Journal of Structural Geology 28 (2006) 1388–1395

JOURNAL OF STRUCTURAL GEOLOGY

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Extraction faults

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Received 17 January 2006; received in revised form 12 April 2006; accepted 10 May 2006

Abstract

We propose the term "extraction fault" for a planar structure that forms at the trailing edge of a discrete block when it is forced or extracted out of the surrounding material. This process results in the merging of two block-bounding faults with opposite senses of displacement. An extraction fault differs fundamentally from other faults in that its two sides have approached each other substantially in the direction perpendicular to the fault. The fault-parallel displacement may be either zero (pure extraction faults) or not (mixed extraction faults). Pure small-scale extraction faults can result from boudinage. A large-scale example may be the S-reflector of the Galicia passive continental margin which is related to rifting and continental breakup. When the strong portion of the lithosphere, i.e. the upper mantle and the lower crust, underwent necking, thermally weak mantle from below and upper crust from above collapsed into the opening gap in the rift centre and an extraction fault formed at the trailing edge of the strong lithosphere. Extraction faults are also potentially important in the exhumation of high-pressure metamorphic rocks in collisional orogens. We propose that the Combin fault on top of the eclogite-facies Zermatt-Saas ophiolites in the Penninic Alps, earlier interpreted either as a normal fault or as a thrust, is in fact an extraction fault.

Keywords: Faults; Tectonics; Rifting; S-reflector; Alps; Exhumation

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1. Introduction

Faults accommodate the displacement of two portions of rock, and in most cases the displacement vector is parallel to the fault. Towards the fault tip, the displacement decreases to zero, which requires some internal deformation of the fault walls. Means (1989) introduced the term "stretching faults" for faults whose walls are stretched or shortened in a direction parallel to the fault during displacement. This can result in variations of the amount of displacement (Pfiffner, 1985) or even in a reversal of the sense of displacement along the fault (Means, 1990). Means (1989) suggested that such faults may be common at deeper levels of the crust where faulting is accompanied by distributed ductile deformation. In this article, we will describe yet another type of fault which results from the special situation that a volume of rock is extracted between two faults with opposite sense of displacement (Fig. 1) and these two faults merge together at the trailing edge of the extracted body. Whereas the extracted body may be rigid (but does not have to), the surrounding material has to deform internally in order to accommodate the extraction. The extraction fault forms behind the trailing edge of the extracted body. In contrast to other types of faults, a pure extraction fault has no displacement of the bounding blocks parallel to the fault. However, the blocks have approached each other in a direction perpendicular to the fault, by an amount h which increases from the tip of the extraction fault, where it is zero, towards the trailing edge of the extracted body to a maximum which equals the thickness of the extracted body (Fig. 1). If earlier stages of deformation, i.e. the movement between the extracted body and its bounding blocks, are recorded by the fault rocks, e.g., mylonites, the shear sense of the fault rocks may change across the extraction fault (in Fig. 1b, it would be dextral above and sinistral below). This situation is particularly likely for pure extraction faults (Fig. 1b). In Fig. 1c, the extraction is combined with a fault-parallel relative

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doi:10.1016/j.jsg.2006.05.002

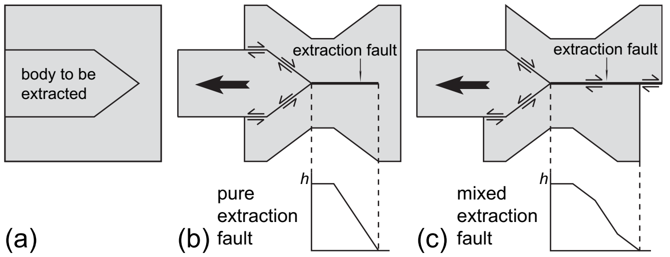


Fig. 1. Kinematic principle of extraction faulting. (a) Starting configuration. (b) Pure extraction fault: a wedge-shaped rock body is extracted along two faults with opposite senses of displacement. Behind the trailing edge of the extracted block, the upper and lower bounding blocks become juxtaposed and the faults merge into an extraction fault. The extraction fault has no fault-parallel displacement. The amount of fault-perpendicular convergence of the bounding blocks (*h*) decreases from the trailing edge of the extracted block to the tip of the fault. The shape of this curve depends on the shape of the extracted body. In lithospheric-scale examples, the physical expression of *h* would be a jump in metamorphic peak conditions across the extraction fault. (c) Mixed extraction fault: relative displacement of the bounding blocks causes fault-parallel offset along the extraction fault. As a result, the distribution of *h* along the extraction fault is modified. Internal deformation of the bounding blocks in (b) and (c) is vertical simple shear.

displacement of the two bounding blocks, resulting in an extraction fault with some offset (mixed extraction fault). Other variants of extraction faults are possible where the bounding blocks are stretched in a direction parallel to the fault, either both by the same amount or differentially. The resulting faults are a combination of extraction and stretching faults.

Extraction faults form during boudinage of competent layers as soon as the boudins are separated and the embedding layers come into contact in the boudin necks (Fig. 2). Such extraction faults are very common but have hardly received particular attention. Extraction faults of tectonic importance, however, may form during rifting and continental breakup and the exhumation of high- and ultrahigh-pressure rocks. In these cases, the extraction fault concept may lead to the reinterpretation of large-scale tectonic features that have not yet been fully understood.

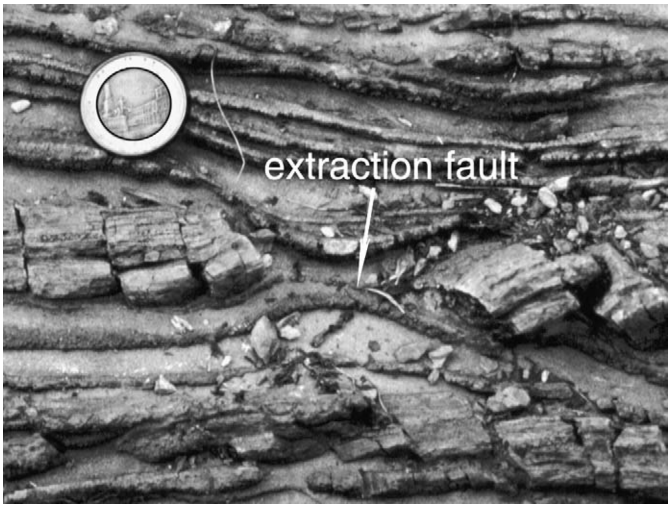


Fig. 2. A small-scale extraction fault between boudins. The boudinaged layers are calc-silicate, the ductile deformed layers are marble. Metamorphosed Triassic limestone–shale sequence in the contact aureole of the Adamello pluton, Southern Alps, Italy.

2. The S-reflector of the deep Galicia passive continental margin, North Atlantic

The Iberian margin of the North Atlantic and in particular its northern part, the Galicia margin, is one of the best-studied examples of a non-volcanic passive continental margin and ocean–continent transition. The extensional tectonics leading to Atlantic opening in this area took place in the Early Cretaceous. The distal part of the passive margin is characterized by an array of oceanward-dipping faults separating tilted blocks of upper continental crust (Fig. 3). These are underlain by a horizon of strong seismic reflectivity, the S-reflector, in which the normal faults separating the tilted blocks are rooted. The array of tilted blocks becomes thinner oceanward and eventually tapers out completely. The S-reflector surfaces at the top of a ridge of exhumed and serpentinized mantle peridotite (Boillot et al., 1995), which is of subcontinental provenance (Chazot et al., 2005). Based on seismic evidence, the footwall of the S-reflector is considered to consist at least partly of serpentinized mantle rocks (Reston et al., 1996).

The S-reflector is interpreted as an extensional fault or shear zone (Boillot et al., 1988; Reston et al., 1996). If it was comparable to the extensional detachment faults observed in the Basin and Range province of western North America, its shear sense should be top-to-the-west, judging from the sense of tilting of the hanging-wall blocks (Reston et al., 1996). However, the opposite shear sense, top-to-the-east, has also been proposed in order to account for the oceanward thinning of the crust overlying the S-reflector (Boillot et al., 1988). In the area where the S-reflector appears at the seafloor, three types of fault rocks were sampled by drilling and submersible diving: (1) peridotites sheared under high temperatures (1000–850 °C) with a top-to-the-southeast shear sense (Beslier et al., 1990); (2) above the sheared peridotites, chlorite-bearing schists derived from greenschist-facies mylonitization of gabbro, in which the opposite, top-to-the-northwest shear sense has been determined (Beslier et al., 1990); (3) a cataclastic breccia which is assumed to be part of the same, top-to-the-northwest fault, formed during late stages of faulting close to the surface (Boillot et al., 1995).

An important and enigmatic feature is that the lower continental crust is not exposed in the area of the Galicia ocean–continent transition, although the subcontinental mantle is. Instead, tilted blocks of upper continental crust rest directly on mantle rocks. Granulite clasts were found in the cataclastic breccia where the S-reflector appears at the seafloor and were tentatively interpreted as remainders of the pre-rift lower continental crust (Boillot et al., 1995). However, zircon fission track dating of these granulites (Fügenschuh et al., 1998) showed that they had already cooled through c. 240 °C at the end of the Variscan orogeny, in Late Carboniferous to Early Permian time. Hence, they belonged to the upper crust when rifting started. The lack of the lower crust is particularly

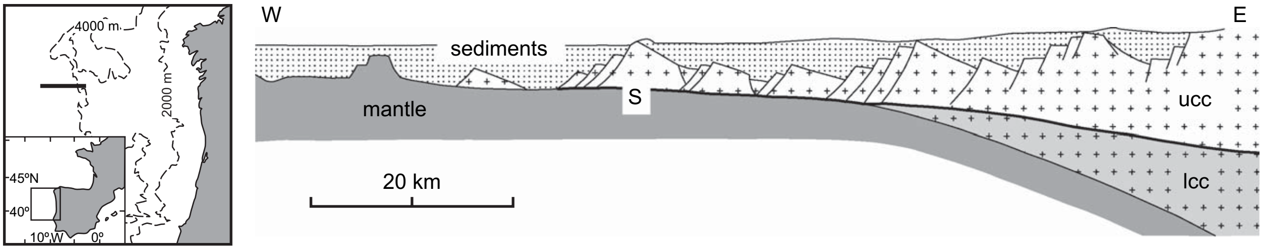


Fig. 3. Schematic cross section through the Galicia margin after Boillot et al. (1995). S, S-reflector; ucc, upper continental crust; lcc, lower continental crust. Thick line in inset map is the cross-section trace.

important since some authors have assumed flow of weak lower crust towards the rift centre during rifting, driven by the gradients in vertical stress which arise from the thinning of the overburden (e.g., Block and Royden, 1990). These hypotheses predict thick lower crust along the ocean–continent transition, which is not the case at the Galicia margin.

The structural characteristics of the ocean–continent transition, namely the absence of the pre-rift lower crust and the finding of high-temperature fault rocks with top-to-the-continent shear sense below low-temperature fault rocks with top-to-the-ocean shear sense, strongly suggests that the S-reflector is not a conventional detachment fault but partly an extraction fault. It is formed by the contemporaneous action of a system of west-dipping normal faults and shear zones in the crust, and an array of east-dipping shear zones in the mantle (Fig. 4). In the continentward part, where the S-reflector is underlain by continental crust, it is a top-to-the-west extensional shear zone or detachment fault. Towards the ocean, where it is underlain by mantle rocks, it becomes an extraction fault. East-dipping reflectors imaged in mantle rocks of the ocean–continent transition further south, in the Iberia abyssal plain (Pickup et al., 1996), may represent such east-dipping shear zones (Boillot and Froitzheim, 2001). This interpretation of the S-reflector closely follows the ideas of Brun and Beslier (1996) and Nagel and Buck (2004), based on physical and numerical modelling, respectively. In these works, the extraction fault interpretation of the S-reflector is implicit. The top-to-the-northwest shear sense registered in the low-grade, chlorite-bearing schists (Beslier et al., 1990) belongs to the oceanward-dipping, crustal normal fault system, and the top-to-the-southeast high-grade shear sense in the mantle rocks (Beslier et al., 1990) to the continentward-dipping system in the mantle. In this case, the two opposite shear senses of an extraction fault are preserved.

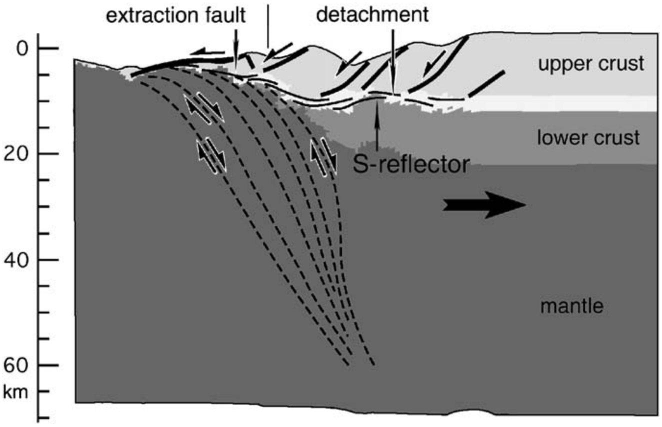


Fig. 4. Interpretation of the oceanward part of the S-reflector as an extraction fault developing during continental breakup, resulting from the extraction of the lower continental crust and underlying upper mantle towards right (arrow). The figure shows the final stage of a numerical simulation of Nagel and Buck (2004). Above the S-reflector, the hanging wall is an array of tilted blocks derived from upper continental crust collapsing oceanward. Shear sense within the mantle beneath the S-reflector is opposite (top-to-the-continent). The continentward part of the S-reflector is an extensional detachment fault, but the oceanward part, beginning at the tip of the lower crust where the first mantle shear zone joins the S-reflector, is an extraction fault. During the simulation, the mantle shear zones formed sequentially from the most continentward to the most oceanward ones.

The mechanical background of extraction faulting along the S-reflector was explored by Nagel and Buck (2004). During the formation of the tilted block array, the extension in the upper crust is decoupled from deformation of the deeper lithosphere along a décollement horizon in the middle crust. The deeper lithosphere yields along two conjugate normal shear zones in the rift centre. These shear zones dip outward away from the rift centre under the two continents that are going to separate from each other. Deeper mantle material is pulled up into the gap, forming a mantle dome flanked by the continentward-dipping shear zones. Also the upper crust collapses into the opening rift centre along the oceanward-dipping brittle faults in the upper crust and ductile shear zones in the middle crust. In terms of kinematics, this is equivalent to an extraction of the lower crust and uppermost mantle. Along the oceanward part of the S-reflector, the fault-parallel displacement may be minor or even non-existent. In the controversy on the shear sense of the S-reflector, both sides may be equally right or wrong. In addition to being an extraction fault, the S-reflector is also a stretching fault in the sense of Means (1989) since at least the hanging wall of the extraction fault, consisting of the tilted blocks, was stretched altogether during the process.

Similar reflectors/shear zones occur in the Iberia abyssal plain south of the Galicia margin (Manatschal et al., 2001), and in the Armorican margin of the Bay of Biscay (the original S-reflector, de Charpal et al., 1978). We suggest that the extraction fault concept applies to these areas as well.

3. The Combin fault in the Penninic Alps

The Penninic nappes of the western Swiss–Italian Alps (Fig. 5) represent a stack of thrust sheets derived partly from continental crust, partly from ophiolites of Jurassic (Rubatto et al., 1998) and Cretaceous age (Liati and Froitzheim, in press). During the Alpine orogeny in Early Tertiary time, the rocks were metamorphosed, imbricated as thrust sheets, and overprinted by several generations of folds and shear zones (Milnes et al., 1981; Sartori, 1987; Steck, 1990; Ring, 1995; Dal Piaz et al., 2001). An important gap in metamorphic pressure exists across the shallowly dipping contact between two such nappes, the Zermatt-Saas zone below and the Combin zone above (Fig. 6a). This contact is known as the Combin fault (Ballèvre and Merle, 1993). The Zermatt-Saas zone is an ophiolite unit formed by basement and sediments of the Jurassic-age Piemont-Ligurian ocean. It was metamorphosed at peak pressures of 2.5–3.0 GPa in the eclogite-facies (Bucher et al., 2005). The overlying Combin zone comprises ophiolites and sediments from a more southerly located sub-basin of the same ocean. Layers of detached and metamorphosed Mesozoic shelf sediments occur at the base of the Combin zone (Cimes-Blanches nappe) and higher up in the Combin zone (Frilihorn nappe). Peak metamorphic pressures in the Combin zone are 1.3–1.8 GPa in the blueschist facies (Bousquet et al., 2004). Hence, there is a pressure gap of c. 1.2 GPa across the fault, equivalent to a vertical section of c. 43 km thickness (assuming crustal lithology with a density of 2.8 g cm^{-3}) or 36 km (assuming mantle lithology with a density of 3.3 g cm^{-3}) that has been removed from between the Combin zone and Zermatt-Saas zone. The high-pressure metamorphism of both the Zermatt-Saas and Combin zones is assumed to result from subduction towards the south or southeast.

There are two conventional ways to explain the pressure gap across the Combin fault. Either the Combin fault is a normal fault that accommodated the exhumation of the Zermatt-Saas zone or a thrust that postdates the exhumation. Both options, however, are contradicted by field evidence.

Ballèvre and Merle (1993), Reddy et al. (1999), and Wheeler et al. (2001) proposed that the Combin fault was, in its original geometry, a southeast-directed normal fault. Wheeler et al. (2001) suggested that the extensional shear zone comprised the entire Combin zone and accommodated a top-to-the-southeast displacement with a vertical component of c. 60 km and a horizontal component of c. 100 km during the Eocene. This would make this shear zone by far the most important syn-orogenic normal fault in the Alps, and one of the largest normal faults on Earth. In fact, mylonites with top-to-the-southeast shear sense occur along the Combin fault. However, structural work along the Combin fault (Sartori, 1987; Steck, 1990; Ring, 1995) has shown that the top-to-the-southeast shearing is indeed predated by top-to-the-northwest (deformation phase D$_1$) and top-to-the-southwest (deformation phase D$_2$) shearing within the same shear zone. D$_2$ and even the late stage of D$_1$ already occurred under greenschist-facies conditions. Hence, top-to-the-southeast shearing (D$_3$) postdates the main exhumation of the Zermatt-Saas eclogites and, in consequence, cannot have produced the pressure gap.

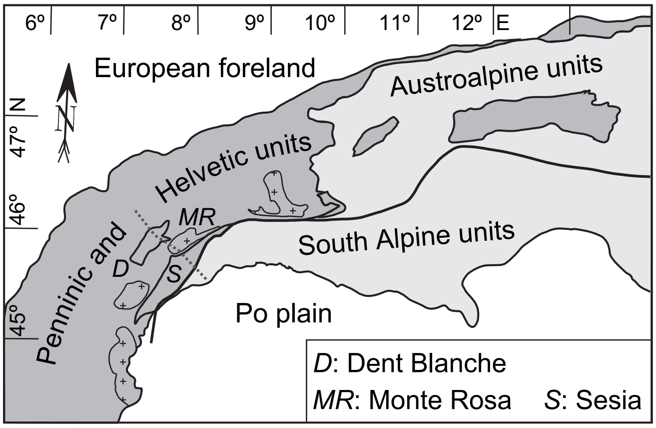


Fig. 5. Tectonic overview map of the Alps. The trace of the cross section in Fig. 6 is given by the dotted line.

Ring (1995) found that the Combin fault actually represents an Eocene-age northwestward thrust, overprinted by later top-to-the-southeast displacement of much lesser importance. However, northwestward thrusting cannot have exhumed the Zermatt-Saas zone, since thrusts do not exhume their footwall rocks but bury them. Therefore, Ring (1995) suggested that the thrusting along the Combin fault was out-of-sequence and postdated the high-pressure metamorphism. In this case, however, a displaced continuation of the eclogite-facies Zermatt-Saas zone should occur in the hanging wall of the Combin fault further to the northwest. As this is not the case, the thrust hypothesis is also unable to satisfactorily explain the observations.

According to our findings, the D$_1$ phase of northwest-directed shearing went on in two stages (D$_{1a}$ and D$_{1b}$). Fig. 6b shows the reconstructed situation after D$_{1b}$ and Fig. 6c the situation after D$_{1a}$. In Fig. 6c, the Combin zone and the Zermatt-Saas zone are shown to be separated to the south by a wedge of continental crust, the later Sesia–Dent Blanche nappe. During D$_{1a}$, preceding the situation shown in Fig. 6c, the Combin zone ophiolites were thrust northwestward over the Sesia–Dent Blanche nappe. In this process, part of the sedimentary cover of the Sesia–Dent Blanche basement was detached and dragged along with the Combin zone ophiolites, forming the Cimes-Blanche nappe. At the same time, the Zermatt-Saas ophiolites were exhumed from below the Sesia–Dent Blanche nappe. Very considerable differential exhumation across this contact is necessary because of the large difference in metamorphic pressure between the frontal part of the Sesia–Dent Blanche nappe (1.0–1.2 GPa, Bucher et al., 2004) and the Zermatt-Saas zone. According to our interpretation, this exhumation was accommodated by normal faulting or shearing at the base of the Sesia–Dent Blanche nappe, simultaneous with the northwestward thrusting of the Combin zone. The normal fault joined the thrust at the tip of the Sesia–Dent Blanche wedge. From there towards north, the Zermatt-Saas zone and the Combin zone came into direct contact along an extraction fault. North of the tip of the Zermatt-Saas zone,

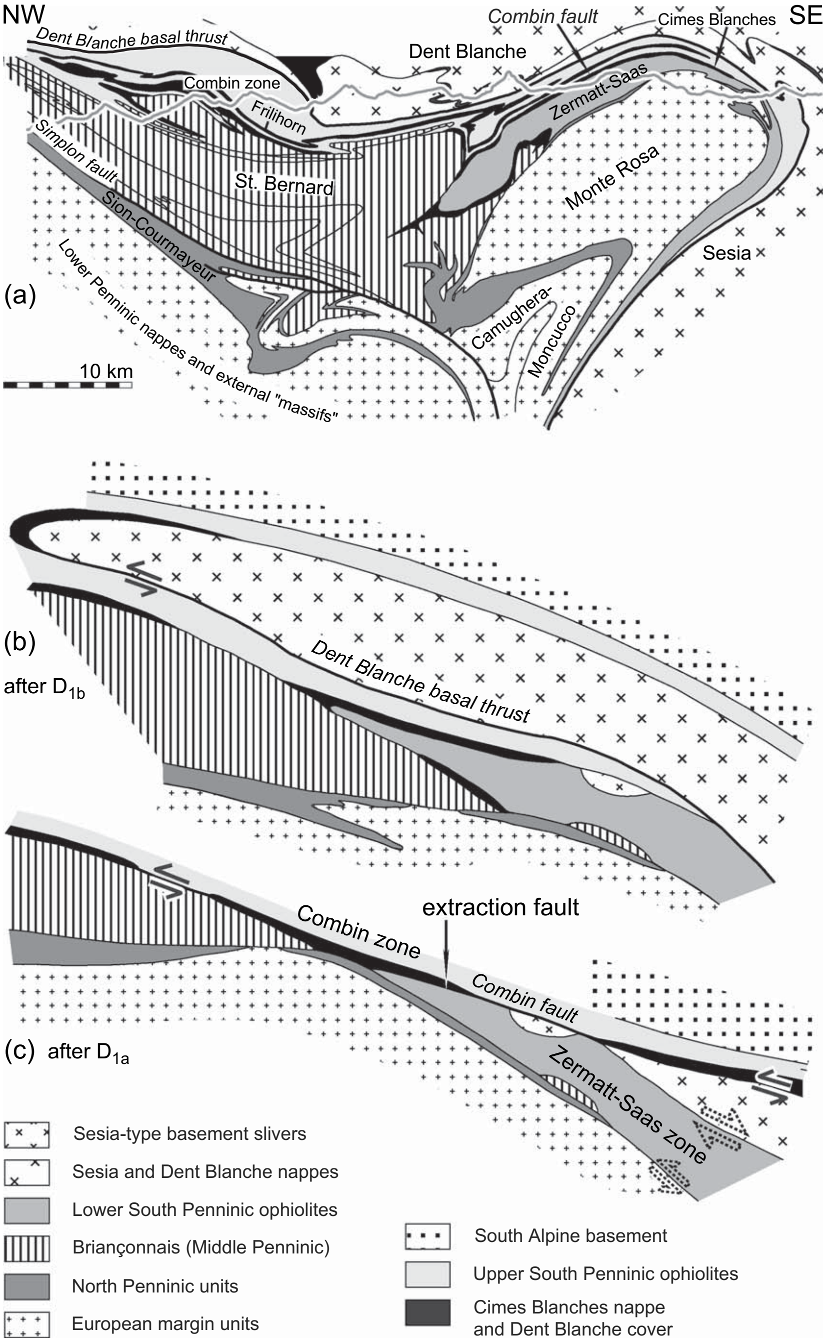


Fig. 6. (a) Present-day cross section through the Swiss–Italian western Penninic Alps. Modified after Escher et al. (1993). (b) Restoration of the nappe stack after the deformation phase D_{1b}, in the course of which the Sesia–Dent Blanche nappe system was emplaced onto the Combin zone along the out-of-sequence Dent Blanche basal thrust. (c) Restoration of the nappe stack after D_{1a}. In this earlier stage of thrusting along the Combin fault, the Combin zone was thrust onto the Sesia–Dent Blanche nappe system to the south, the Zermatt-Saas zone in the middle, and the St. Bernard nappe system to the north. Simultaneously, the Zermatt-Saas zone was exhumed along a normal fault located at its border against the Sesia–Dent Blanche nappe system. The faults merge together at the northern tip of the Sesia–Dent Blanche nappe system. North of this point, this resulted in a mixed extraction fault with a net top-to-the-northwest transport.

the pressure gap across the Combin fault disappears and the fault has the character of a northwest-directed thrust emplacing the Combin zone on the St. Bernard nappe. Hence, the Combin zone is not a pure but a mixed extraction fault (Fig. 1). The normal fault at the base of the Sesia–Dent Blanche nappe was later, during D_{1b}, reactivated to form the out-of-sequence thrust (''Dent Blanche basal thrust'') that emplaced the Sesia–Dent Blanche nappe on top of the Combin zone (Figs. 6b and 7). If there existed top-to-the-southeast mylonites along the normal fault, these may have been completely erased during northwest-directed out-of-sequence thrusting.

The kinematic evolution of the Combin extraction fault is sketched in Fig. 7. The dashed line is an arbitrary isobar in the starting configuration, and the grey shading indicates rocks that underwent pressures above this isobar. Both the Combin and the Zermatt-Saas zone are displaced northwestward

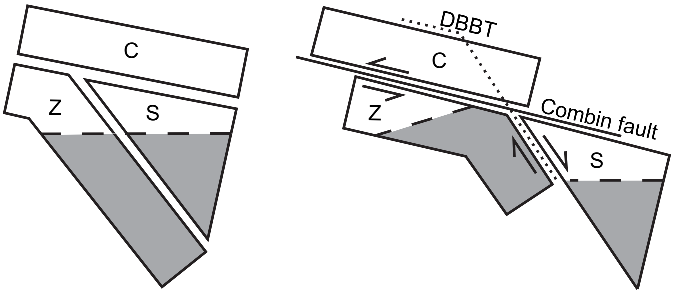


Fig. 7. Kinematic sketch of the extraction of the Sesia–Dent Blanche nappe system (S) during D_{1a}, leading to emplacement of the Combin zone (C) onto the Zermatt-Saas zone (Z) and the exhumation of the latter. Left: Starting configuration. Grey field represents rocks below an arbitrary isobar (dashed line) given to visualize the exhuming effect of extraction faulting. Right: Situation after extraction. Stippled line "DBBT" is the trace of the future Dent Blanche basal thrust which will form during D_{1b} and emplace the Sesia–Dent Blanche nappe system on top of the Combin zone.

relative to the Sesia–Dent Blanche wedge. This is equivalent to an extraction of the Sesia–Dent Blanche nappe towards southeast and it is this extraction that generates the pressure gap between the Zermatt-Saas and the Combin zone. The amount of northwestward displacement relative to the Sesia–Dent Blanche nappe is higher for the Combin zone than for the Zermatt-Saas zone. Therefore, the shear sense along the Combin fault is everywhere top-to-the-northwest during this early stage of deformation (D_{1a}). This model reconciles the observed top-to-the-northwest shear sense along the Combin fault with the observed pressure gap.

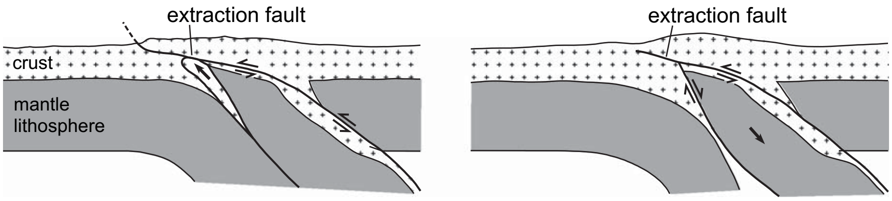
The mechanical background of this process is still speculative. The northwestward thrusting of the Combin zone reflects crustal shortening across the Alps resulting from Europe–Adria convergence. The northwestward and upward motion of the Zermatt-Saas zone relative to the Sesia–Dent Blanche wedge, on the other hand, may represent extrusion of the Zermatt-Saas ophiolites from the subduction zone under the Sesia–Dent Blanche terrane into which they had descended before. This extrusion may have been driven either by buoyancy of the Zermatt-Saas zone which is rich in low-density serpentinite, or by an increase in horizontal compressional stress when the European continental margin entered the subduction zone. Thus, we suggest that the mechanism leading to the extraction fault was, in this case, extrusion in the footwall of a thrust. A further mechanism potentially leading to the formation of an extraction fault is slab extraction (Froitzheim et al., 2003), the downward removal of a wedge of mantle and lower crustal rocks through subduction. Fig. 8 shows schematically these two possibilities of extraction fault formation during continent collision.

4. Discussion and conclusion

Most text-book definitions of the term "fault" require the displacement to be parallel to the fault surface (e.g., Hobbs et al., 1976). According to these definitions, the structures described here would not be faults. However, in many cases where two faults coalesce, e.g., in a network of strike-slip faults, the finite differential displacement of points on both sides of the resulting fault is not parallel to the fault. Such faults would not pass the strict definition. The structures described in this article are discontinuities between rock volumes that have been juxtaposed by a tectonic movement. Therefore, we think it is reasonable to call these structures "extraction faults".

There is no doubt that extraction faults exist, if only at the small scale of boudinaged competent layers as shown in Fig. 2. What we propose in this article is that extraction faults may form large crustal structures such as the S-reflector of the Galicia margin and the Combin fault of the Penninic Alps. In the case of the S-reflector, this is relatively clear and was already suggested implicitly in earlier works (Brun and Beslier, 1996; Nagel and Buck, 2004). The occurrence of high-temperature, top-to-the-continent fault rocks and low-temperature, top-to-the-ocean fault rocks in the same fault zone (Beslier et al., 1990) makes an extraction fault highly probable. The only alternative would be to assume a reversal of the sense of displacement with time, first top-to-the-continent and then top-to-the-ocean. It is not clear what should have caused such a reversal of shear sense. Boudinage of the lower crust and uppermost mantle, which produces both shear senses at the same time, appears more plausible.

In the case of the Combin fault, extraction faulting is less obvious and our interpretation depends on the correctness of our geometric restoration. However, this concept offers an explanation for the fact that some high- and ultrahigh-pressure terranes in the Alps are capped by top-to-the-foreland shear zones, not only the Zermatt-Saas zone but also the Adula nappe in the Eastern Central Alps (Nagel et al., 2002; Pleuger et al., 2003) and the Dora-Maira massif in Western Alps (Michard et al., 1993). There, too, an alternative interpretation as



(a) extrusion in thrust footwall (b) slab extraction

Fig. 8. Two hypothetical kinematic scenarios that may lead to extraction faulting and high-pressure rock exhumation during continent collision. In (a), material extrudes from a subduction channel upward into the footwall of a low-angle thrust. In (b), a mantle and lower crust wedge sinks off (slab extraction) and leaves an extraction fault behind.

either normal faults dipping to the foreland or out-of-sequence thrusts is in conflict with field evidence, because if this were the case, there should exist a hanging-wall cut-off analogous to the footwall cut-off, that is, the high- and ultrahigh-pressure rocks should find their continuation in the more external (towards the foreland) parts of the hanging wall.

To conclude, the concept of extraction faulting explains some enigmatic features of large-scale tectonic structures. In the case of non-volcanic passive continental margins, it explains why fault rocks with opposite shear senses are found in the same shear zone, and why the lower crust is lacking in the area of the ocean–continent transition. In the case of high- and ultrahigh-pressure exhumation in collisional orogens, extraction faulting offers an explanation for the frequently observed paradox that high- and ultrahigh-pressure rocks are capped by large-scale, foreland-directed faults or shear zones.

Acknowledgements

We thank reviewers Adrian Pfiffner and Bernhard Fügenschuh as well as editor Cees Passchier for their corrections and suggestions which have substantially improved the manuscript. Supported by DFG grant No. FR700/6-2 to N.F. and grant No. NA411/1-1 to T.J.N.

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