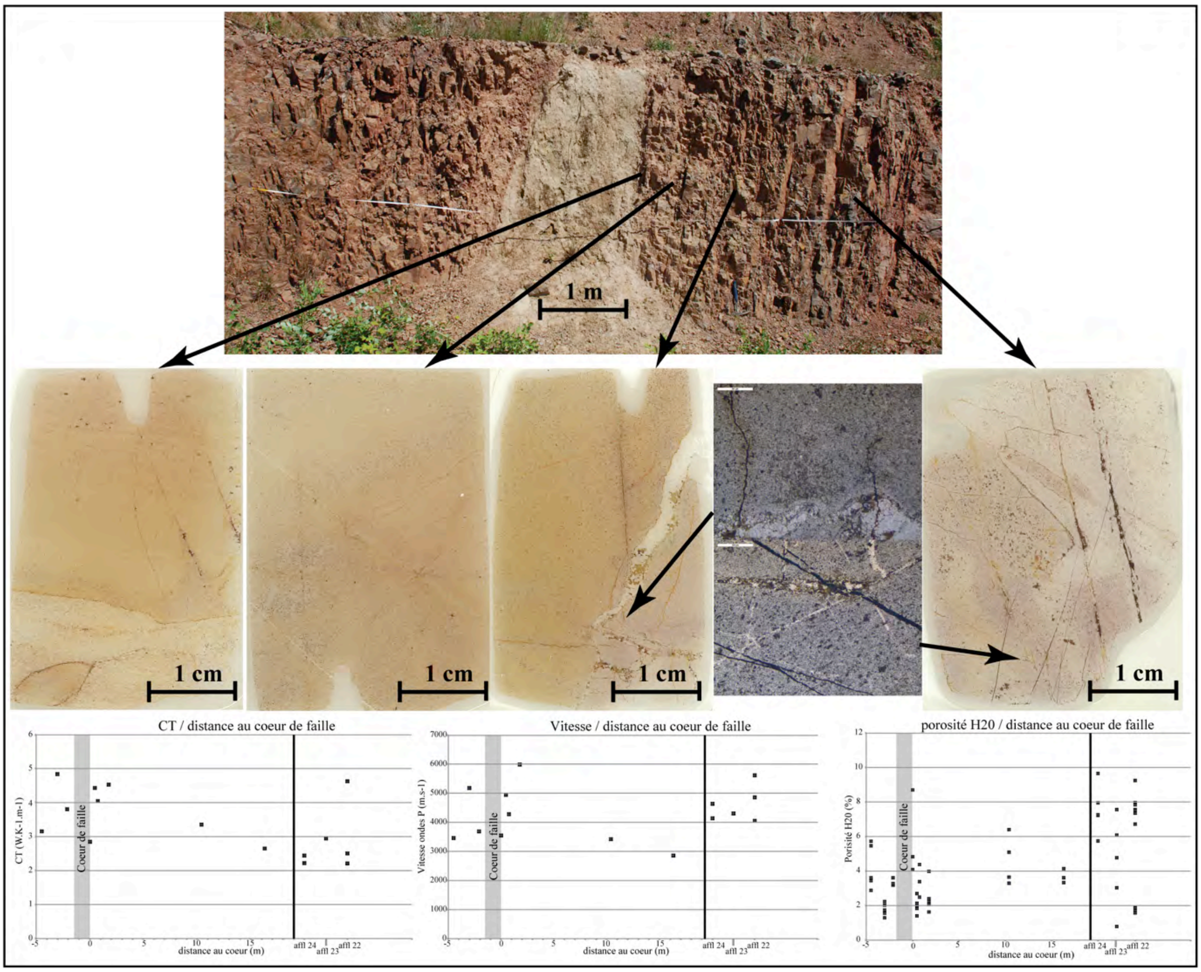

Figure 5: Synthesis of the relation between the structural position and the petrophysical measurements of the grauwackes in the Moyenmoutier fault zone.

6. CONCLUSIONS

The weathering and fault zones architecture controls the location of the suitable areas for geothermal projects in basement rocks, namely by enhancement of porosity and permeability. The location and quality of theses areas depend of many factors, as the host rock lithology, the fault zone history, etc. The use of outcrop analogue samples of the basement of the Upper Rhine Graben allows a first time characterization of the matrix properties of the different lithologies. The model of reservoir properties enhancement linked to the alteration in the fault zones, combined to the study of the fracture and fault zone network (Bertrand et al. in prep), will allow to create double porosity modelization in order to predict the hydraulic behaviour of the fault zones and weathered layers in the basement of the URG.

REFERENCES

Altherr R., Holl A., Hegner E., Langer C., Kreuzer H.: High-potassium calc-alkaline I-type plutonism in the European Variscides: northern Vosges (France) and northern Schwarzwald (Germany). *Lithos* 50 (2000) 51–73.

Autran, A. and Cogné, J.: La zone interne de l'orogenèse varisque dans l'Ouest de la France et sa place dans le développement de la chaîne hercynienne. In: *Géologie de l'Europe*. 26° C.G.I. Paris. Mémoire BRGM, Orléans, 108, (1980) 90 –111.

Bard J.P., Burg J.P., Matte P. & Ribeiro A: La chaîne hercynienne d'Europe occidentale en termes de tectonique des plaques. In : *Géologie de l'Europe*. 26e C.G.I. Paris. Mémoire BRGM, Orléans, 108, (1980) 233 – 246.

Cocks L. R. M., Torsvik T. H.: Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Journal of the Geological Society, London*, 159, (2000), 631-644.

Dewandel, B., P. Lachassagne, R. Wyns, J.C. Maréchal, and N.S. Krishnamurthy.: A Generalized 3-D Geological and Hydrogeological Conceptual Model of Granite Aquifers Controlled by Single or Multiphase Weathering. *Journal of Hydrology 330*, no. 1–2 (October 2006): 260–84. doi:10.1016/j.jhydrol.2006.03.026.

Edel J.B., Schulmann K.: Geophysical constraints and model of the "Saxothuringian and Rhenohercynian subductions – magmatic arc system" in NE France and

SW Germany. *Bull. Soc. géol. Fr.*, (2009), t. 180, no 6, pp. 545-558.

Faulkner, D.R., C.A.L. Jackson, R.J. Lunn, R.W. Schlische, Z.K. Shipton, C.A.J. Wibberley, and M.O. Withjack.: A Review of Recent Developments Concerning the Structure, Mechanics and Fluid Flow Properties of Fault Zones. *Journal of Structural Geology 32*, no. 11 (November 2010): 1557–75. doi:10.1016/j.jsg.2010.06.009.

Franke, W.: The mid-European segment of the Variscides: Tectonostratigraphic units, terrane boundaries and plate tectonic evolution, In: Franke W., Haak V., Oncken O., Tanner D. (eds). Orogenic processes; quantification and modelling in the Variscan Belt. *Geological Society Special Publications*, 179, (2000), 35-56.

Lardeaux, J. M., K. Schulmann, M. Faure, V. Janou ek, O. Lexa, E. Skrzypek, J. B. Edel, and P. tipska. The Moldanubian Zone in the French Massif Central, Vosges/Schwarzwald and Bohemian Massif Revisited: Differences and Similarities. *Geological Society, London, Special Publications 405, no. 1* (June 20, 2014): 7–44. doi:10.1144/SP405.14.

Paris, F. & Robardet, M.: Early Paleozoic paleogeography of the Variscan regions. *Tectonophysics*, 177 (1990), 193-213.

Popov, Y.A., Seminov, V.G., Korosteliov, V.M., Berezin, V.V.: None-contact evaluation of thermal conductivity of rocks with the aid of a mobile heat source. *Izvestiya, Physics of the solid Earth*, 19: 563-567 (1983).

Popov, Y.A., Berezin, V.V., Seminov, V.G., Korosteliov, V.M.: Complex detailed investigation of the thermal properties of rocks on the basis of a moving point source. *Izvestiya, Physics of the solid Earth*, 21, (1985), 64-70.

Popov Yuri A., Pribnow Dan F.C., Sassc John H., Williams Colin F., Burkhardt H.: Characterization of rock thermal conductivity by high-resolution optical scanning. *Geothermics 28*, (1999), p. 253-276.

Robardet, M.: The Armorica «microplate»: fact or fiction ? Critical review of the concept and contradictory paleobiogeographical data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 195, (2003), 125-148.

Rosener, M.: Etude Pétrophysique et Modélisation Des Transferts Thermiques Entre Roche et Fluide Dans Le Contexte de L'échangeur Geothermique de Soltz-Sous Forêts. *Louis Pasteur University*, Strasbourg, (2007), 207p.

Schulmann, K., J. R. M. Catalan, J. M. Lardeaux, V. Janou ek, and G. Oggiano. The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust. *Geological Society, London, Special Publications 405, no. 1* (June 20, 2014): 1–6. doi:10.1144/SP405.15.

Skrzypek E., Schulmann K., Tabaud A.S., Edel J.B.: Palaeozoic evolution of the Variscan Vosges Mountains. *Geological Society, London, Special Publications*, first published March 17, (2014); doi 10.1144/SP405.8.

Tabaud A.: Le Magmatisme Des Vosges : Conséquence Des Subductions Paléozoïques (datation, Pétrologie, Géochimie, ASM). *University of Strasbourg Thesis* (2012), 227p.

Tabaud, A.-S., H. Whitechurch, P. Rossi, K. Schulmann, C. Guerrot, and A. Cocherie. Devonian-Permian Magmatic Pulses in the Northern Vosges Mountains (NE France): Result of Continuous Subduction of the Rhenohercynian Ocean and Avalonian Passive Margin. *Geological Society, London, Special Publications 405, no. 1* (June 20, 2014): 197–223. doi:10.1144/SP405.12.

U.N.E.S.C.O. R.I.L.E.M.: Altération et protection des monuments en pierre, méthodes expérimentales conseillées, *Colloque international*, Paris, 5-9 juin 1978, 1978.

Van der Voo, R.: Paleomagnetism of the Atlantic, Tethys and Iapetus oceans. *Cambridge University press*, Cambridge, (1993) 411p.

von Raumer, J. F., Stampfli, G. M. & Bussy, F.: Gondwana-derived microcontinents-the constituents of the Variscan and Alpine collisional orogens. *Tectonophysics*, 365, (2003), 7-22.