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# Deformation history of a subducted continental crust (Gran Paradiso, Western Alps): continuing crustal shortening during exhumation

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## Abstract

Eclogite-facies continental basement in the Western Alps outcrops as tectonic windows below the oceanic units. In the Gran Paradiso massif, eclogite-facies assemblages in mafic rocks display a N–S stretching lineation ($D_{A1}$). The main-phase foliation formed under epidote amphibolite-facies conditions ($D_{A2}$) and defines a regional dome structure for the whole Gran Paradiso massif. Structural data, including new detailed mapping, microstructural analyses and metamorphic studies in the northern part of the Gran Paradiso (Cogne valley) reveal the occurrence of major thrusts in this continental basement associated with the $D_{A2}$ deformation. E–W-trending stretching lineations and fold axes are associated with this second and main deformation. Nappe stacking of the different units was achieved by top-to-the-west shearing during exhumation of the eclogite-facies basement. The antiformal doming of the Gran Paradiso basement is thus produced by the nappe stacking during exhumation, under epidote amphibolite facies.

*Keywords:* Western Alps; Gran Paradiso; Kinematics; Nappe stacking; Nappe antiform; Exhumation

## 1. Introduction

Eclogite-facies metamorphism implies pressures in excess of about 12–14 kbar (for quartz-bearing eclogites) or about 30 kbar (for coesite-bearing eclogites). When observed in continentally-derived units, this high-pressure metamorphism implies subduction of the continental crust, a fact that is now recognized in the Western Alps (Chopin, 1984) as well as in many other mountain belts, e.g. the Caledonian orogen of Norway or the Dabie Shan, China (e.g. Schreyer, 1995; Chopin, 2003). Despite promising petrological studies aimed at delineating the P–T paths, the tectonic history of a subducted continental crust remains obscure.

One potential area for resolving such topics is the Western Alps. The major units have been recognized since the founding work of Argand (1911) and interpretations in terms of modern, plate tectonic, syntheses are available (e.g. Bigi et al., 1990; Dal Piaz et al., 2003; Schmid et al., 2004b). The Adriatic palaeo-margin (i.e. the Austro-Alpine units) was thrusted over oceanic ophiolite-bearing units (i.e. the Piemont–Ligurian units), the latter being themselves thrust over the distal part of the Iberian micro-continent (i.e. the Internal Massifs) (Fig. 1). The latter outcrop in three major windows below the oceanic units (these are, from north to south, the Monte Rosa, Gran Paradiso and Dora–Maira). Eclogite-facies metamorphism has been identified in both the Austroalpine and the Internal Massifs (e.g. Droop et al., 1990; Spalla et al., 1996).

The metamorphic petrology of the Internal Massifs has been studied in some detail, especially in the ultra-high-pressure unit of the Dora–Maira massif (Chopin, 1984; Schertl et al., 1991; Simon et al., 1997; Nowlan et al., 2000; Compagnoni and Hirajima, 2001). By contrast, structural studies of these units are at a less advanced stage (Gosso et al., 1979; Vearncombe, 1985; Lacassin, 1987; Philippot, 1990; Michard et al., 1993; Avigad et al., 2003; Kassem and Ring, 2004; Keller et al., 2004, 2005). For example, no consensus has been achieved concerning their kinematic history. Moreover, the lack of sustained campaigns of detailed mapping results in the lack of a coherent structural scheme for these windows. This paper represents a preliminary effort toward this goal. As a first step, we provide a detailed structural analysis of the northern part of the Gran Paradiso massif. This area has been chosen because it is deeply incised (up to 2300 m deep) by three N–S-trending valleys, which are almost perpendicular to the strike of the

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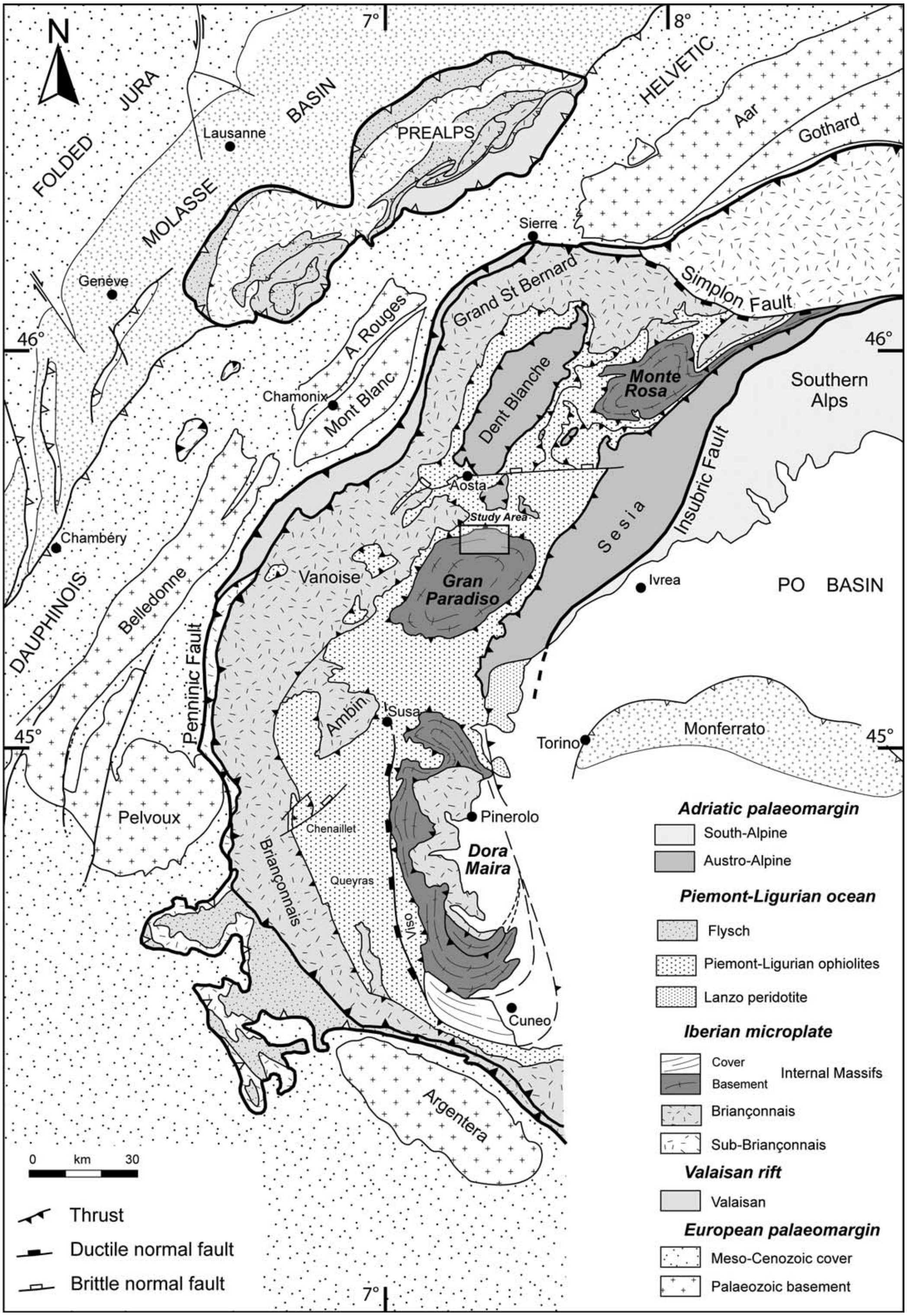

Fig. 1. Simplified tectonic map of the Northwestern Alps (modified after Bigi et al., 1990; Dal Piaz, 1999; Schmid et al., 2004a), asssuming that the Briançonnais domain represents the northernmost extension of the Iberian microplate (Frisch, 1979; Stampfli, 1993). The main units are organised with respect to their palaeogeographical position before the Alpine collision. The Monte Rosa, Gran Paradiso and Dora–Maira (i.e. the Internal Massifs) represent antiformal windows below the Piemont–Ligurian ophiolites and are thus ascribed to the distal part of the Iberian microcontinent.

main lithological boundaries and the main structures. The main lithological boundaries can thus be accurately mapped, the main structures inferred and their relation to the deformation assessed. The present study is thus based on a new geological and structural map of this area drawn on a 1:25000 basis. This map displays the major lithological boundaries, which allows a better interpretation of the tectonic structures in the different units.

## 2. Geological setting

The Alpine belt results from the collision between the European and Adriatic palaeomargins. In the internal zones of the Western Alps, three main types of units are recognized (Fig. 1). First, the Sesia zone and the Dent–Blanche nappe (Dal Piaz et al., 1972; Compagnoni et al., 1977) represent the Austroalpine units derived from the Adriatic plate. The internal part of the Austroalpine units display an eclogite-facies overprint of Late Cretaceous/early Tertiary age (Inger et al., 1996; Duchêne et al., 1997; Cortiana et al., 1998; Rubatto et al., 1999; Liermann et al., 2002). Second, the eclogite-facies oceanic units derived from the Piemont–Ligurian ocean (e.g. Bearth, 1967; Barnicoat and Fry, 1986; Reinecke, 1998) mark the boundary between the Austroalpine units and the underlying continental basement. Third, the Monte Rosa (Bearth, 1952; Dal Piaz and Lombardo, 1986), Gran Paradiso (Compagnoni and Lombardo, 1974; Compagnoni et al., 1974; Dal Piaz and Lombardo, 1986) and Dora–Maira (Vialon, 1966; Michard, 1967; Sandrone et al., 1993) massifs form tectonic windows below this oceanic unit (Fig. 1). These massifs may thus be ascribed to the distal part of the European palaeomargin or, taking into account the presence of a narrow Valaisan ocean, to the Briançonnais micro-continent, which would represent the northernmost extension of the Iberian micro-plate (Frisch, 1979; Stampfli, 1993; Lemoine et al., 2000; Schmid et al., 2004a). These massifs are made of a Variscan basement, largely and variably overprinted during the Alpine orogeny by an eclogite-facies to greenschist-facies deformation. In this paper, we will focus on the Gran Paradiso massif, which consists of two main units, namely the Money Unit and the overlying Gran Paradiso Unit (Compagnoni et al., 1974) (Fig. 2).

### 2.1. The Gran Paradiso Unit

The Gran Paradiso Unit consists of abundant augen-gneisses, derived from porphyritic granitoids (*gneiss occhiadini* of Italian geologists) of late-Palaeozoic age (Chessex et al., 1964; Bertrand, 1968; Bertrand et al., 2000), intruded into metasedimentary rocks. The latter (*gneiss minuti pp*) consists of polymetamorphic paragneisses and micaschists. Relics of Prealpine high-temperature, regional metamorphism, as well as of contact metamorphism (hornfelses) along intrusive contacts have been found in the metasediments (Compagnoni et al., 1974). The polymetamorphic paragneisses contain lenses of mafic rocks, interpreted as Prealpine amphibolites. The Variscan basement is overlain by remnants of a thin metasedimentary cover, presumed to be Permian–Liassic in age (Elter, 1960, 1972; Polino and Dal Piaz, 1978).

Parageneses belonging to the Alpine eclogite-facies overprint have been identified in two main lithologies. Firstly, basic rocks deriving either from Prealpine amphibolites or from late-Variscan gabbros display garnet-omphacite assemblages (Compagnoni and Lombardo, 1974; Battiston et al., 1984; Benciolini et al., 1984; Dal Piaz and Lombardo, 1986; Pognante et al., 1987; Ballèvre, 1988; Biino and Pognante, 1989; Brouwer et al., 2002). These were used for estimating the minimum P–T conditions for the eclogite-facies event, which are about 12–14 kbar, 500–550 °C (Ballèvre, 1988; Brouwer et al., 2002). Secondly, Al- and Mg-rich micaschists display peculiar parageneses, including chloritoid, talc, glaucophane, kyanite and phengite (Compagnoni and Lombardo, 1974; Chopin, 1981), recording even higher Alpine eclogite-facies conditions of the order of 21–23 kbar and 540–570 °C (Vidal et al., 2001; Wei and Powell, 2003, 2004; Meffan-Main et al., 2004). Finally, the porphyritic orthogneisses show limited evidence for transformations at high pressure, the large perthitic K-feldspar and biotite being replaced by phengite, rutile and titanite. Epidote and a Ca-rich garnet could potentially record the eclogite-facies event (Le Goff and Ballèvre, 1990). Estimated P–T for late stage reequilibration are about 500–550 °C and 4–6 kbar, with some authors arguing that it occurred after an initial stage of cooling during decompression (Borghi et al., 1996; Brouwer et al., 2002, 2004).

Geochronological data are still rather preliminary in the Gran Paradiso Unit. The pioneering Ar–Ar data of Chopin and Maluski (1980), as well as recent data provided by Reddy et al. (2003), are unfortunately hampered with excess argon. More recently, Rb–Sr data have been obtained for defining the age of the eclogite-facies event (43 ± 0.5 Ma; Meffan-Main et al., 2004), whereas the greenschist-facies metamorphism would have occurred at about 34–38 Ma (Freeman et al., 1997; Inger and Ramsbotham, 1997; Meffan-Main et al., 2004). The final stages of exhumation are recorded by the fission track data on zircon (30 ± 1 Ma, 225 ± 25 °C) and apatite (20–24 Ma, 100 ± 20 °C) (Hurford and Hunziker, 1989). According to the geologic time scale (Gradstein et al., 2004), the above data suggest a Middle Eocene age for the high-pressure stage, followed by rapid exhumation during the Late Eocene, and final cooling during Early Oligocene.

### 2.2. The Money Unit

The Money Unit outcrops in the northern part of the Gran Paradiso massif (Fig. 2), namely in the Valnontey and Valeille windows. The Money Unit essentially consists of a leucocratic metagranite (Erfaulet orthogneiss) and a thick sequence of metasediments (Money Complex) made of metaconglomerates and graphite-bearing micaschists. Because the mineralogical assemblages are exclusively Alpine (i.e. because of the lack of high-temperature, hence Prealpine, relics in the sedimentary sequence), it has been argued that the Money Complex is Permo-Carboniferous in age (Compagnoni et al., 1974). The boundary between the Erfaulet orthogneiss and the Money Complex is interpreted as a Late Palaeozoic intrusive contact (Le Bayon and Ballèvre, 2004).

The Money Complex is assumed to be the metamorphosed equivalent of the Zone Houillère of the Briançonnais Zone (Fig. 1). Consequently, the Money Unit of the Gran Paradiso massif is thought to be the equivalent of the Pinerolo Unit of the Dora–Maira massif (Fig. 1) (Argand, 1911; Vialon, 1966; Michard, 1967), i.e. the lowest structural unit exposed in the

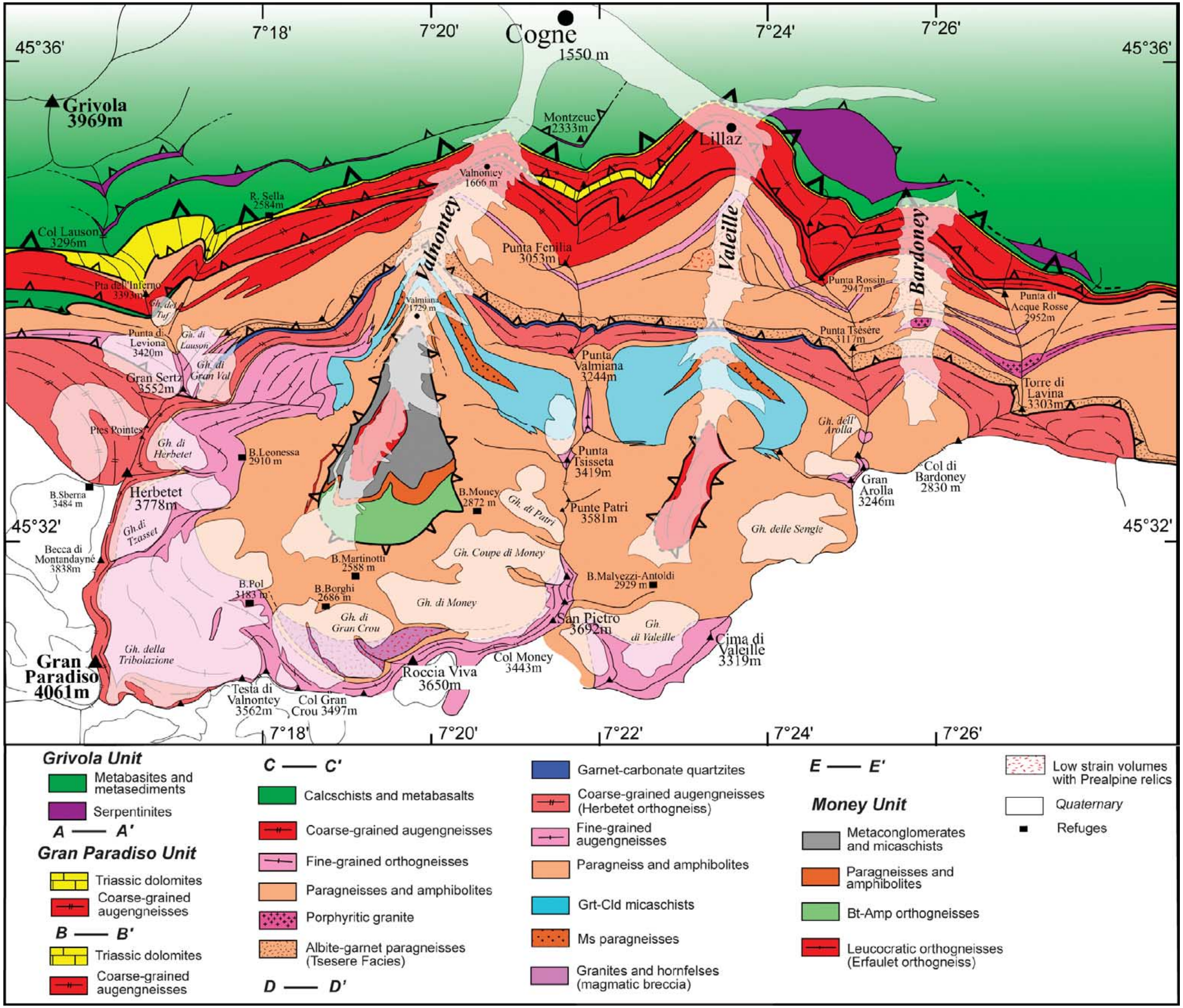

Fig. 2. Geological map of the northern part of Gran Paradiso. This map is based on detailed field work in three N–S-trending valleys (Valnontey, Valeille and Bardoney) deeply incising the Gran Paradiso massif along its northern margin.

internal zones of the Western Alps (Vissers and Compagnoni, 1984; Borghi et al., 1985; Sandrone et al., 1993; Avigad et al., 2003).

Previous studies on the metamorphic history of the Money Unit have emphasized its monocyclic history (Compagnoni et al., 1974; Le Bayon and Ballèvre, 2004), based on the lack of relics of a regional, Prealpine, metamorphism. However, peak P–T conditions of the Alpine metamorphism have not been accurately determined yet. It is difficult to determine whether peak conditions culminated within the eclogite or the blueschist facies, although garnet-chloritoid micaschists and garnet amphibolites have been recognized in this unit. In the equivalent unit of the Money Unit, i.e. the Pinerolo Unit from the Dora–Maira massif, evidence for the high-pressure metamorphism is also scanty (Borghi et al., 1985; Wheeler, 1991; Avigad et al., 2003). Nevertheless, most authors assume that there is a difference in peak P–T conditions between the Money and the Gran Paradiso Units (Oberhänsli et al., 2004).

## 3. Structural data

The structure of the Gran Paradiso massif is dominated by a pervasive, subhorizontal foliation developed in the epidote amphibolite facies (Eskola, 1939), a P–T domain equivalent to the greenschist-amphibolite transition of Oberhänsli et al. (2004). This main-phase foliation is parallel to the contact of the Gran Paradiso Unit with the overlying oceanic units and defines a broad regional dome structure. An E–W-trending stretching lineation is associated with this flat-lying foliation (Ballèvre, 1984, 1988; Carpena and Mailhé, 1984; Vearncombe, 1985; Brouwer et al., 2002; Kassem and Ring, 2004). Several authors proposed that this main deformation is associated with a top-to-the-west sense of shear (Ballèvre, 1984, 1988; Carpena and Mailhé, 1984; Brouwer et al., 2002; Kassem and Ring, 2004). The present study is based on (i) new structural mapping (Fig. 2), (ii) systematic measurements of foliation (Fig. 3a) and stretching lineations (Fig. 3b), (iii) recognition of shear criteria (Fig. 3b), and (iv) identification of strain gradients, from map-scale mylonitic zones of Alpine age to low-strain domains preserving Prealpine structures (Fig. 4).

### *3.1. Gran Paradiso Unit*

#### *3.1.1. Prealpine deformation and metamorphism ($D_V$ and $M_V$)*

Low-strain domains preserve intrusive relationships of the porphyritic granitoids and contact metamorphism of the country rocks due to incomplete Alpine transformation. Such domains were first identified south of the area studied, in the Orco valley (Callegari et al., 1969; Compagnoni and Prato, 1969) and in the Soana valley (Battiston et al., 1984). In the studied area, several examples of low-strain domains have been recognized (Fig. 4).

In the Bardoney valley, many granites and paragneisses were not or only slightly deformed during the Alpine event. The largest outcrop of undeformed rocks has been found along the main torrent in the Bardoney valley, 1.2 km south of the Alpe Bardoney. In the paragneisses, a Prealpine layering ($S_v$; v for Variscan) can be identified because it is crosscut by undeformed Ms and Tur pegmatites of Prealpine age (Fig. 5a) (mineral abbreviations after Kretz (1983)). This layering is defined by the alignment of quartz grains and muscovite flakes and the occurrence of leucocratic Ms–Pl (totally replaced by Czo–Ab)–Tur bearing veins (Fig. 5b). Relics of sillimanite (fibrolite) have been observed as inclusions in muscovite flakes (Fig. 5c and d). A few Alpine mineral phases can also be noted, namely minute (100 μm) idioblastic garnet, chlorite and phengite.

The paragneisses outcrop close to an undeformed porphyritic granite, which can be distinguished from other orthogneisses by a large amount of fine-grained equigranular comagmatic enclaves and xenoliths of country-rocks (Fig. 6a). The lack of Alpine deformation in these rocks allows for a good preservation of the texture of the magmatic assemblages. Magmatic relics consist of quartz, K-feldspar megacrysts, plagioclase, red–brown biotite, ilmenite and allanite.

In the undeformed volumes, the granite shows limited transformations, plagioclase being replaced by fine-grained Ab–Czo aggregates and ilmenite being overgrown by titanite. Clinozoisite rims allanite when in contact with plagioclase. Narrow (1–10 cm) subvertical shear zones with an E–W trend cut across the undeformed granite (Fig. 6b). The foliation in these shear zones is defined by fine-grained quartz, white mica, chlorite and clinozoisite. Chlorite growth at the expense of biotite is mainly observed in the shear zones.

The boundaries of the granites are intensely deformed, with a steeply-dipping foliation defined by quartz, brown biotite, clinozoisite, titanite and albite. Chlorite has not been observed in this foliation. Few magmatic phases have been preserved (partially recrystallized porphyroclasts of K-felspar and broken crystals of allanite).

In addition to the paragneisses and granites, there are also some undeformed mafic rocks displaying eclogite-facies ($M_{A1}$) parageneses that statically overprint the Prealpine amphibolite-facies parageneses ($M_v$) (see description below).

In the Valeille, large volumes of paragneisses (about 200 m × 100 m) with a horizontal or gently-dipping foliation outcrop on both sides of the valley, but are especially well displayed on the eastern side of the valley. No cross-cutting pegmatitic veins have been found in the field, hence the Prealpine age of the foliation cannot be determined by field inspection. Microscopic examination reveals that this foliation is defined by the alignment of large muscovite flakes, quartz and several types of pseudomorphs. The Alpine overprint produced minute, idioblastic, garnet grains, rimming ilmenite or aligned along former grain boundaries, minute phengite flakes with sagenite (rutile) needles in inclusions, interpreted as pseudomorphs after biotite, and pseudomorphs after unknown phases. Phengite crystals display no preferential shape fabric, contrary to the muscovite grains. The muscovite foliation is therefore associated with a Prealpine deformation ($S_v$). Prealpine paragneisses from the Valeille are thus petrographically similar to the Prealpine paragneisses described above in the Bardoney valley. Moreover, they occupy the same structural position, indicating that both outcrops belong

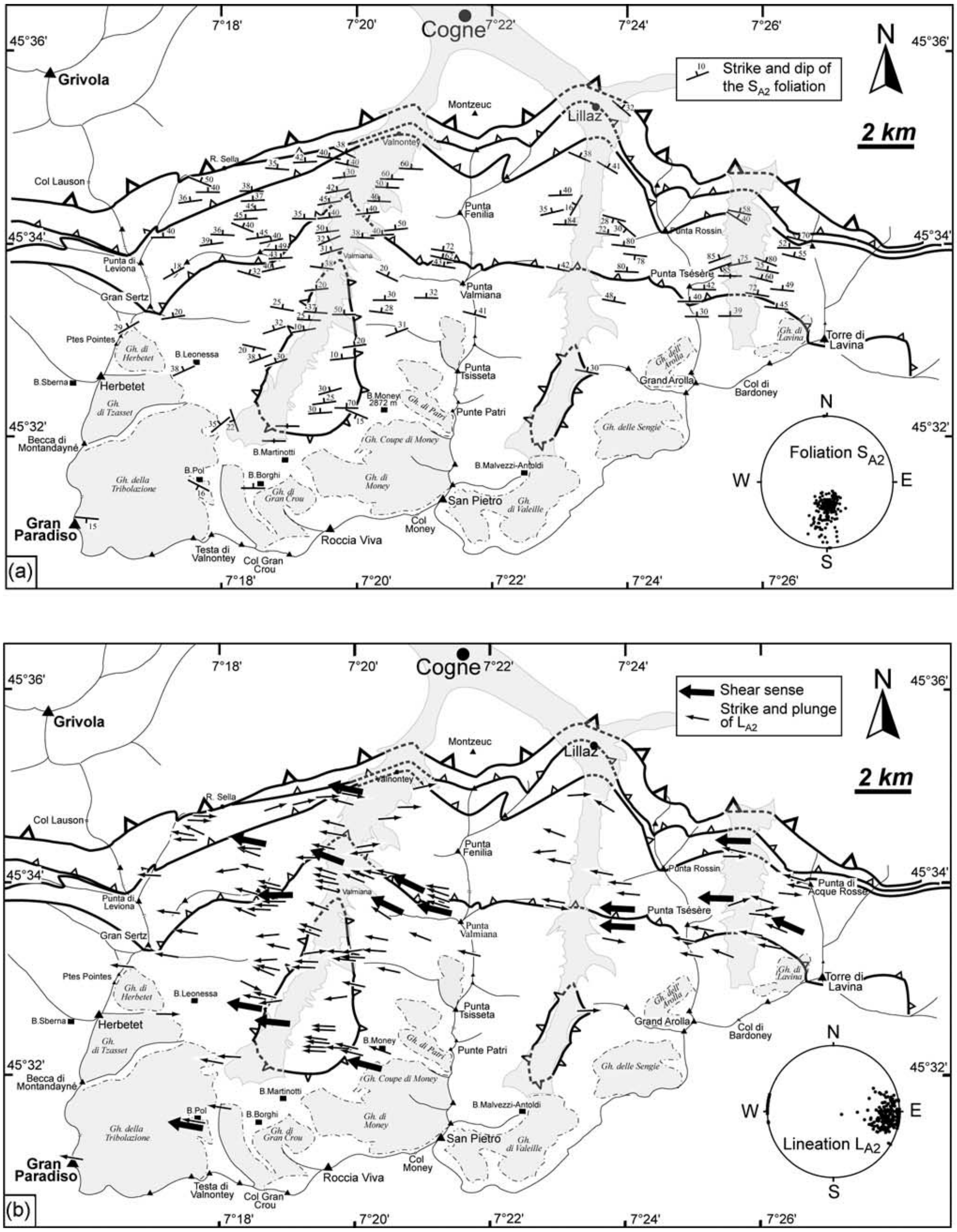

Fig. 3. Structural data measured in the northern part of Gran Paradiso massif, showing (a) the strike and dip of the mainphase foliation ($S_{A2}$) and (b) the strike and plunge of the stretching lineation ($L_{A2}$). Lower hemisphere projections on equal-angle stereonets show lack of dispersal of the data.

to the same volume, which therefore extends from the Bardoney to the Valeille. Careful search of similar gneisses in the Valnontey was unsuccessful, giving an upper bound to their extension towards the west (Figs. 2 and 4).

In the Valnontey, a spectacular outcrop has been found above the Bivacco Borghi, at the foot of the Colle del Gran Crou, at about 2800 m (Fig. 2). There, an undeformed granite with enclaves and xenoliths displays cross-cutting relationships with fine-grained foliated country-rocks (Fig. 7). The undeformed granite preserves magmatic minerals and textures (Qtz, Kfs, Pl and red–brown Bt) with minor Alpine mineral transformations (Ttn, Ms and Chl around Bt). The country-rocks are essentially made of quartz, red–brown biotite, plagioclase displaying polysynthetic twinning (a feature uncommon in albite porphyroblasts of Alpine age) and Kfs. According to microprobe analyses, plagioclase has a relatively high anorthite content (An20–26) and biotite is rich in Ti. The stability of this mineral assemblage indicates high temperatures of metamorphism, typical for hornfelses in contact aureoles. These rocks are thus interpreted as hornfelses that possess a Prealpine foliation ($S_v$) defined by biotite, plagioclase and Kfs, hence document the occurrence of two Prealpine events, a regional deformation and metamorphism followed by the contact metamorphism.

To sum up, two main types of volumes with Prealpine granites and gneisses were left undeformed throughout the Alpine history. The first type, observed in the Valeille and Bardoney, defines an E–W-trending, elongated lens that

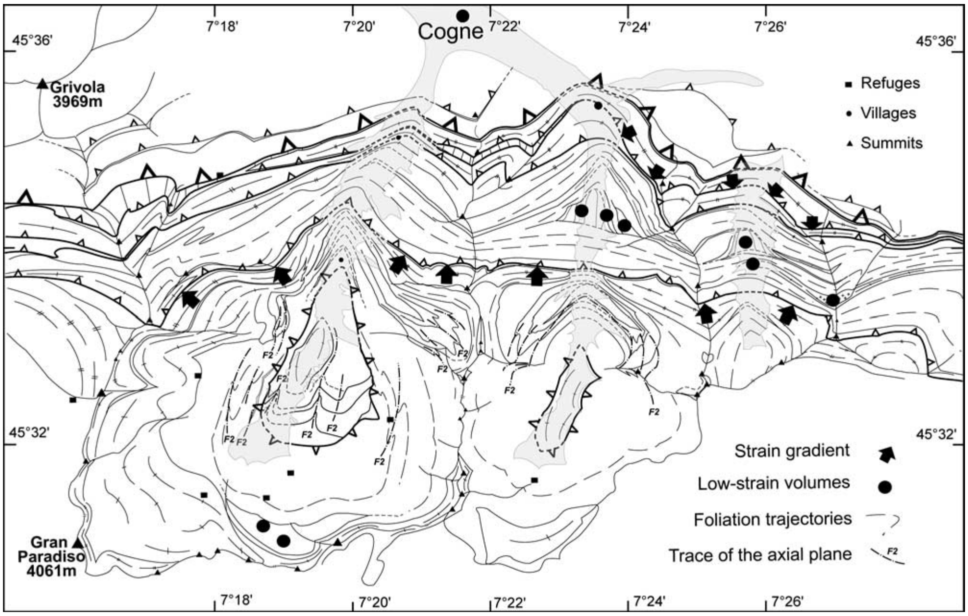

Fig. 4. Foliation trajectories, strain gradients and location of low-strain volumes with preserved Prealpine structures in the northern part of Gran Paradiso massif.

is essentially made up of Prealpine paragneisses. The second type, observed in the higher part of the Valnontey, is made of Prealpine hornfelses and intruding granites.

### 3.1.2. High-pressure deformation and metamorphism ($D_{A1}$ and $M_{A1}$)

Early-Alpine eclogite facies parageneses have been observed in the polycyclic rocks from the Gran Paradiso Unit.

Several types of eclogite-facies, mafic rocks can be distinguished, some of them being undeformed during the eclogite-facies event while others show a well-defined eclogite-facies foliation. An example of the first type is found along the left bank of the Bardoney valley and consists of a fine-grained, layered, mafic lens. In this mafic rock, the sub-horizontal attitude of the layering strongly contrasts with the steeply-dipping foliation observed in the surrounding

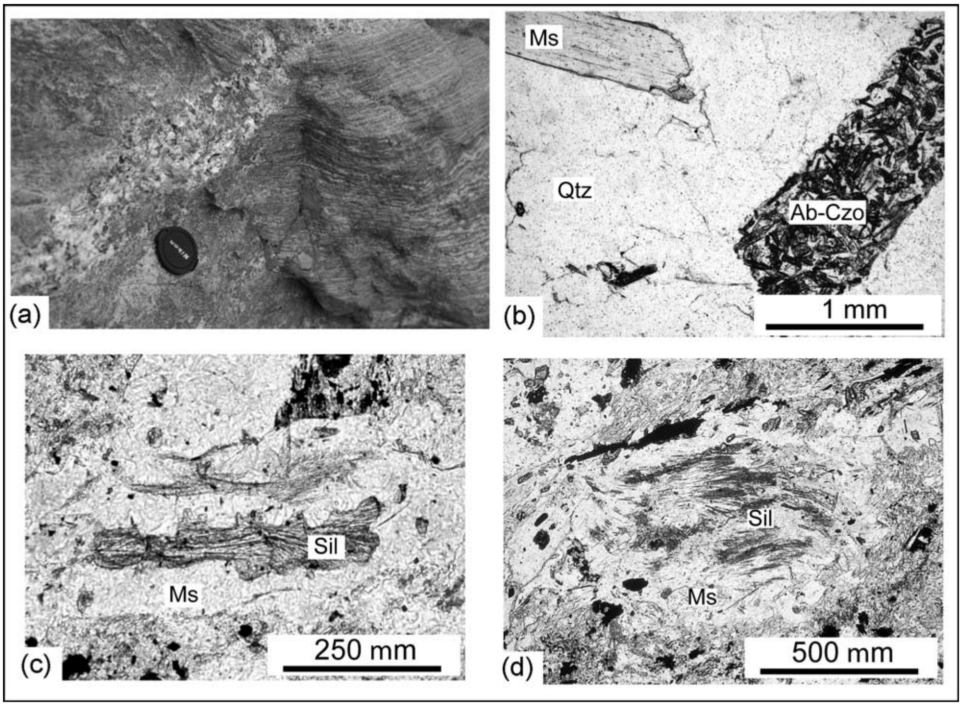

Fig. 5. Preserved Prealpine structures in paragneisses from the Bardoney valley, whose layering is crosscut by tourmaline- and muscovite-bearing pegmatitic veins. Because the pegmatites are Prealpine in age, the layering must also be Prealpine in age. This is confirmed by microscopic observations. In the pegmatitic veins, muscovite laths are undeformed and plagioclase is pseudomorphed by Ab–Czo aggregates. In the paragneisses, muscovite grains sometimes include sillimanite needles.

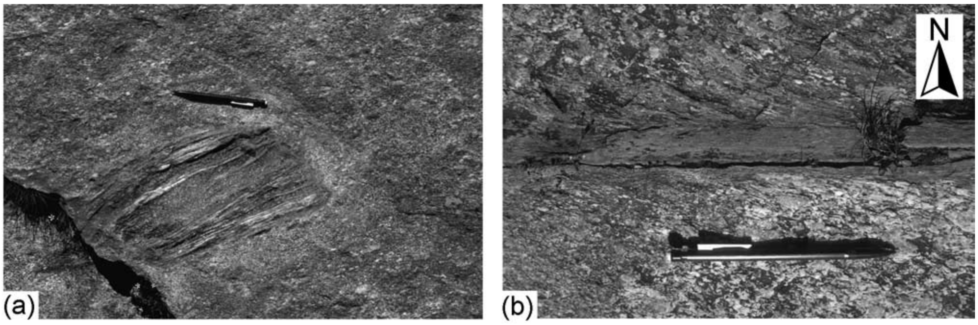

Fig. 6. Preserved Prealpine structures in granites from the Bardoney valley. A fine-to medium-grained granite, still displaying magmatic textures and undeformed xenoliths of foliated country-rocks (a), is cut across by narrow, chlorite-bearing, shear zones (b).

polycyclic paragneisses. Narrow shear veins are either parallel (or almost parallel) or strongly oblique to the layering. The veins contain aligned amphibole fibres up to a few mm long and white micas. The mafic rock essentially consists of minute (0.01 mm) idioblastic garnet crystals, aggregates of omphacite grains, a large amount of a pale green amphibole of barroisitic composition, phengite flakes and rutile. Barroisite and phengite crystals display no preferential shape fabric. A faint layering is perceptible through minor changes in the modal proportions of amphibole and mica. In summary, these mafic rocks display eclogite-facies parageneses that statically overprint a Prealpine fabric, potentially an amphibolite-facies layering ($M_v$). The eclogite-facies deformation in this eclogite lens is therefore limited to narrow (less than 1 mm thick) shear veins containing aligned amphibole and phengite crystals. The association of (i) mineral growth statically overprinting a former layering and (ii) discrete, spaced shear veins, both containing eclogite-facies minerals, indicate an overall brittle behaviour of the mafic lens during the Alpine high-pressure stage.

While some eclogite-facies metabasites lack ductile deformation, others have been intensely deformed. In the Bardoney valley, mafic eclogites outcrop on both sides of the main torrent, where they consist of a sheet with a maximum thickness of 10–15 m within polycyclic paragneisses. There, eclogites are dark, layered, fine-grained rocks, essentially consisting of minute idioblastic garnet crystals, omphacite grains, few grains of stretched glaucophane and aligned rutile grains. Light layers contain large phengite flakes and several grains of zoisite, glaucophane and quartz. Hence, this layering is an eclogite-facies foliation ($M_{A1}$), well defined by the shape fabric of the phengite flakes, omphacite, glaucophane and by the alignment of rutile grains. This eclogite-facies foliation is well preserved because these rocks are not or only slightly affected by the main-phase of deformation under epidote amphibolite facies conditions ($D_{A2}$). The epidote amphibolite facies ($M_{A2}$) is only represented by few plagioclase- and green amphibole-bearing veins cutting across the eclogitic foliation and by green-amphibole rims around the glaucophane. The eclogite-facies foliation is slightly folded and this rock displays a N–S oriented stretching lineation ($L_{A1}$), defined by the alignment of the glaucophane and phengite.

Eclogite facies is not restricted to basic rocks. Eclogite-facies parageneses or relics of eclogitic minerals have also been observed in paragneisses of the Gran Paradiso Unit.

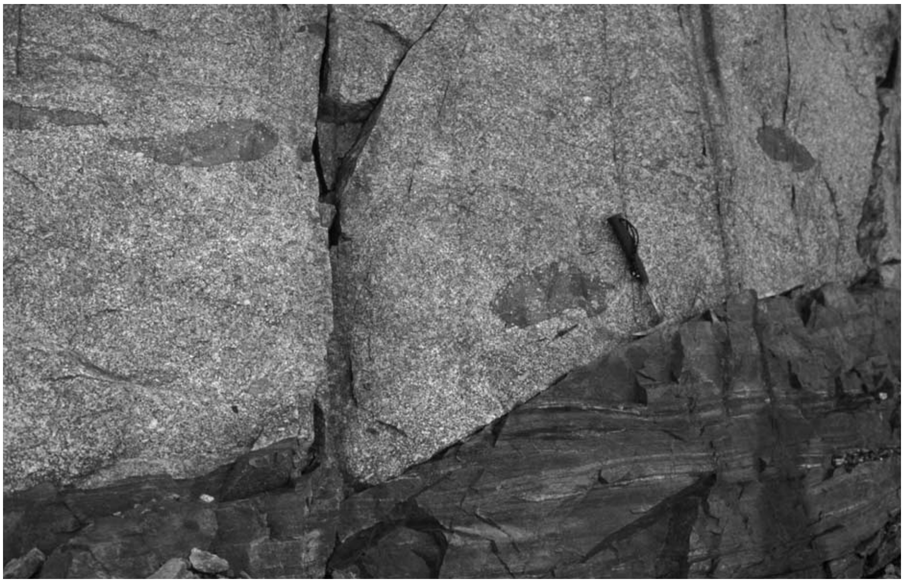

Fig. 7. Preserved Prealpine structures in the Valnontey, above B. Borghi, where an intrusive contact between a granite and Kfs–Bt hornfelses is found. Note hammer for scale.

An example of high-pressure parageneses in paragneisses rocks is given by a sheet of garnet-chloritoid bearing micaschists outcropping through the Valnontey and the Valeille. These garnet-chloritoid micaschists are affected by a kilometre-scale isoclinal fold. The folds associated with a second deformation in the epidote amphibolite facies show E–W-trending axes. The eclogitic foliation is essentially preserved as a folded schistosity ($S_{A1}$) contained in microlithons bounded by narrow foliation planes ($S_{A2}$). The main foliation ($S_{A2}$) is defined by the alignment of stretched phengite flakes and chlorite grains, developing at the expense of porphyroclasts of garnet and chloritoid. The latter, together with phengite, represent relics of the eclogitic foliation ($S_{A1}$).

### 3.1.3. Low-pressure deformation ($D_{A2}$)

The main foliation post-dates $D_{A1}$ and is pervasive in the whole Gran Paradiso massif paralleling the contact of the Gran Paradiso Unit with the overlying oceanic units. It also defines the dome structure of the Gran Paradiso basement (Figs. 8 and 9). Microscopic analysis suggests that the main ductile deformation ($D_{A2}$) occurred under epidote amphibolite facies conditions ($M_{A2}$), because the $S_{A2}$ foliation is associated with the growth of albite. Biotite grows in contact with garnet and phengite, or along phengite rims. Garnet rims have been preserved in albite grains. However, when garnet is in contact with biotite, garnet rims are dissolved. This suggests that biotite grows at the expense of garnet during or after albite development. Rutile inclusions within garnet have been lately replaced by ilmenite in the matrix.

Detailed mapping reveals that a kilometre-scale, isoclinal fold with a surimposed, pervasive schistosity ($S_{A2}$), which formed under epidote amphibolite facies, affects the garnet-chloritoid bearing micaschists in both the Valnontey and the Valeille valleys (Figs. 2, 8a and 9a and b). A paragneiss forms the core of this fold, easily distinguished from the other paragneisses because it displays numerous porphyroclasts of white mica, up to 1–2 cm in size (Ms paragneiss in Fig. 2). Microprobe analyses show that the porphyroclasts of white mica have a muscovite composition (i.e. presents a very low Si content), hence are interpreted as Prealpine relics. Minute grains of phengite (with a high Si content) and biotite define the main foliation ($S_{A2}$). Therefore, the paragneiss in the core

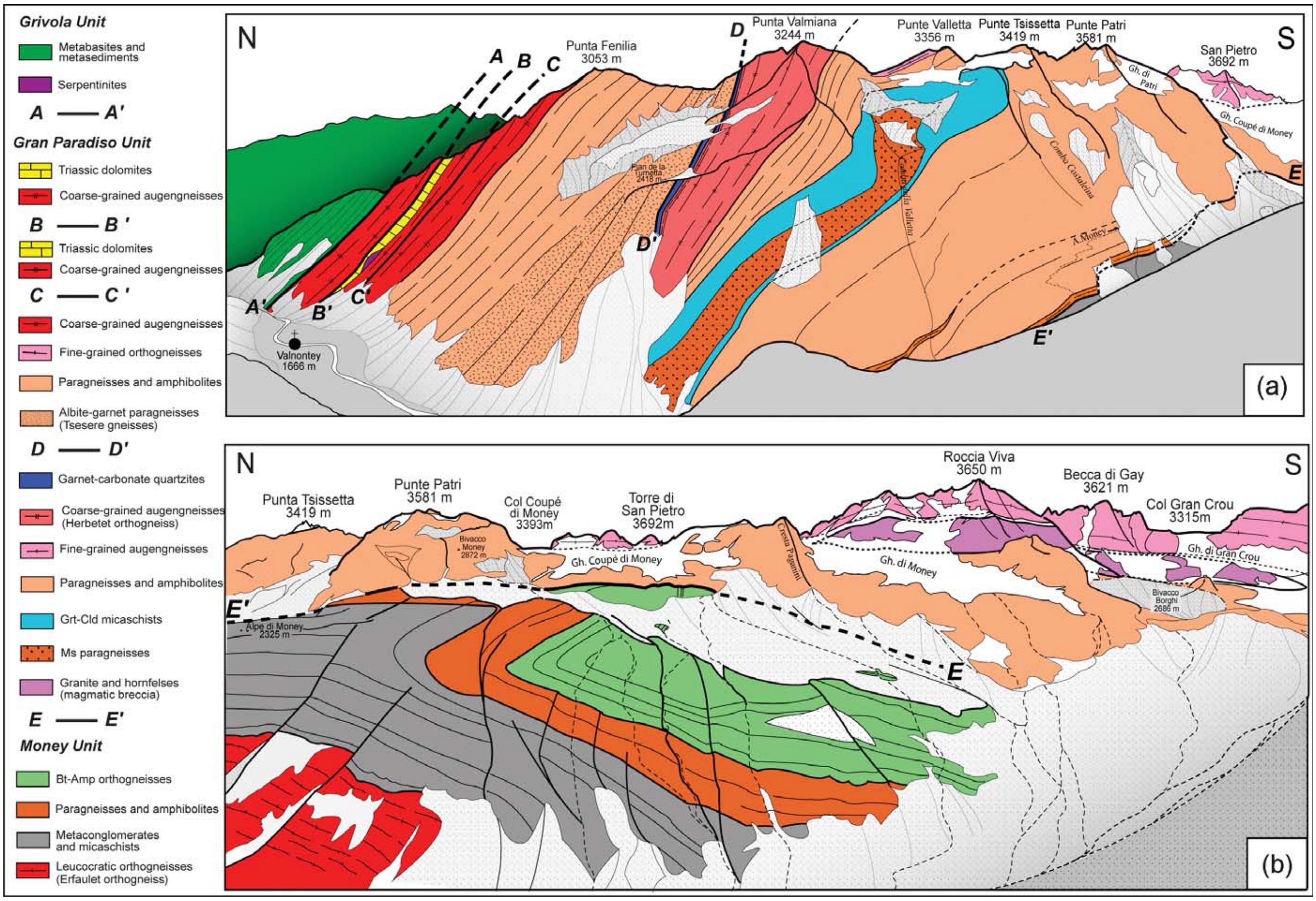

Fig. 8. Two geological panoramas of the right (i.e. eastern) flank of the Valnontey. (a) The upper sketch is taken from Peina Ceinla, along the trail from Rifugio Sella to Pian di Ressello. The panorama illustrates the contact of the Gran Paradiso Unit with the eclogite-bearing, oceanic, Grivola Unit (AA′), and the upper, internal thrusts (BB′, CC′ and DD′). Note also the isoclinal fold with muscovite-paragneisses in its core and formed by Cld-bearing micaschists. (b) The lower sketch (taken from the trail between Casolari dell Herbetet and Pian di Ressello) emphasizes the internal structure of the Money Unit, displaying the Erfaulet orthogneiss (red) in intrusive contact (Le Bayon and Ballèvre, 2004) with the overlying metaconglomerates and metasediments of presumed Permo-Carboniferous age (Compagnoni et al., 1974). Undeformed volumes preserving Prealpine structures outcrop in the background, at the base of the Roccia Viva–Colle Gran Crou ridge.

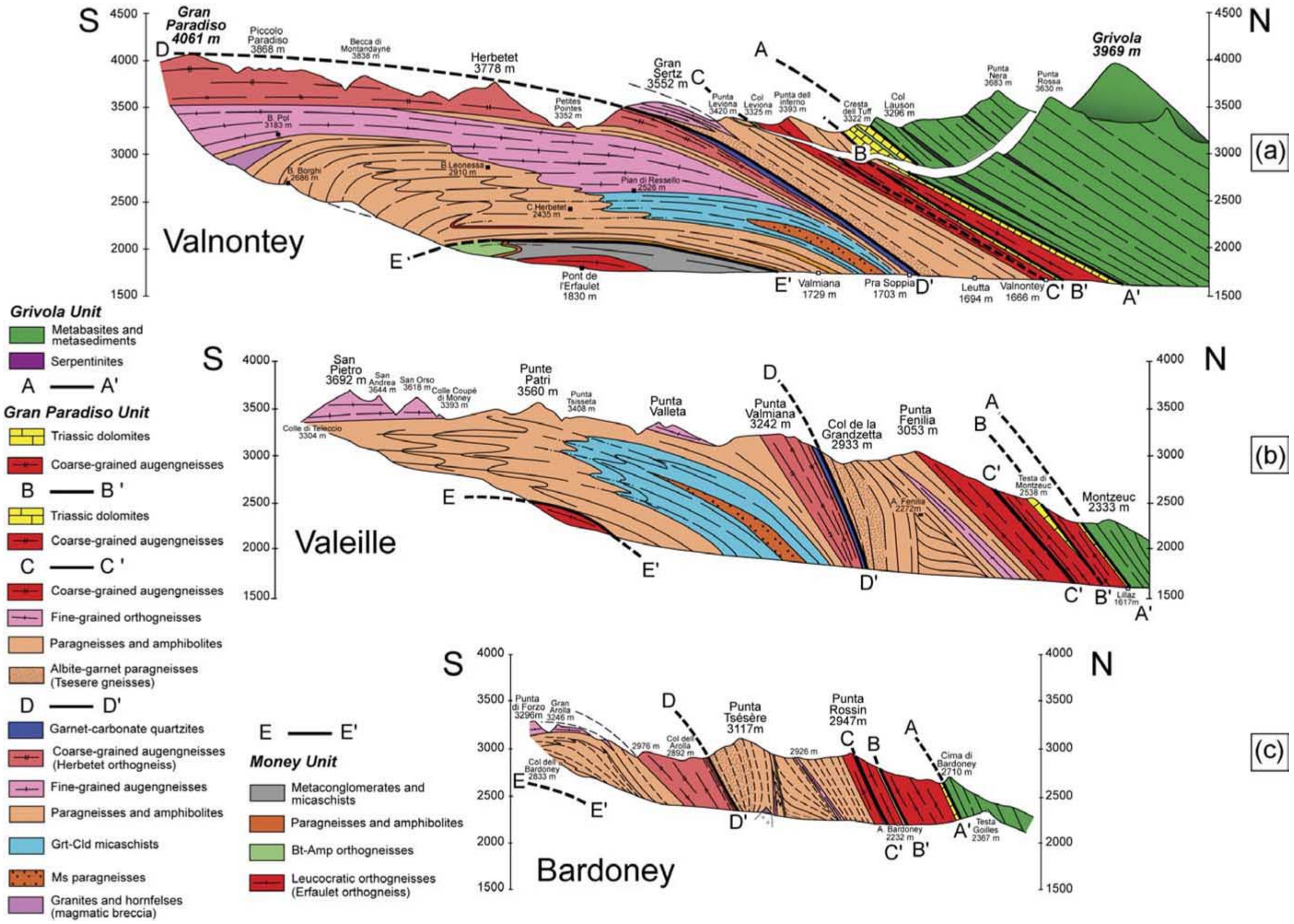

Fig. 9. Simplified cross-sections along the three investigated valleys (i.e. Valnontey, Valeille and Bardoney). Nomenclature of lithologies, units and structures is identical to those used for Fig. 2. The internal structure of the Grivola Unit is not detailed, being out of scope of this paper.

of the fold contains Prealpine relics at grain scale but structures related to this event at outcrop or map scale have been erased during the Alpine deformation. The fold axis trends E–W, and its axial plane dips moderately to the north, flattening towards the south within the studied area (Figs. 8a and 9a and b). Development of the main schistosity $S_{A2}$ is coeval with the folding. Asymmetrical folds are observed along both limbs of this isoclinal fold within the Grt–Cld micaschists.

In the northern part of the investigated area, the $S_{A2}$ foliation gently dips to the north. Towards the south and above the contact with the underlying Money Unit, numerous asymmetrical, tight to open folds are observed deforming the layer-parallel schistosity ($S_{A1}$) within the paragneisses. These folds are therefore attributed to $D_{A2}$. The fold axes present an E–W trend and a poorly- to well-developed axial-plane schistosisty associated with albite, biotite and/or chlorite growth. The axial planes of the $D_{A2}$ folds are parallel to the contact between the Money and Gran Paradiso Units.

### 3.2. Money Unit

Prealpine, high-temperature relics due to a regional metamorphism have not been recognized in the Money Complex. However, some garnet cores in micaschist samples close to the Erfaulet orthogneiss have been interpreted as relics of a contact metamorphism (Le Bayon and Ballèvre, 2004). According to field and microscopic studies, the internal deformation of the Money Unit is characterized by two major stages of deformation (Fig. 10).

Stage 1 is defined by a foliation ($S_{A1}$) parallel to the major lithological boundaries and to the sedimentary layering ($S_0$) within the Money Complex. This stage is associated with the growth of relatively high-pressure assemblages, namely garnet + chloritoid + rutile in the micaschists and albite + epidote + biotite + hornblendic amphibole in the metabasites. Because albite is stable in the earliest foliation recognized in the metabasites from the Money Unit, stage 1 should have occurred at a lower pressure in the Money Unit than in the Gran Paradiso Unit. $D_{A1}$ is associated with an E–W stretching lineation, which is best displayed by the shape fabric of the deformed pebbles in the metaconglomerates and by elongated needles of amphibole in the fine-grained amphibole-biotite orthogneisses (Figs. 8b and 10). In the metabasites, numerous shear bands indicate a top-to-the-west sense of shear (Fig. 11a).

Stage 2 is marked by kilometre-scale, flat-lying folds that deform $S_{A1}$ (Fig. 8) and are associated with a second schistosity

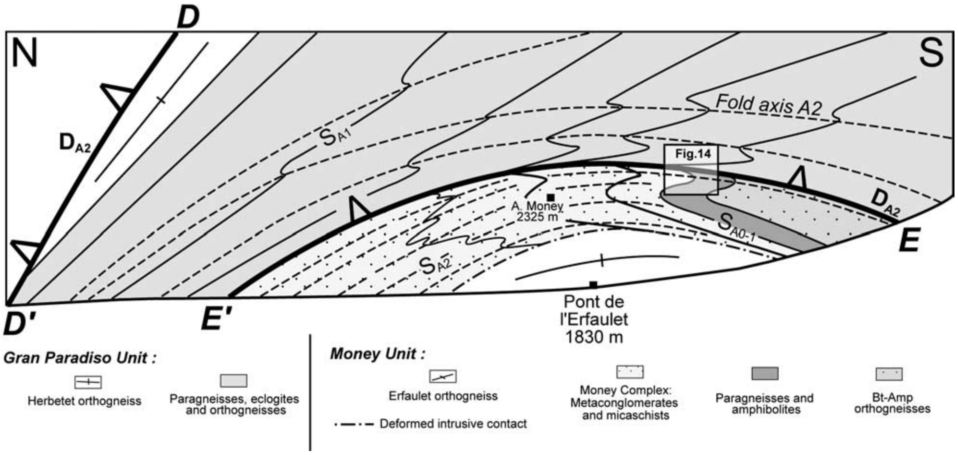

Fig. 10. Schematic cross-section of the right flank of the Valnontey, displaying the overprinting structures within the Money Unit, and the contact with the overlying Gran Paradiso Unit.

($S_{A2}$). The $D_{A2}$ deformation is well developed as a narrow crenulation cleavage in the micaschists from the Money Complex, where $S_{A1}$ is best preserved in albite porphyroblasts. Indeed, sigmoidal inclusions of graphite in albite represent the $D_{A1}$ foliation (Fig. 11b), which is parallel to the sedimentary layering in the Money Complex. The end of this stage 2 is marked by the localisation of the deformation along the contact between Gran Paradiso and Money Units (Fig. 10), a feature that will deserve further attention below. This late ductile deformation is associated with a chlorite foliation (i.e. greenschist facies) mainly developed at the base of the Gran Paradiso Unit.

### 3.3. Brittle deformation ($D_{A3}$)

A late brittle deformation ($D_{A3}$) is displayed by several E–W-trending, high-angle, normal faults that affect the whole

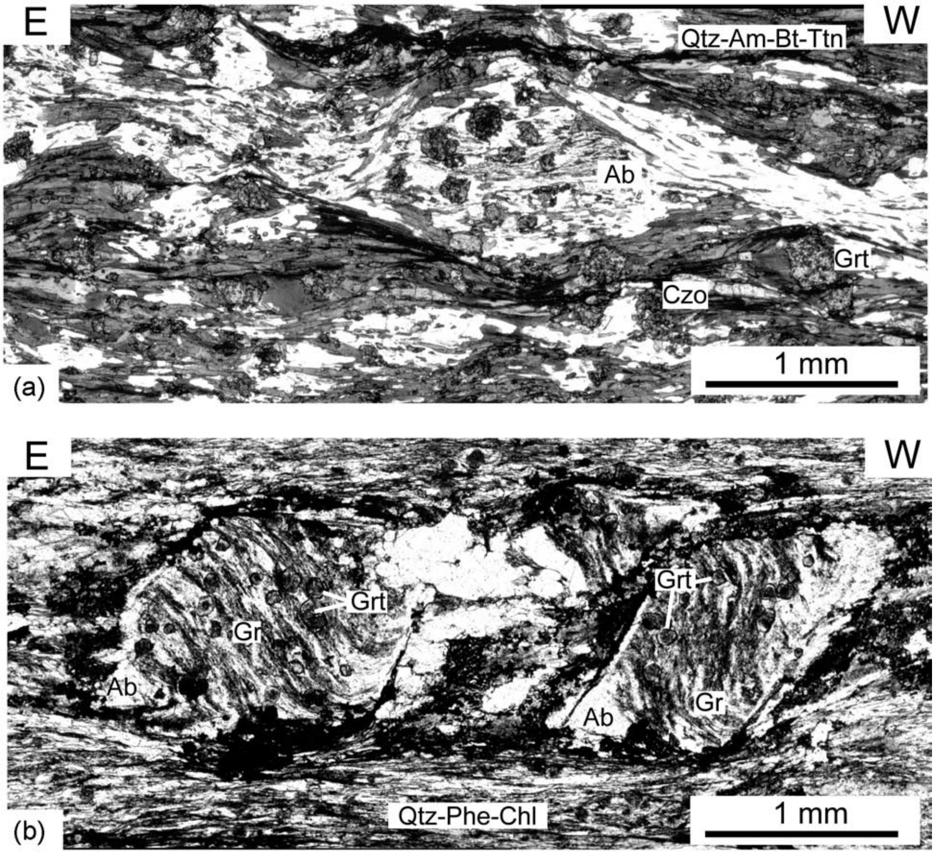

Fig. 11. Photomicrographs showing microstructures in two samples from the Money Complex. (a) Amphibolite with ductile shear bands indicating top-to-the-west sense of shear. (b) Graphite-bearing micaschist showing sigmoidal inclusions of graphite ($S_{A1}$) in the albite and main foliation defined by Qtz–Phe–Chl ($S_{A2}$). The $S_{A1}$ foliation is parallel to the sedimentary layering of the Money Complex.

unit, cutting across lithological as well as tectonic boundaries. In rare instances, their walls contain quartz crystals. These faults show a minor (a few mm) or slight (a few cm to a few dm) offset and are thus of negligible importance for the large-scale structure of the studied area. Similar brittle, post-metamorphic faults are associated with cataclasites in the Orco valley, to the south of the studied area (Perello et al., 2004).

## 4. The kinematics of regional-scale structures

### *4.1. The boundary with the overlying oceanic units*

The Gran Paradiso Unit is overthrusted by the oceanic units and this tectonic contact (AA′ on Figs. 2, 8 and 9) is particularly well displayed along the northwestern boundary of the Gran Paradiso massif. Remnants of a thin metasedimentary cover, presumed to be Permian to early Mesozoic in age (Elter, 1960, 1971, 1972), are found at the contact between the Prealpine basement and the oceanic units. This metasedimentary cover consists of dolomitic marbles and calcschists (of presumed Triassic and Liassic age, respectively). Associated with the above lithologies are brecciated carbonate rocks called cargneules or cornieules (Weidmann, 1971). The cargneules are formed from a starting material of anhydrite and dolomite that has been brecciated (e.g. Warrack, 1974; Vearncombe, 1982). This brecciation could result from hydraulic fracturing due to the very high pore-water pressure (Masson, 1972) or, alternatively, result from Recent weathering of anhydrite-dolomite mylonites (e.g. Brückner, 1941; Jeanbourquin, 1988; Schaad, 1995). This latter hypothesis is supported by the lack of cargneules in deep boreholes that cut across major decollement levels, where anhydrite mylonites are recorded (Jordan, 1992). Whatever their exact genetic mechanism, the protoliths of the cargneules mark the location of a major décollement level (Masson, 1972), allowing for the displacement of the Mesozoic cover with respect to its Prealpine basement, and thus also favouring thrusting of the oceanic units onto the continental units.

The amount (i.e. thickness) of parautochtonous Mesozoic cover preserved along the contact with the oceanic units decreases from west to east (Figs. 2 and 9). For example, in the western part of the studied area, along the crest between the Valsavarenche and the Valnontey, specifically between Punta del Inferno and Col Lauson, the Mesozoic cover is internally duplicated two or three times (Fig. 9a) (Dal Piaz, 1928; Hermann, 1928; Cornelius, 1934; Amstutz, 1962). Towards the east, the Triassic marbles disappear and a thin layer of cargneule is found at the contact between the Gran Paradiso Unit and the overlying oceanic units (Fig. 9b and c) (e.g. at the Lillaz waterfall). The last slices of marbles are found in the Bardoney valley (Fig. 9c). There, the marbles define a few elongated lenses separated from the underlying, coarse-grained orthogneisses by calcschists. The marbles show a prominent stretching lineation defined by the calcite fabric and by elongated needles of actinolite in a few layers. Moreover, the strike and plunge of the stretching lineation shows systematic departures from one marble lens to the other, suggesting late, rigid rotation of the marble lenses after their ductile deformation.

### *4.2. Duplication of the Gran Paradiso basement along the BB′ and CC′ thrusts*

At a lower structural level (BB′ on Figs. 8 and 9), a thin sheet of Mesozoic rocks can be mapped from the Valnontey to the Valeille (Dal Piaz, 1928; Hermann, 1928; Amstutz, 1962). Detailed geological mapping is an essential tool for deciphering the meaning of this sheet. In its westernmost part, into the Vallone dell Lauson, a narrow sheet of cargneules and dolomites is observed along the torrent. Despite poor exposure in the environs of the Rifugio Sella, we assume that this narrow sheet of cargneules merges westwards with one of the imbricated slices of Mesozoic cover observed along the Valsavarenche–Valnontey divide. In the eastern side of the Valnontey, the Mesozoic rocks become much more developed, a serpentinite lens being observed at the contact with the underlying orthogneisses (Amstutz, 1962; Pennachioni, 1988). Eastwards of the Valeille, cargneules and marbles disappear. The overlying orthogneisses display a strong deformation gradient, being mylonitised towards the contact (Fig. 12a and b). The mylonite zone, initially mapped by Amstutz (1962) as a thin sheet of paragneiss intercalated within the orthogneisses, can be followed along-strike up to the easternmost part of the studied area, i.e. the Bardoney–Acque Rosse divide. Shear criteria within the mylonites indicate a top-to-the-west sense of shear (Fig. 12a and b).

Microscopic analysis reveals that the porphyritic orthogneiss consists of Kfs porphyroclasts in a foliation defined by quartz, phengite, clinozoisite, biotite and titanite. Biotite is always in contact with phengite or along phengite rims, the biotite growing at the expense of phengite, and is sometimes partially replaced by chlorite. In the mylonitic zone, the strong deformation induced a decrease in grain size. The mylonite is made of quartz, biotite, phengite, microcline, clinozoisite and chlorite. Foliation is defined by the alignment of quartz, biotite, phengite and chlorite. Contrary to the brown biotite in the porphyritic orthogneisses, the biotite in the mylonitic zone is green. It has been argued that the biotite colour depends on its Ti content. Because green biotites from the mylonites have a lower Ti content compared with the brown biotites from the orthogneisses, the mylonitic zone represents strain localization under decreasing temperatures.

Previous studies have interpreted this Mesozoic sheet found within the orthogneisses as a tight, isoclinal, kilometre-scale fold (Amstutz, 1962; Vissers and Compagnoni, 1984; $D_2$ for Pennachioni, 1988). The along-strike replacement of the mylonitic horizons located within the Mesozoic cover (i.e. cargneules) by the mylonites developed at the base of the augen-gneisses suggests that this zone represents a thrust contact (BB′) rather than an isoclinal fold developed at a late stage of the tectonic history. Indeed, the occurrence of schistose serpentinites implies a two-stage evolution, namely an early emplacement of the oceanic units over the Gran

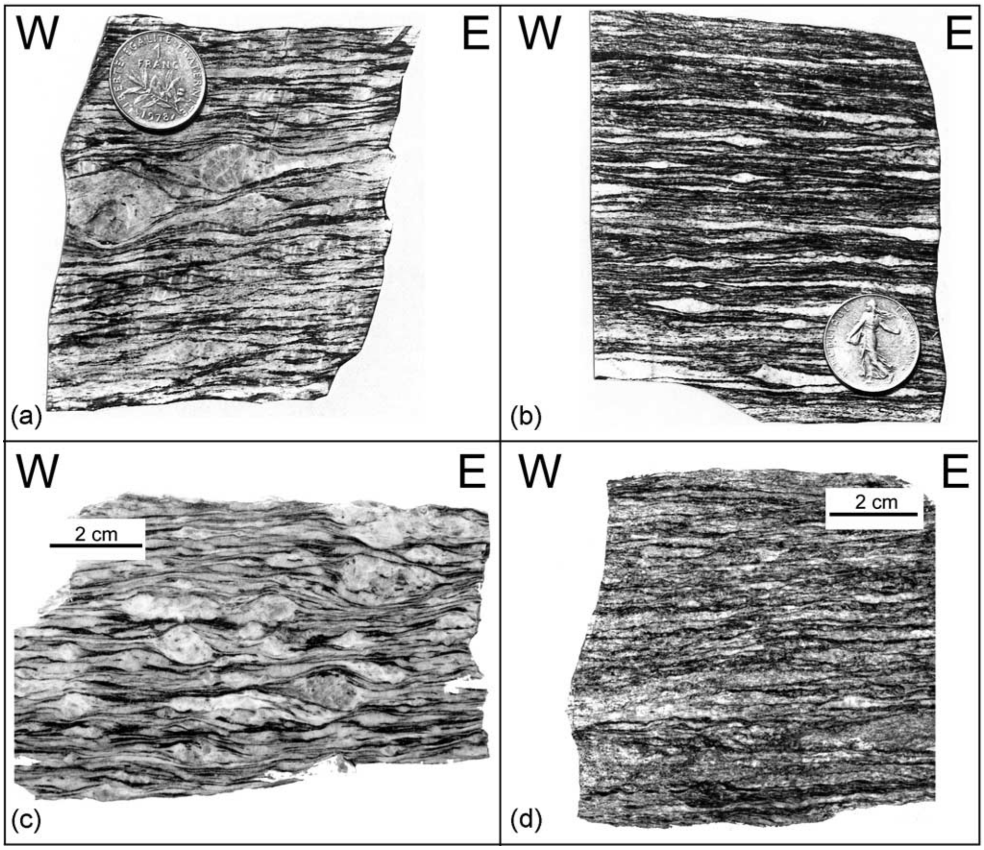

Fig. 12. Two examples of strain gradients in the orthogneisses from the Gran Paradiso Unit. All samples are cut perpendicular to foliation and parallel to the stretching lineation (i.e. in the $\lambda_1\lambda_3$ plane of the finite strain ellipsoid). (a) and (b) Coarse-grained orthogneisses from the northern margin of the Gran Paradiso Unit are mylonitised along the BB′ contact. The photographed samples have been collected along the Valeille-Bardoney divide, north of Punta Rossin. Shear bands indicate top-to-the-west shear sense. (c) and (d) Coarse- to medium-grained orthogneisses located below the garnet-ankerite quartzite layer show a decreasing grain size towards the quartzite layer, along the DD′ contact. Shear bands also indicate a top-to-the-west shear sense. Photographs taken at Pian della Turnetta, on the eastern side of the Valnontey.

Paradiso basement and a reworking of this contact allowing thin slices of continental material to be thrusted over more external parts of the Gran Paradiso basement. The occurrence of synkinematic albite in the mylonites is consistent with the second deformation occurring at some stage during the exhumation history of the eclogite-facies units.

At a lower structural level than the BB′ thrust, a second layer of Mesozoic rocks is found within the Prealpine gneisses (CC′ on Figs. 8 and 9). This sheet is best exposed at Punta Timorion (1 km west of Punta dell'Inferno), where it consists of calcschists and metabasalts (Dal Piaz, 1928; Amstutz, 1962). Eastwards of Punta Timorion, this sheet is marked by a narrow layer of calcschists (a few metres thick on the crest at the Colle di Leviona) (Cornelius, 1934; Amstutz, 1962). Due to ice retreat, the calcschists are now outcropping at the front of the Glacier del Tuf, then disappear eastward below the morainic deposits. At the same structural level, a thin layer of albite-bearing paragneisses, initially mapped by Amstutz (1962) in the Valeille and Bardoney Valleys (Fig. 2), occur within the orthogneisses. These paragneisses are mapped from the western side of the Valnontey to the eastern side of the Valeille. The thickness of the paragneiss sheet increases towards the east, from about 2 m thick in the Valnontey up to about 100 m at the summit of Punta di Acque Rosse. Previous studies have interpreted this paragneiss sheet within the orthogneisses as a tight, isoclinal, kilometre-scale fold (Vissers and Compagnoni, 1984) (Fig. 13). We consider that the eastward-narrowing sheet of Mesozoic rocks and the paragneisses mark the location of another thrust duplicating the Gran Paradiso basement (CC′).

### 4.3. Duplication of the Gran Paradiso basement along the DD′ thrust

The large number of augen gneisses causes a potential difficulty for unravelling the regional-scale structures within the Gran Paradiso unit (Fig. 13). A major task of the mapping work therefore was to discriminate these sheets, which could represent either isoclinal folds resulting from the ductile deformation of a single intrusion, or different (in a favourable case) kinds of orthogneisses juxtaposed along shear zones (Fig. 13).

Amongst the various types of orthogneisses, a huge sheet of porphyritic orthogneisses (Herbetet orthogneiss on Fig. 2) is observed throughout the three mapped valleys, from the cliffs below the Torre di Lavina in the east to the Herbetet in the west, i.e. in an area where the dominant foliation moderately

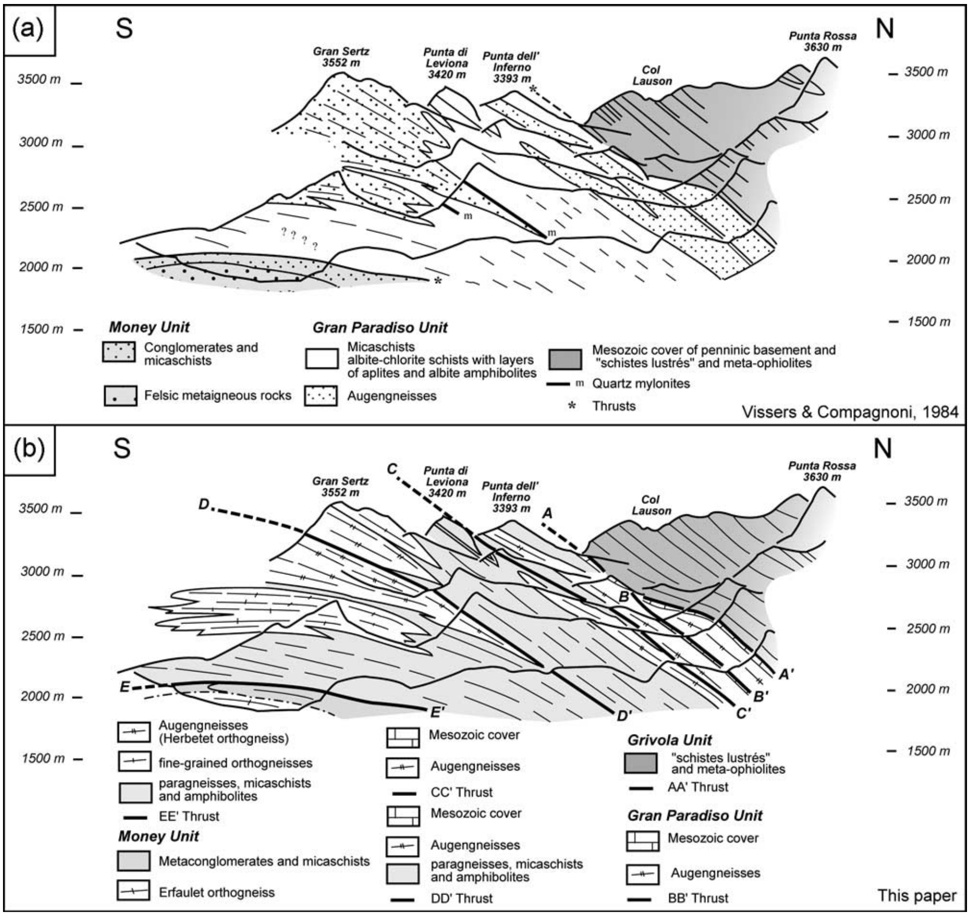

Fig. 13. Two interpretations of the lithological and structural data along the western side of the Valnontey. The pioneering work of Vissers and Compagnoni (1984) needs reinterpretation according to new field data (see text for further details). For sake of comparison, the two versions are here redrawn on the basis of the original figure given by Vissers and Compagnoni (1984).

dips to the north (Figs. 2 and 9). Preliminary reconnaissance studies along the Valnontey–Valsavarenche crest, where the foliation is subhorizontal, suggest that the same sheet extends up to the Gran Paradiso summit. For sake of clarity, it will be hereafter named the Herbetet orthogneiss. As a whole, the Herbetet orthogneiss layer is characterized by abundant K-feldspar porphyroclasts, numerous flattened microgranular enclaves and a few folded aplitic dykes. Contrary to the geological map of Amstutz (1962), according to which the orthogneiss sheet is continuous from the Valnontey to the Bardoney valleys, other authors—in accordance with our observations—indicate that this sheet does not outcrop at the bottom of the Valnontey and Valeille valleys (Compagnoni et al., 1974; Vissers and Compagnoni, 1984; Elter, 1987; Ballèvre, 1988). The thickness of the orthogneiss sheet decreases from the highest crests, where it attains about 500 m, and disappears at an altitude of around 2000 m along both flanks of the Valnontey. Further east, the Herbetet orthogneiss can be followed along both flanks of the Valeille (except close to its floor, below about 2100 m) and is continuous across the Bardoney valley, whose floor is located at 2200–2300 m.

The lower boundary of the Herbetet orthogneiss sheet cuts across the layering of the underlying gneisses. In addition, several xenoliths of metasediments have been observed along the lower part of the orthogneiss. These observations suggest that the lower boundary of the Herbetet orthogneiss represents a deformed intrusive contact.

The upper boundary of the Herbetet orthogneiss is intensely deformed, showing a progressive transition upwards from augen-gneisses to fine-grained, augen-free gneisses (Fig. 12c and d). The upper boundary thus corresponds to a mylonitic zone, up to 10 m thick. Shear bands in the mylonitic zone indicate a top-to-the-west sense of shear (Fig. 12c and d). The Herbetet orthogneiss is overlain by a garnet-ankerite quartzite (of probable Permian age) (Fig. 2), then albite-bearing paragneisses displaying numerous centimetre-sized garnet grains (Fig. 2). The above lithologies have been identified previously by Vissers and Compagnoni (1984) (m on their fig. 3, here reproduced as Fig. 13a), and by Borghi et al. (1994), who called them Tsesere gneisses. These two lithologies are easily distinguished in the field, only found in this structural position, and can be followed through the Valnontey and Valeille valleys: they are thus first-order lithological markers. To the east, the garnet-ankerite quartzite disappear laterally in the Bardoney valley and the garnet-albite paragneisses are juxtaposed with the Herbetet orthogneiss (e.g. at the summit of the Torre di Lavina). In the westernmost part of the Valnontey,

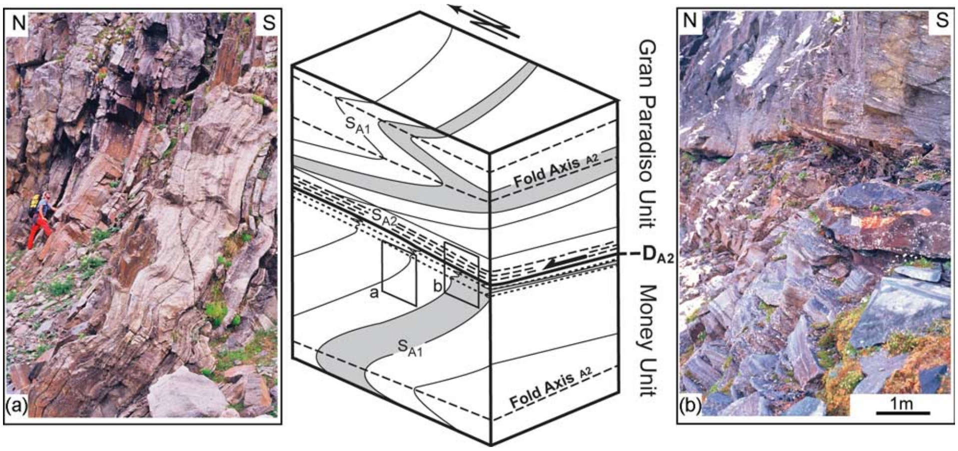

Fig. 14. A close-up of the contact between the Money and Gran Paradiso Units at the foot of the Coupè di Money glacier. This area is now safely accessible due to ice retreat. The contact is marked by a chlorite-bearing mylonitic zone at the base of the Gran Paradiso Unit and a flat-lying schistosity develops in the underlying gneisses.

the quartzite layer and the overlying gneisses disappear at the frontal margin of the Gran Val glacier and the shear zone juxtaposes higher up two different orthogneisses (Fig. 13b). We thus consider this mylonitic zone as a regional-scale shear zone (DD′), recognized through the three mapped valleys, where it divides the Gran Paradiso Unit into two sub-units (Fig. 13b). The occurrence of a narrow sheet of alleged Permian metasediments (i.e. the garnet-ankerite quartzites) is consistent with the interpretation of the DD′ shear zone as a first-order duplication within the Gran Paradiso basement.

Geological mapping indicates that the DD′ shear zone moderately dips to the north in the northern part of the studied area, but becomes flat-lying towards the south. The orientation of the stretching lineation ($L_{A2}$) (about E–W) and shear sense (top-to-the-west) are remarkably constant regardless of the dip of the foliation (Fig. 3). Microscopic observations indicate that the synkinematic assemblage consists of quartz, albite, phengite, biotite and epidote. Hence shearing occurred in the epidote amphibolite facies ($M_{A2}$), i.e. during the deformation phase $D_{A2}$. The shear zone DD′ represents a late (i.e. post-eclogitic) thrust, which internally duplicates the Gran Paradiso basement.

### 4.4. The Money window

The structure of the Money window also needs to be assessed. The Permo-Carboniferous Money Complex might be considered as an inverted limb of a major, regional-scale, flat-lying fold (e.g. Debelmas and Kerckove, 1980). However this possibility is ruled out for two main reasons.

First, detailed mapping shows that the lithologies south of the Money metasediments have no equivalent higher up. Specifically, the fine-grained biotite-amphibole orthogneisses that outcrop in the core of the late fold cannot be followed southwards along the normal limb of this fold (Figs. 2 and 8b).

Second, a mylonite zone (EE′ on Figs. 8–10) has been discovered at the top of the biotite-amphibole orthogneisses, at the foot of the glacier 'Coupé di Money'. A spectacular outcrop—now accessible due to ice retreat following the late warmest summers—shows the contact between the Money and the Gran Paradiso Units (Fig. 14). Below this contact, the $S_{A1}$ foliation in the biotite-amphibole orthogneisses and in graphite-bearing micaschists is subvertical (Fig. 14a). This foliation is deformed by open to tight, decimetre-scale folds whose axial plane is parallel to the contact with the overlying gneisses. This folding event is associated with an axial-plane crenulation cleavage, post-dating albite growth and associated with a chlorite foliation ($S_{A2}$). The deformation intensity increases higher up until a narrow, locally developed, cataclastic zone (about 0.20 m thick) is attained (Fig. 14b). The gneisses from the Gran Paradiso Unit outcropping above the cataclasites show a prominent chlorite foliation, which is parallel to the contact (Fig. 14b). The mylonites bear an E–W stretching lineation and a top-to-the-west sense of shear. Therefore, we interpret the contact between the Money Unit and the Gran Paradiso Unit as a westward thrust evolving from ductile deformation in the epidote amphibolite facies ($D_{A2}$) to localized, greenschist facies, ductile to semi-brittle deformation.

Therefore, we consider that a tectonic contact separates the Money Unit from the overlying Gran Paradiso Unit. Nevertheless, three geometrically valid hypotheses can be put forward for delineating the geometry of the tectonic contact between the Money Unit and the overlying Gran Paradiso Unit (Fig. 15). In a first hypothesis, the thrust would be located at the boundary between the Money metasediments and the overlying (undifferentiated) gneisses (Compagnoni et al., 1974; Vissers and Compagnoni, 1984), the thrust contact being later folded (Fig. 15a). This hypothesis, although qualitatively correct, does not take into account the folded amphibole-biotite orthogneisses cut across by the mylonitic zone described above. A second hypothesis considers that two thrusts are present, an earlier ($D_{A1}$) thrust located at the contact between the Money Complex and the paragneisses and amphibolites, a later ($D_{A2}$) thrust cutting across the whole sequence (Fig. 15b). According to a third hypothesis, the Money Complex would have been

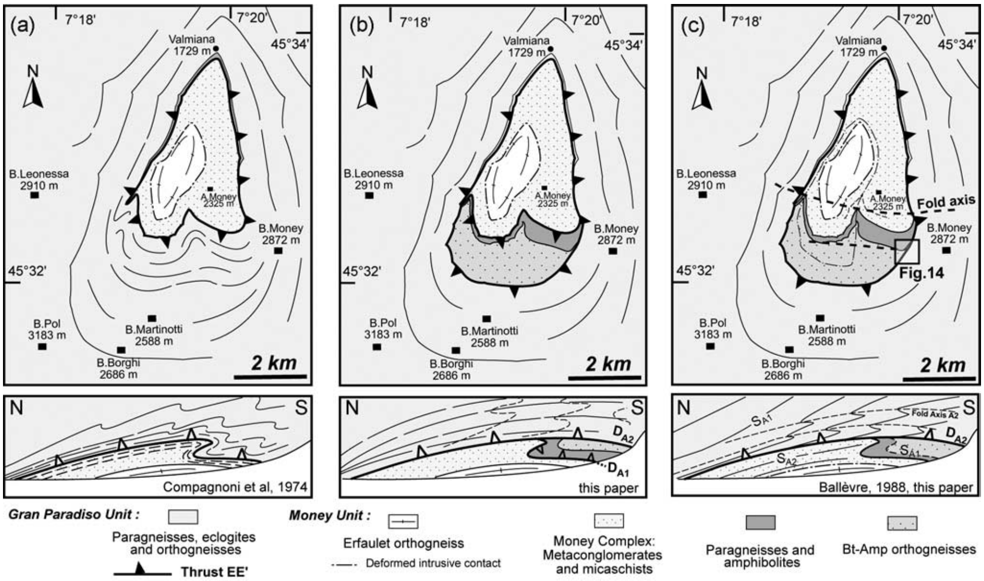

Fig. 15. Alternative models for explaining the structure of the Money Window. See text for details.

deposited on top of the paragneisses and amphibolites (Fig. 15c). Discriminating between hypotheses 2 and 3 is difficult. The spatial distribution of the metaconglomerates, which are preferentially found close to the paragneisses, would favour the third hypothesis.

## 5. Discussion

### *5.1. Kinematics of the Alpine deformation in the Gran Paradiso basement*

In summary, the deformation history of the Gran Paradiso during Alpine orogeny can be subdivided into three main episodes (Figs. 16 and 17).

A first eclogite facies event is only locally preserved in the Gran Paradiso Unit, either in mafic rocks that have not been deformed later or as a relic schistosity ($S_{A1}$) in some micaschists. The kinematics associated with this deformation ($D_{A1}$) is at best poorly defined. In the Gran Paradiso massif, eclogite-facies assemblages in mafic rocks display a N–S stretching lineation ($D_{A1}$), which is related to the burial stage of the continental basement. An eclogite-facies, N–S-trending, stretching lineation has been also reported in the eclogitic micaschists of the Sesia zone (Vuichard, 1986). Later studies have also revealed an early stage of top-north thrusting along the Penninic Fault (Ceriani et al., 2001; Ceriani and Schmid, 2004). The N–S deformation could be related either to the plate convergence direction at that time (Choukroune et al., 1986;

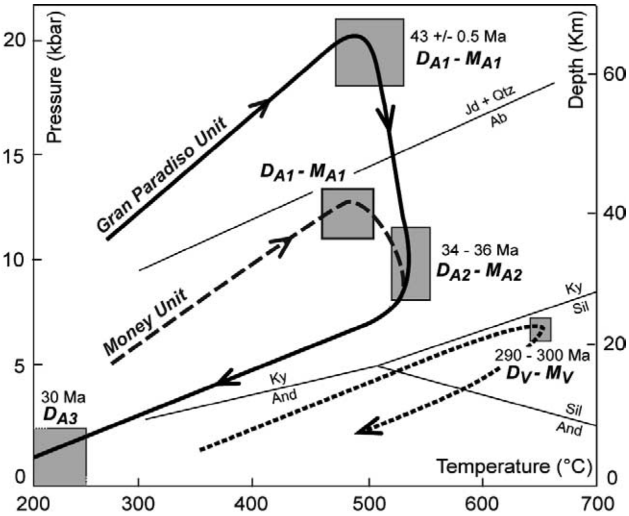

Fig. 16. Summary of the petrological data on the P–T–time evolution of the Gran Paradiso and Money Units (see text for sources of data). The Prealpine history results from cooling after a regional, amphibolite-facies, metamorphism (Le Bayon et al., submitted). Peak P–T conditions are higher in the Gran Paradiso Unit, where eclogite-facies relics are found, than in the Money Unit, where the earliest foliation ($S_{A1}$) developed in the albite stability field. Both Units were deformed together at epidote amphibolite facies conditions ($D_{A2}$) before final cooling and brittle deformation ($D_{A3}$). Geochronological data constraining the timing of the P–T path are taken from Meffan-Main et al. (2004) and Hurford and Hunziker (1989).

| | | Ages | Gran Paradiso Unit | Money Unit | Interpretation |
|---|---|---|---|---|---|
| Alpine collision history | $D_{A3}$ | 20-24 Ma FT apatite<br>30+/-1 Ma FT zircon | Late E-W trending normal faults with negligible or minor displacement | | |
| | $D_{A2}$ - $M_{A2}$ | 34-36 Ma Rb-Sr muscovite | Open folds with subhorizontal axial planes. E-W trending stretching lineation with top-to-the-West shear sense. Epidote amphibolite-facies conditions (P = 7-11 kbar, T = 520-540°C) | | Main phase of deformation, associated to westward shearing during duplication of the Gran Paradiso basement by several thrusts. |
| | $D_{A1}$ - $M_{A1}$ | 43+/-0.5 Ma Rb-Sr micas | Transposition of the sedimentary layering in monocyclic rocks and of the Prealpine fabric in polycyclic rocks. A few undeformed volumes. Eclogite-facies metamorphism ( P = 17-20 kbar, T = 500°C) | Transposition of the sedimentary layering in monocyclic rocks. Epidote amphibolite-facies metamorphism (P = 10-12 kbar, T = 500°C ?). | Décollement of the Mesozoic cover along the Triassic evaporites and burial of the continental basement in the subduction zone. |
| | | | Calcschists ( Lias)<br>Carbonates and evaporites (Triassic) | | Sedimentation in the palaeomargin |
| Pre-Alpine history | Dv - Mv | 270-300 Ma U-Pb zircon | Granitic intrusions (Herbetet, …) and associated hornfelses | Granitic intrusion (Erfaulet) | Variscan Orogeny |
| | | | | Money Complex (Permo-Carboniferous) | |
| | | | Regional metamorphism and associated deformation. Amphibolite metamorphism (P = 6 kbar, T = 650°C) | | |

Fig. 17. A summary of the deformation history of the Gran Paradiso massif. Sources of petrological and geochronological data are acknowledged in the text.

Platt et al., 1989) or, more plausibly, to a sinistrally transpressive collision (Schmid and Kissling, 2000).

The second and major deformation event took place in the epidote amphibolite facies (i.e. during albite growth). This $D_{A2}$ deformation is associated with a top-to-the-west sense of shear. Displacement along four major thrusts (AA′, BB′, CC′ and DD′) took place during this episode. This main deformation ($D_{A2}$) is characterized by a gently dipping foliation in the northern part of the area and a sub-horizontal foliation toward the south. This foliation, defining a broad regional dome structure of the Gran Paradiso massif, occurred in the epidote amphibolite facies ($M_{A2}$). Hence, this foliation ($S_{A2}$) is produced during a low-pressure metamorphic event, associated with the late exhumation stage of the eclogitic basement. Stretching lineations and fold axes associated with this deformation show an E–W trend. Stretching lineations, fold axes and sense of shear are consistent over the whole area studied here. A top-to-the-west sense of shear associated with the $D_{A2}$ deformation in the epidote amphibolite-facies, indicates a top-to-the-west displacement during the exhumation. Localization of the deformation close to the thrust contact between the Gran Paradiso and Money Units characterizes the waning stages of the $D_{A2}$ event.

Brittle, E–W-trending, normal faults cut across the entire nappe stack ($D_3$). The observed pattern of faulting indicates an overall N–S to NNE–SSW direction of extension, an observation consistent with data from nearby areas (Ring, 1994; Bistacchi et al., 2001; Champagnac et al., 2004). This faulting event has not been studied here in detail, because the amount of displacement along the faults is negligible and because it post-dates the main exhumation of the nappe stack.

### 5.2. Exhumation mechanism of the Gran Paradiso basement

Three main classes of models are able to explain the domal structure of the basement windows in the Western Alps.

The first model involves a large-scale fold nappe (‘Penninic fold’) (Argand, 1911; Debelmas and Kerckove, 1980; Vissers and Compagnoni, 1984; Schmid and Kissling, 2000; Schmid et al., 2004a), the domal structure resulting from post-nappe folding during further horizontal shortening. Although kilometre-scale isoclinal folds have been mapped in the course of this study in the Gran Paradiso massif, it has also been shown that they occur inside volumes bounded by major ductile shear zones cutting across the whole Gran Paradiso massif. These internal thrusts (named BB′, CC′ and DD′) duplicate the continental basement. Another major tectonic contact (EE′) separates the Money Unit and the overlying Gran Paradiso Unit. Therefore, we consider that the occurrence of mylonitic zones between the different subunits indicates that the domal structure of the Gran Paradiso does not simply result from post-nappe folding of an early, flat-lying fold.

According to a second model, the domal structure of the Gran Paradiso massif would result from an antiformal stack of thin (less than about 2 km) sheets of deformed Prealpine basement rocks. Such a model is consistent with the occurence of a growing collisional wedge with major ductile shear zones always displaying an E–W stretching lineation associated with a top-to-the-west sense of shear and therefore duplicating the Prealpine basement. These major shear zones would have been active during exhumation of the eclogite-facies continental basement of the Gran Paradiso massif. Some of the shear zones could potentially derive from extreme attenuation of the inverted limbs of former, flat-lying, isoclinal folds. In this sense, the second model would represent a more advanced stage of ductile deformation compared with the first model.

A third model, based on field observations in the south-western part of the Gran Paradiso massif, involves "vertical indentation of the high pressure units by the stacking of deep crustal slices, in front of the rigid Adriatic mantle back-stop, during continuous convergence" (Rolland et al., 2000). Early ductile structures (i.e. the flat-lying foliation and the associated E–W-trending stretching lineation) would have been due to vertical shortening, with opposite shear sense depending upon the foliation attitude. These early structures are overprinted by late, steeply-dipping, brittle, normal faults. A similar model has been invoked for explaining, late, brittle normal faults westward of the Dora–Maira massif (Tricart et al., 2004). In the area studied, we consider that the kinematics of the early, ductile, structures indicates top-to-the-west shearing and that the amount of displacement involved during the brittle stage is negligible. Rather than putting emphasis on the vertical displacement (Rolland et al., 2000), we consider it as a corollary effect of displacement along slightly-dipping thrusts, combined with erosion at the surface (and eventually extension at higher structural levels than those presently exposed in the Gran Paradiso massif). This would be consistent with field data from adjoining areas (Bucher et al., 2003; Reddy et al., 2003) and geometrical and numerical models of the Alpine belt (Escher and Beaumont, 1997; Pfiffner et al., 2000).

## 6. Conclusion

Integration of the structural, stratigraphical, petrological and geochronological data allows for a kinematic model to be presented (Fig. 18). The first cross-section shows the Alpine domain during the Paleocene (60–55 Ma), at a moment where subduction of the Austroalpine domain (i.e. the Sesia Zone) had already taken place (Fig. 18a). A narrow rift (i.e. the Valaisan rift) separates the European palaeomargin to the west and the Briançonnais microcontinent to the east. The Gran Paradiso basement is considered to have belonged to the ocean-facing part of the Briançonnais microcontinent. Plate convergence first resulted in the subduction of part of the Adriatic palaeomargin (the future Sesia zone), dated at about 65–70 Ma (Duchêne et al., 1997; Cortiana et al., 1998; Rubatto et al., 1999; Liermann et al., 2002). Erosion of the resulting mountain belt, which was located at the emplacement of the Southern Alps, is recorded in the deep-water sedimentation of the Upper Cretaceous–Palaeocene Helminthoid flysch (dotted area of Fig. 18a), deposited at the top of the oceanic (=pre-collisional) accretionnary wedge and now part of the nappe pile constituting the Prealpine klippen.

Continuing convergence led to final closure of the Piemont–Ligurian ocean, in the range of 50–40 Ma (Duchêne et al., 1997; Rubatto et al., 1998; Amato et al., 1999; Lapen et al., 2003), followed by subduction of the Briançonnais microcontinent, as recorded by peak P–T conditions in the internal part of this microcontinent. Indeed, the Gran Paradiso unit record P–T conditions of the order of 21–23 kbar and 540–570 °C (Vidal et al., 2001; Wei and Powell, 2003, 2004; Meffan-Main et al., 2004) or 17–20 kbar, 500 °C (Le Bayon et al., submitted). Recent data suggest a Middle Eocene age (40–45 Ma) for this high-pressure stage (Meffan-Main et al., 2004). Thus, the Gran Paradiso basement is subducted down to a depth of around 60–70 km (Fig. 18b). Even at such great depths, some volumes escaped the Alpine deformation and were left undeformed during the subsequent history. Consequently, these volumes record the Prealpine structures within the continental crust of the Briançonnais microcontinent (Figs. 5–7), despite having been submitted to eclogite-facies conditions. This second cross-section shows that the Money Unit was subducted at lower depths (around 40 km) than the Gran Paradiso Unit, because the high pressure metamorphic stage (stage 1) occurred at a lower pressure in the Money Unit than in the Gran Paradiso Unit (see above). Because the main décollement of the Mesozoic cover along the Triassic evaporites should have occurred at this stage, the Mesozoic cover escaped the Alpine metamorphism and was finally accreted at the front of the orogen (i.e. the Prealpine nappes). At the same time, the Prealpine basement of the Briançonnais microcontinent was subducted at great depth.

Further horizontal shortening led to thrusting of the Gran Paradiso basement over a more external part of the Briançonnais microcontinent, namely the Money Unit (Fig. 18c). Nappe stacking is associated with the main ductile deformation, characterized by a top-to-the-west sense of shear. It occurred at decreasing pressure conditions (down to about 5 kbar) and at about 34–39 Ma (Freeman et al., 1997; Meffan-Main et al., 2004). It is here suggested that thrusting of the Gran Paradiso basement was accompanied by a décollement at the boundary between the lower (predominantly granulitic) and upper (predominantly granitic) crust, explaining why only middle to upper crustal rocks are presently found in the Gran Paradiso basement.

At higher structural levels, the nappe stack is lately deformed by the classical E-verging backfolds or backthrusts ('pli en retour' of the Valsavarenche; Argand, 1911) (Fig. 18d), whose interpretation remains controversial. While backthrusting (i.e. steeply-dipping E-verging thrusts) is favoured by some

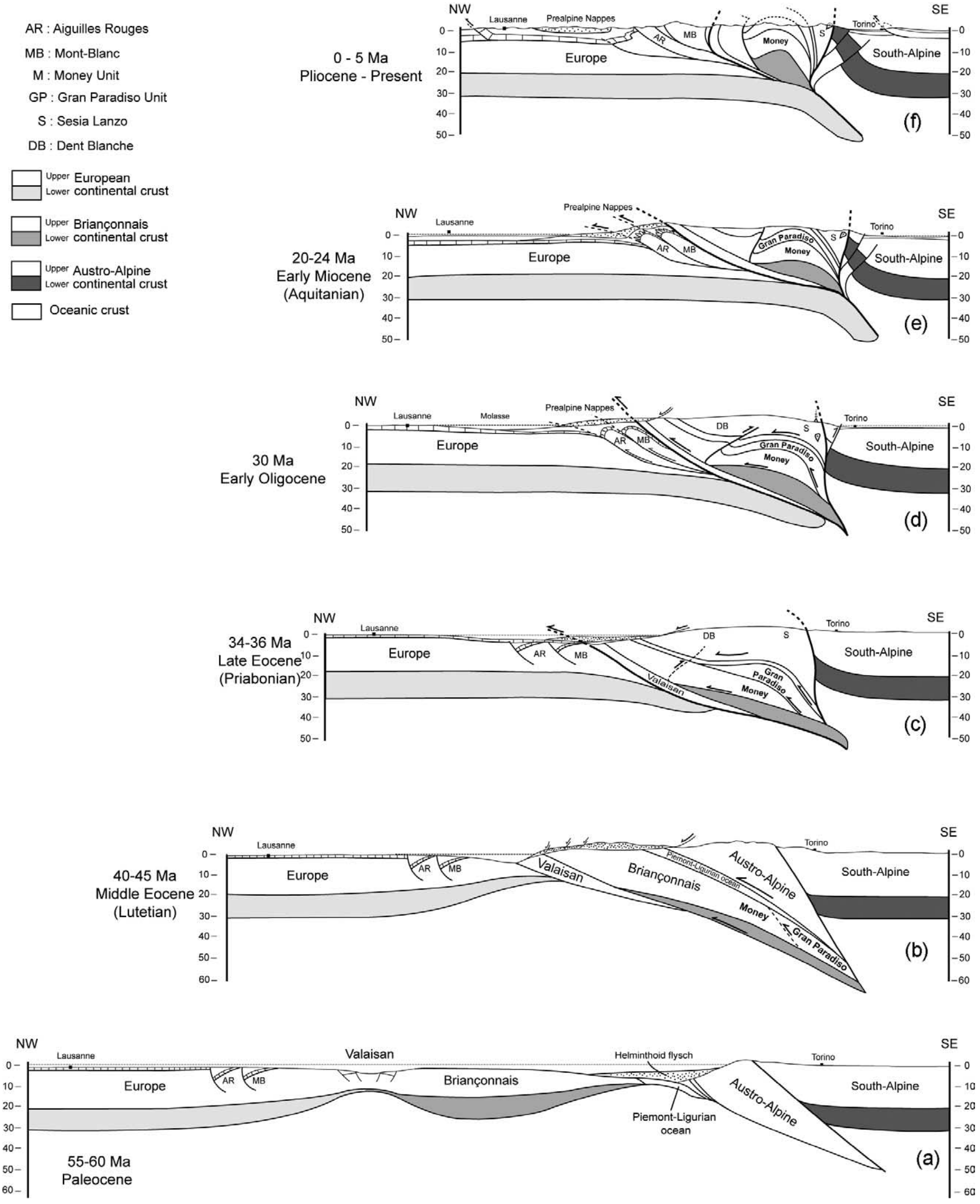

Fig. 18. Tectonic evolution of the Western Alps along a Lausanne–Torino traverse. The scheme emphasizes continuing crustal shortening during exhumation of the eclogite-facies Gran Paradiso massif.

authors (Ballèvre et al., 1986; Freeman et al., 1997), other authors argue that the earlier thrusts have been lately refolded by folds with subhorizontal axial planes (Bucher et al., 2003, 2004). Further constraints on the large-scale setting are provided by fission-track ages on zircon of around 30 Ma (Hurford and Hunziker, 1989), indicating that the Gran Paradiso was located at a depth of around 8 km during the Early Oligocene. The emplacement of a few granitoids along the Insubric Fault (Rosenberg, 2004), like the Biella and Traversella intrusions, dated at around 33 Ma, could have been triggered by slab breakoff (Von Blanckenburg and Davies, 1995).

From the Early Miocene onwards (Fig. 18e), the thrusts will continue to propagate towards the foreland of the Western Alps. Crustal shortening was still active, but the main displacement took place along thrusts located in the external zones, recorded by the inversion of the tilted blocks of the European palaeomargin (Mont Blanc, Aiguilles Rouges), e.g. Leloup et al., 2005) and the westward propagation of the foreland (flysch to molasse) basin (e.g. Sinclair, 1997) (Fig. 18e). Deformation in the internal zone is now dominated by E–W-trending, normal faults ($D_{A3}$). Displacement along these faults is negligible and cannot account for the main part of the exhumation history.

The Plio-Quaternary evolution is marked by the Jura displacement over the Bresse graben and by northwestward thrusting south of Torino, at the leading edge of the Apennine collision zone (Fig. 18f). This has allowed denudation of the Oligo-Miocene sequence of the Torino and Monferrato areas, which nicely preserves the sedimentary record of the erosion of the eclogite-facies units of the Western Alps (Polino et al., 1991).

Therefore, the antiformal doming of the Gran Paradiso basement was produced during crustal shortening, coeval with erosion-driven exhumation of the eclogite-facies continental basement, a conclusion consistent with earlier models (e.g. Dal Piaz, 1999; Schmid and Kissling, 2000).

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