Continental breakup by detachment faulting: field evidence and geochronological constraints (Tasna nappe, Switzerland)

N. Froitzheim and D. Rubatto

1 Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistrasse 32, CH-4056 Basel, Switzerland. 2 Institut für Isotopengeologie und Mineralische Rohstoffe, ETH-Zentrum, CH-8092 Zürich, Switzerland. 3 Present address: Research School of Earth Sciences, The Australian National University, Mills Road, 0200 Canberra ACT, Australia

ABSTRACT

The Lower Tasna Detachment (LTD) is a low-angle fault contact between serpentinitized peridotite below and continental basement above. It was formed during Jurassic to Early Cretaceous rifting of a Tethyan continental margin and later captured in a thrust nappe during Tertiary plate convergence. Foliated gabbro, gabbro mylonite, and granitoid mylonite occurring along the LTD record shearing under decreasing temperatures. U-Pb dating of zircon from the gabbro mylonite yielded a Permian age, interpreted as the age of gabbro intrusion, whereas the breakup of the passive margin occurred as late as Early Cretaceous. This suggests that the gabbro belongs to a prerift, lower to middle crustal intrusion ’smearred out’ along the detachment by extensional faulting. The juxtaposition of mantle and upper crust along the Lower Tasna detachment may serve as a model for several seismic reflectors observed in distal passive continental margins (e.g. S reflector of the Galicia margin).

Introduction

Low-angle seismic reflectors are recorded in the basement of passive continental margins, e.g. the S reflectors of the Armorican and Galicia margins. One interpretation is that these are rift-related extensional detachments (Krawczyk and Reston, 1995). The continental basement above them is a layer of tilted blocks decreasing in thickness oceanward and finally wedging out. In its oceanward part, the footwall to the Galicia S-reflector has acoustic properties compatible with an interpretation as serpentinitized peridotite, and where the footwall is exposed at the oceanward edge of the margin, a ridge of serpentinitized peridotite was indeed encountered by diving and drilling (Bollot et al., 1992). Thus, the oceanward part of the Galicia S-reflector may be a rifting-related crust-mantle boundary fault.

In this article, we describe for the first time the Lower Tasna Detachment (LTD), a crust–mantle boundary fault found in a former passive margin in the Alps, which was captured in a thrust nappe and only mildly deformed during Alpine orogeny. It is accessible for field studies and may potentially serve as a model for the Galicia S-reflector. The fault rocks along the detachment include sheared gabbro and gabbro mylonite. U-Pb dating of zircons from the gabbro mylonite was carried out in order to determine whether the gabbro protolith is pre- or synrift in age.

Regional setting

The study area is in the western part of the Engadine tectonic window (Central Alps) which exposes a stack of Penninic nappes including the Tasna nappe (Fig. 1). The latter thrust sheet originated from the ocean–continent transition zone between the former Briançonnais terrane and the Valais oceanic basin ( Florineth and Froitzheim, 1994). The Tasna nappe comprises four rock complexes listed below.

1 Serpentinitized peridotite with relic parageneses of clinopyroxene, orthopyroxene, and chrome spinel rimmed by chlorite, originating from theralantic mantle ( Florineth and Froitzheim, 1994; references therein). Mantle structures include pyroxenite layering and a weak foliation outlined by spinel. Rodingitized basaltic dykes cut across the peridotite. The base of the peridotite is an Alpine thrust fault.

2 Continental basement complex, comprising metamorphic rocks (biotite and chlorite schist, sericite phyllite, gneiss) and Variscan magmatic rocks intrusive into the former (Tasna granite, minor diorite, and quartz diorite; Cadisch et al., 1941, 1968).

3 Pre-and synrift sedimentary cover, including Triassic dolomite, quartzite, arkose, gypsum, cagneule and shale (Güler, 1995), which lie on top of the continental basement complex and represent its prerift cover. The Triassic is overlain by Jurassic series including Upper Jurassic limestone with breccia layers (Falknis breccia), which is synrift with respect to the formation of the Valais ocean.

4 Postrift sediments and flysch. The postrift cover series comprises Neocomian to Palaeocene or early Eocene formations (see references in Florineth and Froitzheim, 1994).

Postrift sediments and flysch in the structurally higher parts of the Tasna nappe were strongly deformed by Alpine shearing and folding, but the lower part was only mildly deformed by SE-verging folds (Fig. 1). Hence, the pre-Alpine geometry can roughly be restored by E-W projection (Fig. 2). This restoration illustrates geometric features of the Tasna nappe that are inherited from Mesozoic rifting. The continental basement complex is 7.5 km long in N–S direction and reaches its maximum thickness of about 600 m in the lower Val Tasna. The point of maximum thickness approximately coincides with the northern tip of the pre- and synrift sediments. North of this point, the postrift sediments onlap the continental basement, and north of the tip of basement, they onlap directly the serpentinitized peridotite ( Florineth and Froitzheim, 1994). Hence, the continental basement complex appears as a thin block of continental crust, prerift, and synrift sediments that was tilted towards south and buried by postrift sediments.

The upper boundary of the continental basement complex north of the tip of
Continental breakup by detachment faulting. N. Froitzheim and D. Rubatto

500 m

Fig. 1 Tectonic map of the Tasna area, and profile across Piz Minschun. Inset gives location in eastern Switzerland.

Fig. 2 Schematic, palinspastic section of the Tasna nappe, constructed by E-W projection. Legend as in Fig. 1. Note that the overall geometry is a southward tilted block of continental crust 'stranded' on exhumed mantle and buried by post rift sediments.

Granitoid mylonite, probably derived from tonalite or granodiorite, overlies the gabbro and gabbro mylonite, respectively. It consists of layers and porphyroclasts of altered plagioclase and amphibole, and layers of chlorite and titanite. In addition, about 30% of the rock are cataclasites (Florineth and Froitzheim, 1994). Further north, the shale directly overlies serpentinitized and brecciated peridotite.

The Lower Tasna Detachment (LTD)

This is the contact between the continental basement complex and the underlying serpentinitized peridotite. Very good exposures of the detachment exist near the northern tip of the continental basement. There, a narrow mylonite zone is found between the serpentinitized peridotite below and the continental basement complex above (Fig. 3). The base of the fault zone is formed by serpentinitized peridotite with only a weak foliation outlined by spinel and without any mylonitic fabric. Towards the fault zone, the serpentinitized peridotite is increasingly veined with calcite and locally brecciated, indicative of low-temperature, cataclastic deformation.

A lens of gabbro occurs at one locality (Fig. 3a) along the contact between peridotite and gneiss. It consists mainly of plagioclase and brown amphibole. A distinct foliation is defined by bands of plagioclase and large (up to 2 mm), elongate crystals of brown amphibole with undulose extinction and bent cleavage lamellae. The plagioclase was largely replaced by sericite and the brown amphibole by actinolite, chlorite, and epidote. Actinolite also fills spaces between disrupted fragments of brown amphibole. In a profile about 200 m farther south (Fig. 3b), the gabbro is represented by a thin layer of gabbro mylonite. This rock is strongly foliated and segregated into layers of plagioclase and amphibole, and bears a SE-NW-trending stretching lineation. Porphyroclasts of both plagioclase and amphibole have asymmetric, recrystallized tails. In one sample, a top-SE shear sense could be determined from these. After mylonitization, plagioclase was replaced by a fine-grained, sericite-rich aggregate, amphibole by chlorite, titanite, and epidote. This fine-grained aggregate is cut by pumpellyite-bearing veins formed during Alpine peak metamorphism (Tertiary).

©1998 Blackwell Science Ltd
layers of dynamically recrystallized quartz with a stretching lineation trending SE–NW. The crystallographic preferred orientation and the oblique grain shapes of the recrystallized quartz indicate top-SE sense of shear, consistent with the one observed in the gabbro mylonite. This mylonitic fabric ("s" in Fig. 3) is crosscut by Riedel shears ("r") which are cataclastic in thin section and along which chlorite has grown. These indicate an opposite, top-NW shear sense. Hence, the shear sense in these mylonites was top-SE under elevated temperatures (> 300°C, allowing complete dynamic recrystallization of quartz; see Voll, 1976) and changed to top-NW when the temperature decreased. The LTD is sealed by Early Cretaceous sediments a small distance north of the localities described above (Fig. 1). The mylonitic shearing must therefore be pre-Alpine.

**Geochronological data**

One sample of gabbro mylonite (coordinates 814 350/190 600, Fig. 1) has been dated by conventional U-Pb isotope dilution techniques using aragonite. The zircon cores are variable in dimension from 30 pm to 150–200 pm. They are transparent and generally preserve some crystal faces, even though euhedral grains are rare. A few zircons were investigated by cathodoluminescence (CL) in order to check for inherited cores. The CL images showed two main zircon typologies. A first type of zircons (Fig. 4a) displays sector zoning as typically observed in magmatic zircons from gabbroic rocks (Rubatto and Gebauer, in press). These zircons may show inherited zircon cores (Fig. 4b) and generally preserve euhedral crystal faces. The second zircon type (Fig. 4c) is characterized by smaller size and different CL patterns within single grains, which either crosscut or overgrow each other. The CL zoning suggests a polyphase evolution of these second-type zircons. They are most likely inherited.

A single grain and three multigrain fractions were analysed for U and Pb (Table 1). Three of the data points (4/2, 4/1 and 4/3a) define a linear array with little to moderate discordance (Fig. 5). Best fit regression (Ludwig, 1992) yields Concordia intercept ages of 254 ± 9 Myr and 565 ± 56 Myr. This regression line is preferred to the possible discordia line defined by analysis 4/1, 4/2 and the analysis from a multigrain fraction (4/3b) that lies far away from the Concordia curve. This second possibility would give a lower intercept with larger error (263 ± 33 Myr) and within error limit with the age of 254 ± 9 Myr.

According to the CL images of the zircons, which show typical magmatic zoning, the lower intercept of the discordia line defined by three analyses is

**Table 1** Zircon description and U-Pb data of the four zircon fractions analysed

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Zircon description</th>
<th>Grains</th>
<th>U (ppm)</th>
<th>Model Th/U</th>
<th>Pb rad. (ppm)</th>
<th>206/204</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/2</td>
<td>large rounded (&gt; 150 μm)</td>
<td>1</td>
<td>351.01</td>
<td>0.24</td>
<td>14.12</td>
<td>2872</td>
</tr>
<tr>
<td>4/1</td>
<td>large, nearly euhedral, isometric or slightly elongated</td>
<td>6</td>
<td>176.76</td>
<td>0.20</td>
<td>7.16</td>
<td>628</td>
</tr>
<tr>
<td>4/3a</td>
<td>&lt;100 μm, preserve some crystal faces, not euhedral</td>
<td>5</td>
<td>335.88</td>
<td>0.28</td>
<td>16.39</td>
<td>4084</td>
</tr>
<tr>
<td>4/3b</td>
<td>small (~ 50 μm), preserve some crystals faces, not euhedral</td>
<td>6</td>
<td>294.24</td>
<td>0.19</td>
<td>16.49</td>
<td>389</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Age (Myr)</th>
<th>± (Myr)</th>
<th>Age (Myr)</th>
<th>± (Myr)</th>
<th>Age (Myr)</th>
<th>± (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/2</td>
<td>261.8</td>
<td>0.8</td>
<td>262.8</td>
<td>0.8</td>
<td>271.7</td>
<td>5.8</td>
</tr>
<tr>
<td>4/1</td>
<td>266.6</td>
<td>0.7</td>
<td>268.0</td>
<td>1.2</td>
<td>280.3</td>
<td>10.0</td>
</tr>
<tr>
<td>4/3a</td>
<td>311.7</td>
<td>0.9</td>
<td>318.0</td>
<td>0.8</td>
<td>364.5</td>
<td>3.8</td>
</tr>
<tr>
<td>4/3b</td>
<td>333.9</td>
<td>0.8</td>
<td>405.1</td>
<td>1.6</td>
<td>834.0</td>
<td>8.2</td>
</tr>
</tbody>
</table>

©1998 Blackwell Science Ltd
Fig. 4 Cathodoluminescence images of zircons from the Tasna gabbro mylonite, which display different types of zoning-patterns. (a) Zircon with magmatic sector zoning. (b) Zircon with magmatic sector zoning and a small inherited core. (c) Zircon with different CL-patterns that cut across each other. The variation in CL-patterns argues for a polyphase evolution of this second zircon type, which was most probably inherited in the mafic magma.

Fig. 5 Conventional Concordia plot for the four U–Pb analyses of zircons from the Tasna gabbro mylonite. See text for discussion.

interpreted as dating the intrusion of the gabbro. The little to moderate discordance of these analyses is most probably due to the presence of inherited Pb components (small, inherited cores as in Fig. 4b) in some of the zircons of the fractions analysed. Indeed, the single crystal dated (data point 4/2) contains least inherited Pb. However, it cannot be excluded that the discordance of the youngest data points is due to lead loss after gabbro crystallization. In this case, 254 ± 9 Myr would represent a minimum age for the gabbro intrusion, which could be slightly older. The age defined by the upper intercept of the discordia line with the Concordia indicates that the inherited Pb component was most probably of Early Cambrian age.

Datum 4/3b that plots off the discordia line shows the presence of a much older Pb component in the zircons. This suggests that at least one inherited zircon similar to that shown in Fig. 4 (c) was present in this fraction.

Fig. 6 Hypothesis for rifting and breakup of the Valais ocean. (a) prerift situation (Triassic). Permian gabbro is situated in lower or middle crust. (1) is trace of future Lower Tasna detachment (LTD). (b) First phase of rifting (Jurassic?) with top-SE faulting along LTD emplacing upper crust on mantle rocks, with displaced gabbro lenses in between. Geometry of upper-crustal faulting hypothetical. (2) is trace of future Upper Tasna Detachment (UTD). (c) Continental breakup (Early Cretaceous) by top-NW (?) faulting along UTD. Minor top-NW reactivation of LTD. (d) Present-day situation from reflection-seismic profile (Pfiffner and Hitz, 1997). Tasna nappe was sheared off the southward descending lithospheric slab during Alpine (Tertiary) subduction and accreted to the orogenic wedge. Bündnerschiefer from Valais basin was then accreted below the Tasna nappe. Finally, antiformal stacking of underthrust European crust at depth caused upwarping and exhumation of Engadine window, and surface exposure of Tasna nappe.

Discussion

Dating of magmatic zircons constrains the LTD gabbro intrusion as Permian. Pre-oceanic rifting in the Penninic zone...
of the Alps began only in latest Triassic to early Jurassic time, that is, about 50 Myr later. The first oceanic basement was formed at 160 Ma in the Piemont-Ligurian basin (Rubatto et al., 1998) and after 145 Ma in the Valais basin (Florineth and Froitzheim, 1994; references therein). Hence, surprisingly, the gabbro intrusion is unrelated to Mesozoic rifting. However, when compared to ages of other gabbro intrusions in the Alps, the Permian age is typical. Permian gabbros are found, for example, in the Margna and Malenco nappes (270 Myr old, Hermann et al., 1997) and in the Ivrea zone (270 Myr old, Voshage et al., 1990; references therein). It has been shown for these gabbros that they intruded at the crust–mantle boundary and into the lower crust during Permian transtensional deformation of the Variscan chain. Widespread mafic underplating in the lower crust is assumed for this period (e.g. Voshage et al., 1990).

The occurrence of mylonitized gabbro along the LTD indicates that this fault postdates gabbro intrusion and is hence younger than ≈ 254 Myr old. Part of the deformation of the gabbro may already be syn-intrusive (G. Manatschal, pers. comm.), but the ‘smearing-out’ of the gabbro to form the presently observed thin layer along the fault contact is clearly postintrinsic. On the other hand, the fault is pre-Neocomian because it is sealed by sediments of this age, at the point where it reaches the basement-cover interface (Fig. 1).

The LTD must have formed at higher temperature than the UTD, because mylonites are observed along the LTD and only cataclasites along the UTD. The top of the serpentinite north of the continental basement represents the northern prolongation of both the UTD and the LTD, because along this contact, relics of the cataclasites characteristic for the UTD occur, but also gabbro and gabbro mylonites (near Piz Tasna; Fig. 1). Hence, the LTD appears to merge into and reactivate the northern part of the LTD. The following sequence of events is suggested (Fig. 6): Intrusion of gabbro (Permian) – LTD faulting – UTD faulting – deposition of postrift sediments (beginning in Early Cretaceous). The LTD emplaces upper crustal Variscan rocks (Tasna granite and its country rocks) onto mantle rocks and therefore represents an important extensional structure which omitted a large thickness of middle and lower crust. The Permian gabbro is interpreted as an extremely reduced remnant of these omitted levels. A similar case of extensional unroofing of a Permian, prerift gabbro during Mesozoic rifting has already been described from the Malenco area by Hermann and Müntener (1996).

The LTD may have formed during late Jurassic–earliest Cretaceous rifting preceding opening of the Valais oceanic basin, or, alternatively, during early to middle Jurassic rifting of the Piemont-Ligurian basin, the earlier-opened, main basin of the Mesozoic Tethys ocean. This question can only be solved by dating the mylonitization of the gabbro or the granitoid mylonite.

The LTD may serve as a field model for the S reflectors of the Armorican and Galicia margins. As discussed by Krawczyk and Reston (1995), the Galicia S reflector is close to the base–sediment interface (never more than 3 km below, and in places less than 1 km), underlies tilted blocks of continental basement, represents a sharp increase in acoustic impedance, and is probably a single interface. The LTD has similar characteristics.

Conclusions

The Lower Tasna detachment is a Mesozoic low-angle normal fault that emplaced upper continental crust directly upon subcontinental mantle material. Zircons from gabbro mylonite found along the LTD yielded a discordia with a lower intercept at 254 ± 9 Ma, interpreted as the (minimum) age of gabbro intrusion. Gabbro and gabbro mylonite in the Tasna nappe are found either between mantle and continental base- ment, or along the top of completely exhumed mantle. Therefore, they are interpreted to represent remnants of the omitted prerift lower or middle continental crust.

Products of synrift melting are absent in the study area, except the rodobitized basaltic dykes in the peridotite, which presumably intruded towards the end of rifting. Hence, the breakup of the continental crust was accommo- dated mainly by extensional shearing and faulting. This is in line with the results of thermal modelling by Latin and White (1990) who found that, if rifting is accommodated by detachment faulting, ‘it is extremely difficult to generate melt from the asthenosphere’.

Our findings indicate that strongly localized extensional faults emplacing upper crust on mantle do exist in passive margins, as was proposed for the S reflector of the Galicia margin (Krawczyk and Reston, 1995), and may play a crucial role in the process of continental breakup. An important difference between the Tasna case and the Galicia case is that the Tasna gabbro is prerift, whereas gabbro in a similar position in the Galicia margin yielded Cretaceous (i.e. synrift) ages (Schärer et al., 1995).

Acknowledgements

This paper was improved by the careful reviews of Renaud Caby and Othmar Müntener. NF thanks Gianreto Manatschal for discussions and suggestions. DR is grateful to Urs Schaltegger for careful supervision of the U-Pb dating. Dieter Gebauer is acknowledged for comments on the geochronological data. Supported by Swiss National Science Foundation grants Nr. 21-39182.93 and 20-45714.95 to NF and Nr. 20-35253.91 to DR.

References


Appendix: Analytical techniques

The zircons were air-abraded, washed in warm 4N nitric acid, and rinsed with distilled water and acetone in an ultrasonic bath. Dissolution and chemical extraction of U and Pb were performed following Krogh (1973) using bombs and anion exchange columns scaled down to 1/10 of their original size. Total procedural blanks were better than 2 pg Pb and 0.1 pg U. A mixed 206Pb/235U tracer solution was used for the analyses. Pb and U were loaded together on a single Re filament with Si-Gel and phosphoric acid and measured on a Finnigan MAT 262 mass spectrometer using an ion counting system. Error ellipses are drawn at the 95% confidence level, intercept age uncertainties are 2 σ.

Cathodoluminescence investigation was carried out on a CamScan 4 scanning electron microscope (SEM) at the Institut für Metallforschung und Metallurgie at ETH Zürich. The instrument is supplied with a ellipsoidal mirror for cathodoluminescence. Operating conditions for the SEM were 13 kV at the cathode and an emission current of ~120 µA.

Received 23 July 1998; revised version accepted 5 November 1998