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The geological and metallogenic map of the Baccu Locci mine area (Sardinia, Italy)

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Abstract

The study area is in the nappe zone of the Sardinian Variscides in the southeast part of the Island of Sardinia (Italy), and extends between 39°33'14"/9°30'14" (NW corner) and 39°30'09"/9°35'36" (SE corner). The area shows a section of the Variscan orogen in Sardinia with three tectonic units that were stacked and folded during the Middle Carboniferous Variscan tectonics.

The presented 1:10,000 scale geological map, the cross sections and the 3D models illustrate the complicated tectonic setting of the area, resulting from the polyphasic Variscan collisional evolution as well as from later extensional stages. The geometry resulting from progressive deformation is strongly non-cylindrical; it is not balanceable because the polypahsic deformation with different tectonic transport directions and the loss in volume in the different formations occurred under greenschist facies metamorphism. The use of 3D modelling of geological surfaces greatly improved both the map and cross-sections.

The Variscan basement of the study area hosts one of the most important mining zones of SE Sardinia (Baccu Locci mine area), which was active until 1961 for the extraction of AsPy, PbS and ZnS. Recent studies also found a noteworthy occurrence of Au. The Baccu Locci mine is assumed to be the eastern part of a mineralized corridor linked with the Variscan shear zone.

A metallogenic map of the Baccu Locci mine area at 1:7,500 scale is included in this paper. The primary map associated with this paper actually represents a 4D model (spatial and time dimensions) of ore bodies hosted in a crystalline basement and highlights the overprinting of different paragenetic sequences of mineralizations and their relationships with pre-existing structures.

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1. Introduction

1.1 Geological outline

The study area is located in the *Nappe zone* of the Variscan metamorphic basement of Sardinia (Figure 1), which is a part of the Southern Variscan realm (Rossi et al., 2009). In the Nappe zone all of the tectonic units are emplaced with a top-to-the-south transport direction; metamorphism and internal deformation of rocks increase northward: from anchizone in the south, up to medium grade in the northern part of the Island (Figure 2). The Variscan basement that crops out in the study area is metamorphosed in greenschist facies conditions.

In the study area three tectonic units are mapped (from the bottom): Riu Gruppa Unit, Gerrei Unit (with the Monte Lora and Arcu de su Bentu sub-units) and Meana Sardo Unit. They show more or less the same lithostratigraphic succession, with some differences in the Ordovician volcano-sedimentary succession.

The Variscan successions are characterized by:

- metasandstones and metasiltstones of Middle Cambrian - Lower Ordovician age;
- a volcano-sedimentary succession of Middle Ordovician age, with metatuffites, metavolcanoclastites with interlayered metaepiclastites with an andesitic composition at the bottom, and meta-rhyolithic rocks, with a porphiric texture and phenocrysts of quartz and feldspar at the top;
- a silici-clastic to carbonate succession of Upper Ordovician - Lower Carboniferous age, with metaarkose, metasiltstones, marls, black shales and metalimestones;
- a Lower Carboniferous thick silici-clastic sequence with metaconglomerates, metasandstones and olistolites that unconformably rest on the Devonian formations, and probably represents Culm-like (i.e. mainly siliciclastic) flysch, but which does not crop out in the study area.

The metamorphic basement is intruded by a Late Palaeozoic (Upper Carboniferous to Lower Permian) Intrusive complex. Granitoid bodies outcrop outside of the study area, where just a complex dyke swarm crop out. Unconformable on the metamorphic basement, the Lower Eocene Monte Cardiga fm. was deposited, with conglomerates, sandstones and marls.

The Variscan tectonic evolution of the study area is characterized by a shortening phase (D1) related to the continent-continent collisional stage, that produced the nappe stack,

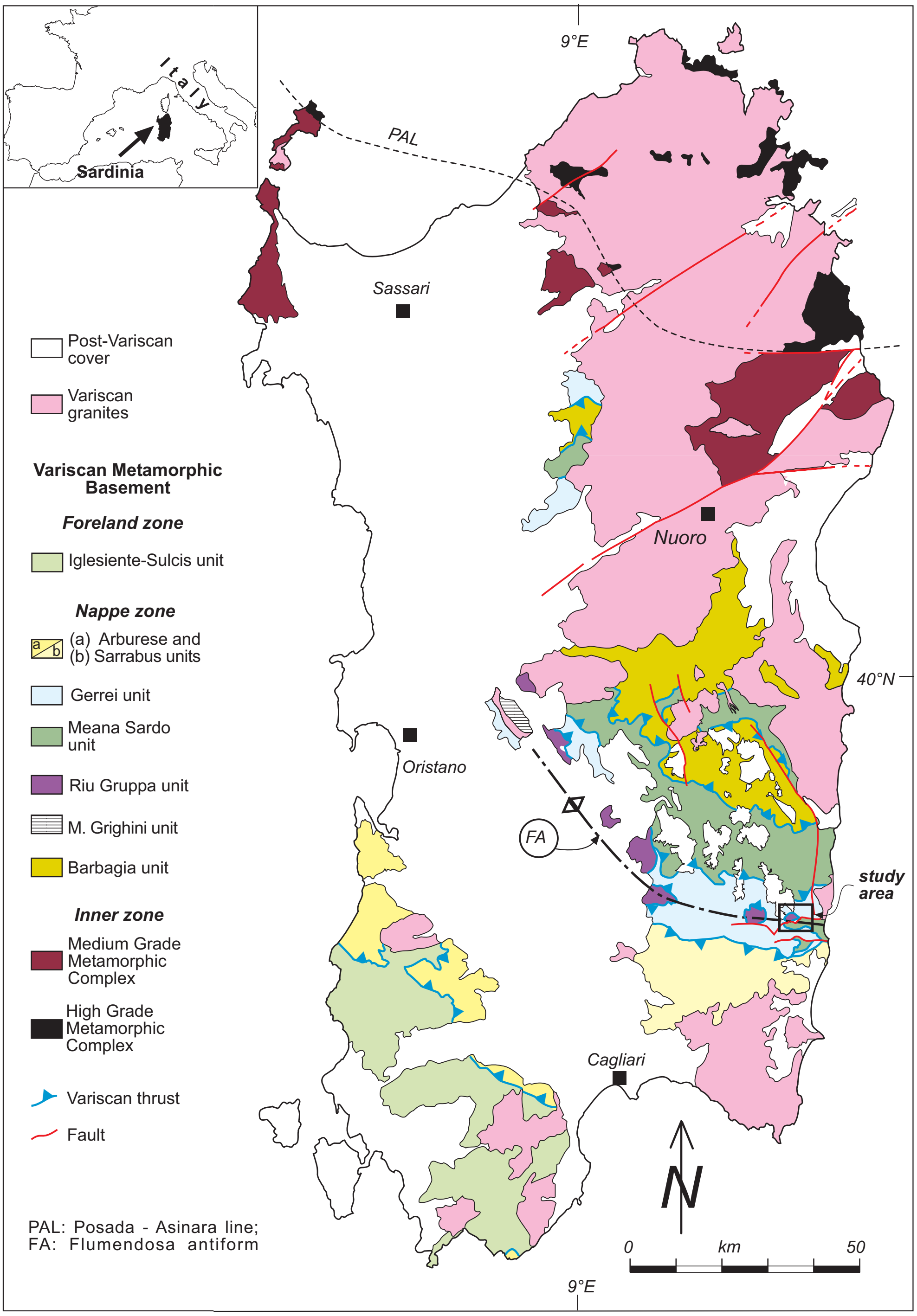

Figure 1. Generalized tectonic map of the Variscan basement of Sardinia (after Carmignani et al., 2001b, modified).

and by a later phase related to post-collisional extension (D2). We use the classical nomenclature applied to polyphasic orogens: D followed by a number to indicate deformation phases, the smaller the number the older the phase; in the same way we

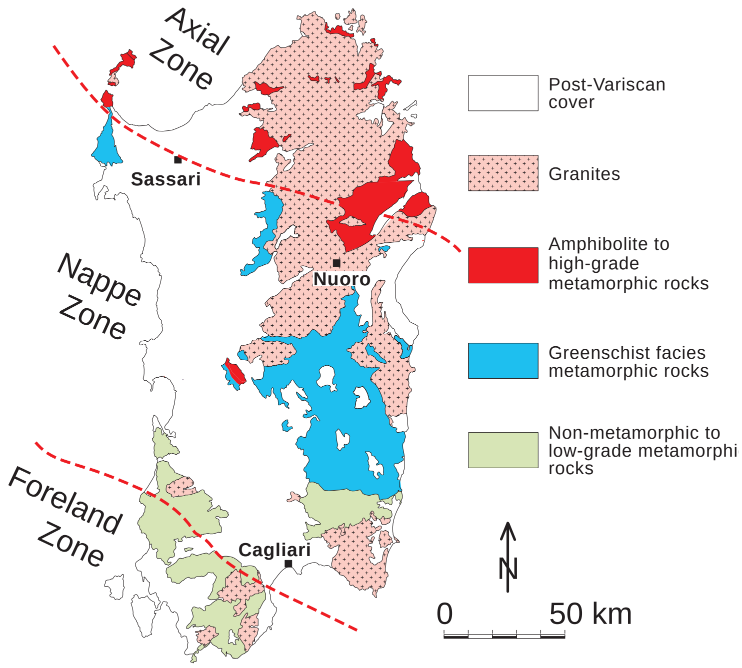

Figure 2. Tectono-metamorphic zones of the Variscan basement of Sardinia (after Carmignani et al., 2001b, modified).

indicate S1, S2, etc. for the related tectonic foliation. For a more detailed description of the deformation evolution see Conti et al. (2001).

The main D1 structures are kilometric recumbent isoclinal folds facing to SSW, with a well developed axial plane foliation (S1) in low-grade metamorphic condition, and overthrusts between the tectonic units (with top-to-south transport direction). Cross-section C-C′ that crosses the Pranu Meurras area and cross-section D-D′ that crosses the Bruncu S'Arettori relief show some of these folds. The S1 axial plane foliation, depending on the lithotype, could be a slaty cleavage in phyllites or a non-continuous cleavage in quartzites. It is the main planar surface at outcrop scale and usually transposes the original bedding. Between the Gerrei Unit and the underlying Riu Gruppa Unit the Baccu Locci shear zone (Conti et al., 1998) occurs, it is a thick (up 700 m) mylonite zone developed during D1 deformation. Locally the main foliation in the mylonite zone (Sm) overprints the S1 foliation.

In the study area all of the D1 structures are affected by late shortening events (Late D1) that produced large upright antiforms, with a wavelength of about 10 km, and more than 20 km of axial plane length. At larger scale these antiforms form the Flumendosa Antiform, recognized from the eastern coast of Sardinia and extending for 50 km in a WNW direction (Figure 1). The Baccu Locci antiform (BLA), that refolds the Baccu Locci shear zone, is one of these upright antiforms. At its core is the Rio Gruppa Units. Small

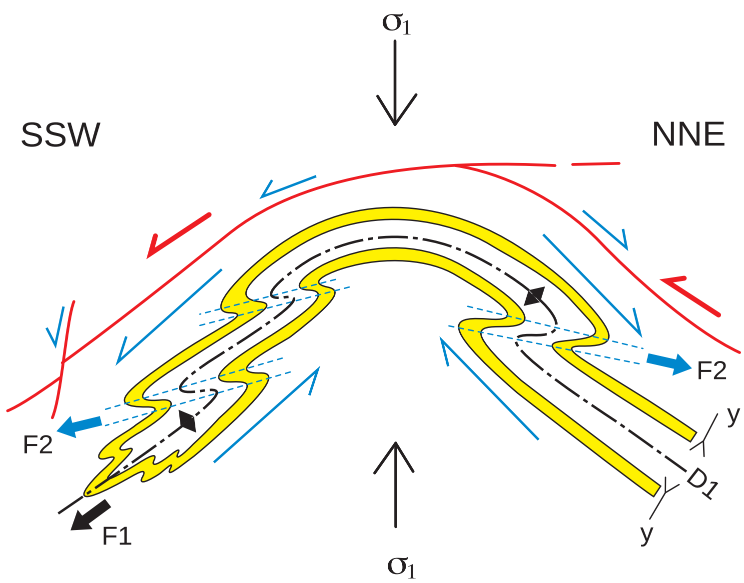

Figure 3. Synoptic sketch of Variscan deformation stages in the external nappe. D1: axial plane of folds related to D1 shortening phase; F1: facing direction of D1 folds; F2: facing direction of asymmetrical folds related to D2 extensional phase (after Carmignani et al., 2001b, modified).

antiforms are mapped in the northern side of the study area where they influenced the geometry of the mined ore bodies.

During the post-collisional D2 phase all of the nappe stack described above was uplifted and extended and the antiformal structures were enhanced by low-angle ductile normal shear zones. As a result of this, they become structural high zones. Inside the normal shear zone, asymmetric folds developed, and they overturned away from the hinge zone of the antiforms (Figure 3). At outcrop scale, limbs of the BLA do not show a clear evidence of reactivation as normal faults, but in the eastern side, close to Pranu Meurras, minor D1 thrusts acted as D2 normal faults. An older D1 thrust then reactivated as low angle normal faults: this is the Riu Corr'e Cerbos Fault, between the Meana Sardo Unit and the Gerrei Unit. Also related to post collisional evolution are D3 upright folds, trending N-S. These are best exposed in the Pranu Meurras and Bruncu S'Arrettori zone, and are responsible for the elongated shape of the BLA.

The latest structures affecting the area are a set of right strike-slip reverse faults, striking about N150°E. They generally dip towards the west, cut all the previous structures and are sealed by Eocene sediments.

1.2 Metallogenic outline

During past mining activities (1866 to 1963), two types of ores have been exploited in the area:

1. Zn-Pb-Cu mixed sulfide lenses of the Su Spilloncargiu sector (NW part of the map);
2. Qtz-As-Pb sulfide veins that are located throughout most of the study area and were also mined in the Is Codis and Su Spinosu/San Riccardo and Bruncu Spinosu mineworks.

The geological and ore mapping that we conducted allowed for the recognition of the relationships between these two ores and the structures of the host rocks. Also the overprinting relationships and the paragenesis (i.e. mineral association) sequence have been unravelled.

1.2.1 The Su Spilloncargiu ore

The Su Spilloncargiu mineralization (indicated as "a" in the mine-work sketch incorporated in the map) crops out just below the Eocene cover and is characterized by extensive supergene alteration. It consists of several Zn-Pb-Cu mixed sulfide lenses, parallel to the main (mylonitic) foliation and dipping to west, it attains a maximum thickness of 6-7 m and a maximum extension in strike of 80-100 m. The three largest lenses have been mined by the room and pillar method and are now considered fully exploited, although explorations performed during the 1980s (EMSA, former Mining Regional Agency of Sardinia) did not exclude the possible presence of further lenses at depth or under the Eocene cover. Despite their insignificant economic importance, these small deposits have been discussed in the past because they are key to understanding the metallogenic framework of the area (Zucchetti, 1958; Schneider, 1972; Bakos et al., 1991). They also appear to be of great interest for helping to understand recent regional models as they show a rare case of possible interference of different kinds of Variscan mineralizations (Garbarino et al., 2003; Funedda et al., 2005).

According to previous authors the Spilloncargiu lenses can be interpreted as lateral expansions of discordant quartz-arsenopyrite veins (Zucchetti, 1958) or remobilized old sinsedimentary mixed sulfide ore (*protore*) (Schneider, 1972; Zucchetti, 1958). These two models propose only partial explanations of the relationships between the two ores. Indeed, as observed by Conti et al. (1998) and Funedda et al. (2005), the Su Spilloncargiu

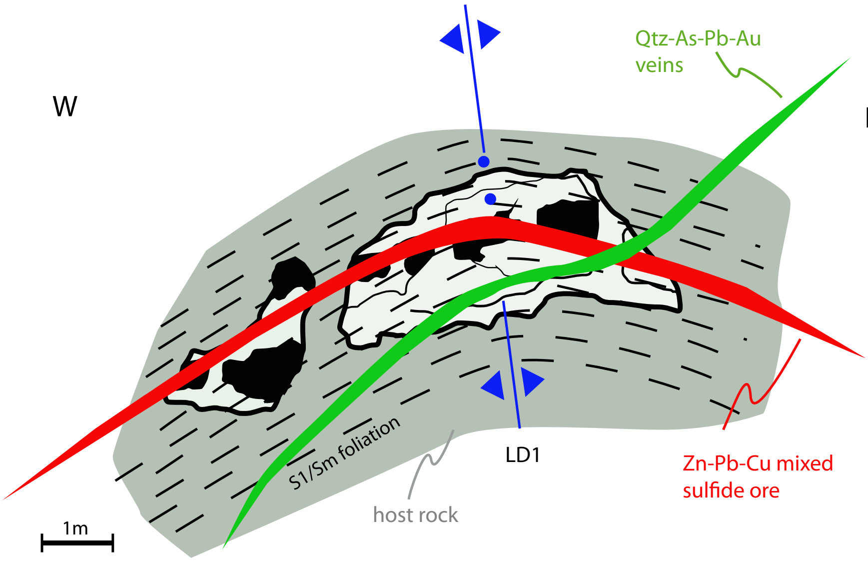

Figure 4. Relationships between two types of mineralizations (lenses and veins) of the Spilloncargiu ore; room and pillars exploitation of Sant'Eugenio mine-work.

sulfide beds are hosted by mylonitic foliation planes; furthermore, as noted before, the mineral association of the Splloncargiu-type ore shows distinct textural and mineralogical differences when compared to quartz-arsenopyrite veins. New observations of the upper mine-works of the Su Spilloncargiu sector and on the paragenesis of the primary ore allows us to define the following framework (Figure 4):

1. quartz-sphalerite mineralized lenses are hosted in folded mylonitic rocks;
2. folds are hectometric in scale and overturned, with axes in the NW-SE direction;
3. overturned limbs of folds are sheared, faulted and infilled by quartz-arsenopyrite veins that cut the mineralized lenses;
4. part of the mineral associations in the lenses and in the veins are comparable, and refer to a second stage (chalcopyrite-galena-sphalerite-sulfosalts) of mineralization.

1.2.2 The As-Pb-(Cu, Zn, Ag, Au) quartz-sulfide veins

Quartz-sulfide occurrences crop out in several locations along the Riu Baccu Locci/Rio Corr'e Cerbu valley and in nearby N-S trending valleys such as the Baccu Foxi, Baccu s'Olioni, Baccu Trebini, and, west to Baccu Locci in the Baccherutta valley. In these localities, sulfide-bearing quartz veins, sheeted veins, stockworks and/or disseminations crosscut the Gerrei Unit mylonitized rocks of the Baccu Locci Shear Zone, and the underlying Riu Gruppa Unit rocks of the Baccu s'Olioni/Baccu Trebini inlier. These different mineralized bodies show similar paragenetic and structural features.

In the Baccu Locci mine area, vein swarms attain thickness of greater than 10 m in thickness (Su Spinosu/San Riccardo and Bruncu Spinosu mineworks); single veins are 2-3 cm to 1 m thick. The veins strike N140°-160°E, dipping 50-80°WSW. Structural studies indicate that these directions are related to a NW-SE system of dextral-reverse faults and that quartz lodes are essentially hosted in large dilational jogs in their hangingwall. The same NW-SE directions also persist in the minor lodes and in the disseminations of arsenopyrite related to cataclastic shear zones in the Baccu Trebini and Baccu S'Olioni. As a whole, the continuity of similarly directed mineralized structures in two different tectonic units (Gerrei Unit and Riu Gruppa Unit) indicates a wide framework, with a km-scale system that must be related to the development of the stress field in the area, with strong and repeated cataclasis of the mylonites and fracture filling by quartz-sulfide veins.

Textural and mineralogical observations of the ores permitted us to present the general paragenetic sequence expressed in the table included in the map layout. After the data reported by Zucchetti (1958), it is worthy to note that geochemical explorations confirmed that gold in the Baccu Locci ores, in general, occur in the 1-12 g/ton interval, with a good persistence in several quartz-arsenopyrite veins. A recent survey of the area has revealed a spread occurrence in the area of mafic dikes (spessartitic dikes, 0.1-10 m thick) of presumed late Variscan age, also revealing complex mutual geometrical relationships with the ores. Even though the mine-works ended 50 years ago, their impact on the environment persists, especially arsenic contamination from diffuse waste rocks and tailings (Frau and Ardau, 2004; Frau et al., 2009).

2. Methods

The main map associated with this text results from detailed field work conducted between 1993 and 2007. Mapping first started in 1993-95 as part of PhD thesis work in structural geology (Funedda, 1996) and then was enhanced and finished by the Italian Geological Survey (Carmignani et al., 2001a). The mapping was at a scale of 1:10,000 and higher, and relied on the classical tools of structural geology which joined together field and laboratory work with meso- and micro-structural studies. During the field work a thick ductile shear zone (The Baccu Locci Shear Zone) was recognized for the first time and described in Conti et al. (1998). From 2005-2007 the authors of this map worked together on a national research project with a goal to understand the relation-

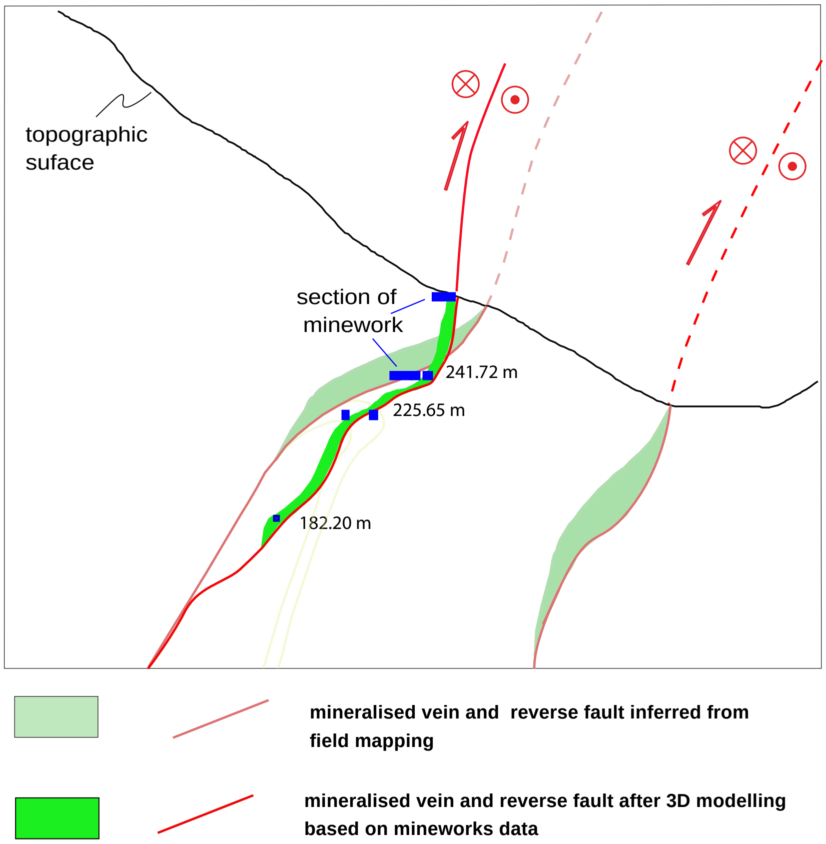

Figure 5. Fine-tuning of cross-sections using georeferenced underground mine-works in the Baccu Locci mine area.

ships between late Palaeozoic mineralizations and late Variscan evolution. Therefore, the structural and stratigraphic analyses were joined with investigations on ore bodies, and their geometries, their relationships with ductile and brittle structures, and paragenetic sequences. Many of these investigations were conducted underground, while exploring old mine tunnels, that were not easily accessible. During mapping, the 3D modeling of the area was made, based on interpolation of surfaces outlined in "quasi-balanced" geological cross sections (Buttau and Funedda, 2008); a complete and correct restoration and balancing is largely prevented because the original volume of rock can not be considered preserved for a widespread pressure solution mechanism operating during the Variscan deformation. The 3D models allowed the construction of a more realistic geometry of the geological structures (Buttau, 2008). Where it was possible, the geometries of the ore bodies inferred from underground mine-works have been used to control the cross sections (Figure 5). By doing this, the accuracy of the map was improved.

During model construction, it was discovered that in some places the 3D model did not agree with the mapped geology, i.e. contact mapped in the field were different from those shown by the model, which was based on combining surface and 3D geometries of units with a Digital Terrain Model (DTM) (Figure 6). This compelled us to re-check contacts in the field, verify if they were geometrically consistent, and also ascertain the best solutions between several options. This iterative approach significantly improved the final map.

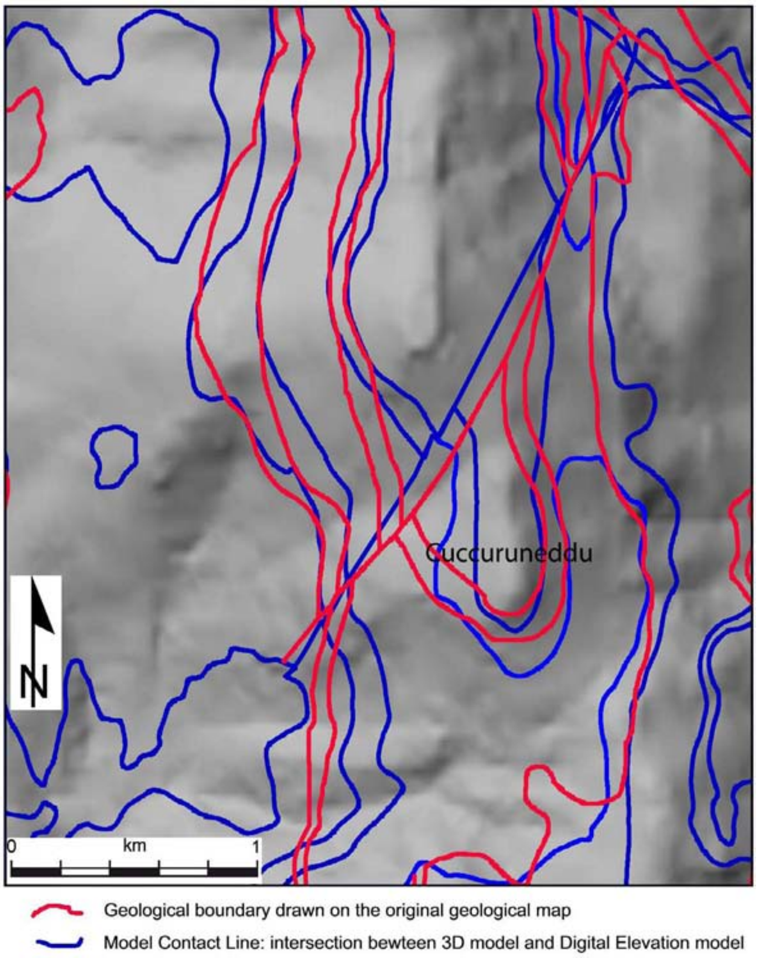

Figure 6. Differences between unit contacts on a map compiled from field data and those shown on a 3D model using a DTM in a folded succession (example does not refer to the study area, after Buttau (2008)).

3. Conclusions

This map is an example of an integrated approach to the study of an area with valuable ore bodies. Classical geological investigations (field mapping) are integrated with structural and microfabric studies, and subsequently these investigations are linked with parageneses and ore development investigations. Three dimensional representation of the geometry of geological structures is achieved by trial and error procedures during compilation of the geological 3D model. All these efforts are summarized in the enclosed 1:10,000-scale geological and metallogenic map.

Software

The map was produced in several stages. First, the traditional map and cross-sections compiled on paper were imported in to ESRI ArcMap. The data was exported to the CAD software Rhinoceros 3D v.4.0 (MCNEEL & Co.). The 3D model was built using the iterative procedure described above, as well as the 3D models of relationships beween structures and ore bodies. Finally the data were exported in a PDF file format to Adobe Illustrator CS2 for final editing of the map (cross-sections, legend, tectonic sketch map etc.).

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