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Tilting of the Bergell Pluton and Central Lepontine area: Combined evidence from paleomagnetic, structural and petrological data

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Key words: Alps, Bergell, Lepontine, steep belts, paleomagnetism, tectonics, tilting

ABSTRACT

Paleomagnetic data from two undeformed sites in the steep N-dipping tonalite tail of the Oligocene Bergell pluton indicate a mean natural remanent magnetization (NRM) with declination D = 303.5° and inclination I = 38°. Restoration of the measured NRM direction to the NRM direction of stable Europe in the Oligocene is achieved by three different rotations corresponding to three distinct post-crystallization deformation events.

1) 25° dextral rotation around a vertical axis in order to restore the sinistral block rotation suffered by each segment of the tonalite tail during dextral shearing along Insubric Riedel faults. 2) 20° dextral rotation (looking westward) around an horizontal E-W striking axis in order to restore the rotation suffered by the tonalite tail during backthrusting along the Insubric Line. 3) 11° sinistral rotation (looking northward) around an horizontal N-S striking axis in order to restore the effect of eastward tilting of the Bergell pluton.

The similar inclinations of the Oligocene NRM of stable Europe and that of the Bergell tonalite after rotation of only 20° around an E-W horizontal axis indicate that the Bergell tonalite tail was in a steep orientation at the time it passed through its solidus. Moreover, the concordant contact of the tonalite tail with the enclosing rocks of the Southern Steep Belt of the Central Alps implies that the Southern Steep Belt already existed when the tonalite tail reached its solidus. It is suggested that vertical uplift of the western Lepontine induced eastward tilting of the Central Lepontine area. This rotation around a N-S striking horizontal axis explains deviation of paleomagnetic directions (Heller 1980) from the orientation of stable Europe in the Oligocene.

RIASSUNTO

Dati paleomagnetici misurati nella coda tonalitica del plutone oligocenico di Masino-Bregaglia evidenziano una magnetizzazione naturale rimanente (NRM) con declinazione D = 303.5° e inclinazione I = 38°. Questa orientazione può venire riportata a quella della NRM dell'Europa nell'Oligocene grazie a tre distinte rotazioni, ciascuna delle quali corrisponde a una fase deformativa post-intrusiva.

1) Una rotazione destrale di 25° attorno ad un asse verticale per restaurare la rotazione sinistrale subita da ogni segmento della coda tonalitica compreso fra due faglie di Riedel Insubriche. 2) Una rotazione destrale (guardando verso W) di 20° attorno a un asse orizzontale con direzione E-W per restaurare la rotazione subita dalla tonalite durante il retrocarreggiamento lungo la Linea Insubrica. 3) Una rotazione sinistrale (guardando verso N) di 11° attorno a un asse orizzontale con direzione N-S, per restaurare il basculamento verso E subito dal plutone.

L'inclinazione della NRM oligocenica dell'Europa è molto simile a quella della tonalite del Bregaglia ruotata di soli 20° attorno a un asse orizzontale con direzione E-W. Di conseguenza, quando il plutone raggiunse il solidus, la coda tonalitica del Bregaglia si trovava già in una posizione verticale. Inoltre, essendo il contatto della coda tonalitica concordante con le rocce incassanti della "Southern Steep Belt" delle Alpi Centrali, se ne deduce che quest'ultima doveva già esseresi formata quando la tonalite raggiunse il solidus. Si ritiene che il sollevamento verticale del Lepontino occidentale abbia causato il basculamento verso E del Lepontino centrale. Questa rotazione attorno a un asse orizzontale con direzione N-S spiega la deviazione delle direzioni paleomagnetiche del Lepontino centrale (Heller 1980) rispetto alla direzione dell'Europa nell'Oligocene.

1. Introduction

Paleomagnetic data are an important tool for the recognition of past block rotations, allowing reconstruction of the tectonic history of a particular domain (e. g. Sonder et al. 1994). However, restoration of the measured paleomagnetic directions is rarely unequivocal, because different rotations around variously oriented axes may lead to the same final orientation of a measured NRM direction. In order to constrain the orientation of the rotation axes and the angles of rotation during the Oligo-Miocene deformation history of the Bergell area (Central Alps), this study combines information from structurally-oriented field work (Fumasoli 1974; Berger et al. 1996), petrological and geochronological data (Reusser 1987; Villa & von Blankenburg 1991; Davidson et al. 1996; Oberli et al. 1996) with new paleomagnetic data. After reconstruction of tilting in the Bergell area, previous paleomagnetic data of the Central Lepontine area (Heller 1980) are reinterpreted in the light of the tectonic scenario developed for the Bergell pluton. This leads to a new tectonic model for the uplift and exhumation of the Lepontine dome in the Miocene.

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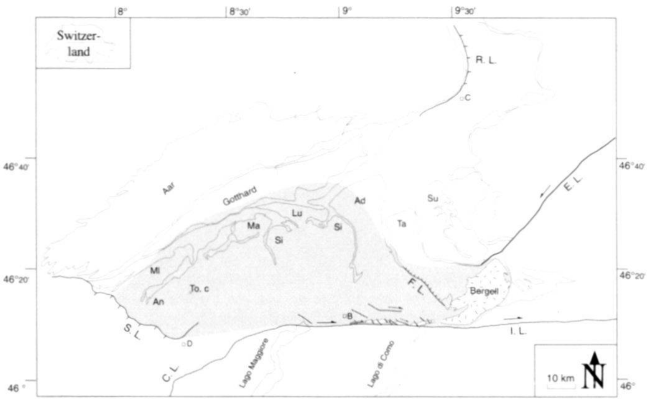


Fig. 1. Simplified tectonic map of the Lepontine area (shadowed), modified from Bigi et al. (1990). Nappe abbreviations used: Ad., Adula; An., Antigorio; Lu., Lucomagno; Ma., Maggia; Ml., Monte Leone; Si., Simano; Su., Suretta; Ta., Tambo; To. c., Toce culmination.
C.L., Canavese Line; E.L., Engadine Line; F.L., Forcola Line; I.L., Insubric Line; R.L., Rhine Line; S.L., Simplon Line. B., Bellinzona; C., Chur; D., Domodossola.

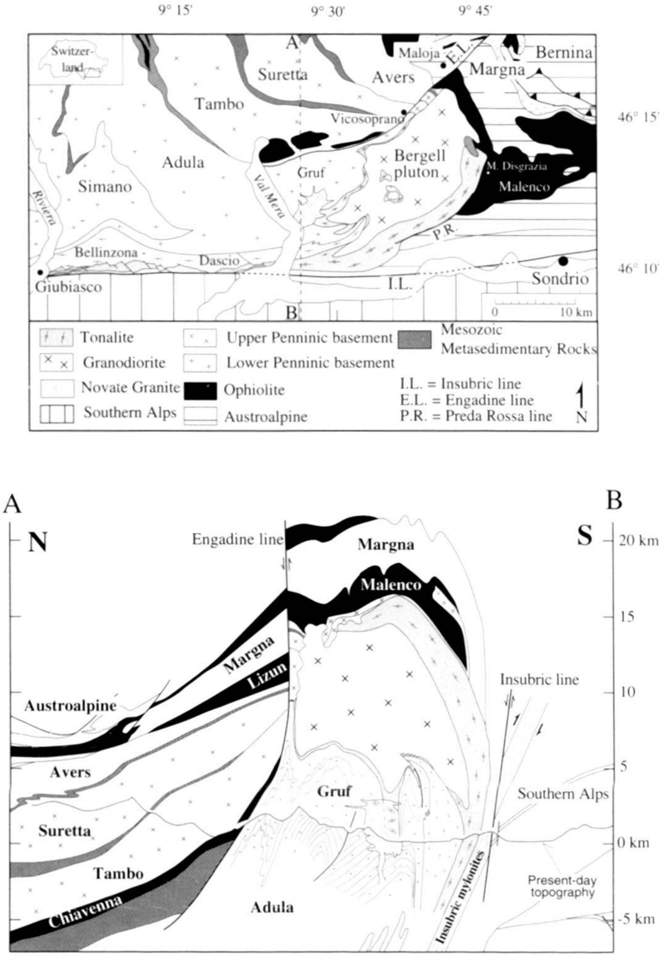


Fig. 2a. Geologic map of the Bergell area, modified from Rosenberg et al. (1995).
2b. N–S cross section of the Bergell pluton, modified from Rosenberg et al. (1995). Profile trace is shown in Fig. 2a as dashed line.

2 Geologic setting

The Lepontine area (Fig. 1) is characterized by a dome shape, in which the domed nappe pile can be compared to a sliced onion (Merle et al. 1989). This dome shape approximately coincides with a concentric zonation pattern of the metamorphic isogrades (Niggli 1970), which are discordant with respect to the nappe boundaries (Bearth 1958). In more detail the Lepontine dome is subdivided into two subdomes (Merle et al. 1989), both confined to the north and to the south by two east-west striking steep belts (Milnes 1974). The Northern Steep Belt is only pronounced in the western half of the Lepontine area, whereas the Southern Steep Belt can be followed along the whole southern border of the Lepontine.

The development of both steep belts is generally considered to postdate the main deformation and metamorphic events of the Lepontine dome (Milnes 1974; Merle et al. 1989). Merle et al. (1989) consider the formation of the Southern Steep Belt to be coeval with backthrusting of the Penninic nappes, which would have occurred between 25 and 20 Ma. Hurford (1986) and Hurford et al. (1989) calculated rapid cooling between 23 Ma and 16 Ma along the Southern Steep Belt, and suggested that it could result from backthrusting along the Insubric Line. Considering that the beginning of exhumation due to Neoalpine deformation probably predates the onset of rapid cooling (e. g. Werner 1980), Hurford (1986) tentatively bracketed the age of backthrusting between 25 and 30 Ma.

The Bergell pluton (Figs. 1 and 2a) is located at the eastern margin of the Lepontine. Purely geometrically speaking, it is a nappe (Wenk 1973) with a steep tonalitic root zone in its southern part (Fig. 2b) and a flat lying, nearly concentrically zoned body towards the north. The root of the pluton, being part of the Southern Steep Belt is an east-west striking, steeply north-dipping tabular body of tonalite, considered to be the feeder of the pluton (Rosenberg et al. 1995).

The main body of the pluton intruded into greenschist facies enclosing rocks along its eastern border (Trommsdorff & Evans 1976) and amphibolite to granulite facies rocks along its western contact. This westward increase in metamorphic grade is accompanied by an increase in pressure: Reusser (1987) and Davidson et al. (1996) showed that the pressure of crystallization of the Bergell tonalite gradually increases from the East (ca. 5 kb) to the West (ca. 8 kb) of the pluton, implying that the western side of the pluton represents a deeper tectonic level than the eastern side, as already observed by Cornelius (1915) and Staub (1918). This difference of approximately 3 kb is consistent with a previous estimate based on geological

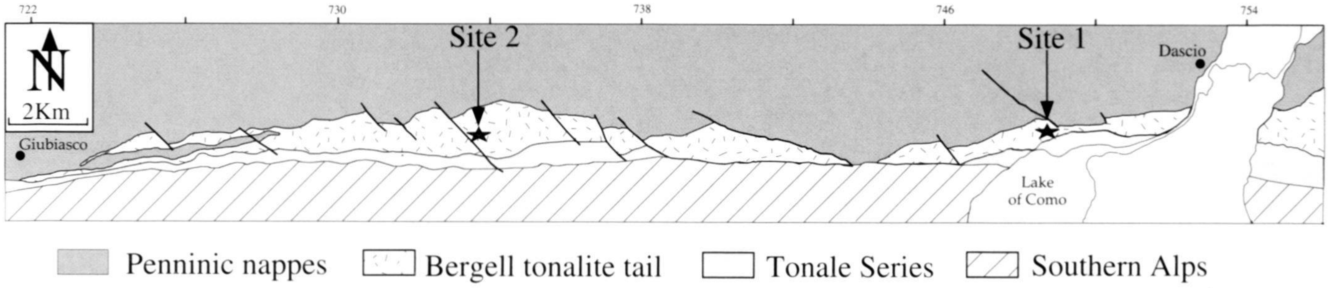


Fig. 3. Geologic map of the "tonalite tail" of the Bergell pluton, with site locations.

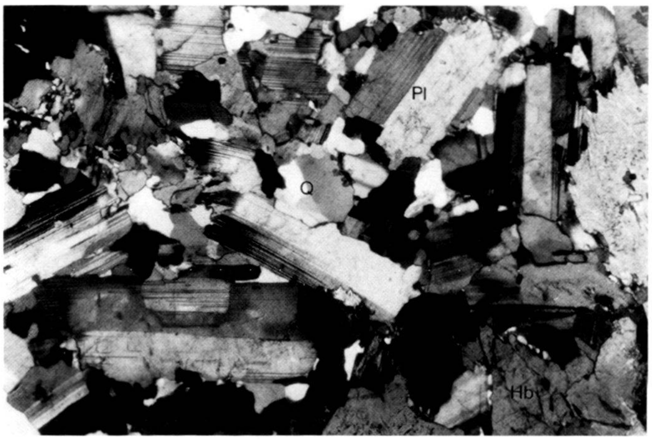


Fig. 4. Thin section of tonalite from Site 2. Longer sides of picture are 5 mm. No shape preferred orientation nor plastic deformation are present within this sample. Q: quartz, Hb: hornblende, Pl: plagioclase.

observations. In fact, Trommsdorff & Nievergelt (1983) suggested that the nappe pile intruded by the pluton had an original thickness of 10 km, estimated between its easternmost and westernmost margins. Reusser (1987) interpreted this westward pressure increase as the result of post-intrusive tilting.

3 Paleomagnetic data

3.1 Site location and description

Samples for paleomagnetic measurements were collected from the tonalite tail of the Bergell Pluton. The very intense deformation of the Bergell tail (Vogler & Voll 1976; Berger et al. 1996) transformed most of the tonalite into a high-temperature mylonite (Rosenberg 1996). Undeformed samples appropriate for NRM measurements are thus very rare. Only two sites (see Fig. 3 for location) were found where fully undeformed tonalite bodies are still preserved within the mylonites. These tonalites are not foliated, and mafic enclaves which are present in one of the sampled outcrops do not show any significant deformation.

Thin sections of these tonalite samples show randomly oriented euhedral grains of plagioclase, hornblende and biotite, with interstitial spaces filled by quartz (Fig. 4). No evidence of internal deformation is shown by these grains (Fig. 4), indicating that they did not undergo any solid state deformation.

The tonalite from site 1 covers an area of approximately 1 square metre while that of site 2 occupies approximately 10 square metres. Five cylindrical core samples 2.5 cm in diameter were collected from site 1 and 6 from site 2.

3.2 Natural remanent magnetization (NRM)

Mainly thermal, but also alternating field (AF) demagnetization, was used to isolate stable NRM directions (Fig. 5 and 6).

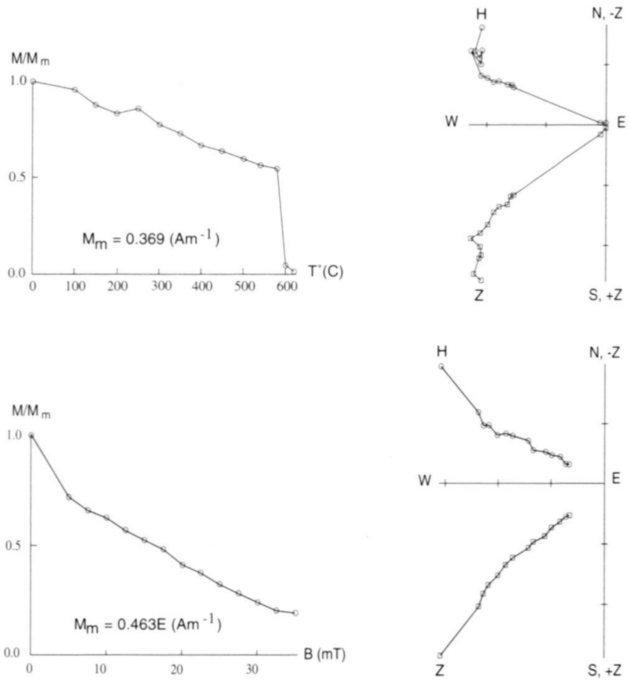


Fig. 5. Sample K2 (site 1). Thermal demagnetization (top figures) of sample K2b with northwesterly (H) and downwards (Z) directed characteristic NRM component and AF demagnetization of sample K2c (bottom figures). Demagnetization is in milliteslas (mT) and degrees Celsius.

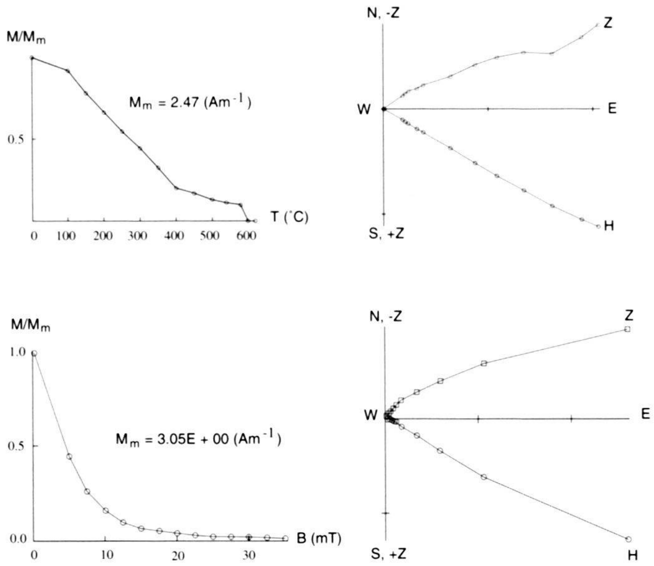


Fig. 6. Sample S1 (site 2). Thermal demagnetization (top figures) of sample S1b with southeasterly (H) and upwards (Z) directed NRM and AF demagnetization of sample S1c (bottom figures). Demagnetization is in milliteslas (mT) and degrees Celsius.

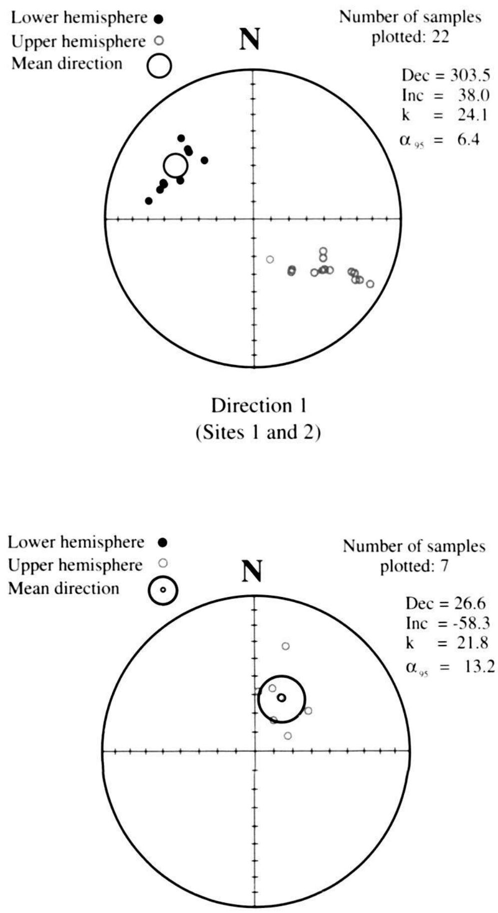


Fig. 7. Stereographic projection of stable NRM directions. Dec, Inc, k, and α_{95} denote mean declination, inclination, Fisher's (1953) dispersion parameter and the 95% confidence angle, respectively. Top figure shows direction 1 from all measured samples (site 1 and site 2). Bottom figure shows direction 2, which was only found in samples from site 2. Both mean directions are plotted on the upper hemisphere of projection.

The thermal behaviour during demagnetization is often characterized by a smooth intensity decay up to ca. 580°C. The intensity is lost suddenly at 600°C suggesting that impure, probably titaniferous hematite is carrying this part of the NRM. Since AF demagnetization demonstrates contributions from a low coercivity mineral, the presence of magnetite is indicated, which carries similar NRM directions to that of the "hematite" (Fig. 6), but also deviating directional components, for instance along the present-day field (Fig. 5) or in directions which are difficult to interprete. The magnetic mineralogy seems to closely resemble that observed in the main granodiorite body within the Bergell Pluton (Heller 1972).

Two characteristic and stable main directions were observed in the two sites from the tonalite tail of the Bergell Pluton (Fig. 7). Direction 1 occurs at both sites in normal and reversed polarity with a normal NW mean direction (303.5/38). It is observed in all 22 specimens measured. Direction 2 occurs less frequently, only within the samples of site 2, but sometimes even above 580°C. It has a NNE, steeply upwards plunging direction (28/-58).

3.3 Age of the measured NRM directions

A geological interpretation of the NRM directions can only be achieved if the age of magnetization is also known. Therefore, the stable NRM directions must be correlated with mineral ages measured for the same rocks. The age of a mineral whose closing temperature is nearest to the highest demagnetization temperature (maximum unblocking temperature) of the measured stable NRM direction, may be chosen for this correlation.

Mineral ages have not been directly measured on the samples collected for the paleomagnetic study. However, Ar-Ar hornblende ages and K-Ar biotite ages from tonalites sampled along an east-west traverse in the Bergell tonalite tail were measured by Villa & von Blankenburg (1991). Their sample location IORIO2 corresponds to Site 2 of this study, and their sample SOR1 is very close to Site 1 of this study (Fig. 8). Mineral ages of samples SOR1 and IORIO2 should be a good approximation for the mineral ages of Site 1 and Site 2, respectively.

Closing temperatures for hornblende and biotite are around 550°C and 330°C respectively (Hunziker et al. 1992 and references therein). Therefore, Ar-Ar ages of hornblende are appropriate to define the age of magnetization of direction 1.

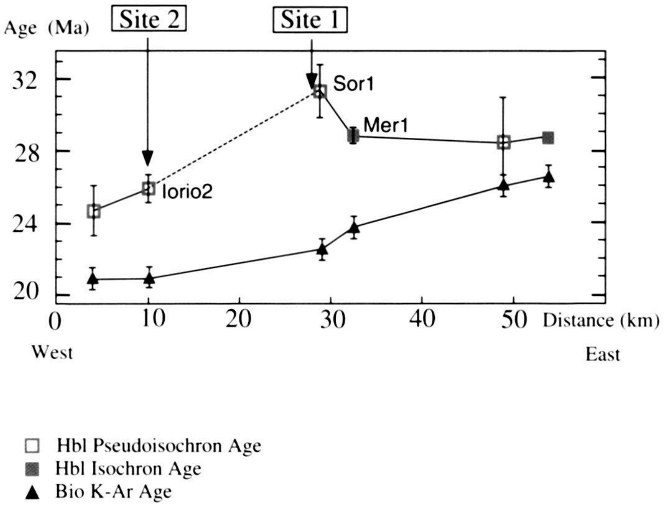


Fig. 8. East-west traverse of Ar-Ar hornblende and K-Ar biotite ages across the Bergell pluton, from Villa & von Blankenburg 1991. Arrows indicate localities sampled for this study.

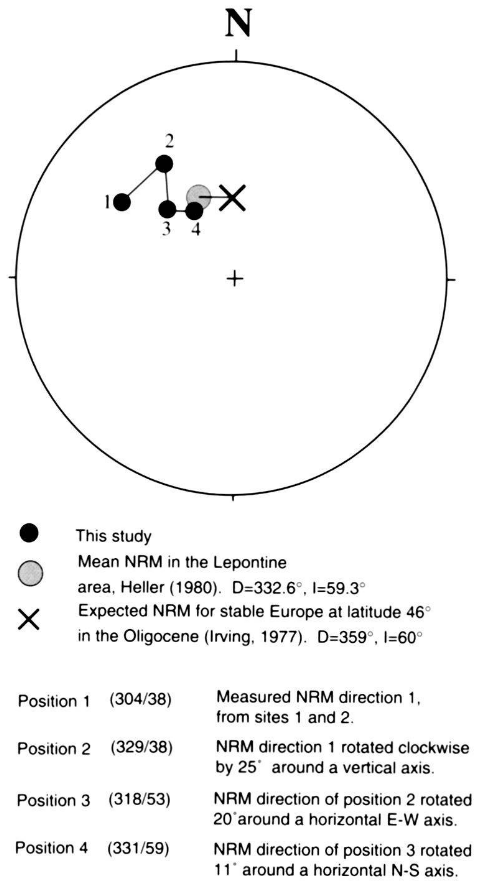


Fig. 9. Restoration of the measured NRM Direction 1 (lower hemisphere).

Because the highest temperature in the demagnetization curve of direction 1 (Figs. 5 and 6) is approximately 580°C (i.e. slightly above the closing temperature for hornblende), hornblende ages will give a minimum age for magnetization of direction 1.

As shown in Figure 8 the hornblende ages are 26 Ma and 31 Ma for IORIO2 and SOR1, respectively. Since the data for SOR1 are not well defined (see Villa & von Blankenburg 1991, for discussion), we refer to the age measured from sample MER1 which is located 4.5 km to the east of. Site 1 of this study (Fig. 8). Hence, we consider the age of 29 Ma obtained for MER1 as the age of magnetization of our stable direction 1 at Site 1.

4 Restoration of paleomagnetic data

The orientation of the characteristic NRM directions plotted in Figure 7 should reflect the orientation of the magnetic field at the time of magnetization, modified by any post-magnetization rotation due to regional deformation. These post-intrusive rotations need to be removed in order to restore the measured directions to the direction of the geomagnetic field at the time of crystallization of the Bergell tonalite.

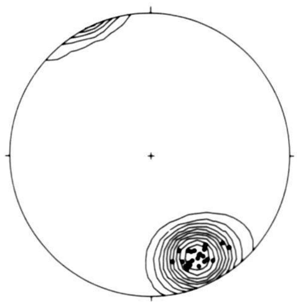
The following sections deal with the post-intrusive deformation events that affected the Southern Steep Zone and with the estimated rotations caused by deformation. The tonalite tail is tentatively "retrodeformed", proceeding from younger to older deformation events. In this way the NRM direction is rotated back to the orientation it had at the time the hornblende cooled through their closing temperature.

Three stages of deformation events can be recognized: a first (and youngest) rotation due to dextral Insubric Riedel faults, followed by a rotation due to Insubric backthrusting and finally a rotation due to eastward tilting. However, it is suggested that the last two stages operated contemporaneously, i. e. the eastward tilting is a consequence of eastward decrease in backthrusting (Schmid et al. 1989). The separation into two different rotations simplifies restoration of the NRM direction.

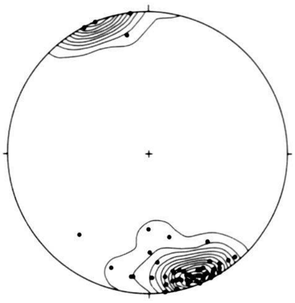
As discussed above, alternating field and thermal demagnetization has established the existence of two different NRM directions (Fig. 7), but only one of them (direction 1 of Fig. 7) is present in both sampling sites. For the sake of clarity, the following paragraphs first discuss the restoration of direction 1 without considering direction 2, whilst the significance of the latter direction is discussed at the end of this section.

4.1 Riedel faults along the Insubric Line

The youngest deformation which affected the tonalite tail is evidenced by dextral Riedel faults related to brittle dextral movements along the Insubric Line (Fumasoli 1974; Fig. 1 and 2). These faults dissect the tail of the Bergell pluton, causing an east-west extension of the tail and a sinistral block rotation of



a) 23 Data. Contoured at 1, 3, 5, ... 10 times uniform.
Max. 335/68



b) 52 Data. Contoured at 1, 3, 5, ... 12 times uniform.
Max 339/83

Fig. 10. Stereographic projections (lower hemisphere) showing contoured poles to foliation planes in the tonalite (top figure) and in the northern Zone of Bellinzona-Dascio (bottom figure).

the segments bounded by adjacent pairs of Riedel faults. The rotation axis of the single "blocks" may be assumed to be vertical, because the Riedels are steeply-dipping and contain sub-horizontal striations (Fumasoli 1974). The rotation angle corresponds to the angle between the strike of the present-day northern contact of the tonalite and the strike of the Insubric Line, which is exactly east-west. This angle is approximately 25°, although it varies in the different "blocks".

Thus, 25° clockwise back-rotation brings the NRM direction 1 from its normal polarity direction 304/38 (Fig. 7) into a NNW direction (329/38), as shown by position 2 in Figure 9.

4.2 Tilting around an east-west horizontal axis, along the Insubric Mylonitic Belt

NRM vector 1, once restored for the sinistral rotation due to the Riedel faults, is less inclined by about 20° than expected for an Oligocene site at latitude 46° N belonging to stable Europe (Fig. 9). This angular difference of 20° corresponds approximately to the angle between the steep north-dipping foliation within the tonalite (which is parallel to the northern tonalite contact), and the almost vertical foliation occurring in the northern part of the Zone of Bellinzona-Dascio (Fig. 10).

Shear sense indicators from the steep north-dipping foliation within the Bergell tonalite indicate N-side-up displacements, related to backthrusting of the Penninic nappes (Fisch 1989; Berger et al. 1996) which postdates a phase of vertical extrusion (Merle 1994; Berger et al. 1996). Continuous northward indentation (Schmid et al. 1996) causes vertical extrusion, which gradually passes into backthrusting. The 20° rotation of the NRM direction is therefore interpreted to result from drag caused by backthrusting along the Insubric Mylonitic Belt.

In order to restore the inclination of NRM direction 1 to that of stable Europe in the Oligocene, a sinistral (looking eastward) rotation of 20° around an east-west striking horizontal axis has been made (Fig. 9). This brings NRM direction 1 into the orientation 318/53.

4.3 Tilting around a N-S horizontal axis

Post-crystallization tilting of the Bergell Pluton was first suggested by Reusser (1987) in order to explain the east-west pressure gradient observed along the southern and southeastern margin of the pluton, with increasingly higher crystallization pressures towards the west. This interpretation was supported by Villa & von Blankenburg (1991) to explain the progressively younger biotite ages found towards the west, and by Rosenberg et al. (1994) and Rosenberg (1996) to explain the westward increase in the temperature of deformation of the tonalite mylonites generated during backthrusting of the Penninic nappes.

Davidson et al. (1996) showed that the westward pressure increase is not restricted to the tonalite tail, but also occurs further north within the main body of the Bergell pluton. Therefore, tilting must have affected the entire Bergell area.

Alternatively to tilting of a large rigid block (the eastern Lepontine, or even the whole Lepontine plus the Bergell pluton), a series of discrete north-south striking faults with west-side-up shear sense can be envisaged. Faults showing this geometry and kinematics in the Bergell area are top-to-the east normal faults (Turba Mylonite Zone, Nievergelt et al. 1996; Forcola Line, Weber 1966). The Turba Mylonite Zone predates the Bergell intrusion, and therefore only the Forcola Line could explain the westward pressure increase within the Bergell pluton. However, as a single fault cannot explain the gradual character of the pressure increase, eastward tilting of the Bergell pluton provides the best explanation.

4.4 Estimate of the angle of eastward tilting

Reusser (1987) estimated an angle of tilting of 10° by transforming the measured pressure data into depths and plotting them against the present day east-west distance between the sampled localities. This angle is in good agreement with the depth estimates based upon geological arguments (Trommsdorff & Nievergelt 1983). However, Davidson et al. (1996)

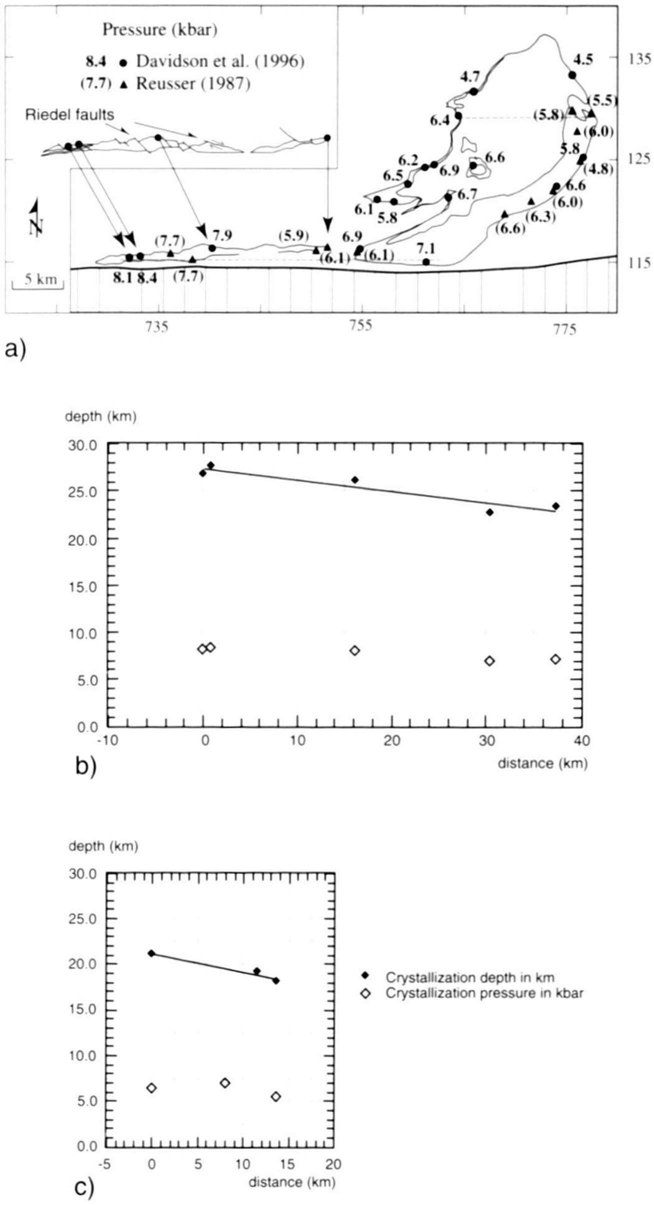


Fig. 11. (a) Regional distribution of the pressure of crystallization within the Bergell pluton, calculated from Al-in-hornblende geobarometry, modified from Davidson et al. (1996). Dashed lines indicate traces of E-W profiles of Figs. 11b and 11c. (b) E-W pressure gradients along the tonalite tail. (c) E-W pressure gradients within the main body of the pluton.

have shown that the crystallization pressure in the Bergell tonalite increases westward as well as northward (Fig. 11a). Therefore, samples selected to calculate the angle of tilting must be collected from the same latitude within the pluton. The following assumptions and considerations about the present-day geometry of the tonalite body have been taken into account in order to tentatively estimate the angle of tilting.

(1) Pressures have been normalized to the same topographic height (Davidson et al. 1996).

(2) The present-day east-west exposure of the Bergell tonalite tail has been shortened (Davidson et al. 1996; Fig. 11a), because post-intrusive Insubric Riedel faults caused approximately 13% east-west stretching. The restored east-west length of the tonalite tail is 45 km instead of the present-day 51 km.

(3) The geometry of the tonalite tail during crystallization must be defined before evaluating the angle of tilting from the pressure data. If crystallization of the tonalite took place while the tail was in a gently south-dipping orientation and the steep geometry resulted from post-intrusive deformation, the angle of tilting needed to generate a 1 kb east-west pressure difference would be much greater than if the tonalite had crystallized in a steep position. This suggests that the pressure gradient of the tonalite tail alone cannot be used to infer the rotation angle of the tail, nor its geometry at the time of crystallization.

(4) Tilting sensu stricto refers to the passive rotation of a rigid body. This is certainly not the case for the Bergell tonalite tail which is internally strongly deformed (Vogler & Voll 1976). Therefore, the pressure difference recorded along an east-west traverse through the tonalite tail, might give information on the differential vertical displacements, rather than tilting in the strict sense. As shown in Figure 11b, the angle calculated from the geobarometry data in the tonalite tail amounts to less than 7° (assuming crystallization took place as the tonalite tail was vertical).

A better constraint on the angle of tilting may be taken from the east-west pressure gradient present in the central part of the main body of the pluton (Fig. 11a). This area is more appropriate because post-intrusive deformation is only weak or absent (Davidson et al. 1996), Riedel faults do not occur, and finally post-crystallization tilting around an east-west horizontal axis (backthrusting) did not affect this part of the pluton. The resulting angle corresponds to an angle of tilting of approximately 11° (Fig. 11c).

(5) The last point to be considered is that emplacement of the tonalite in the west took place into country rocks under amphibolite to granulite facies conditions. As a consequence, melt-crystallization must be slower compared to the east, where the country rocks were at greenschist facies conditions. Therefore, the pressure recorded at the solidus of the tonalite by the Al-in-hornblende geobarometer has a younger age in the west than in the east. Since uplifting (backthrusting and vertical extrusion) of the pluton along the Insubric Line is synmagmatic (Rosenberg et al. 1995), pressure continuously decreases with ongoing crystallization. Hence, "solidus-pressures" measured in the western tonalite are lower than the pressures which prevailed in these rocks while the eastern tonalite reached its solidus. As a consequence, the angle of tilting calculated from the east-west pressure gradient within the tonalite is only a minimum estimate.

Restoration of NRM direction 1 by a sinistral (looking northwards) rotation of 11° around a north-south horizontal axis brings the NRM vector to the orientation 331/59 (position 4 in Fig. 9). Considering that the estimated angle of 11° eastward tilting was a minimum value and taking into account the analytical error (Fig. 7), the restored NRM direction is in good agreement with the Oligocene NRM direction of stable Europe (Fig. 9).

Changing the sequence of rotations leads to a slightly different result. If the rotation of 20° around an E-W horizontal axis is applied to the NRM orientation after rotation of 11° around a N-S striking horizontal axis, the final orientation is 324/61 instead of 331/59.

4.5 Restoration of NRM direction 2

NRM direction 2 (28/-58; Fig. 7) which is nearly 180° off the expected stable Europe Oligocene directions has only been detected within samples from site 1 and at demagnetization temperatures above 580°C. As it can be imagined from Figure 9, the 3 rotations required to restore NRM direction 1 bring the declination of direction 2 to an angle of approximately 150° off the Oligocene NRM direction of stable Europe. A further dextral rotation of more than 150° around a vertical axis is needed to restore NRM direction 2. None of the available structural data allows us to integrate these rotations into a tectonic scenario. Moreover, direction 2 is present only in one of the two studied sites, and the paucity of the available data (see Fig. 7) makes any interpretation of this second direction very speculative and doubtful.

5 Discussion

5.1 The Bergell area

5.1.1 Southern Steep Zone

Retrodeformation of the Bergell tonalite tail has shown that a rotation of less than 20° around an east-west horizontal axis is sufficient to restore the present-day inclination of the characteristic NRM mean direction to the Oligocene orientation of stable Europe at latitude 46°N. This rotation brings the Bergell root zone from its current north-dipping geometry into a vertical position (rotation from position 2 to position 3 in Fig. 9).

Since the NRM direction is at least 29 Ma old (see section 3.3), the 20° rotation away from the vertical position is younger than 29 Ma. Oberli et al. (1996) showed that the westernmost part of the tonalite tail reached the solidus only at 28 Ma. Therefore, the vertical orientation of the tonalite tail predates final crystallization of the tonalite in the western part and vertical extrusion is synmagmatic with respect to the Bergell tonalite. Because the magmatic foliation in the tonalite tail is parallel to the foliation in the country rocks north of the tonalite (Berger et al. 1996), the formation of the Southern Steep Zone of the Lepontine likely predates full crystallization of the Bergell tonalite tail.

The rotation of 20° from a vertical to a north-dipping orientation of the tonalite tail is younger than 29 Ma. This suggests that backthrusting along a north-dipping shear zone postdates final crystallization (and also the highest demagnetization temperature of the samples measured for this study, i.e. 580°C) which took place as a result of vertical extrusion.

5.1.2 Eastward tilting

Rotation of the Bergell NRM direction around a horizontal N-S axis by 11° (as calculated from the Al-in-hornblende geobarometer), brings the measured NRM declination closer to the Oligocene field direction in stable Europe (Fig. 9), thus supporting the geological and petrological evidence for eastward tilting. The declination of the restored direction (position 4 in Fig. 9) is still quite far from that of stable Europe, but the applied rotation of 11° is a minimum estimate only. Moreover, the errors involved in each step accumulate by the time this third restoration is applied.

A NE-SW structural cross section through the Bergell pluton indicates a general easterly dip of structures, with an angle of approximately 25° (Berger & Gieré 1995). The angle of tilting estimated from the crystallization pressures in the tonalite is lower. Hence it is assumed that part of the east-dipping angle (14°) predates final crystallization of the Bergell tonalite.

5.1.3 Timing of eastward tilting

As stated earlier, tilting in the Bergell area is a long-lasting process which starts before final crystallization of the tonalite and continues after the tonalite has reached its solidus. Only this latter part of the tilting is "recorded" by the NRM in the tonalite. The following discussion only concerns the age of that part of the tilting which postdates final crystallization of the Bergell tonalite.

Villa & von Blankenburg (1991) argued that apatite fission track data (Wagner et al. 1977), corrected for the sampling elevation yield similar ages of 13 Ma all along an east-west traverse in the Bergell area, implying that tilting stopped before 13 Ma.

An age limit for the onset of post-crystallization tilting is difficult to define. The westward younging of the biotite ages (Villa & von Blankenburg 1991; Fig. 8) may be interpreted as evidence for ongoing tilting. The oldest K-Ar biotite age in the eastern Bergell tonalite is 25.5 Ma and the youngest biotite age in the western tonalite is 21.5 Ma. Considering the time delay between uplift and cooling (Werner 1980; Hurford 1986), tilting in the Bergell tonalite tail may be tentatively constrained between 29.5 and 25.5 Ma.

5.2 Central Lepontine Area

NRM directions from the Central Lepontine area and the northern Bergell Pluton (Heller 1980; Figs. 9 and 12) show a consistent NNW down-dipping direction, with a mean value of D = 332.6° and I = 59.3°. This direction differs from that of stable Europe in the Oligo-Miocene and from that to the north of the Lepontine area in the Aar Massif (Heller 1980; Fig. 12).

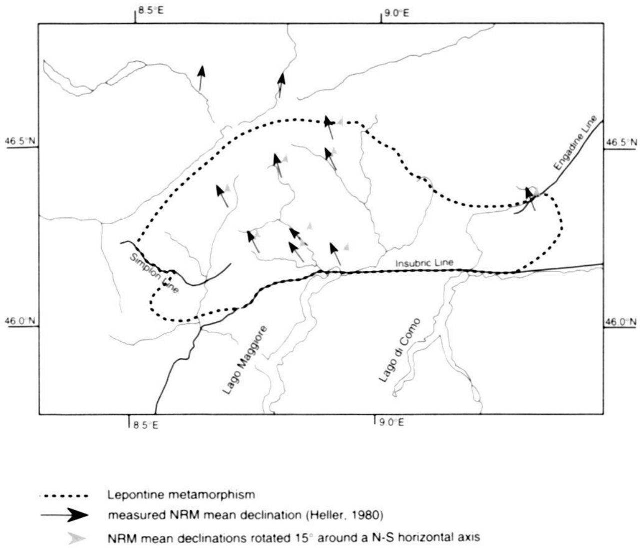


Fig. 12. Map of the Lepontine area (Modified from Heller 1980) showing the regional distribution of the NRM direction and the restored orientation of the NRM after rotation of 15° about a N-S horizontal axis.

If a rotation of 15° around a N-S striking axis is applied to these data, the resulting mean vector acquires an orientation (D = 360°, I = 63°) which corresponds almost exactly to the Oligocene NRM of stable Europe in this region (Figs. 9 and 12). This suggests that eastward tilting might not only have affected the Bergell area, but the Central Lepontine area as well. Moreover, an east-west-cross section through the Lepontine (Steck & Hunziker 1994) indicates that the Lepontine dome is asymmetric, dominated by east-dipping structures from the Bergell Pluton to the "Toce culmination" (Fig. 1), i.e. west-dipping foliations are restricted to the region adjacent to the Simplon fault zone. The same asymmetry is shown by the isobars of the Lepontine area (Engi et al. 1995) which exhibit eastward decreasing pressures.

The deformation history of the Lepontine is very complex, and the superposition of different deformation phases can still be recognized in the field (e.g. Milnes 1974; Grujic & Mancktelow 1996). However, with the exception of the steep belts, high-temperature metamorphism outlasted these deformation events (e.g. Grujic & Mancktelow 1996) and reset the magnetization of the rocks. Therefore, restoration of the paleomagnetic directions of the Central Lepontine by simply tilting around a N-S striking axis is suggested to be a plausible mechanism.

In the central Lepontine area, the youngest U/Pb monazite ages yield 20.6 Ma (Köppel & Grünenfelder 1975). The closing temperatures for the U/Pb system in monazite is estimated at 650–730°C (Hunziker et al. 1992). The maximum unblocking temperature for the samples measured by Heller (1980) is above 600°C, and therefore the U/Pb monazite data may be used to constrain the maximum age of magnetization of the measured samples of Heller (1980). Consequently, the onset of eastward tilting postdates 20.6 Ma in the Central Lepontine and is therefore younger than tilting in the Bergell area.

5.3 Faults which may be related to eastward tilting

The following paragraphs, deal with timing and kinematics of the major faults bounding the Bergell and the Lepontine areas, in order to test whether late-Alpine eastward tilting is consistent with the tectonic settings of these regions.

Simplon Line (Fig. 1): It is a west-dipping normal fault (Mancktelow 1985), bounding the western margin of the Lepontine. Rapid motion along this fault is constrained between 18 and 15 Ma (Grasemann & Mancktelow 1993). Hunziker (1970) suggested vertical displacements in the range of 5–8 km, but Grasemann & Mancktelow (1993) estimated a relative vertical displacement of 15 km (including both brittle and ductile components) based on two-dimensional thermal modelling.

A west-dipping normal fault at the western margin of a nappe stock that is being preferentially uplifted due to eastward tilting is required for kinematic continuity. The Simplon Line is therefore consistent with a model of eastward tilting. Considering 15 km of vertical displacement and 15° of eastward tilting, the length of the tilted area amounts to 56 km. As a consequence, an axis of tilting located in the area of the Como Lake (Fig. 1), would explain tilting of the Central Lepontine area from the western Bergell pluton to the eastern margin of the Toce culmination.

Insubric Line (Fig. 1): The evidence of tilting of the Bergell root zone itself (Reusser 1987; Villa & von Blanckenburg 1991; Davidson et al. 1996) together with the absence of tilting in the Southern Alpine basement, suggests that differential displacements which accommodated the eastward tilting must have occurred between the Bergell tonalite tail and the Southern Alps, i.e. within the Insubric mylonitic belt (Tonale Series). Indeed, vertical stretching lineations associated with N-side up displacements have been reported from the Tonale Series (Heitzmann 1986, Fisch 1989).

Engadine line (Fig. 1): Schmid & Froitzheim (1993) suggested a rotation of 10.5 degrees around a NW-SE horizontal axis positioned close to St. Moritz, uplifting the southwestern sector, i.e. eastward tilting with the same rotation angle estimated for the Bergell pluton on the basis of hornblende barometry.

Therefore, the southeasternmost Lepontine- and Bergell area is bounded by two faults (Engadine- and Insubric Line), both showing block rotation-type movements. These movements caused the differential uplift of the southeasternmost Lepontine (Bergell) area with respect to its northern and southern boundaries.

Rhine-Rhone Line (Fig. 1): Little is known about this fault and its kinematics. Heller (1980) and Ricou & Siddans (1986), considered it to be a dextral strike-slip zone on the basis of paleomagnetic data. Müller et al. (1980) suggested a possible N-side-up displacement, on the basis of seismic data. However, this lineament and the above-mentioned kinematics have never been recognized by field-oriented structural studies in the Rhine-Rhone Valley, and even its exact trace in map view is very questionable.

Considering the well established kinematics of the Simplon Line (Mancktelow 1985) and the estimated relative vertical displacement of 15 km (Grasemann & Mancktelow 1993), it can be inferred that important vertical displacements occurred along the Rhine-Rhone area (east of the Simplon fault) in order to accommodate the uplift of the foot-wall of the Simplon fault.

At its eastern end, in the area of Chur, the "Rhine-Rhone" line turns into a N-S direction (e. g. Laubscher 1992; Fig. 1). If this segment is interpreted as an eastward-dipping normal fault, as postulated by Trümpy (1992), the sense of shear along the eastern Rhine-Rhone line has to be sinistral. A normal fault character for the eastern end of the Rhine-Rhone line is also suggested by new vitrinite reflectance and illite crystallinity data, showing higher temperatures of metamorphism in the Helvetic nappes with respect to the Bündner Schiefer, near Chur (Fig. 1; Ferreiro Mählmann, pers. comm.). Therefore, relative vertical displacements of the Lepontine area along the "Rhine-Rhone" line only occurred in its western part, implying a differential uplift, i. e. eastward tilting of the Lepontine.

In summary, it can be stated that eastward tilting of the Lepontine is consistent with the kinematics of the major faults bounding the Lepontine area.

In map view (Fig. 1), the N-S extent of the Lepontine area gradually increases from the Simplon Line to the area of the Adula nappe. In fact, the narrowest section of the Alps occurs in the area of the Simplon Line (Laubscher 1992). The converging geometry of the east-west striking axial planes of the western Lepontine as they approach the Simplon line (see Fig. 4 in Steck 1990), and the increasingly reduced width of the Gotthard Massif in proximity of the Simplon area, suggest that the reduced N-S exposure of the Lepontine is due to increased shortening in a direction perpendicular to the steep belts.

East of the Leventina-Lucomagno nappe (Fig. 1), the Northern Steep Belt gradually disappears (Frey 1967), and the N-S width of the Lepontine dome rapidly decreases, becoming less than 20 km wide in the area of the Bergell pluton. It is interesting to note that the N-S cross section through the Lepontine along the western margin of the Bergell pluton, shows a continuous steep zone, which never passes into a flat-lying nappe geometry (Fig. 2b). This suggests that the reduced width of the Lepontine in this area results from the concentration of N-S shortening into a narrow zone, as witnessed by the 20 km wide Southern Steep Zone.

Tertiary N-S shortening also occurred east of the Bergell pluton, as shown by the Passo d'Ur backfold (Spillmann 1993). However, further east, these folds become gradually more open and finally they die out completely, indicating that the amount of Tertiary N-S shortening gradually decreases eastwards. Hence, there is a similarity between the Simplon and the Bergell areas. They both coincide with a region of maximum shortening that gradually decreases eastwards. In both areas eastward tilting is inferred.

It is therefore suggested that increased N-S shortening in the western parts of the Central Lepontine and of the Bergell pluton results in increased uplift of the western parts of both these areas. Accommodation of differential N-S shortening by differential uplift induces tilting of the Central Lepontine and of the Bergell pluton.

However, N-S shortening is not only accommodated by vertical uplift. In fact eastward extension is known from the Forcola Line and other areas within the Central and Eastern Lepontine region: ENE directed extensional structures east of the Lepontine dome (Tambo- and Suretta nappes) were found by Schreurs (1990) and Ring (1992), who considered them younger than 25–20 Ma. Baudin et al. (1993) have described top to the ENE extension, affecting the Adula, Tambo and Suretta nappes, and the sedimentary units in front of the Tambo nappe. They linked this extensional deformation to the Simplon fault and considered it coeval with dextral transpression along the Insubric Line.

6 Conclusions

Structural, petrological and paleomagnetic data indicate consistent evidence that the steep geometry of the Bergell tonalite tail is at least 29 Ma old. This age yields a minimum time constraint for the development of the Southern Steep Zone. Since the solidus within the western tonalite tail was only reached at 28 Ma (Oberli et al. 1996), final crystallization of the Bergell tonalite tail occurred in a steep position. The present-day north-dipping geometry of the tonalite tail and consequently backthrusting along the Insubric Line probably postdates final crystallization of the pluton, which took place during vertical extrusion along the Southern Steep Zone. This is consistent with the models of Merle (1994) and (Berger et al. 1996), which postulate first a stage of synmagmatic vertical extrusion, followed by backthrusting during ongoing N-S shortening in a second stage.

The onset of eastward tilting in the southeastern Lepontine (Bergell) area predates the solidus of the Bergell pluton, but this process continued during uplift and cooling of the pluton after final crystallization of the tonalite, inducing a westward increase in the pressure of crystallization of the Bergell tonalite.

Deviation of the paleomagnetic data from the Central Lepontine area (Heller 1980) with respect to the Aar Massif and to the NRM orientation of stable Europe in the Miocene, is also explained by eastward tilting of 15° around a N-S horizontal axis. Tilting is due to vertical uplift of the western Lepontine area, as a consequence of increased N-S shortening, and it is accommodated along the Northern and Southern Steep Zones and the Simplon Fault Zone.

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