

Integrative 3D geological modelling along the Lyon Turin Railway Project (Internal Briançonnais Domain of the Western Alps)

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Introduction

A good knowledge of the surface and underground geology is necessary prior to any large infrastructure project. This knowledge is assessed during field investigation campaigns, combining geological and geophysical methods, applied at the surface and at depth (drill hole, exploration galleries). These methods produce a large amount of data coded under various formats. The variety of data (map, cross section, logs) complicates their integration and their geological interpretation.

In the Modane Aussois area (French Alps), quartzite layers are extremely hard to excavate and have very poor hydrological properties. A key geotechnical issue is thus to avoid these layers as much as possible, along the tunnel trajectory. To reach that goal, the Alpetunnel society and SAS Lyon Turin Ferroviaire have conducted intensive field investigations between 1990 and 2004. These investigations include the drilling of 27 boreholes. Because of the multiple deformation phases, the main question was to determine how many quartzite layers are present in the area and what their 3D geometry is. We attempted to answer to that question by combining field investigations, analysis of metamorphic minerals (phengites) and 3D modelling of the Modane Aussois zone.

We present a method of three dimensional modelling that allows the integration of the whole dataset. The model is realized in the framework of the Lyon Turin Railway Project, and more precisely (Figure 1) on the middle part of the 52 km long planned tunnel between St Jean de Maurienne (France) and Venaus (Italy).

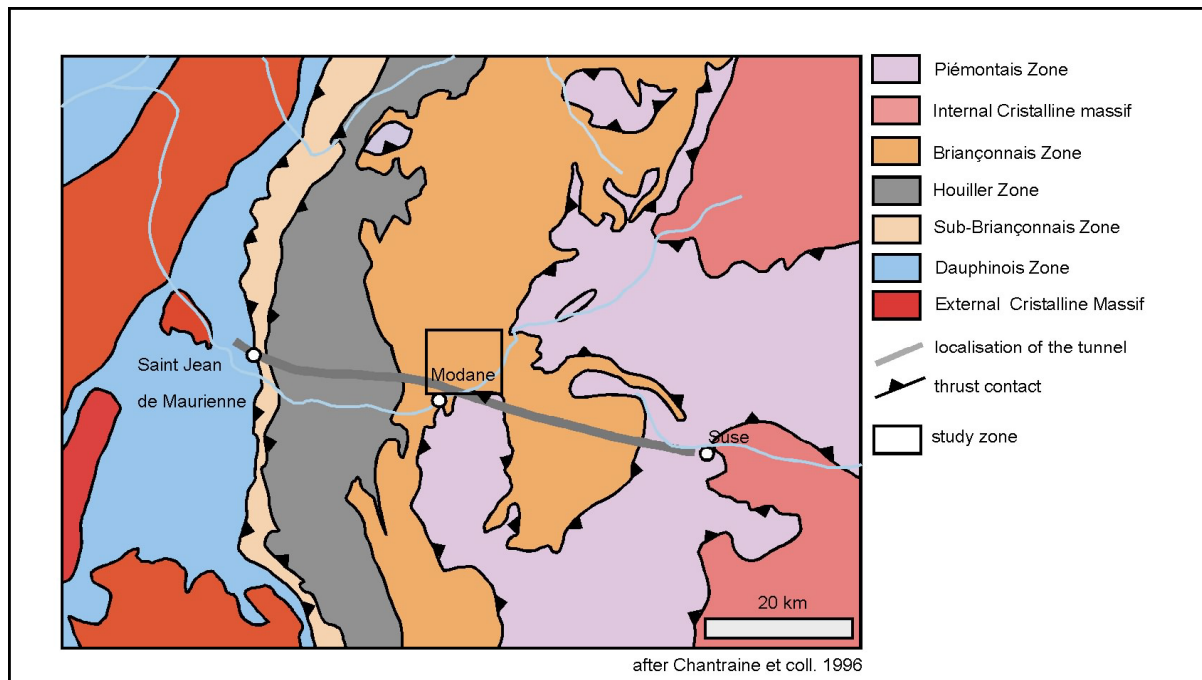


Figure 1 : structural map of the Alps around the laying out of the Lyon Turin tunnel project.

Geological setting and structural evolution of the Modane Aussois area

Our study focused on the Modane Aussois area, in the Internal Briançonnais zone (Figure 1). The Internal Briançonnais zone consists of passive margin series including micaschist (Permian to Permian-Triassic in age), quartzite (Lower Triassic) and carbonate (upper Triassic to Cretaceous) (Figure 2). The alpine tectonic history of the Internal Briançonnais domain is characterized by ductile deformation that occur prior to brittle deformation. The ductile deformations phases are marked by four successive deformation phases (D1, D2, D3, D4) (platt and Lister, 1984) underlined by different schistosity and folds. All these deformations occur during rock exhumation. The first (D1) is associated to top to the N to NW directed nappe stacking and occurred under blueschist to eclogite facies conditions (Ganne, 2003). The second (D2) tectonic phase consists of northwest verging folds that affect both the stratification and the foliation F1. It occurs probably in continuity with the previous one. The third tectonic event is associated to a top to the E to SE tectonic event. This D3 tectonic event accommodates most of the exhumation, under greenschist facies conditions. The fourth tectonic event (D4) is characterized by a N-S extension at the brittle-ductile transition.

Brittle deformation is characterized by two successive stress state: the oldest one (F1) is associated with N-S extension direction and E-W to vertical shortening direction. This tectonic event is continuity with the D4 extensional tectonic phase. The second stress state (F2) is characterized by E-W extension direction and N-S to vertical shortening direction. This second stress state is still active (Delacou et al 2004, Strzeczynski 2005).

A Structural map of the Modane Aussois zone

We propose a new interpretative structural map of the Modane Aussois area (Figure 2) based on previous mapping (Debelmas et al., 1989, Menard and sacchi, 2000, [rapport LTF, 2003](#)), and new field investigations. The main units, i.e. Paleozoic Basement, Permian conglomerate, Micaschist and quartzite, carbonate and gypsum are represented. Several tectonics contacts are also distinguished : the first are D1 tectonic contacts. A first D1 contact is the limit between the Gypsum nappe and the rest of the Briançonnais domain. This limit is a major decollement zone at the alpine belt scale underlining the lower limit of the Piemontese zone (Figure 1). An other D1 related tectonic contact is evidenced by abnormal high thickness of quartzite or intercalation of Triassic carbonate, cagneule or basement discontinuous level between two quartzite layers. This contact has a complex shape: it dips towards the east, east of the Modane Aussois domain, further west it dips towards the west. On the western limit of the map, this contact is strongly folded and outcrops in reverse position. The D1 tectonic contact and sedimentary contacts are crosscutted by post-metamorphic faults: dextral NE-SW and sinistral NW-SE strike slip faults forms diedra that are compatible with the N-S direction of extension. These faults are compatible with the F1 brittle event. These faults are cutted by N-S normal faults corresponding to the F2 tectonic event.

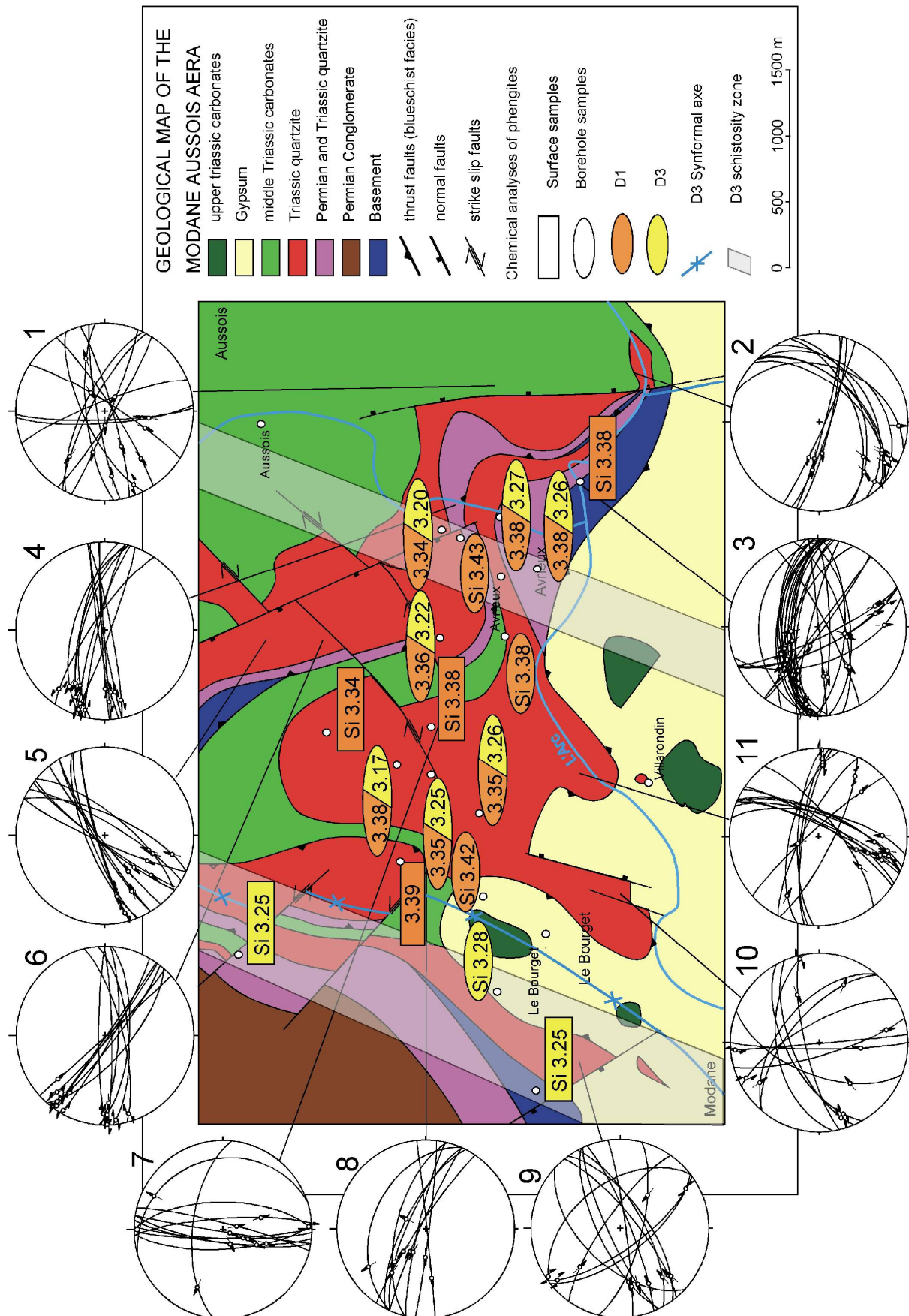


Figure 2 : new structural map of the Modane area. Microtectonic faults from eleven sites are displayed on stereoplots (equal area, lower hemisphere). After Debelmas et al., 1989, Menard and Sacchi, 2000, Bianchi et al. 2003 and new observations.

Chemical analyses of metamorphic phengites

Given the complexity of contacts and tectonic phases, correlations between boreholes data and surface geology are often difficult. In many boreholes, two quartzite layers are found and for two boreholes three layers are crosscutted. In order to improve the best correlation between boreholes and to take into account the relative importance of the different tectonic phases, we performed chemical analysis of white micas underlying the different foliation planes along most tectonic contacts (Figure 2). The measurements have been performed on sample thin sections using the camebax electron microprobe of Lyon. The major elements of rock minerals can be measured with a precision lesser than 0.1%Wt oxide. The diameter of the electron spot is around 6 μm . The first measurements performed on surface samples (Figure 2) show that the white micas are phengites. The Si and Al content of the phengites depend of the P-T conditions at the time of the deformation: the Si⁴⁺ content decreases from 3.45 to 3.15 and Al^{IV} content increases from 2 to 2.6 (Figure 3) from blueschist conditions (D1 and D2) to greenschist metamorphic facies conditions (D3). On the basis of chemical analysis of phengite, the D1 and D2 generation of phengite (Figure 4) cannot be distinguished. It implies that the two foliations have been formed under the same pressure conditions and then confirm that they are linked.

Results on borehole samples indicate that the phengites related to the D1-D2 events are present in a majority of the samples. These deformation phases are thus the most important in the Modane Aussois area. Two main D3 shear zone are also observed (Figure 2). One crops out on the western part of the domain (figure 2). That structure previously documented (Detraz, 1987, Debelmas, 1989) induce the folding of the whole nappe pile to a reverse polarity and the outcropping of the lowest structural levels at high altitude in the western part of the area (Fig. 2, 3 and 4). The second shear zone is observed at the bottom of three boreholes located in the middle part of the studied zone. Toward the east, the altitudes of D3 shear zone increase progressively and crop out on the eastern limit of the studied zone (Figure. 2). At the surface, the tectonic contact between the lower and the upper siliceous nappe shows metamorphic phengites of D1-D2 Si content. This confirms that duplication of the quartzite layer occurred early in the tectonic history.

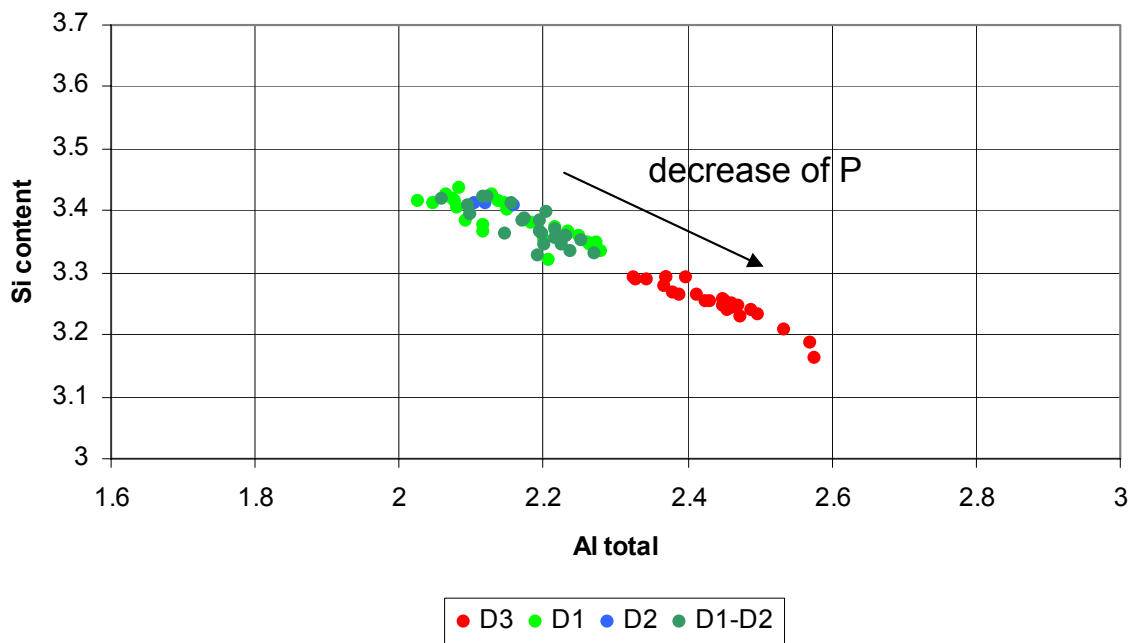
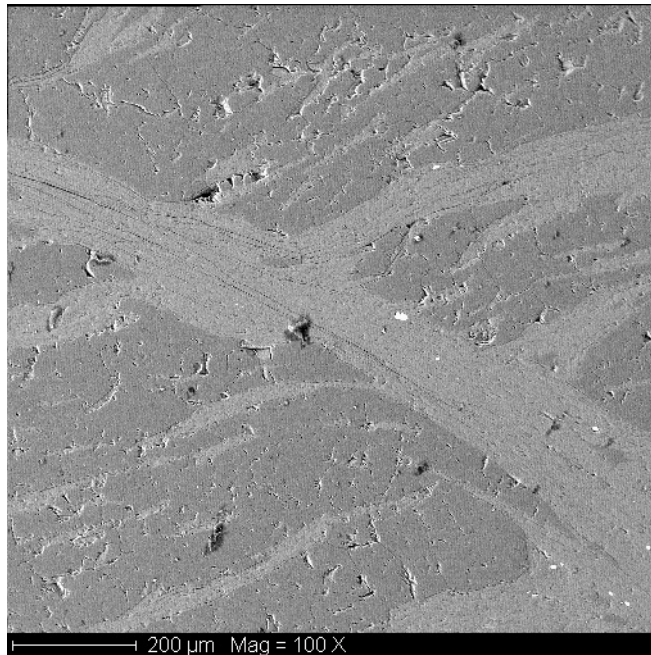


Figure 3: Si vs. Al content diagram of field and borehole samples.



S1 phengites

S2 Phengites

Figure 4: two generations (D1 and D2) phengite observed on BSE microprobe.

3D Modeling

We built the 3D geological model of the area using the BRGM software called "Editeur Geologique". That software allows incorporating data of various formats: they are the localisation of the contacts on the geological map and in the borehole data base (figure 5), the orientation of the contact or of the main rock anisotropy (bedding, main schistosity...) and the geometrical relationship between the units. As the modelling method only includes contact position, the boreholes that don't meet any contact have not been integrated. However, compatibility between these boreholes and the model has been verified after proceeding. 3D geometry of the geological units is inferred by interpolation (cokriging) of a scalar field (Lajaunie et al, 1995). This method assumes that a constant value is assigned to the locations of the lithological contacts and the direction of the contacts and of the stratification planes correspond to the derivative of this scalar field.

We present here a first attempt to investigate the main geometrical properties of the Modane Aussois domain. That model is composed by the six different units. The different tectonic units are from bottom to top: 1) the pre-Permian basement and its Permian cover, 2) the siliceous units, 3) the calcareous nappe, 4) the gypsum nappe and 5) the schistes lustres nappe. The Permian cover includes basement unit and schist and Permian meta-conglomerate from the Echelle massif. The siliceous unit contains Lower Triassic quartzite and Permo-Triassic micaschist and quartzite. Thin layer of basement and/or micaschist that are pinched into a thrust zone (Figure 2) have also been include in this unit. The Calcareous nappe includes Triassic carbonates that are situated under a thick gypsum layer of Carnian in age. The gypsum nappe includes the Carnian Gypsum layer, carbonates and schist of younger age (upper Triassic to cretaceous). The schistes lustrés unit contains meta-sediments and basic rocks of oceanic affinity related to the Piemontese alpine domain (figure 1). Calcareous nappe and gypsum nappe overlies all lower tectonic layers. The gypsum nappe is covered by the schistes lustres unit. The siliceous unit lies conformably on the basement and Permian cover unit. It corresponds in fact to two distinct thrust sheets: the upper and lower siliceous nappes (Figure 2).

At the surface, the resulting model (Figure 6a) is coherent with the proposed structural map. At depth, the 3D geometry contacts are good agreement with the contacts position observed in the boreholes (Figure 5).

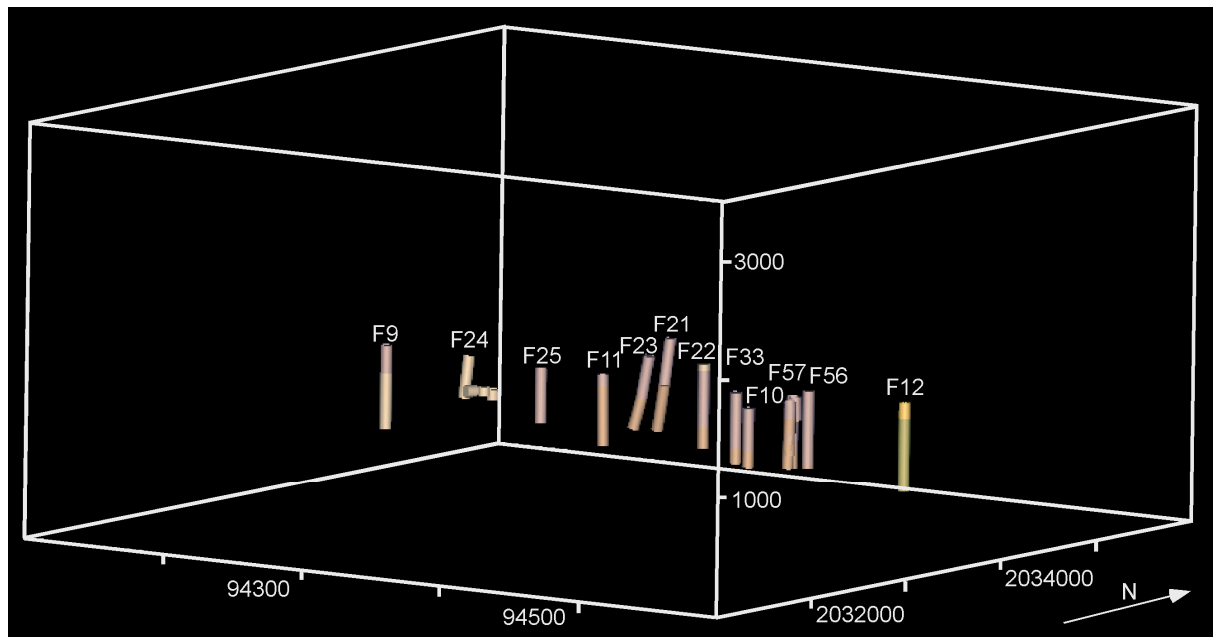


Figure 5 : 3D view of the borehole dataset (coordinate system : Lambert II étendu)

The modelled contacts are nappe contacts and quartzite tectonic layers related to the D1 event. Considering that the D1 structures initiated as flat lying plane, deformation and folds that affect the contacts surface are related to latest D2, D3 and D4 tectonic phases. The contacts between the basement and the lower siliceous nappe and between the lower and the upper siliceous nappe are folded (Figure 6b). A first fold located on the western part of the studied area, has an axis oriented N30 and is dipping to the south (figure 6b and 6c). This fold is situated on the D3 shear zone (Figure 2). It corresponds to a D3 related fold that tilts the layers on a reverse polarity (Figure 6b). The southern dip of the axe's fold is related to the tilt toward the south of the studied zone. This tilting is related to the D4 tectonic phase. On the eastern part and on the central part of the studied area, two domes like structure are observed (Figure 6c). The first one is located near an important D3 structure and its formation is probably related to interferences with D3 tectonic phases and D4 southward tilting of the whole zone. The second dome like structure is not related to D3 shear zone. It may correspond to interferences between D4 structure and D2 fold that cannot be highlighted by chemical analyses of phengite.

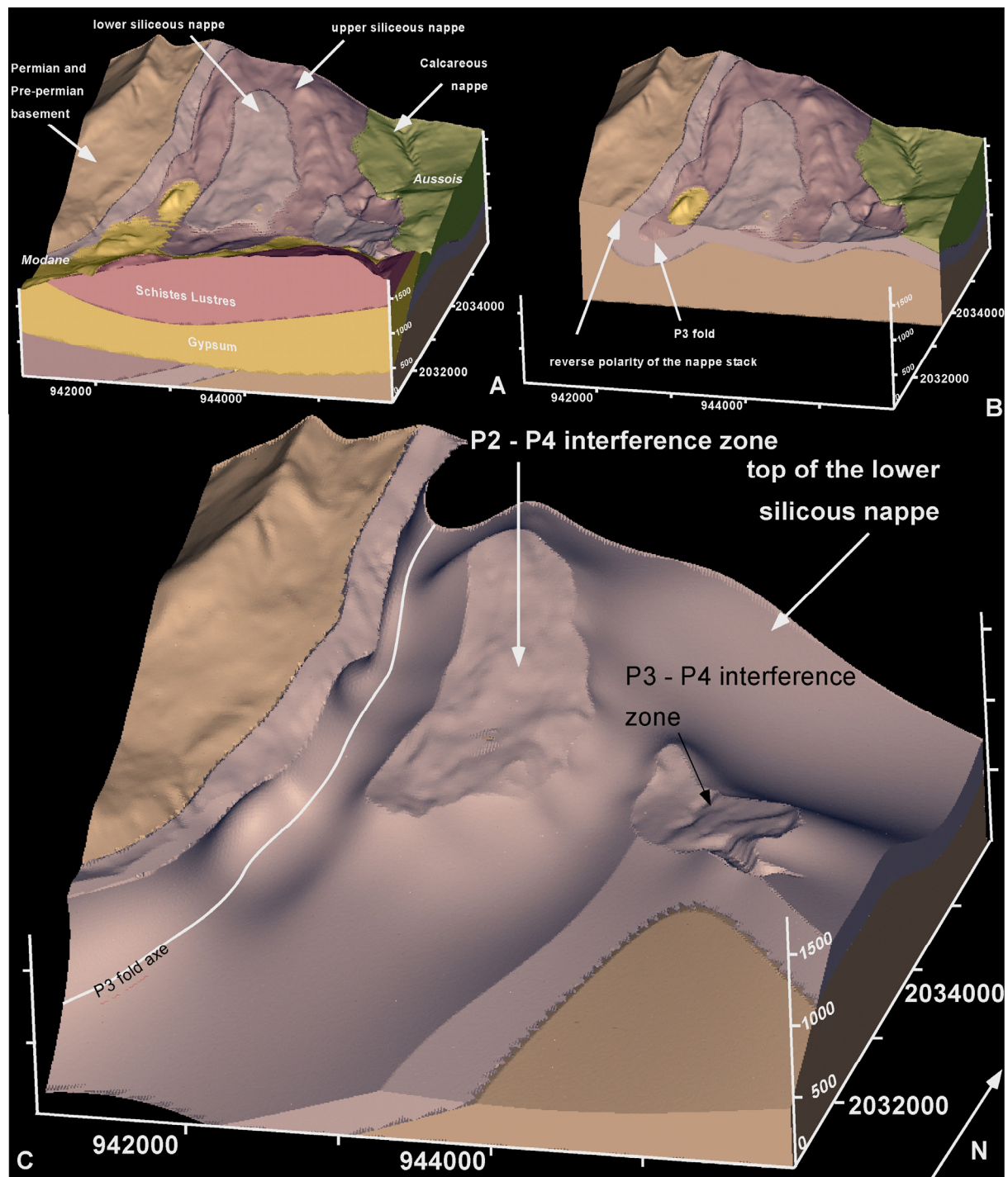


Figure 6: 3D views of the Modane–Aussois model. A) Whole layer model, B) northern half whole layer model, C) top of the lower siliceous nappe.

Discussion

This model with only 6 units is a very simplified 3D map of the Modane Aussois area. However it is a first approach of the tectonic complexity of this area and validates the coherence of both the tectonic map and the borehole dataset. This model also reflects the different tectonics phase scenario. As the model fits most of the data at the cartographic scale, it can form the geometrical framework of further models. As it takes into account a simplified series, then it is not fully representative of the complex geology of the Modane Aussois area. Future models taking into account the whole series will give accurate information on the continuity of quartzite layers, in depth. In the same way, by taking into account S2 and S3 schistosity orientations from field measurements and borehole datasets, the geometry of related fold structures will be better constraints.

New borehole correlations, chemical analysis of phengites and 3D modelling allow determining the importance of the D3 tectonic phases and the number of quartzite slices. Two kilometre scale folds have been recognized and attributed to the D3 tectonic phase. On the eastern part of the Modane Aussois area, they are responsible of some minor quartzite layers duplicates. Considering the D3 main structures on the surface map and along borehole logs, the number of tectonic layers of quartzite can be estimated: two tectonic layers of quartzite are observed on the surface map and have been modelled. One quartzite layer of small size is observed only in borehole on the central part of the studied zone. This quartzite duplication may be related to D1 nappe stacking or D2 nappe folding.

Although the chemical analyses of phengite have not permitted to distinguish D2 structure from D1 structure, the 3D modelling highlighted some kilometre scale folds, which we relate to the D2 deformation phase (Figure 7).

Conclusion

The Modane Aussois area is a quite complex zone in term of lithostratigraphy and superposed tectonic events (4 ductile phases and 2 brittle deformation events) and then remains difficult for underground geological prediction. The building of the 3D model is made step by step: new datasets are progressively taken into account and at each step the model is validated or not by comparing the model and the geological history of the studied area. On the Modane area, the presented 3D model is constrained by field and borehole dataset. It is consistent with the tectonic evolution of that part of the Alps. More constraints have to be added in order to get a predictive model at the tunnel scale.

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