3D geological modelling as a tool for geothermal prospection in the Argentera Massif (south-western Alps)

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ABSTRACT

This paper aims at reporting the 3D modelling criteria for complex crystalline geological setting for geothermal prospection studies. In this study the available data of the Argentera Massif, in the south-western Alps, have been used to come out with 3D models at different scales using the software 3D Geomodeller by Intrepid Geophysicis which is based on a potential field interpolator. Large scale models helped reconstructing the relationship between major faults, the geometries of the metamorphic formation and of the intrusive granitic bodies in the subsurface. Small scale models were used to better constrain the geological formations and fracture systems related to the thermal fluid circulation at the thermal sites of Bagni di Vinadio and Terme di Valdieri, located on the Italian side of the Massif, where hot waters discharge at temperatures up to 70°C.

1. INTRODUCTION

In the framework of geothermal prospection 3D modelling has become a crucial phase to get e better insight of the subsurface to plan the following exploration phases. In fact 3D modelling allows collecting the usually sparse data (e.g. geological observations, maps, cross sections, boreholes logs) to produce an a-priori model, which helps reconstructing the geological features with respect to the collected data and to mathematical and geometrical rules. Moreover a realistic 3D geological model can be integrated, calibrated and validated using geophysical observation, to eventually be employed for post-processing computations such as thermo-hydraulic modelling, fracture characterization, etc.

The Western Alps show widespread evidences of geothermal anomalies even though the heat flux is not particularly high (80-100 mW/m^2). In this region thermal waters naturally discharge from thermal springs and are manly exploited for thermal bathing or are collected from water inflows in deep tunnels to produce heat for space heating.

The presence of geothermal anomalies at the surface in Alpine regions is related to local geological conditions such as fault systems, which allow the water circulation in the subsurface and formation of hot springs. The circulation of these waters is related to deep dynamic groundwater systems, which are considered as low or medium enthalpy geothermal systems. In fact, in such geothermal systems, thermal waters derive from the circulation of infiltrating meteoric waters, which are heated up due the local geothermal gradient conditions. The heat transfer is dominated by advective processes and the upflow is driven both by tectonic effects, which bring to locally enhanced permeability where different active fault systems intersect, and topography which affects the thermal distribution in the subsurface and the hydraulic gradient (Kohl, 2010).

The understanding of thermal water circulation paths in Alpine regions is a difficult task because of the complexity of the pathways through the host rock and because of the lack of data about the subsurface. Geological mapping and geochemical investigations are the most employed methods to get an overview of the geological conditions controlling the thermal fluids circulation in such regions. One of the fastest ways to get an insight of the geology in the subsurface is to collect all the available data to create 3D geological models. Building 3D geological models not only allows visualizing the geometries of the geological bodies in three dimensions but also aims at understanding and constraining these geometries in the subsurface in respect to geological observations and interpretations, geophysical and borehole data and mathematical and geometrical rules. 3D geological models can be used as a tool to plan further explorations, such as geophysics or drilling, which data can then be used to further validate and calibrate the models. Finally a realistic 3D model can be employed in advanced modelling (e.g. thermal, hydraulic, stochastic fracture simulations) to increase the understanding and characterisation of the subsurface.

The present study deals with the creation of 3D geological models using a potential field interpolator to integrate the available geological data (field observations, maps, cross-sections) of the Argentera Massif to come out with 3D models at different scales for the entire Massif and for the two study sites of Bagni di Vinadio and Terme di Valdieri.

2. GEOTHERMAL FRAMEWORK

The Argentera Massif is the area of the Western Alps with the highest concentration of thermal activity related to fault systems and the highest temperatures. The thermal springs are located at Bagni di Vinadio and Terme di Valdieri in Italy and at Berthemont-Les-Bains in France. The highest temperature is reached at Vinadio where hot waters discharge at up to 70°C with a flow rate of 20 kg/s, at Valdieri the average temperature is about 48°C and the flow rate is estimated to be 50 kg/s (Baietto, 2009) and at Berthemont-les-Bains temperature reaches 29°C and flow rate is up to 3 kg/s.

The two sites present waters with different chemical compositions even though they are located in the same lithological setting and only 17 km apart. The thermal springs are concentrated within two small areas surrounded by high relief massifs. At both sites deep waters have a meteoric origins and infiltrate between 1800 and 2000 m a.s.l. At Valdieri a mixing process occurs between cold and hot springs both showing a NaSO4 composition that is typical of water circulation within the crystalline massifs of the Alps. At Vinadio it is evident a mixing process between a deep saline NaCl end member and a shallow and cold NaSO4 end-member. Geothermometers and Saturation indexes indicate reservoir temperature of about 130°C at Bagni di Vinadio and 110°C at Terme di Valdieri (Tab. 1).

Table 1: Resuming table of the main chemical and physical parameters of thermal waters from study area (from Guglielmetti et al, 2010)

Thermal area	T max (°C)	Q (kg/ sec)	TDS max (mg/kg)	pH	Reservoir T (°C)
Bagni Vinadio	72	2	2700	9,1	130
Terme di Valdieri	65	3	300	9,5	110

3. GEOLOGICAL SETTING

The Argentera Massif (AM) is the southernmost of the External Crystalline Massifs of the Western Alps and it is located at the border between Italy and France. It covers an area of about 1000 km^2 and has an NW-SE oriented elliptical shape, 25 km wide and 60 km long. The maximum elevations exceed 3000m a.s.l. and the landscape is the product of glacial, periglacial, hillslope and fluvial processes (Musumeci et al, 2003).

The AM (fig. 1) comprises generally vertical metamorphic units trending N120-140°E which can be divided into two main complexes: the Tinée Complex (TC), on the western side of the massif (anatectic gneisses derived from sedimentary and intrusive protoliths, (Bogdanoff, 1986) and the Malinvern-Argentera Complex (MAC), on the eastern side of the massif, (migmatitic gneisses related to pre-Alpine, high-grade metamorphism of both para- and ortho-derivatives). These formations are locally intruded by syn-anatectic, leucocratic, granites and tardive calc-alkaline granites. The crystalline rocks are unconformably overlaid by Triassic to Early Cretaceous carbonates that are mostly detached above the Late Triassic evaporite (Malaroda, 1970)

The Alpine structures cross-cutting the AM are represented mainly by ductile shear zones, strike-slip and reverse faults, often reactivating pre-Alpine and early-Alpine structures (Bogdanoff et al., 1991). Three are the main structures: the Valletta Shear Zone (VSZ) and the Bersezio Shear Zone (BSZ), NW-SE trending with a dextral sense of shear, and the Fremamorta Shear Zone (FSZ) which crosses the massif East-West. The NW-SE trending VSZ crosses the entire massif and separates the two complexes. It is constituted by up to 1 km-thick mylonitic rocks (Musumeci and Colombo, 2002). The NW sector of BSZ, which runs parallel to the VSZ with a N150-N160 trend, is characterized by a dense set of faults that strike NW-SE and they show a right lateral component. In both shear zones, the mylonitic foliation, striking NW–SE, steeply dipping toward SW and NE, bears a gently dipping lineation and indicates transcurrent movements with a dextral sense of shear: they are both interpreted as high angle shear zones, along which micaschists and mylonitic rocks crop out.

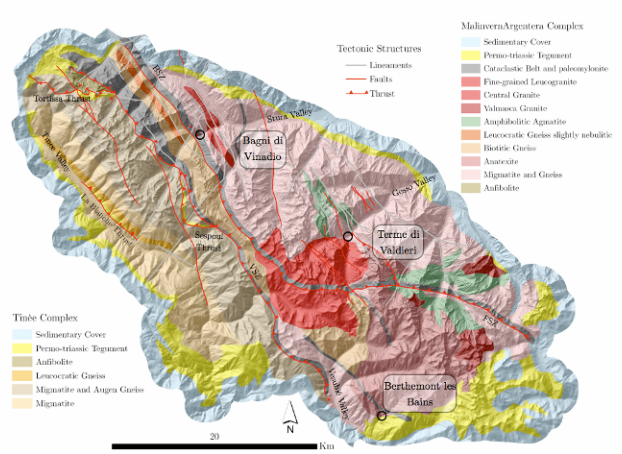

Figure 1: Geological map of the Argentera Massif. BSZ: Bersezio Shear Zone; VSZ: Valletta Shear Zone; FSZ: Fremamorta Shear Zone; (mod. from Malaroda, 1970, Bogdanoff 1986, Musumeci 2003, Corsini 2004, Ribilini 2008 and Baietto 2009)

The ensemble of the VSZ and BSZ was interpreted by Baietto (2006) as a unique 3 km-wide zone of fracturing and pervasive cataclasis, named Bersezio Fault Zone (BFZ).

In the southern part of the massif, the E-W oriented FSZ crosscuts the Central Granite formation and connects to the BSZ. The FSZ is mainly composed by mylonitic and ultramylonitic rocks that crystallized in green schist metamorphic conditions. Along the FSZ the mylonitic foliation progressively dips to the north (30-50°) as it bends, while the lineation keeps consistently a N-S trend, indicating a oblique-inverse sense of shear (Baietto et al., 2009). In the SE sector a reverse mechanism dominates the FSZ structures.

The structural features of the AM result from the superimposition of two main deformative events that occurred during the Alpine tectonic evolution. During the first phase folding and thrusting occurred, the latter being responsible for the cover detachment at the level of the Triassic evaporites. Coeval reverse and strike-slip fault systems (i.e. BFZ) reactivated the older Variscan tectonic lines with the development of cataclastic rocks along narrow bands nearly parallel to the late Variscan mylonites. Most of these structures were activated at different times along the same tectonic lines with SW vergent and right lateral compressive movements (Labaume et al., 1989).

The recent upflow and exhumation of the Argentera (Debelmas and Kerckhove, 1980b, Bigot-Cormier et al., 2000) is due to both active tectonics and isostatic release. Most part of the process occurred along thrust systems and oblique strike-slip faults in response to NE–SW Late Alpine transpressive tectonics (Bogdanoff et al., 2000; Fry, 1989; Tricart, 2004). Seismic and GPS data document that the area is tectonically active, with crustal shortening of 2–4 mm/yr induced by N–S to NE–SW compression (Calais et al., 2000; Madeddu et al., 1996). Exhumation is characterized by mean denudation rates of 0.25mm/yr in the late Miocene–Pliocene (8–3 Ma) and underwent an increase at 3.5 Ma to rates of 0.8–1 mm/yr (Bigot-Cormier et al., 2000). Apatite fission track analysis and geomorphologic analysis (Bigot-Cormier et al, 2000) shows variable denudation rates that have been interpreted in terms of differential vertical upflow of crustal blocks.

4. DETAILED GEOLOGICAL OBSERVATIONS AT THE STUDY SITES

At Bagni di Vinadio (Fig. 2), thermal springs discharge through intensely fractured leucogranites and migmatitic gneiss. The hot springs are located at the step-over zone between two brittle shear zones. In particular, the Bersezio Fault is here represented by a 200 m wide mylonitic belt involving biotitic and mylonitic gneiss of the AM Complex and, in correspondence of the thermal springs a small outcrop of micro-fined leucogranite probably connected, in the subsurface, to the micro-fined granite intruding the gneiss east of the thermal area.

North of the thermal site, highly tectonized and mylonitized potassic migmatitic gneiss of the BSZ crops out. In the proximities of the thermal springs leucogranites two main sets of fractures were observed. The main system is dominated by the alpine structures of the Bersezio and Picial faults trending NW-SE (F1 system), and is associated to a pattern of perpendicular and strike-slip subvertical conjugate faults (F2 system). East of the thermal area the same systems were observed, but an increase in fracture density was observed approaching to the fine-grained granitic body which crops out in the external sector of this study area. The increase in fracture pattern in granites with respect to the gneiss is described by Stober & Bucher (2007). They correlated the hydraulic properties of several crystalline samples collected in deep geothermal boreholes. They observed that zones with enhanced hydraulic conductivity strongly depend on the presence of fine-grained granite, which tends to be more pervious than gneiss and amphibolite even of 2 orders of magnitude.

In the proximities of the thermal spa, an outcrop of highly fractured fine-grained granite was pointed out. Moreover, in correspondence of the leucogranites, a low angle NE-SW system of fractures develops coupled to the two main systems (F3 system). All thermal springs seem to be aligned along this latter system, which might extend up to 1 km in the subsurface, according to the 3D modelling simulations, where it connects to the main structures of the Bersezio fault hence might control the final upflow of the thermal waters along the Bersezio shear zone.

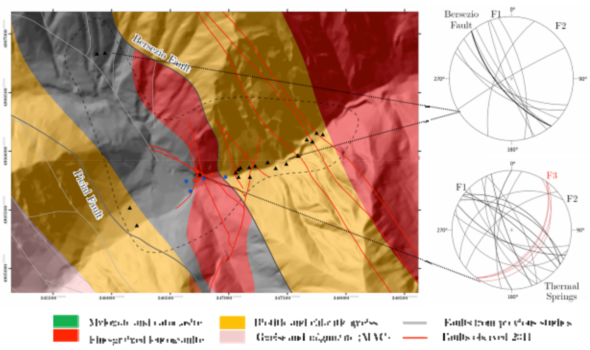

Figure 2: Fracture networks in the Bagni di Vinadio area with the location of the observations (black triangle) and the water sampling points (blue circles: cold water; red circles: thermal water)

The thermal springs of Terme di Valdieri are located in correspondence of the intersection between the northern termination of the 200 m-wide cataclastic shear zone of the Lorusa Fault and the Gesso River. The Lorusa Fault represents the south-eastern border of a zone of intense fracturing limited to the NW by the Cougne Fault, a strike slip fault with dextral sense of shear that crosses both the migmatites and the granite. Both faults dip south-westward while two other main strike slip faults, the S. Giovanni and the Valcuca faults in the SW part of the area, show a progressive north-eastward rotation of the dip direction.

Also in this case, the springs discharge in correspondence of high fractured aplitic dykes. The main outcropping lithologies around the thermal springs are migmatitic gneisses (biotite-rich embrechites and by leucocratic anatexites) and, to the south, the medium grained granite of the Central Granite formation which locally grades to fine grained leucogranites, in particular in correspondence of the thermal springs. The structural setting of Terme di Valdieri (Fig. 3) is controlled by pervasive en-echelon NW–SE to NNW–SSE directed faults showing evidences of right-lateral displacement and cutting the migmatites and the granitic body with persistence up to 10 km. These main faults are locally coupled to ENE-WSW and NE-SW faults characterized by left-lateral movements. The strike slip faults architecture is characterized by an internal gouge zone intermediate cataclasitic domain and an outer brecciated and highly fractured zone. The fracture spacing ranges from a few centimetres to a meter and the opening is usually of a few millimetres. The thickness of these zones (Baietto, 2009) varies whether the fault crosses the mylonites (between decimetres and metres) or the granites (hundreds of metres thick).

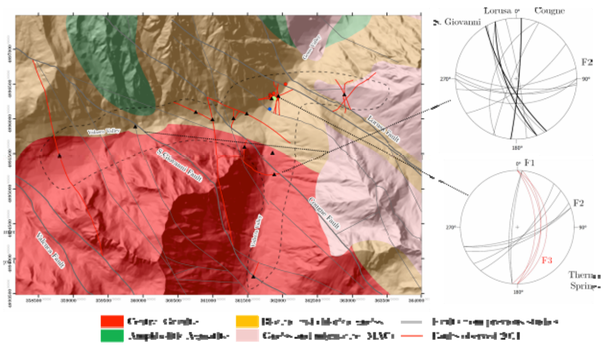

Figure 3: Fracture Networks in the Terme di Valdieri area with the location of the observations (black triangle) and the water sampling points (blue circles: cold water; red circles: thermal water)

Along the Valasco valley it was possible to follow the contact between the biotitic gneiss of the Malinvern Argentera Complex and the medium grained granites of the Central Granite formation. Moreover it was possible to perceive the Cougne Fault, few hundreds of meters E the thermal springs and S. Giovanni fault (Fig. 4), which are the two major strike slip faults (F1 system) in this sector and crosscut the Granito Centrale formation to then reach the Valletta valley towards SE. These two faults are associated with a conjugated system dipping 60-70˚ towards SSE. Along the Valletta valley that crosses the Central Granite, it is possible to realize that the medium granite is highly fractured compared to the gneiss outcropping N of the thermal area. Along the Lorusa valley the same intense fractured biotitic gneiss and amphibolic gneiss outcrop and are crossed by the Lorusa Fault and the same sets of main fractures as those along the Valasco Valley.

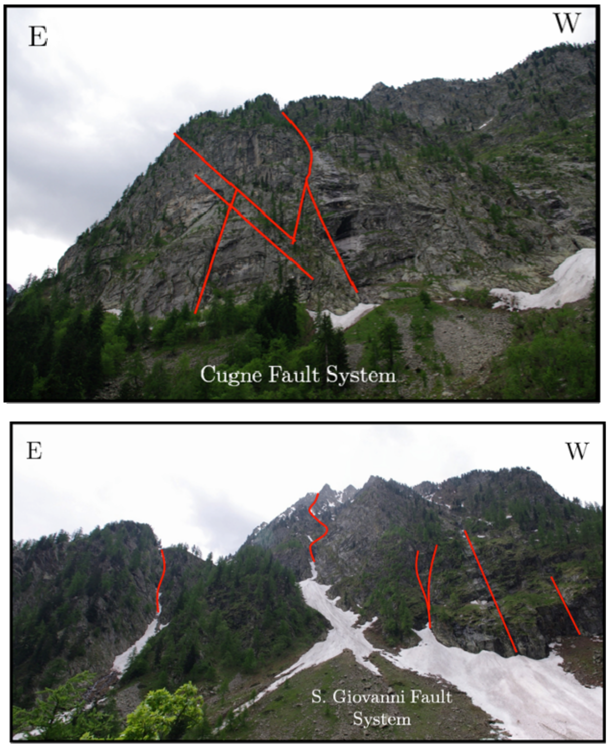

Figure 4: Cougne and S. Giovanni faults systems from the Valasco Valley

In the caves of the thermal springs it was possible to get a three dimensional overview of the fracture systems and of the outcropping rocks (fig. 5). Three caves were analyzed. The upper cave shows the highest concentration of hot springs which discharge through leucogranite and mylonite at the intersection of the three systems of fractures respectively oriented 130/70°, 275°/75° and 90/35°. The same systems were observed in the wellness cave where the low angle seems to be more pervasive. Finally, at the lower cave shows how two main hot springs. When entering the cave the mylonitic gneiss crops out on the floor whilst the wall is composed by leucogranite, intensely fractured. The fracture spacing within the granite was here estimated to be 5-10 cm. Thermal springs discharge in correspondence of a cataclastic outcrop, which follows the low angle F3 set of fractures, in the upper right corner of the cave.

5. COMPUTING THE 3D MODELS

The potential field interpolation is a common method to create 3D implicit models starting from sparse and scarce data. The selected software 3D Geomodeller by Intrepid Geophysics allows constructing 3D geological models starting from scattered and scarce data from geological maps, cross sections and boreholes and to calibrate the built *a-priori* models using geophysical data (gravity, magnetic and seismic). The main data needed to compute a model are the topographic surface (e.g. a Digital Terrain Model DTM), which represents the upper border of the model, contact points or *interfaces* (representative of the geological limit of each formation) and dip data (named *foliations* in the software) which can be obtained from field observations and geological maps. More needed information are the stratigraphic pile, the reference of the pile specifying if the data points define the *top* or the *bottom* of the formation. Modeling is carried out by means of an implicit method based on a potential field method, taking into account contact points and dips located on topography and cross sections using a co-kriging interpolation (Calcagno et al, 2008).

5.1 Definition of the topography

Topography behaves as the upper border of the 3D model. A 30-meter NASA Shuttle Radar Topography Mission SRTM30+ DEM was employed for the Argentera Massif model and the 10-meter DTM provided by the Regione Piemonte was employed for the two smaller models of Vinadio and Valdieri. For this study the used topographic grids were converted, via ESRI ArcGis®, to ASCII files and then to .grd to be finally imported in 3D Geomodeller.

5.2 Definition of the extent of the model

For the Argentera Massif model the extent was set to be the Massif itself with a buffer of some hundreds of meters to include the Trias formation, cropping out around the crystalline basement, and the surrounding autochthon sedimentary cover. The depth for all models was set to 4500 meters below the sea level. This depth allowed computing a 5km-deep models which is the expected depth for the thermal fluids circulation according to geochemical investigations (Guglielmetti et al, 2010). The two smaller models of the sites of Vinadio and Valdieri, covering the field observations carried out by the authors, have the goal to show in detail how the complex fracture systems, that were detected in the proximities of the thermal springs, are connected to the major faults to justify the final upflow of the hot waters.

Among the available geological maps and cross sections, those containing useful information, enough detail and accuracy were imported to constrain the geological limits, faults and dips. Some of the maps used only reported the milonitic foliation dip data (that not necessary is representative of the effective dip of the formation) or didn't show any dip at all. Moreover any detailed geophysical data were available as in this region geophyisical studies (e.g. Masson et al, 1999), especially gravity, were conducted in the past but to detect deep structures and were not functional to the purposes of this study. Hence the models were computed exclusively on the basis of the surface data and few interpretative cross-sections such as those cited in the previous paragraphs (Guglielmetti, 2011).

Figure 5: Detail of one of the thermal springs' cave where the low angle F3 set of fractures cuts the fine grained granite in correspondence of the thermal springs

5.3 Modelling criteria

The study areas are mainly represented by several types of metamorphic formations locally intruded by granitic bodies and surrounded by the autochthonous Carbo-Triassic sedimentary cover and the detached carbonate Mesozoic succession. Other important geological features are the fault zones such as the Valletta, Bersezio and Fremamorta shear zones, which are representative of the reactivation of Variscan structures during the Early (22 Ma) and Middle Miocene (12 Ma).

The geological bodies were modelled according to the available geological data, however some simplifications and modelling choices were needed. For instance the selection of the lithologies was based on two main criteria: geometrical extension and geological relevance in terms of mineralogical composition and fracture conditions. Hence the heterogeneities in terms of mineralogical composition and/or fracture network density within a formation were modelled as separate bodies to prepare a model which not only was geological realistic and respective of the geological data but which also could be representative of geological conditions that could be significant for post-processing modelling. The available cross-sections were not deep enough to constrain the underground geometries down to 5 km, therefore the geological bodies were assumed to have constant dip on the basis of the field observations and the cross sections or maps.

Some draft models were computed to figure out the best way to come out with a realistic model without requiring an excessive amount of constraints in terms of contact points, dips, hence of computing time. A simple model including just 3 formations (Tinée Complex, Valletta Shear Zone and Malinvern Argentera Complex) was firstly computed to set the stratigraphic pile in terms of chronological hierarchy of the series and their relationship. This phase aimed at defining whether the formation had to be grouped into series (hence a group of formations having the same geological behavior) a separate, individual series. Finally that the best way to model the several formations was to consider each formation as individual with an *erode* relationship and the contact points were placed at the *bottom* of the formation. The entire model of the Argentera Massif was then modelled following an iterative process that allowed gradually adding the several formations, faults and shear zones and adjusting the model step by step. The final result is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. This images also shows how the Argentera Massif had to be split into 6 main geological/geometrical "blocks" to make the model respectful of the interpreted geometries of the formations in the subsurface:

- Western carbonate and evaporite cover (French side);
- Tinée Complex including the Valletta Shear Zone;
- Malinvern Argentera Complex between the Valletta shear zone and the Bersezio shear zone (included);
- Malinvern Argentera Complex between the Bersezio shear zone, the Cover and North of the Fremamorta Shear Zone;
- Malinvern Argentera Complex South of the Fremamorta Shear Zone (included);
- Eastern carbonate and evaporitic cover (Italian side).

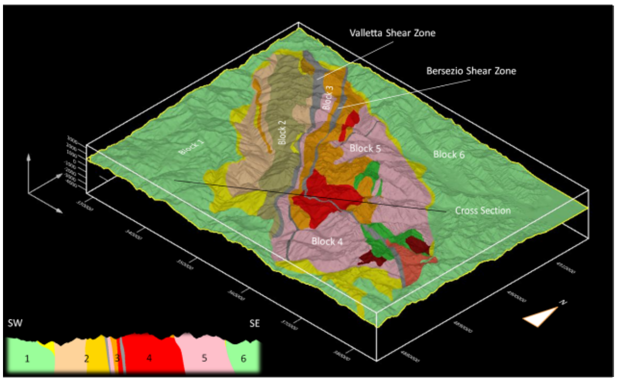

Figure 6: 3D geological model of the Argentera Massif computed on the topography and on a cross section

Faults were modelled to represent the main features for the large scale model of the Argentera Massif and the detailed and complex fault systems for the areas of Vinadio and Valdieri (Fig. 7) The main data sources were the studies of Perello (2001) Baietto (2009) for the detailed models of Vinadio and Valdieri but other geological maps and structural sketch were useful for large-scale information such as the extension at depth of fault zones and outcropping formations. Moreover some data collected, during this thesis, in the proximities of the thermal springs were integrated into the detailed models to better figure out which fracture systems were directly connected to the presence of the springs.

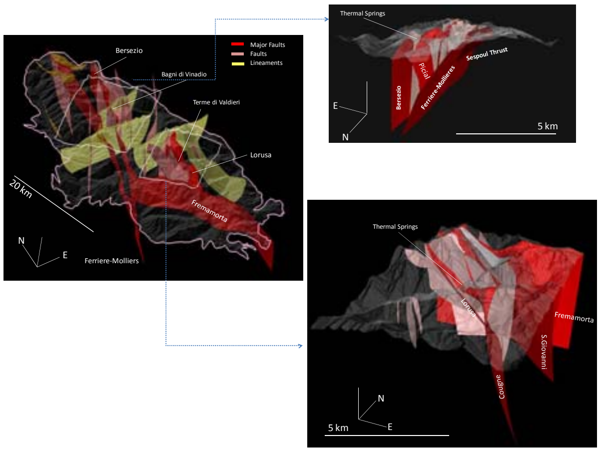

Figure 7: 3D fault network at in the Argentera Massif and detailed structures at Bagni di Vinadio and Terme di Valdieri

5.4 Modelling the shear zones

These structures are mainly composed by mylonitic rocks which thickness ranges between 100 and 2000 m and, because of their importance for the fluid circulation, as pointed out by Perello (2001) and Baietto (2009), they were modelled as separate geological formations, hence defined by a volume, and not simply as fault planes. The modelling drafts mentioned above also helped constructing the fault zones and the cataclastic belts.

The first approach was to try keeping a chronological order of the fault zones with respect to the crystalline formations. Hence the first test was to set and erosional behaviour placing these bodies at the top of the stratigraphic pile. These formations are characterized by a strong geometrical anisotropy (e.g. the Valletta and Bersezio fault zones are 40 to 60 km long whereas they are up to 2km large). In this case the software showed some computation limits as too many control points were needed to correctly reproduce the geological maps, but they were poorly modelled in the subsurface, sometimes reaching only few hundred meters in depth. Hence several horizontal and vertical sections were created to force the software to properly compute these formations. The results were quite satisfying on a geometrical point of view but the computation time just to build the fault zone was strongly increased. Finally, to keep the geometries realistic and in agreement to the interpretations, the main fault zones were considered as formations within the stratigraphic pile and not at the top of the pile. This solution reduced the computation time and, even though it is not chronologically strict, the geometries were well constrained and the results also can be quite reliable on the lithological point of view. In fact fault zones are composed by mylonites deriving from the alteration of the original gneissic and granitic formations.

The Valletta zone was modelled with a 80° constant dip, parallel to the gneiss formations of the Tinée Complex, the Bersezio mylonites were considered almost vertical having a dip of 85-90°. The Fremamorta Fault Zone shows a milonitic foliation of an average angle of 50-60° dipping towards North. Moreover this region shows the highest exhumation rate of the entire massif because of a transpessive regime where the FMZ behaves as a ramp. Therefore the Fremamorta Shear Zone was modelled according to the mylonitic foliation as dipening towards N with an angle of 60°. The minor cataclastic belts (e.g. Rio Freddo and C.me de la Vallette) were modelled as vertical. The highly milonitized areas, East of the Terme di Valdieri site, are composed by paleomilonites and several milonitic belts which are hardly mapped as separate, hence they were modelled as volumes as well.

Moreover all the fault zones which crossed more than one formation were split into separate volumes to be able to take into account the presence of portion of enhanced permeability or reduced density within each formation caused by the presence of the fault zones.

5.5 Modelling the metamorphic formations

These formations have been involved, during the Upper Miocene-Oligocene, by the intense tectonic activity which brought to the development of thrusts faults and to the reactivation of older Variscan tectonic lines. The Bersezio and the Valletta shear zones are two mylonitic corridors related to these latter events and are mainly composed by paleo-mylonite and cataclasite. On the geometrical point of view these formations show an average 70-80° dip towards NE and are crossed by the Valletta, Bersezio and Fremamorta shear zones.

The Tinée Complex was modelled considering three main metamorphic formations (embrichites, leucocratic gneiss, eye-shaped gneiss) and the Triassic formations pinched within the La Blanche, Tortissa and Sepsoul Thrust. The leucocratic gneiss as well as the Trias composing the Sespoul Thrust compose lense-shaped bodies, which showed the same modelling issues as the fault zones: Hence we had to split the embrichites into three separate bodies.

The modelling of the Malinvern-Argentera Complex was based on five metamorphic formations (migmatitic gneiss, leucocratic gneiss, biotitic and chloritic gneiss, biotitic anatexites, amphibolitic agmatites), which are locally intruded by leuco-granitic bodies in correspondence of the thermal site of Bagni di Vinadio, by the Granito Centrale formation at Terme di Valdieri and by the Valmasca Granite in the south-eastern sector of the Massif. All the metamorphic formations are unconformably overlapped by the sedimentary formations having a maximal thikness of 3000m (Faure-Muret, 1955) and the Triassic evaporites, The carbonate cover was modelled with an onlap relationship over the crystalline formations of the Argentera Massif. The geometry of the crystalline basement underneath the sedimentary cover was modelled as an undifferentiated crystalline basement. With the exception of the granitic bodies which were separately modelled as intrusive all the gneissic formations have been geometrically interpreted as parallel units steeply trending NE. As 3D-Geomodeller needs a stratigraphic pile to be defined, the Tinée Complex formations were chosen to be at the bottom of the stratigraphic pile below the Malinvern Argentera Complex. The southern part of the MAC Complex, in particular the biotitic gneiss are characterized by a zone on intense fracture density between the Valletta and the Bersezio Faults which was not modelled in the AM model.

6. DISCUSSION ABOUT THE MODELS

In the Bagni di Vinadio region, metamorphic formations owing both to the Tinée and the Malinvern-Argentera Complex crop out. These formations have been involved, during the Upper Miocene-Oligocene, by the intense tectonic activity which brought to the development of thrusts faults and to the reactivation of older Variscan tectonic lines. The Bersezio and the Valletta shear zones are two mylonitic corridors related to these latter events and are mainly composed by paleo-mylonite and cataclasite. On the geometrical point of view these formations show an average 70-80° dip towards NE and are crossed by the Valletta and Bersezio shear zones. These two mylonitic corridors appear to be slightly steeper. The Valletta zone was modelled to have a constant dip of 80°, parallel to the gneiss formations, the Bersezio mylonites were considered almost vertical having a dip of 85-90°.

The Tinée Complex was modelled considering the four main formations including the sedimentary cover, pinched in the Sepsoul Thrust, and the metamorphic basement (embrichites, leucocratic gneiss, eye-shaped gneiss), while the Malinvern-Argentera Complex is composed by five metamorphic formations (migmatitic gneiss, biotitic and chloritic gneiss, biotitic anatexites,, amphibolitic agmatites, granites) locally intruded by leuco-granitic bodies in correspondence of the thermal site and East from it. With the exception of the granitic bodies, which were separately modelled as intrusive, all the gneissic formations have been geometrically interpreted as parallel units steeply trending NE and unconformably covered by the sedimentary sediments. As 3D-Geomodeller needs a stratigraphic pile to be defined, the Tinée Complex formations were chosen to be at the bottom of the stratigraphic pile below the Malinvern Argentera Complex. The southern part of the MAC Complex, in particular the biotitic gneiss are characterized by a zone on intense fracture density between the Valletta and the Bersezio Faults (dark orange in Figure), which was modelled not modelled in the AM model, but was here introduces as a separate block to take into account for the integration with gravimetric data.

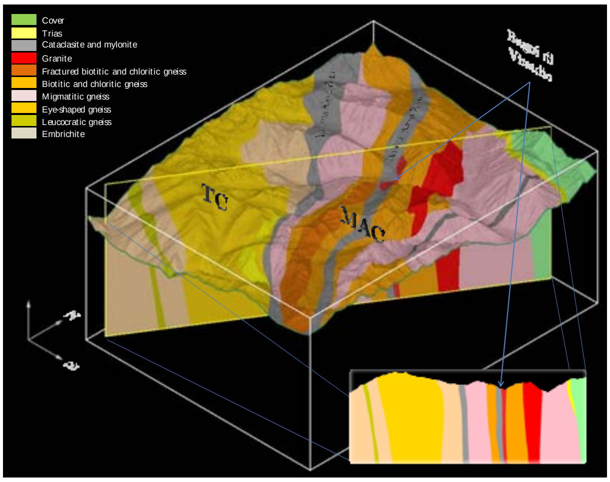

Figure 9: 3D model of the Bagni di Vinadio area plotted on the topography and in cross-section

In the Terme di Valdieri region, metamorphic formations owing to the Malinvern-Argentera Complex crop out. These formations include biotitic and chloritic gneiss, biotic anatextite, amphibolitic agmatite, which are intruded by the Central Granite formation in the south-eastern part of the model. The two main tectonic features are the Lorusa fault zone and the Fremamorta shear zone which crops out in the south-eastern part of the area (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

Granitic intrusive bodies are localized in all the External Crystalline massifs but their geometrical shape of their roots is usually hard to define and model in 3D (Strzerzynski et al., 2005). The Central Granite formation covers an area of about 50km^2 in the Valdieri area, West of the thermal springs and it is crossed, East to West, by the Fremamorta Shear Zone. It has a roughly circular shape and its emplacement post-dates the three migmatitic events (Debon and Lemmet, 1999). Moreover its extension in the subsurface is complex and was estimated taking into account the Ciriegia Tunnel cross-section (Bortolami and Grasso, 1969) and the S.Anna Borehole (Baietto, 2006b).

Particular focus was given in the modeling of this granitic intrusion In the central sector of the AM the metamorphic formations owing to the Malinvern-Argentera Complex are intruded by the Central Granite formation. Granitic intrusive bodies are localized in all the External Crystalline massifs but their geometrical shape of their roots is usually hard to define and model in 3D (Strzerzynski et al., 2005). The Central Granite formation covers an area of about 50km^2 in the Valdieri area, West of the thermal springs and it is crossed, East to West, by the Fremamorta Shear Zone. It has a roughly circular shape and its emplacement post-dates the three migmatitic events (Debon and Lemmet, 1999). Moreover its extension in the subsurface is complex and was estimated taking into account the Ciriegia Tunnel cross-section (Bortolami and Grasso, 1969) and the S.Anna Borehole (Baietto, 2006b).

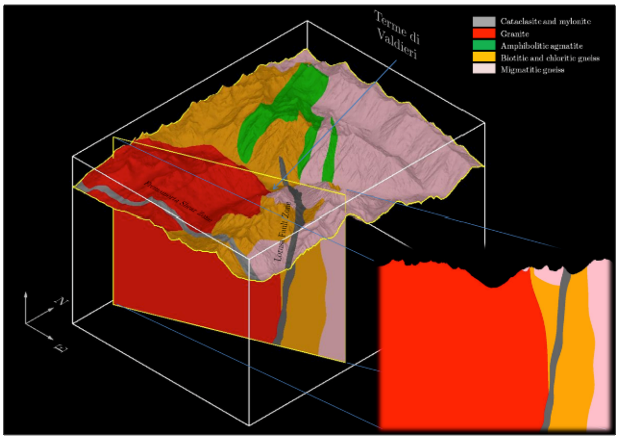

Figure 10: 3D model of the Terme di Valdieri area plotted on the topography and in cross-section

The 3D shape of the Central Granite formation was built in four modelling steps (fig. 8):

1. the vertical foliation roughly trending NW-SE, indicated on the geological map b (Malaroda, 1970) and which was developed during the emplacement of the granite, was assumed to be representative and of the initial intrusive contact. This first stage brought to a constrained model of the granitic body on the basis of the geographical localization of the contact points and foliations;
2. the second step was to integrate the Fremamorta Shear Zone cutting the granite. Because of the above mentioned software limits in modelling the shear zones, the Central Granite formation was split into two main bodies divided by the FSZ;
3. the third step was to consider the subsurface granite/gneiss contact at the roof of the granite. The plunge of this contact is low towards NE and then becomes vertical in the proximities of the entrance of the Ciriegia tunnel. This contact is indicated on the Cirigia Tunnel cross section (Bortolami and Grasso, 1969). This step led to the modification of the geometry of the northern portion of the granitic body, which was extended towards NE;
4. the fourth step was to integrate the S. Anna Borehole. This borehole is 1150 m long, 60˚ deviated towards NE and reaches a depth of 850m. Its log shows two main granitic bodies. The first is located at 35 meters in depth is 100 m thick and is described as “micro-granite”, the second at 860 m in depth is more than 400m thick and described as “fractured granite”. The former was interpreted as a local intrusion or dyke very similar to the outcropping granite in the proximities of the Vinadio springs, the latter as part of the Central Granite formation. However, as it is an

arbitrary interpretation, we preferred not to modify the previously modelled geometry but to model this extension towards North as a separate body.

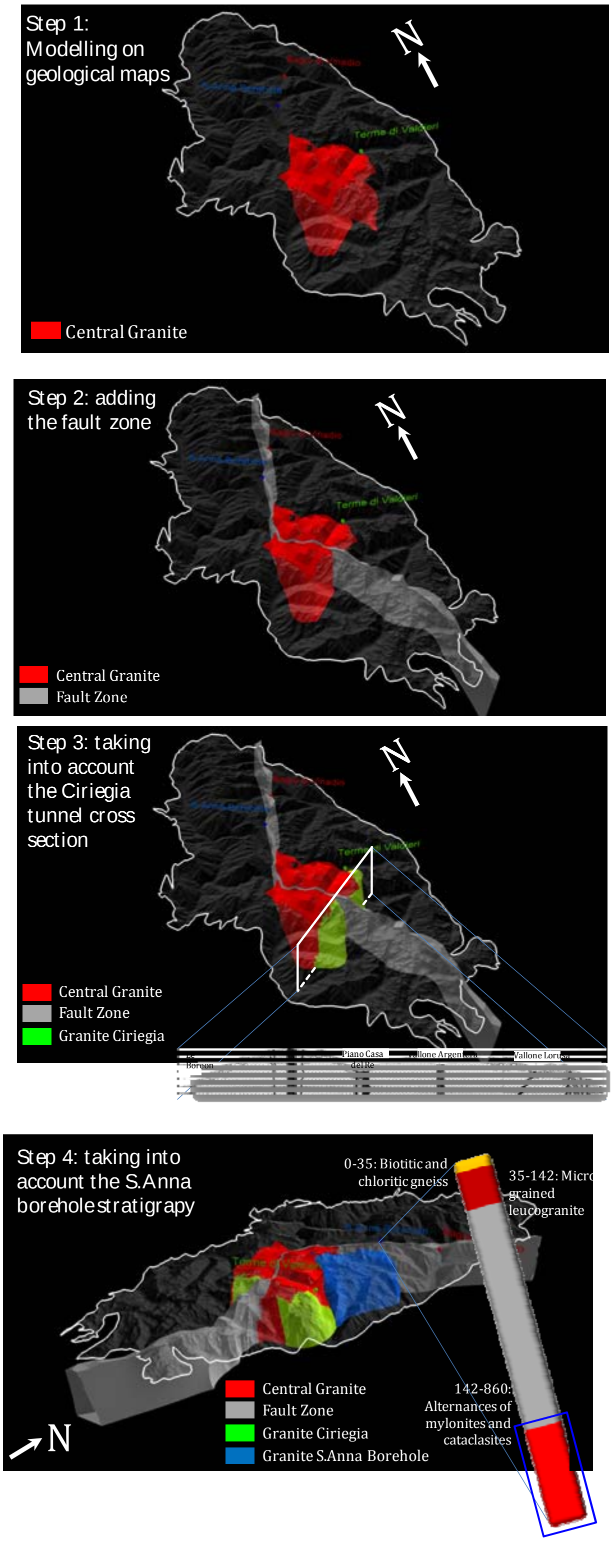

Figure 8: Modelling sequence for the Central Granite formation

7. CONCLUSIONS

The utilization of 3D models allowed to group together all the scattered geological data coming from direct field observations and from maps and cross sections from previous studies. Even though creating 3D models implied some simplifications, the goal of the preliminary phase was to keep the geological complexity on the basis of strict interpretations but at the same time to produce models, which can be used as the basic tool to integrate geology and geophysical data. A model of the entire Argentera Massif was computed to understand the efficacy of the modelling software and then 2 more detailed models were created for the two study sites.

The authors point out that the proposed models are not intended to be a simple representation of the geology but a primary tool to plan subsurface investigations which might help at better constraining the geological structures involved in the deep thermal fluid circulation. Hence the modelling procedure had not only to be geological correct but must also took into account the physical properties variations (e.g. density, fracture density), which might occur within formations to eventually set the model whether new geophysical data (e.g. gravity or magnetotellurics, which are two methods that can be employed in such regions and which assure an investigation depth of some kilometres) might be available.

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