Brittle deformation between the Ambin and Vanoise domes in the frame of the structural evolution of the internal Alpine belt

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Abstract: New geophysical data and geological observations emphasize the importance of brittle tectonics in the Neogene to present day evolution of the Western Alps. The oldest Neogene stress state (F1) is characterized by extension direction parallel to the orogen and shortening direction vertical or perpendicular to the Alpine belt whereas the youngest tectonic event (F2) is characterized by brittle extension perpendicular to the mountain belt. According to new brittle microtectonics data from the High Maurienne valley near Modane and a synthesis of the available geochronological and microtectonics data at the scale of the internal Alps, we discuss a timing of the brittle tectonics phases and their role in the formation of basement domes (Internal Crystalline massifs and Briançonnais domes). We propose that the F1 event spans from 32-30 Ma to 22 Ma south of the Simplon fault and was probably active up to 5 Ma on the Simplon fault. The F2 event started at about 6-5 Ma and is still active. In this scheme, basement domes observed in the Western Alps are the results of interference between an early E-W extension along NE-SW ductile to brittle faults and the two F1-F2 brittle tectonic events documented here.

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Introduction

In the light of new data such as seismicity (Sue and Tricart, 2003, Delacou et al., 2004), Geodesy (Sue et al., 2000, Calais et al., 2001) and geological observations (Lazarre et al., 1996, Bistacchi and Massironi, 2000, Sue and Tricart, 2002, Agard et al., 2003, Sue and Tricart, 2003, Champagnac et al., 2004, Grosjean et al., 2004, Malusa, 2004, Tricart et al., 2004, Schwartz et al., 2005), a stimulating discussion has started on the significance of extensional structures developed in the Western Alpine belt since the Neogene. In accordance with the present day stress field (Calais et al., 2001, Delacou et al. 2004), brittle extension perpendicular to the mountain belt is recorded (Tricart et al., 2001, Tricart et al., 2004, Sue and Tricart, 2003, Malusa, 2004, Agard et al., 2002, Champagnac et al., 2004, Grosjean et al., 2004, Schwartz et al., 2005). An older stress state is characterized by extension direction parallel to the orogenic alpine belt and shortening direction vertical or perpendicular to the belt (Bistaccchi et Massironi, 2000, Champagnac et al., submitted). Ages and duration of the two brittle tectonic phases are poorly documented. Time constraints on the brittle tectonic evolution of the alpine belt is an important challenge in order (1) to better understand how orogen parallel extension switched to extension perpendicular to the mountain belt and (2) to highlight the relationships between the brittle tectonic phases and the formation of the internal basement domes.

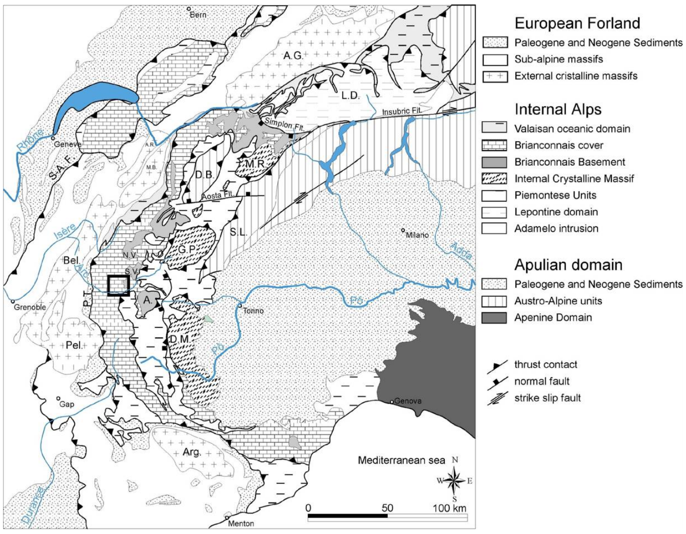
In this paper, we present new brittle microtectonic data from the High Maurienne valley near Modane between the basement domes of Vanoise and Ambin (Figure 1). We then discuss these data with respect to available geochronological data, brittle micro-tectonics dataset and mapping of the main faults of the Vanoise area. Finally, we propose an alternative model for the formation of the basement domes of the internal Alps.

Geological Context

Metamorphic evolution of the internal Alps

The Alpine belt (Figure 1) is the result of the convergence between the European and the African plates during the closure of the western Tethyan oceanic domain. The Maurienne valley cross cuts the main units of the European margin and of the oceanic units, and then records the complete alpine evolution from Cretaceous subduction to late basement domes formation. Subduction of the oceanic unit occurred between 60 and 55 Ma (Chopin and Maluski, 1980, Cliff, 1998, Agard et al., 2002) and was responsible for the burial of the oceanic crust down to the eclogite facies metamorphic conditions (Rolland et al., 2000). The European continental margin was involved in the subduction processes at circa 45 Ma (Chopin and Maluski, 1980, Ganne et al, 2005) and continental rocks from the Gran Paradiso massif were affected by eclogite metamorphism (Ballèvre, 1988, Borghi et al., 1996, Ganne et al., 2005). This metamorphic event is associated with a top to the north nappe stacking in the Briançonnais and Schistes Lustrés zones (Ganne et al., 2005). Part of these rocks was next exhumed in greenschist metamorphic facies conditions at circa 35 Ma (Agard et al., 2002, Reddy et al., 2003) along top to the east shear zones (Platt and Lister, 1985, Ganne et al., 2004). These shear zone are interpreted as tilted thrusts (Platt and Lister, 1985, Butler and Freeman, 1996) or as normal faults (Wheeler et al., 2001, Ganne et al., 2004).

Figure 1. Structural map of the Alps



Structural map of the Alps (after Chantraine et al., 1996 and Schmid et al., 2004). A. : Ambin, A.G. Aar and Gothard, A.R. Aiguilles Rouges, Arg. Argentera, Bel. Belledonne, D.M. : Dora Maira, D.B. Dent Blanche, G.P. Gran Paradiso, L.D. Lepontine Dome, M.B. Mont Blanc, M.R. : Monte Rosa, N.V. : Northern Vanoise, Pel. : Pelvoux, S.L. Sesio-Lanzo, S.V. : Southern

Vanoise.

Basement dome formation.

The major structures that complicate the nappe stack of the internal Alps are basement domes that crop out through their sedimentary cover and the overlying nappe units (

Figure 1). The basement domes of the internal Alps are the Dora Maira, Gran Paradiso and Monte Rosa Internal Crystalline massifs (ICM) associated with more external structures like the Ambin massif and the Southern and Northern Vanoise dome. The basement dome of the internal Alps are characterized by largely open folds of the metamorphic foliations and the occurrence of surrounding normal faults (Rolland et al., 2001, Ganne et al., 2004). The dome formation began under ductile conditions and ended under brittle conditions (Rolland et al., 2000, Ganne et al., 2004). Many models of alpine basement dome formation have been proposed. The first models gave a major role to the thrust tectonics: the basement culmination of the ICM is explained in this case by the formation at depth of an anticline (Malavielle et al., 1983, Bucher et al., 2004) which formed and was exhumed along a crustal scale ramp structure. In this hypothesis, the formation of both the Ambin and Vanoise basement domes would have been formed in the same shortening context but on two different thrust ramps. However, such early formation of the domes is in contradiction with the observation that the east verging folds affected by the doming, developed under greenschist facies conditions. In the next models, an important place is given to the extensional processes that occurred during exhumation. The culmination of the Monte Rosa massif could be related to an extensional tectonic event that occurred between 42 and 35 Ma (Reddy et al., 2003). Vertical pinching is also proposed in the case of the Gran Paradiso Massif (Rolland et al., 2000). In the Dora Maira massif, both early (Henry et al., 1993) and recent extensional processes are proposed (Tricart et al., 2004, Schwartz et al., 2005). Thus, the dome shape of the ICM has been related to exhumation processes: extension and vertical shortening is frequently proposed. However, the non cylindrical shape of these structures remains to be explained.

Post-metamorphic faults in the internal Alps.

Geological maps of the Alps (Chantraine et al., 1996, Schmid, 2004) do not show many post-metamorphic faults. Three mains structures (Figure 1) are to be highlighted: the Insubric line, the Simplon fault and the Aosta fault.

The Insubric Line is a 200 km long dextral fault along which a magmatic activity is recorded. This fault forms the limit between the South Alpine and the Austroalpine domains on its eastern part and the limit between the Austroalpine, Brianconnais and Piemontese domains on its western part. The strike slip motion of this fault occurred between 32 and 20 Ma (Stipp et al., 2004) and estimation of the lateral offset ranges from 30 to around 100 km (Lacassin 1989, Schmid and Kissling, 2000). The magmatic activity is related both to crustal anatexis produced by shear heating on the fault (Rosenberg, 2004) and to mantle-derived magmas.

The Simplon fault is a 40 km long normal fault. It forms the western boundary of the Lepontine domain. Ages and duration of activity on the Simplon fault are still debated: on te one hand, some authors propose that the normal motion of the fault is linked with the dextral motion of the Insubric line implying that the motion of the Simplon fault occurred between 32 and 20 Ma (Stipp et al., 2004). On the other hand, 5 ± 2 Ma K/Ar age on phengite fraction lower than 2µm sampled along the Simplon fault indicates that its motion occurred until at least 5Ma (Zwingmann and Mancktelow, 2004)

The Aosta fault is a 30 km long E-W fault with northward dip ranging from 50 to 70° (Bistacchi et al., 2001). It forms the southward limit of the Dent Blanche Austroalpine klippe (Figure 1). Estimates of the vertical displacement along this fault vary from 3000 to 400 m (Bistacchi et al., 2001 and reference therein). Age and duration of the Aosta fault motion are still debated It has been proposed that motion may started at the time of andesitic and lamprophyric dikes emplacement i.e. between 31 and 29 Ma (Dal Piaz et al., 1979) and gold bearing veins between 32 and 30 Ma (Diamond, 1990). Differences in age between apatite fission track analysis across the fault suggest a motion restricted between 28 and 12Ma (Hunziker et al., 1992).

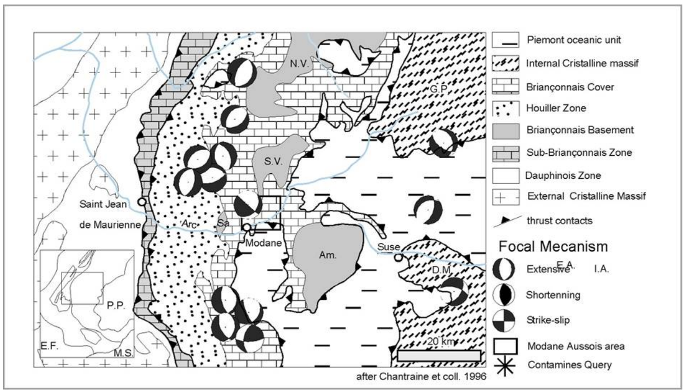
Post-Metamorphic Evolution of the Vanoise Domain

Faults pattern of the Vanoise domain

We present a structural scheme of the Vanoise that includes a synthesis of the faults described on the 1/50 000 geological map of Modane, Lanslebourg, Tignes, Moutier and Bardonecchia, the 1/100 000 map of the Vanoise National Parc (Debelmas and Rampnoux, 1995) and the 1/1 000 000 Geological map of France (Chantraine et al., 1996). On the basis of orientations and motion histories, the post-metamorphic faults have been classified in four groups. Geometrical relationships between these faults allow us to propose a relative chronology: the faults from the first group are the most recent, those from the second and the third groups may be synchronous and the faults from the fourth group are the oldest.

The first group is composed of N-S faults (a, b, c; Figure 1) 2) that show two successive motions: the first one is sinistral strike slip and the second one is normal. The Modane-Chavière fault (a. on Figure 1) 2, Ellenberger, 1958) stretches for more than 20 km (Fudral, 1998) and underlines in many places the contact between the Houiller zone and the Briançonnais zone of the Vanoise. Another unamed fault (b) underlines the contact between the Briançonnais zone of Vanoise and the Schistes Lustrés unit.

Figure 2. Structural scheme of the Vanoise



Structural scheme of the Vanoise including a synthesis of the main post-metamorphic fault (a, b, c, d, e, f, g, h, I, j, k, l, m) and the focal mechanism that occurred since 10 years in the internal domain.

The second group consists of NW-SE faults (d, e, f, g and h; Figure 1) 2) that also records two successive motions: the first one is a dextral strike slip and the second one is normal (e.g. Malusa 2004). This group includes the Modane Termignon fault (f) (Fudral, 1998) that forms the south eastern limit of the Southern Vanoise dome, the Susa fault (g) (Malusa 2004) that underlines the southeastern limit of the Ambin dome and the col de la Vanoise and col du Chardonnet fault (e) that forms the southeastern limit of the northern dome of North Vanoise. A third group is composed of NE-SW faults (i, j, k, l; Figure 1) 2). All these faults have a late normal motion. One of them had a first dextral strikes slip motion (l) (Marion, 1984). The fourth group includes different faults developed at the ductile-brittle transition. Orientation of these faults is N-S and they have a normal motion. One forms the limit between the Lower Schistes Lustrés unit and the Middle Schistes Lustrés unit (Deville 1992). This limit is a major alpine structure emplaced after the main ductile phases and along which the eclogitized oceanic and pelitic rocks are finally exhumed. The same tectonic contact is observed on the western boundary on the Dora Maira massif and is called the West Dora Maira Detachment (Tricart et al., 2004).

Seismicity of the Vanoise area

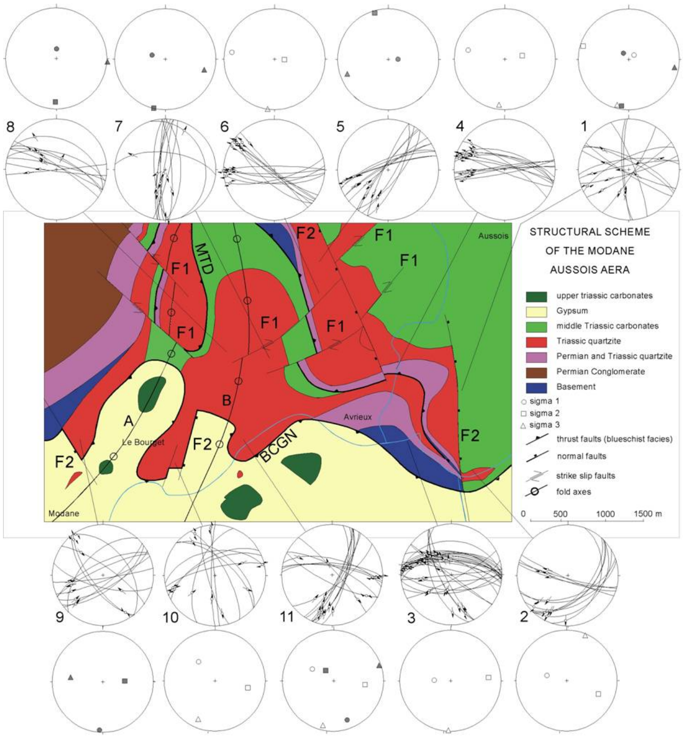
The focal mechanisms of 14 earthquakes extracted from a published database (Delacou et al., 2004) have been displayed on the figure 2. Only focal mechanisms that occurred in the internal part of the Alps, east of the Penninic Thrust, have been plotted. The seismic activity of the internal part of Alps is characterized by shallow earthquakes (< 10 km) with magnitudes ranging from 1 to 4 (Figure 2). Most of the focal mechanisms indicate a vertical shortening and an NW-SE to SW-NE direction of extension. The two strike-slip mechanisms are characterized by the same direction of extension and a horizontal shortening. Such stress states, with an extension direction roughly perpendicular to the strike of the alpine belt are observed all along the internal zones and are interpreted as the result of gravitational spreading (Delacou et al., 2004).

Brittle micro-tectonic data

Modane-Aussois area

The Modane-Aussois area is located in the Briançonnais zone at the southern end of the South Vanoise basement dome (Figure 2). The Briançonnais series contain micaschists, conglomerates, quartzites and carbonates (Figure 3). Micaschists and Carbonate have recorded a polyphased tectonic history in where both early blueschist and late greenschist structures can be distinguished. However, within the quartzites, sedimentary structures are still well preserved and schistosities are not well developed unless locally in shear zones or tight folds.

Figure 3. Structural scheme of the Modane Aussois area



Structural scheme of the Modane Aussois area. A and B fold axes (see text for detail), MTD : Main Thrust Duplicate and BCGN : Basal Contact of the Gypsum Nape. Strereoplots and plot of the calculated stress axis has been added. Blank symbols: F1 tectonic event, Grey symbols: F2 tectonic event.

The first tectonic event is associated with nappe emplacement, formation of a first schistosity and folds into the carbonates and the micaschists. Tectonic contacts related to this event are the basal contact of the gypsum nappe and a major thrust duplicating the underlying series (Figure 3). Afterwards, initial planes, bedding schistosity and thrust contacts have been folded. At the map scale recent 3D modelling (Strzerzynski et al., 2005) have permitted the visualisation of two main folds: the first one is an open anticline with a fold axis oriented N-S and dipping towards the south (Figure 3A) and the second one is a pinched syncline with a fold axis oriented N30 and dipping also towards the south. The dip of the axes suggests that the folds were tilted by 20° towards the south after their formation, together with the whole part of the studied area. This southward tilting is responsible of the location of the structuraly higher units (the Schistes Lustrés) on the southern flank of the Maurienne valley at lower altitude than the Briançonnais units (Figure 2).

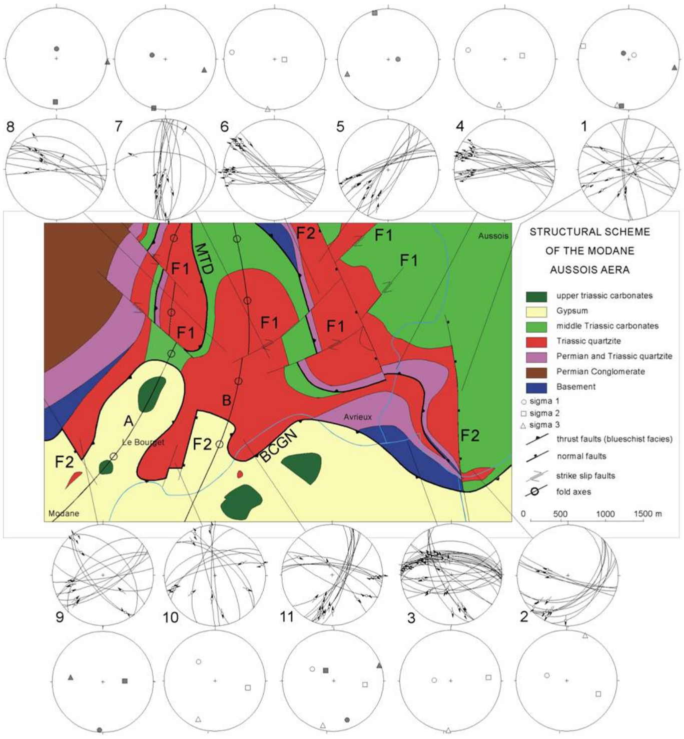
All rocks are affected by brittle faults. They bear slickensides that allow determining the slip direction. Depending on the siliceous or carbonate composition of rocks, quartz or calcite crystallizes on the faults plane. Accessory minerals are also present: chlorite, or various oxides. The brittle deformation at the outcrop scale has been studied in eleven stations (Figure 3). For each station, the orientation of the fault planes, striae and the slip-senses have been measured for 10 to 35 micro faults. Relative chronology between faults has also been observed. Fault plane azimuth is highly variable and most dips are greater than 60°. Slips are mainly strike-slip while normal and reverse movements are scarce (Figure 3).

In order to estimate the paleostresses that led to fault formation, a direct inversion method (Angelier, 1990) has been applied to each fault dataset using the TectonicFP software (Ortner et al., 2002). For eight stations, the whole dataset can be explained by a single state of stress, while for the three others, two states of stress are necessary to explain the whole dataset (Table1, Figure 1) 3). All computed states of stress (table1) are characterized by a horizontal orientation of the minimum axis 3 and values of the ratio ranging from 0.01 to 0.7. However, most of the ratio lower than 0.2 have been calculated using only conjugate faults and are thus not significant (Angelier, 1990). All significant ratios are thus comprised between 0.20 and 0.6 implying triaxial stress ellipsoids. On the basis of 3 orientation, two groups of stress state can be distinguished. The first one is characterized by 3 trending around N-S, while the second one is characterized by 3 trending around E-W (table 1, Figure 1) 3). In the field, faults associated with the 3 oriented E-W systematically cross-cut those associated with a 3 oriented N-S. We propose that the two states of stress affecting the Modane-Aussois area are the expression of two successive tectonic phases that we will later call F1 and F2, respectively (Figure 3).

Contamines quarry (Lanslebourg)

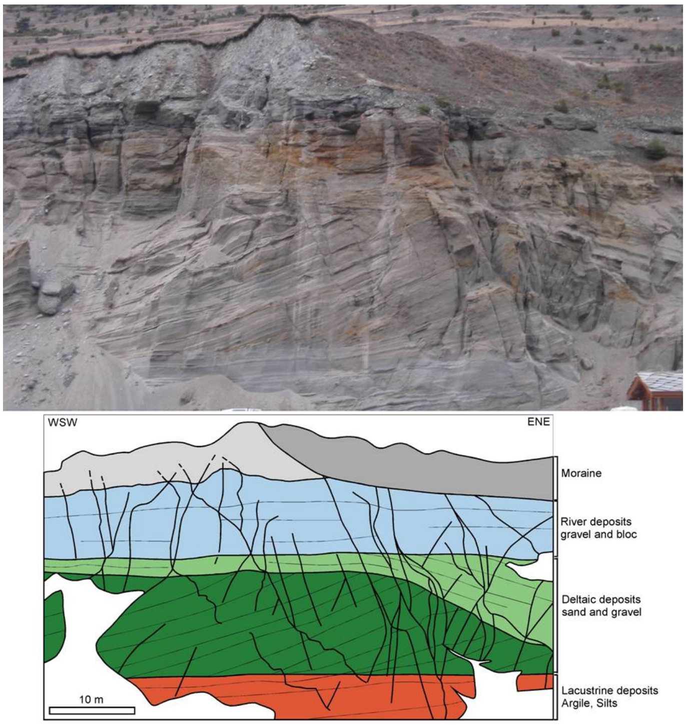
The Contamines quarry is located near Lanslebourg in the upper part of the Maurienne valley (Figure 2). It is carved in silt, sand and gravel layers that have been interpreted as a recent lacustrine to fluviatille deposit system (Figure 5). These layers are covered by a 3 m thick deposit composed of angular blocs of rocks from the Schistes Lustrés units. Those deposits have been interpreted as a moraine (Fudral et al., 1994) indicating that a glacier may have covered the lacustrine to fluviatille layers. The age of the deposits depend closely of the age of the moraine deposit: it is possibly related to the Riss or the Wurm deglaciation periods (Fudral et al., 1994). Independently of the precise age of the morainic sediments, the Contamine quarry rocks are deposited during the last 80000 years and then are recording very recent stress states regarding to the alpine tectonic history. Faulting affects both the lacustrine to fluviatile and the moraine deposits indicating that it post-dates deposition and are not related to sedimentary processes (Figure 4). The position of the Contamines quarry at the bottom of a valley side might be favourable to slope movement related deformation. Moreover, some landslides are described downstream (Giraud, 1994) and upstream (Fudral, 1998) along the Maurienne Valley. However, there is no evidence of any slope movements near and over the Contamines quarry. As the formation of faults is not related to sedimentary process nor slope movements, we interpret them as tectonic features created by recent(s) crustal stress state(s).

Figure 4. F1 and F2 related stress axes plotted on stereodiagram



F1 and F2 related stress axes plotted on stereodiagram. Red circles: σ1, empty squares: σ2, blue triangles: σ3

Figure 5. General view of the Contamines quarry



General view of the Contamines quarry. Botton to top succession of lake, deltaic and river deposits is coeval with the filling of an ombilic lake formed during climatic warming (Fudral et al., 1994). The moraine located on the top of the outcrop is related to a late glaciation event.

40 faults have been observed and measured at the bottom of the quarry wall (Figure 5). The fault planes are underlined by a 5 mm thick silt level that is preferentially preserved from erosion. Unfortunately, no striae are preserved along those fault planes, and thus the slip directions can not be constrained nor the true offsets measured. However, we have observed the apparent vertical offsets along the faults at the bottom of the quarry wall where the bedding is horizontal (Figure 4).

The main geometrical properties of the Contamines quarry's faults are summarized below (Figure 5a):

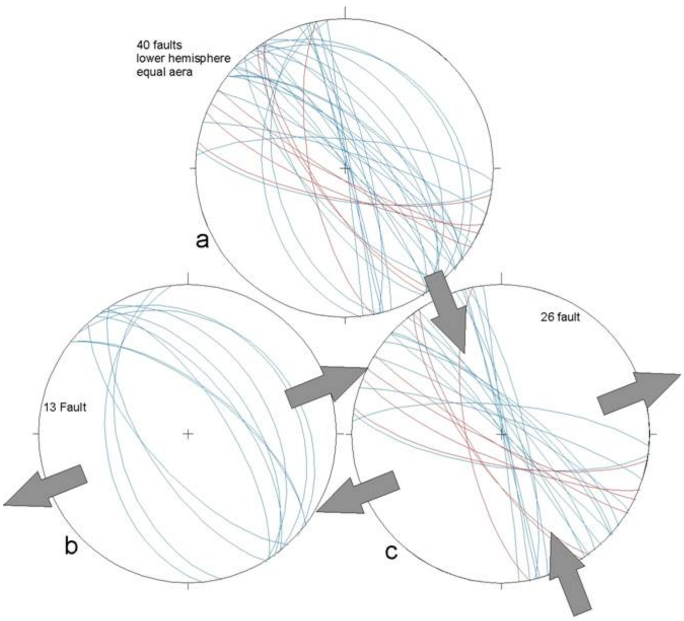
- Azimuths of the 40 faults are all comprised between N100 and N170. Dips are directed to the SW or the SE.

- Dip values are between 30° and 90° and more than 80% of the dips are greater than 60°.

- Apparent movements are mainly normal. Inverse apparent movements are limited to faults steeply dipping (i.e. more than 70°) to the west.

On the basis of their dips, we have distinguished two faults groups: the first one is composed by the faults which have a dip value lower than 70° and second group contains the faults that have a dip greater than 70°. The first group (Figure 6b) is composed by 12 faults that show exclusively normal apparent movements. The azimuth of the faults does not vary by more than 10° around N150. Faults planes plunge to the NE and to the SW. The azimuth, the dip direction and the apparent movement of faults are all compatible with a set of conjugate normal faults formed during vertical shortening with a ~N60 direction of extension (Figure 5b). The second group is composed of 26 faults (Figure 5c). The azimuth of faults shows to distinct populations: between N160 and N170 with dips either to the E or W and between N110 and N140 with dips either to the NE or SW (Figure 5c). All faults dipping to the east show apparent normal offsets while all dipping to the west show apparent inverse offsets. The high dip value of the fault, the two azimuth populations and the association of reverse and normal apparent movement is compatible with a strike slip conjugate faults pattern in which faults of N160 to N170 azimuths are possibly left-lateral faults and faults of N110 to N140 azimuths are possibly right-lateral faults. Such a fault pattern is compatible with a N150 direction of shortening and a N60 direction of extension (Figure 5c). In absence of relative chronology evidence between the fault populations, we conclude that vertical and N150 shortening direction occur simultaneously in a context of N60 direction of extension. This stress-state, which occurred probably after 80000 yr. ago, is broadly compatible with that deduced from the regional focal mechanisms (Fig. 2: Delacou et al., 2004). It is also compatible with the N80 direction of extension of the F2 tectonic phase observed in the Modane area (Figure 3). This suggests that the present-day field stress is active since several thousands years and has produced micro-brittle faults now observable in Quaternary deposits as well as older consolidated rocks.

Figure 6. Fault planes of the Contamines quarry



Fault planes of the Contamines quarry displayed on stereoplots. a) whole dataset, b) faults of plunge lower than 70° and c) fault of plunge greater than 70°. In blue : apparent normal faults, in red : apparent reverse faults.

We conclude that, after metamorphism and southward tilting of the nappe pile south of the South Vanoise dome, two stress-states have affected the Modane-Aussois-Lanslebourg area. The first one was characterized by ~N-S direction of extension while the second one characterized by ~E-W direction of extension is still active today.

Discussion

Geographical repartition, ages and duration of the brittle tectonic phases

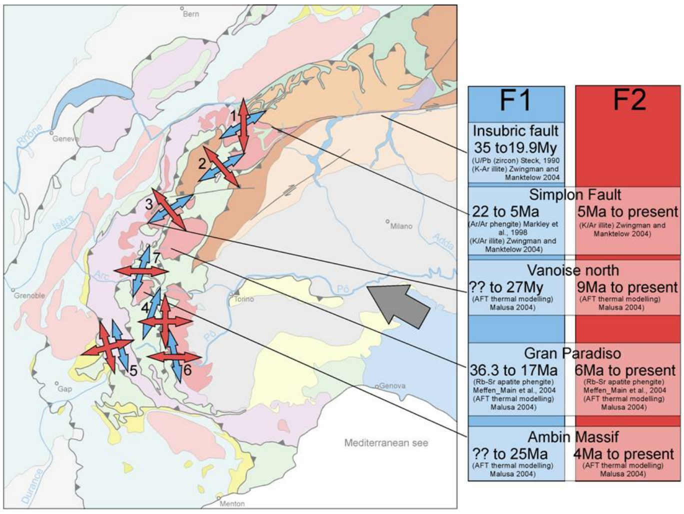
Since 10 years, many studies on the brittle deformation of the alpine belt have been performed. North to the Maurienne valley, two successive stress-states are described (Grosjean et al., 2004, Champagnac et al., 2004): the oldest one has a 3 axis parallel to the strike of the belt (Fig 8) and a latest one with a 3 axis perpendicular to the strike of the belt (Figure 7a,b). Immediately to the south of the Modane-Aussois area, two deformation phases are also described (Malusa 2004). The first one is defined by 3 axis oriented parallel to the strike of the belt, followed by a multidirectional extension phase (Figure 8). South of the city of Briançon, a multidirectional extension has been inferred from brittle micro tectonics (Sue and Tricart, 2003).

However, on a recent synthesis on the Alpine belt, Champagnac (2004) proposed that the brittle tectonics of this part of the Alps is also characterized by polyphased tectonics where an extension direction parallel to the strike of the belt occurred before an extension direction perpendicular to the strike of the belt (Figure 8). It thus appears as proposed by Champagnac (2004) that polyphase brittle tectonic evolution is not limited to the Modane-Aussois-Lanslebourg area but is widespread in the whole western internal Alps. It is first characterized by a 3 axis parallel to the strike of the belt (F1) and the second one perpendicular to it (F2).

Figure 7. Detail view of a fault system located in the Contamines quarry

Detail view of a fault system located in the Contamines quarry. Both apparent normal and reverse faults coexist.

Figure 8. Age and spatial evolution



Age and spatial evolution of the σ_3 axes for F1 and F2 brittle event at the western Alps scale. (1) Grosjean et al., 2004, (2) Bistacchi et al., 2000, (3) Champagnac et al., 2004, (4) Malusa 2004, (5) Sue and Tricard, 2002, (6) Tricart et al., 2004, (7) This study.

Age and duration of the brittle tectonic phase is bounded by the youngest age obtained on ductile deformation and the present day stress field. Classically, an age of 35 Ma is given for the latest ductile deformation in the internal part of the Alps (Hunziker 1992 and references therein). This deformation is related to the top to the east shearing of the whole nappe stack. However youngest ages are also proposed for late ductile-brittle structures like extensional crenulation cleavage and gouge formation or reactived foliation (Bistacchi and Massironi, 2000). The same kind of structures that postdate the top to the east shearing are also described in the Ambin (Ganne, 2004) and in the Gran Paradiso massifs (Rolland et al., 2000). Near the Aosta fault, Gold bearing veins and calc-alkaline dikes associated with these structures give ages between 32 and 29 Ma (U/Pb zircon). Another age of 31.6 ± 0.33 Ma (Ar/Ar on separated phengite) has been obtained on the latest ductile structures of the Modane Aussois area (Strzerzynski et al, in prep).

In order to estimate the age of the end of the F1 event and the beginning of the F2 event, two different geochrological methods can be used. The first one consists of dating minerals that crystallize along faults and the second one consists of dating the latest stage of cooling of the rocks by apatite fission track measurement. Further north to the Maurienne valley, the motion of the Insubric fault (Figure 1) is estimated by dating the emplacement of syn-tectonic granite. The dextral movement of this fault occurred between 32 and 20 Ma (Stipp et al., 2004). Some authors (Lacassin, 1989, Hubbard and Mancktelow, 1992, Schmid and Kissling, 2000) proposed that the normal motion of the Simplon fault is related to the lateral motion of the Insubric line. In this hypothesis, the extension parallel to the chain axis, represented by the Simplon fault motion, occurred between 32 and 20 Ma. If the motion of the Insubric and the Simplon faults are not linked, Ar/Ar on phengite (Markley et al., 1998) and K/Ar age on lower than 2µm fraction of phengite (Zwingmann and Mancktelow, 2004) suggest that the normal motion of the Simplon faults occurs between 22 Ma and 5 ± 2 Ma. In this case, the F1 tectonic event spans from 22 to 5 Ma. Thermal modelling using apatite fission track length patterns to estimate the temperature-time travel of rocks for the last 150°C of the exhumation. Results on the internal zone of the Alpine belt cover a period since around 30 Ma (Hunziker et al., 1992). Results of Malusa (2004) close to the studied area suggest that the late cooling of rocks occurred in three stages: the first stage is related to rapid cooling from 150 to 100°C ended at 22 Ma. The second stage consists of a period of thermal stability until 5 Ma. The third stage is characterized by a rapid cooling of rocks since 5Ma from ~ 100°C to surface temperature. We propose that this thermal-time travel coincides with the whole brittle evolution i.e. that the F1 tectonic event ended at around 22 Ma and the F2 tectonic event started at 5 Ma.

The two independant methods of dating suggest that the F2 event start at 5Ma from the Simplon fault zone to the Gran Paradiso area (i.e. the central part of the Western Alpine belt). This age is also supported by fission track ages (Figure 8) for the denudation of the External Crystalline massifs (Mt Blanc-Belledonne-Pelvoux) that occurred at around 6 Ma (Seward and Mancktelow, 1994, Seward et al., 1999, Tricart et al., 2001, and Fugenschuh and Schmid, 2003, Leloup et al., 2005) and that may reflect the tectonic inversion of the Penninic Front as a normal fault (Tricart et al., 2001). Duration of the first brittle tectonic phase remains unclear: according to thermal modelling of apatite fission tracks (Malusa 2004) and the link between Insubric and Simplon faults, the first brittle tectonic phase ended at around 22 Ma. Taking into account the 5 ± 2 Ma K/Ar age on a fraction of phengite lower than 2µm (Zwingmann and Mancktelow, 2004), the first brittle tectonic phase ended at around 5Ma. This difference in age may result from the migration of the deformation from the south-western to the north-eastern part of the belt. This hypothesis is also supported by the repartition of the apatite fission tracks in the Houillère zone (Figure 2) as noticed by Fugenschuh and Schmid (2003) where ages increase from north-east to south-west. Then the first brittle tectonic phase started between 32-28 Ma and ended at ~ 22 Ma, south of the Simplon fault and started at 32 Ma and ended at ~ 5 Ma further north, along the Simplon fault zone. Wherever, the end of the F1 tectonic event occured, the second event F2 starts everywhere at ~ 6-5 Ma and is still active.

Tilting, Fault pattern and basement dome formation.

At the scale of the Modane Aussois area, the formation of a dome is related to the local southward tilting of the Briançonnais and Piemontese domain. For both tectonic events F1 and F2, the 3 axes cluster around a common orientation, while the orientations of the 1 and 2 stress axes vary from one station to another (Figure 4). This variation amounts ~60° for F1 and ~ 90° for F2. Different processes such as stress axis permutation, tilting related to folding of faultings, and a inhomogeneous stress field at the Modane Aussois scale can be proposed to explain the variation of axes orientations. The values of significantly lower than 1 (Table 1), indicate triaxal (oblate) stress ellipsoids with 1 significantly different from 2. Permutation of the 1 and 2 axes because 1 ~ 2, does thus not appears a satisfactory explanation for 1 and 2 variations in direction. These variations cannot be related to folding because at the outcrop and at the map scale all the brittle structures cut the folds (Figure 3). Tilting of the bedrock related to faulting is necessarily limited to few tens of degrees an canot explain tilt angles reaching 90°. An inhomogeneous stress field at the Modane Aussois scale thus appears to be the main explanation for 1 and 2 stress axes variation of orientation during F1 and F2.

3D modelling (Strzerzynski et al., 2005) and structural analyses suggest that the whole studied zone, including the main fold axis, has been tilted by ~20° towards the south. One may wonder if this tilting was antecedent or posterior to F1 and F2. The F1 3 axes trend ~N-S and are thus optimally oriented to record any southward tilting around an ~E-W axis. If one assumes that during F1 3 axes were horizontal, it follows that tilting after F1 was maximum in station 10 (~25°) and negligible in stations 2, 3 and 6 for an average value of ~10°. The E-W directions of the F2 3 axes, and the great dispersion of 1 and 2 axes, render any discussion on the post F2 southward tilting based on the paleostress orientations, difficult. However, the pattern of 3 axis suggests that an episode of local E-W tilting may have occurred during or after F2. We thus suggest that tilting towards the south of the southern flank of the South Vanoise dome occurred after the last folding phase and during the first brittle tectonic event F1. Later some local tilting on ~N-S axes may have occurred during F2.

At the Modane Aussois scale, faults are related both to F1 and F2 tectonic events (Figure 3). Faults related to the F2 event are mainly oriented N-S and dip to the east or the west. As the orientation of the F2 faults planes is perpendicular to the direction of the tilting axis, the southward tilting cannot have been only accommodated by motion along these faults. The orientation and the kinematics observed along the F1 faults are mostly compatible with this southward tilting: most of the F1 faults have orientation around an E-W direction and dip to the south or the north. Then a part of the tilting of the whole Modane Aussois area is related to an early normal motion of ENE-WSW and ESE-WNW faults. Then the tilting of the Modane Aussois is probably related to the normal motion of the F1 main faults. However, as the tilting probably affects both the F1 and the F2 event, a part of the tilting may be more recent.

At the Vanoise domain scale, most of the boundaries of the basement domes are underlined by post metamorphic faults (Figure 2). These are mainly NE-SW faults (i, j, k, l on figure 2) and the N-S fault (m on figure 2) that occurred at the ductile-brittle transition. Late N-S normal fault (i, b on figure 2) locally formed the eastward and westward boundaries of the basement domes. As NE-SW normal faults can be related to the F1 tectonic event, it appears that the formation of most of the southward limit of the basement dome is related to this tectonic event. The formation of the eastward and westward limits of the basement dome appears to be polyphased: an early step occurs before the F2 event and is well recorded at the western boundary of the Gran Paradiso and Dora Maira massifs. A second step occurs after the D1 event and is possibly related to the F2 tectonic event. This last event is well recorded on the most external part of the Vanoise domain i.e. in the Briançonnais units.

Conclusion

In the Maurienne valley, the post-metamorphic evolution is composed by two tectonic phases. The first one occurs between 32 and 22 Ma and is related to N-S direction of extension and vertical to E-W direction of shortening. The second tectonic phase occurred between 6-5 Ma and the present. It is related to E-W direction of extension and vertical to N-S direction of shortening. This post metamorphic evolution occurs after the normal motion of a major fault that forms the western limit of the ICM. Basement domes observed in the ICM and in the Briançonnais are the results of interference between an early E-W extension and the two brittle tectonic events documented here.

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