

Out-of-sequence thrusts and paleogeography of the Rhenodanubian Flysch Belt (Eastern Alps) revisited

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Abstract The Oberstdorf nappe of the Western and the Laab nappe of the Eastern Rhenodanubian Flysch (ERF) were independently identified as out-of-sequence thrust units by facies studies (Mattern 1999) and zircon analyses (Trautwein et al. 2001a, b, c), respectively. A new look at both areas reveals mutual similarities and new evidence for the out-of-sequence concept. Paleocurrent and heavy mineral data make it possible to reconstruct the sediment influx directions. From the Barremian to the mid-Campanian, the western and eastern basin segments were fed with south-derived garnet and north-derived zircon/“ZTR” (i.e., zircon, tourmaline, and rutile). Because both out-of-sequence units are relatively rich in zircon/ZTR they must have occupied the northernmost basin position. In the Western Rhenodanubian Flysch segment, the Sigiswang nappe occupied the central and the Üntschen nappe the southernmost basin position. In the ERF segment the central basin is represented by the Greifenstein nappe and the southernmost basin by the Kahlenberg nappe. Both out-of-sequence units do not occur in the northernmost and tectonically lowest position in their respective nappe piles as they were thrust over the other nappes. The reconstructed basin positions of the thrust units are suggested by the observation of a gradient in heavy mineral content in the thrust units. This paleogeographic arrangement is least

problematic and renders models with differently positioned thrust units, requiring debris-shedding intrabasinal ridges, as unnecessarily complicated. Instead, we suggest that gradual changes in heavy mineral composition existed in across-basin direction. Garnet may stem from the Central Gneiss Complex of the Tauern window and formerly exposed lateral equivalents, all representing the southern Mid-Penninic zone. We assign the Falknis/Tasna nappe and formerly exposed lateral equivalents to the northern Mid-Penninic zone which served as the zircon/ZTR source. Interpreting Ebbing’s (Ph.D. thesis, Freie Universität Berlin, pp 1-143, 2002; Fig. 6.10) density section, we suggest that Mid-Penninic crust exists beneath the Central Gneiss Complex. During the latest Cretaceous much garnet was also N-derived. This may reflect processes related to the consumption of the North Penninic basin.

Keywords Eastern Alps · Rhenodanubian Flysch Zone · Out-of-sequence thrusts · Heavy minerals · Paleocurrents

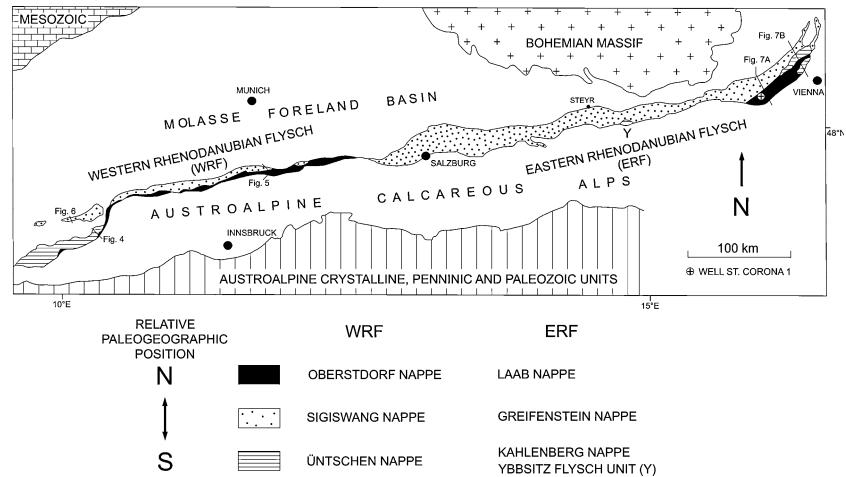
Introduction

Mattern (1997, 1999) and Trautwein et al. (2001b) independently concluded that the Western and Eastern Rhenodanubian Flysch (WRF/ERF, Fig. 1), respectively, contain out-of-sequence thrusts. We outline similarities between both areas as related to the out-of-sequence structure. Moreover, we reevaluate heavy mineral and paleocurrent data for possible support of the out-of-sequence concept. In line with that, we reconstruct sediment/heavy mineral influx directions to deduce the nappes’ relative basin positions. We also address the issue of whether gradual intrabasinal changes in heavy mineral composition existed in across-basin direction.

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Fig. 1 Study area (after Mattern 1997; Trautwein et al. 2001b) with Rhenodanubian nappes. The Üntschen nappe represents a basin segment paleogeographically south of the Sigiswang nappe because outliers of flysch rocks north of the Üntschen nappe display basal structures similar to the hanging-wall ramp geometry of the Sigiswang nappe (Mattern 1999)



The WRF contains Cretaceous, the ERF Cretaceous–Eocene strata (Figs. 2, 3). The thickness of individual thrust nappes measures 1–3 km. The flysch was overthrust mainly by Austroalpine nappes during the Eocene (Trautwein et al. 2001b). The Helvetic thrust units and the Molasse foreland basin were overthrust by the flysch until the Early Miocene (Decker et al. 1993).

South Alpine paleogeographic units are dominated by garnet (Woletz 1980; Wildi 1985), northern ones by zircon/“ZTR association” (i.e., zircon, tourmaline, and rutile; Woletz 1980; Wildi 1985). The latter include (1) Helvetic units of Europe’s former passive margin, (2) Niesen nappe, Feuerstätt mélangé, Prättigau, and Vaduz flyschs of the adjacent North Penninic ocean basin, and (3) Falknis/Tasna nappe from the continental Mid-Penninic region south of the ocean basin (Gasser 1967; Woletz 1980; Wildi 1985). South of the Mid-Penninic realm, the South Penninic ocean basin was located represented by the Arosa mélangé, with the Cenomanian Verspala Flysch, bearing high amounts of chrome spinel (Burger 1978; Woletz 1980; Wildi 1985; Winkler 1988; Faupl and Wagreich 1992). Further south was the continental Austroalpine/Adriatic region.

The main ZTR mineral source is the granitic European basement including the Alps’ external massifs (Wildi 1985). The main garnet sources include South Alpine/Adriatic

basement units as well as the Central Gneiss Complex of the Tauern area (Wildi 1985; see also Oberhauser 1964, 1968; Frisch 1976). Wildi (1985, p. 91) also reflected on the possibility of Mid-Penninic garnet sources.

In contrast to, e.g., Schmid et al. (2004), some authors favor the idea that the Mid-Penninic region extends far into the Eastern Alps (e.g., Clar 1965; Tollmann 1965, 1978, 1990; Faupl 1978; Frisch 1978; Frisch et al. 1987; Oberhauser 1995; Faupl and Wagreich 1992, 2000; Mattern 1999) which is significant concerning the presence of a possible southern garnet source. Oberhauser (1995) had shown the paleogeographic relationships between the Eastern Alps, including the Mid-Penninic Rhenodanubian Flysch, and the West Carpathian Mountains.

Concerning European sources from the north, Wildi (1985) considered the Bohemian Massif (Fig. 1) as a possible garnet source. It was uplifted during the Late Cretaceous (e.g., Wildi 1985; Ziegler 1987, Peterek et al. 1997) shedding increasing amounts of garnet to adjoining areas (Fuchs et al. 1985). According to Fuchs et al. (1985), the change from zircon to garnet dominance occurred at the Santonian–Campanian transition in pre-Molasse foreland basin deposits.

Although the flysch’s paleogeographic origin is commonly believed to be North or South Penninic, Oberhauser

Fig. 2 Stratigraphy of the WRF, mainly after Schwerd (1996). Age of the Gault-Flysch of the Oberstdorf nappe is after U. Wortmann (personal communication). Occurrence of the Piesenkopf Fm. in the Oberstdorf nappe and of the Obere Bunte Mergel in the Sigiswang nappe is local

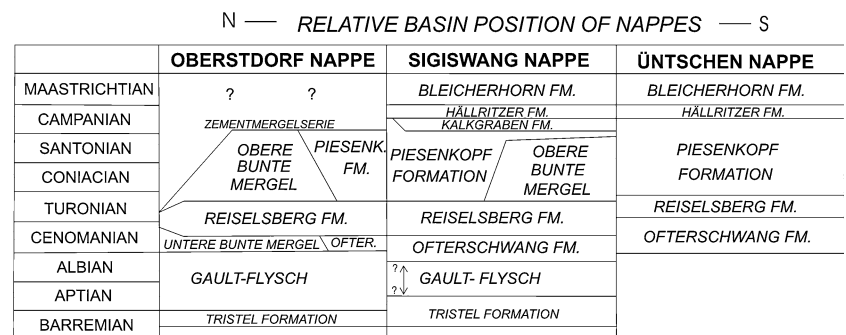
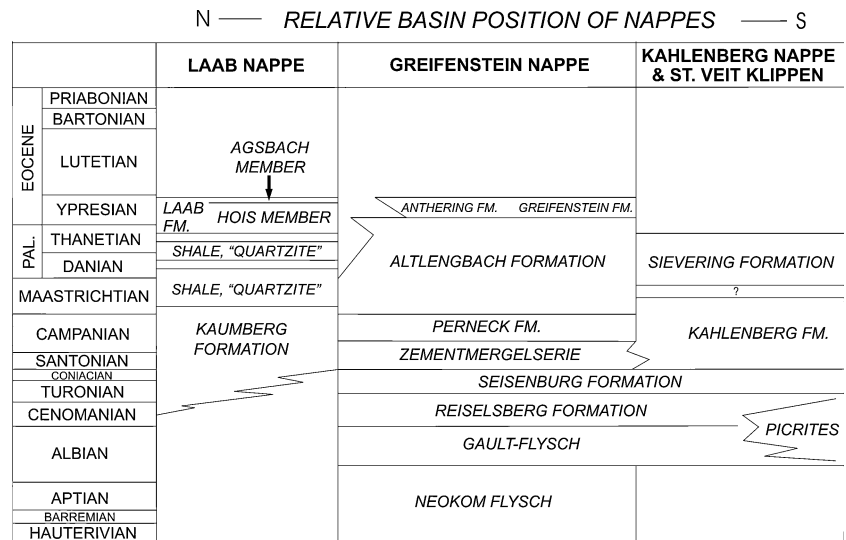


Fig. 3 Stratigraphy of the ERF, mainly drawn after Trautwein et al. (2001b) on the basis of Prey (1980), Plöchinger and Prey (1974), Egger (1995), and Faupl (1996), Agsbach Member, Greifenstein Fm. and Anthering Fm. according to Egger (1995) and H. Egger (personal communication). Other information according to Tollmann (1985) and Wessely (2006)



(1995) and Mattern (1997, 1999) deduced a Mid-Penninic position. It is not intended to elaborate on the flysch basin's Mid-Penninic position and, thus, duplicate existing literature but rather to further establish the out-of-sequence concept by showing relevant similarities of both flysch areas.

Thrust structure

The structure of the WRF has been documented in 54 cross-sections (Mattern 2004) that are used in the following description. The WRF consists of the Oberstdorf nappe, Sigiswang nappe, and Üntschen nappe. The latter is restricted to the westernmost area (Fig. 1). The out-of-sequence Oberstdorf nappe, as the structurally highest and southernmost flysch nappe, was thrust over the other two nappes (Figs. 1, 4, 5). This thrust is marked by fault-bound slices of units that are tectonically lower than the flysch and by slices of the flysch itself.

The base of the Sigiswang nappe tends to display a hanging-wall ramp geometry with relatively young basal, frontal rocks and relatively old rocks at the trailing edge (Fig. 6). The basal, frontal rocks of the Üntschen nappe (Oferschwang Fm.) and Oberstdorf nappe (Tristel Fm. or Gault-Flysch) are the oldest ones known in these nappes

(Figs. 4, 5). For the Oberstdorf nappe this can be attributed to a hanging-wall flat geometry (Figs. 4, 5). The structure of the Oberstdorf nappe differs from that of the other two nappes by more intense deformation with common internal thrusts (Figs. 4, 5).

The ERF consists of the Kahlenberg, Laab, and Greifenstein nappes. Only the latter extends along the entire ERF (Fig. 1). It displays internal thrusts in the Vienna and Salzburg areas (Fig. 7; Schnabel 1992a; Egger 1989). Approximately 40 km west of the center of Vienna, the structure is simple with the Laab nappe thrust over the Greifenstein nappe (Fig. 7a). Close to the location of the structural cross-section depicted in Fig. 7a, well St. Corona 1 is located (Fig. 1) which penetrated a thin slice of the Kahlenberg nappe between the Laab and Greifenstein nappes (Wessely 2006). Northwest of Vienna the structure is more complex. There, the Greifenstein nappe represents the frontal, northernmost nappe occupying the tectonically lowest position. At the surface, a part of the Kahlenberg nappe rests on top of the Greifenstein nappe (Fig. 7b). In the subsurface, the Laab nappe also has overridden the Greifenstein nappe (Fig. 7b). The Kahlenberg nappe, representing the tectonically highest nappe, also occurs on top of the Laab nappe (Fig. 7b; Faupl 1996). A traditional view implies divortication of the Kahlenberg nappe to a degree that its northern part became isolated from the rest of the

Fig. 4 Cross-section showing the Üntschen nappe overthrust by the Oberstdorf nappe. Note the internal thrusts within the Oberstdorf nappe. For location of section, see Fig. 1; drawn after Zacher (1972)

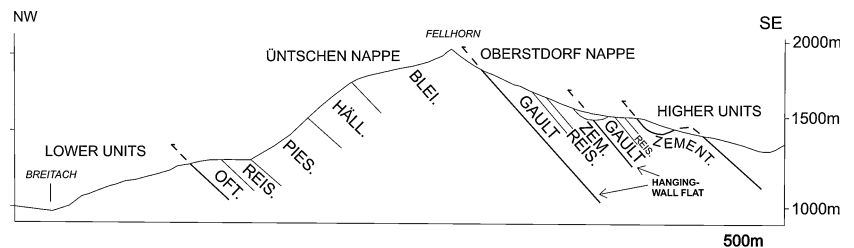


Fig. 5 Depth-extrapolated cross-section. Note the internal thrusts within the Oberstdorf nappe and their hanging-wall flat geometry. For location of section, see Fig. 1; drawn after Mattern (2004)

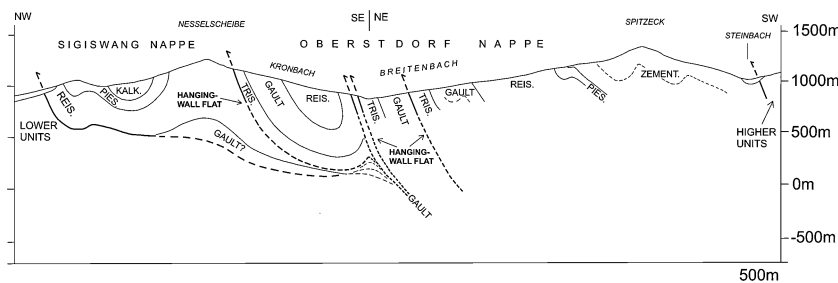


Fig. 6 Cross-section of the Sigiswang nappe. Note the hanging-wall ramp geometry. For location of section, see Fig. 1; drawn after Zacher (1972)

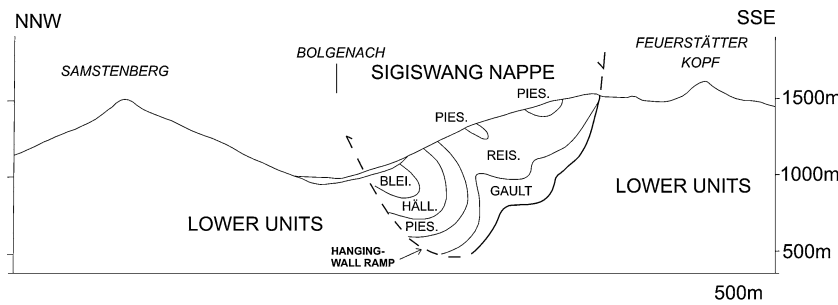
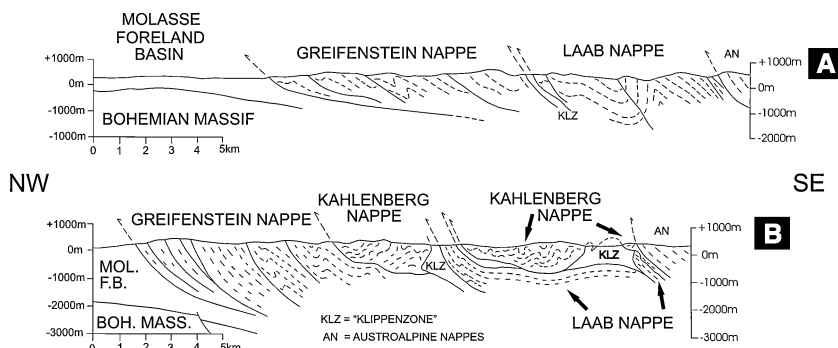


Fig. 7 Cross-sections of the ERF; **a** simplified after Prey (in Plöching and Prey 1974); **b** simplified after Prey (1980). For locations of cross-sections, see Fig. 1



nappe (Prey 1979). Subsequent shortening and folding may have given the impression in some sections that the Laab nappe generally rests on the Kahlenberg nappe (Faupl 1996). A different view attributes the present structure to out-of-sequence thrusting, implying emplacement of the Kahlenberg nappe on the Laab and Greifenstein nappes before the out-of-sequence thrust at the base of the Laab nappe emplaced the Laab nappe on both the Greifenstein nappe and the northern part of the Kahlenberg nappe.

Heavy mineral and facies gradients: analysis of relative paleogeographic positions of nappes

Western Rhenodanubian Flysch Zone

The Tristel Fm. and Gault-Flysch (Fig. 2) occur in the Oberstdorf, Sigiswang, and Falknis/Tasna nappes. The Tristel Fm. contains submarine fans; a major fan existed in the Tasna nappe (Schwizer 1984). The Gault-Flysch of the

Falknis/Tasna nappe also contains a submarine fan which supplied the basin plain of the WRF with sediment (Hesse 1973). High zircon contents characterize both formations. For new data on the Lower Cretaceous rocks see Wortmann (1996) and Wortmann et al. (2004).

Schwizer (1984, quoting Woletz), who investigated the Tristel Fm. mainly in the Falknis/Tasna nappe and the WRF, reported the dominance of zircon, presence of rutile and tourmaline, and absence of chrome spinel and garnet in the western part of his study area. Farther east, Hesse (1966) observed the dominance of zircon over garnet (Fig. 8).

Zircon dominates the Gault-Flysch south of Munich and in the Falknis/Tasna nappe (Fig. 9; Woletz 1967, 1980; Faupl and Wagneich 1992). A comparison of spectra from both areas is problematic since the authors did not reveal the actual percentage figures. However, garnet is less common in the Falknis/Tasna nappe than south of Munich (Fig. 9), reflecting a gradual compositional change in across-basin direction and indicating that the Falknis/Tasna

Fig. 8 Heavy mineral distribution and main paleocurrent direction in the Tristel Fm. Toward the east, the garnet content increases where paleocurrent information is lacking

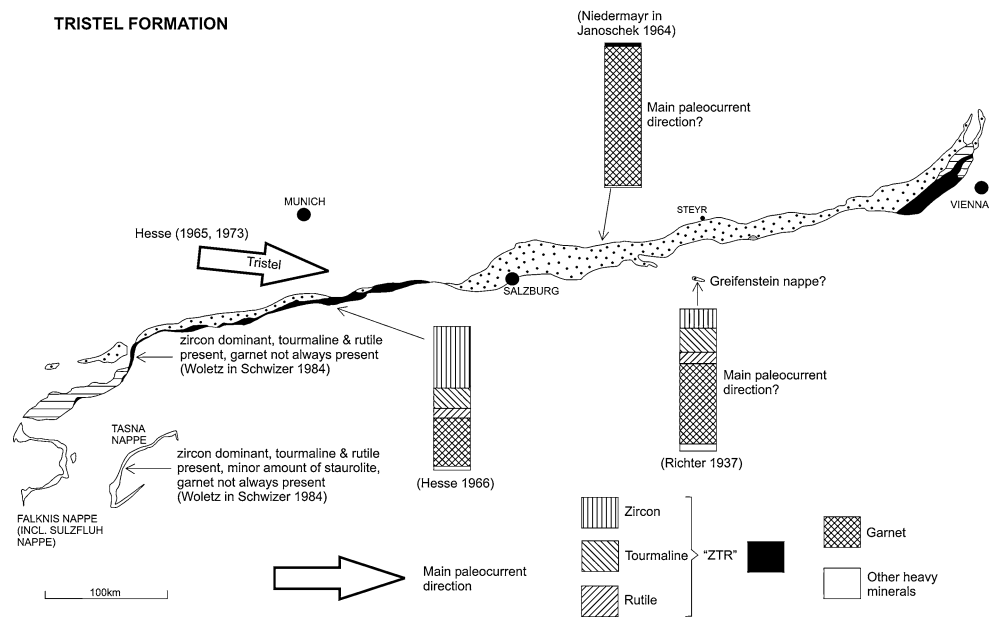
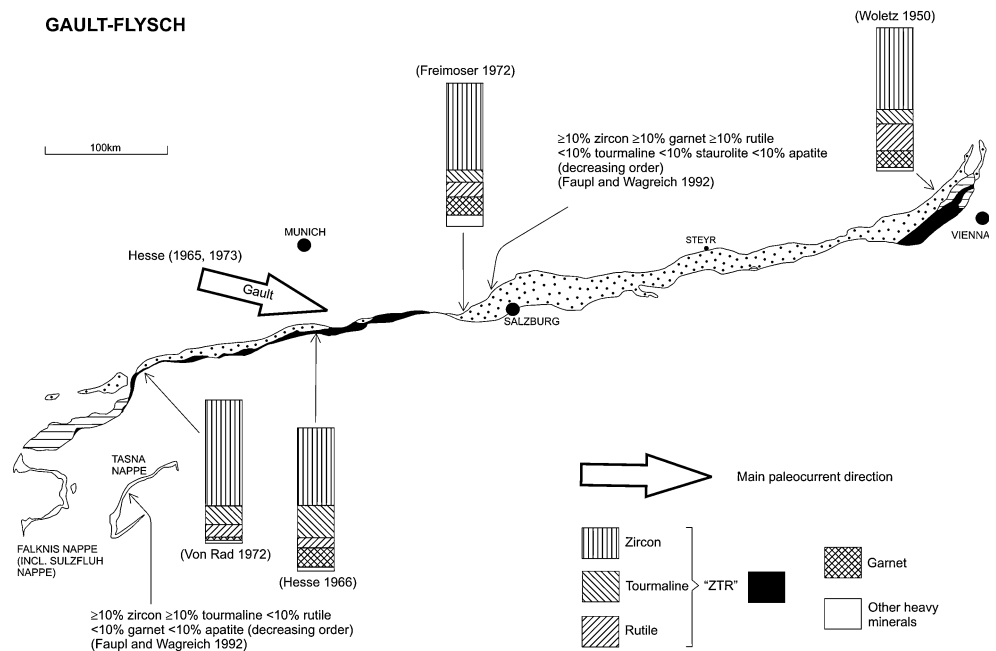


Fig. 9 Heavy mineral distribution and main paleocurrent direction in the Gault-Flysch



nappe occupied a basin position north of the WRF belt, considering Wildi's (1985) finding that garnet stems from southern Alpine units. The garnet content of the Gault-Flysch in the westernmost parts (Oberstdorf and Tasna nappes) is very low and, thus, similar to the distribution pattern observed in the Tristel Fm. (Figs. 8, 9).

During the early Cretaceous, the Rhenodanubian Flysch was supplied with sediment from the Falknis/Tasna area (Hesse 1973; Schwizer 1984). Although Hesse (1973; Fig. 13) depicted a sediment influx from the south, he also considered a possible sediment influx from the northwest (Hesse 1973, p. 11). Schwizer (1984, p. 76) mentioned the

orientations of paleoflow indicators of the Falknis/Tasna area but did not mention the polarity of the currents. Early Cretaceous paleocurrents in the Rhenodanubian Flysch are mainly ESE-directed, intersecting with the flysch zone's trend from the north (Figs. 8, 9). Thus, these data indicate a northern sediment influx for the Tristel Fm. and Gault-Flysch which is compatible with Wildi's (1985) concept of northern ZTR sources.

With the Ofterschwang Fm. (Fig. 2), a new source was activated in addition to the zircon-rich source. Samples exhibit a dominance of zircon over garnet or vice versa (Von Rad 1972). The new source became pre-dominant

during deposition of the Reiselsberg Fm. (Figs. 2, 10). A high garnet content also occurs in this formation of the Üntschen nappe (Woletz 1967) from where also small amounts of chrome spinel are known (Oberhauser 1995). Southwest of Munich, the Reiselsberg Fm. of the Oberstdorf nappe contains more zircon, tourmaline, and rutile and less garnet than the neighboring parts of the Sigiswang nappe (Fig. 10; Von Rad 1972, pp. 107–109, 128). This observation concerns the Allgäu fan (Fig. 11). Farther east, in the Oberstdorf nappe, the garnet content in the Isar fan is higher than in the Allgäu fan (Figs. 10, 11). There, the Oberstdorf nappe includes a southern basin segment with inner fan facies (Fig. 11; Mattern 1998). The Falknis/Tasna nappe lacks “Rhenodanubian Flysch formations” younger than the Gault-Flysch.

The Reiselsberg Fm. contains sand-rich, submarine fans, two of them exposing the inner fans in a lateral distance of 65 km (Fig. 11). This is significant since the inner fan always occurs adjacent to the basin slope (Normark 1970). Thus, it is established that the flysch was tectonically removed from the basin parallel to its Cenomanian–Turonian basin slope contiguous to the fans—a prerequisite for the interpretation of paleocurrents and lateral sediment influx directions in the WRF. Since the WNW-directed paleocurrents (Hesse 1965; Von Rad 1972; Mattern 1999) intersect with the general trend of the WRF, a southern sediment influx across the inner fans can be confidently deduced. It also validates the deduced northern zircon influx during the Early Cretaceous.

The higher ZTR and lower garnet contents in the Reiselsberg Fm. of the Oberstdorf nappe compared to that of the Sigiswang nappe (above) is explained by a gradual

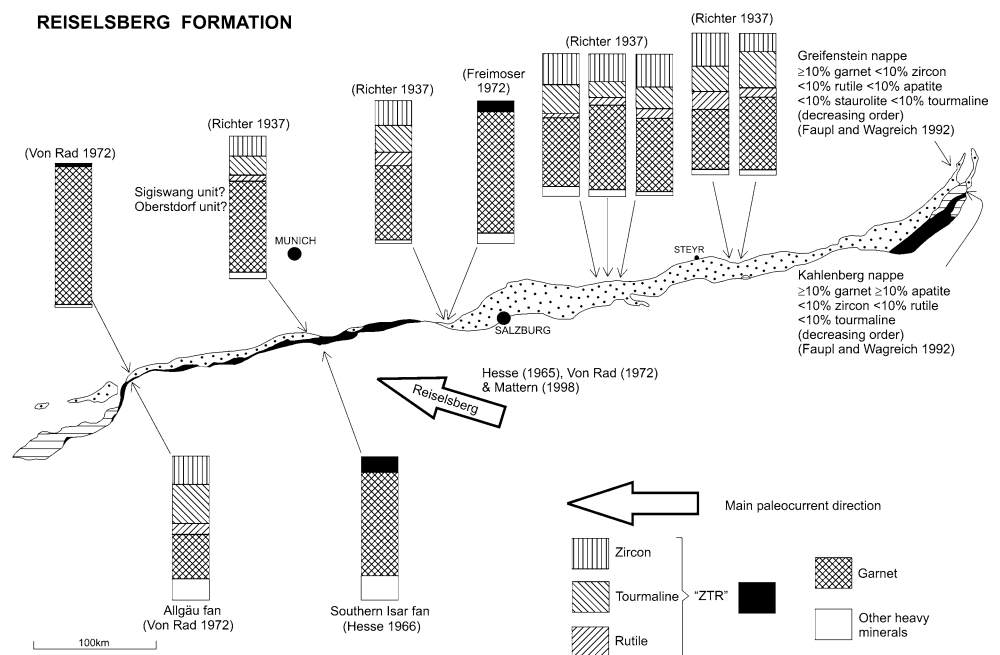
compositional change in across-basin direction due to the influence of the depositional system of the northern basin slope and sediment-mixing affecting the sediments of the Oberstdorf nappe. Thus, the Oberstdorf nappe must have occupied a basin position north of the Sigiswang nappe all the more so since the Reiselsberg Fm. of the former is thinner than in the latter (being the thickest in the Üntschen nappe; Mattern 1998).

The change in paleocurrent direction from ESE-directed (Tristel Fm. and Gault-Flysch) to WNW-directed (Reiselsberg Fm.) coincides with the deposition of the Ofterschwang Fm. (Fig. 2) which displays zircon- and garnet-dominated samples and a great scatter of paleocurrent directions (Von Rad 1972).

The Piesenkopf Fm. (Fig. 2) is interpreted as a basin slope deposit (Mattern 1998). The high garnet content of this formation (garnet >ZTR despite its fine-grained character; Richter 1937; Von Rad 1972) and its greatest formation and bed thickness in the Üntschen nappe shows that it was supplied with sediment from the depositional system of the southern basin slope. The above analysis of formations establishes that garnet derived from the south and zircon/ZTR from the north. It is the key for interpreting the remaining Cretaceous formations, allowing for less detailed explanations.

During deposition of the Zementmergelerde of the Oberstdorf nappe and the facies equivalent and partly time equivalent Kalkgraben Fm. of the Sigiswang nappe (Fig. 2), a second major change in the depositional pattern occurred. Both formations represent basin plain deposits (Hesse 1995) and contain significantly more ZTR material and less garnet than the Reiselsberg Fm. (Fig. 12). Since the paleocurrents

Fig. 10 Heavy mineral distribution and main paleocurrent direction in the Reiselsberg Fm. Note that the samples of Von Rad (1972) reveal for the paleogeographically northern Oberstdorf nappe less garnet than in the neighboring Sigiswang nappe which occupied a position south of the Oberstdorf nappe



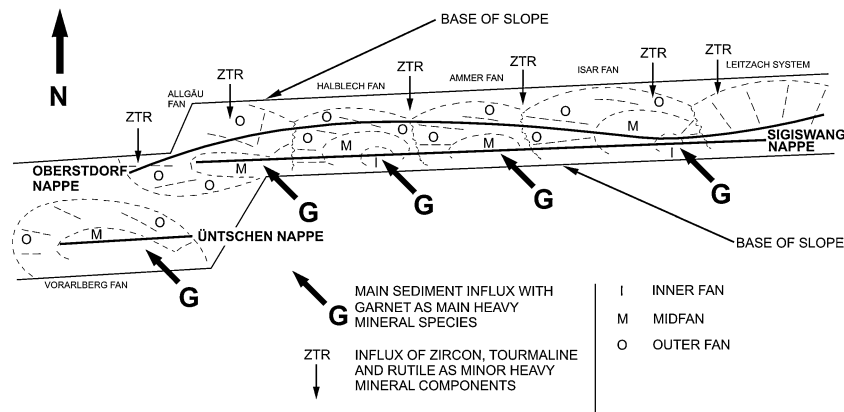


Fig. 11 Reconstruction of the submarine fan system of the Reiselberg Fm. and basin positions of the WRF's nappes (*bold lines*); modified after Mattern (1998, 1999). Note the inner fan facies in the Halblech and Isar fans. Also note that the Oberstdorf nappe contains the most distal and, thus, thinnest fan deposits while the main sediment influx was from the south. Reconstruction is based on 87 measured sections (Mattern 1999) and considers (1) paleocurrents, (2) southern garnet-rich sediment influx centers, (3) relatively high ZTR

and relatively low garnet content of the formation in the Oberstdorf nappe in comparison to that of the Sigiswang nappe, (4) lateral thickness, grain size, and facies variations as observed in the different nappes, (5) distribution of (southern) basin slope deposits, (6) bed correlations between thrust units, and (7) the distribution of the Untere and Obere Bunte Mergel, Zementmergelserie, Piesenkopf, and Kalkgraben fms. as discussed in Mattern (1998, 1999). All data dictate to assign the Oberstdorf nappe to the northern basin position

of both formations are similar to those of the Gault-Flysch and since there is more ZTR material and less garnet in the Zementmergelserie (Fig. 12), a northern sediment influx to and basin position of the Oberstdorf nappe is concluded. The heavy mineral spectra of both formations show again the presence of gradual across-basin compositional changes.

The Hällritzer and Bleicherhorn fms. of the Sigiswang nappe (Fig. 2) are dominated by garnet (Hesse 1972; Von Rad 1972). The depositional systems of both formations have not yet been identified. Only 17 paleocurrent directions are known from the Hällritzer Fm., 11 of which intersect with the trend of the flysch belt from the north, four from the south, the remainder being parallel (Hesse 1965). From the Bleicherhorn Fm. the only paleocurrent direction (Hesse 1965) indicates SW-directed transport. The limited data tentatively suggest that the paleogeography had changed during the latest Cretaceous. Since the Zementmergelserie is ZTR-dominated and the Hällritzer and Bleicherhorn fms. garnet-dominated and all were mainly fed with sediment from the north, it is concluded that garnet was now being shed from the north along with ZTR material.

Since the Oberstdorf nappe occupied the northernmost basin position (Fig. 11, note caption) but represents the tectonically highest flysch element (Figs. 4, 5), it is an out-of-sequence thrust unit.

Eastern Rhenodanubian Flysch Zone

The trend of eastward increasing garnet content in the Tristel Fm. is continuous into the ERF. Garnet may even dominate the spectrum (Fig. 8; Niedermayr in Janoschek

1964). For this eastern segment, however, paleocurrent information is lacking (Fig. 8).

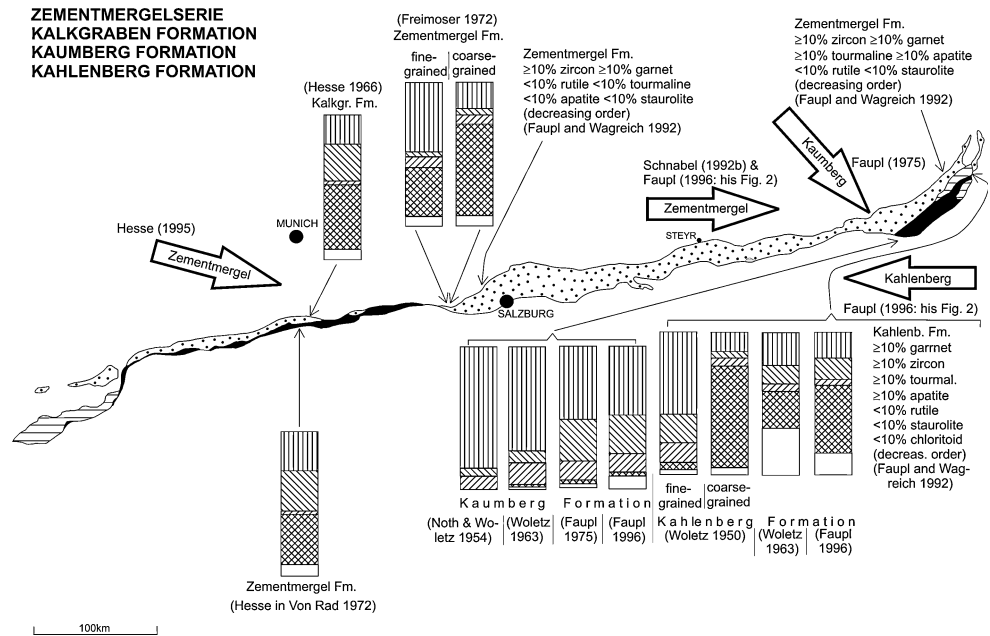
The Gault-Flysch (Fig. 3) is zircon-dominated (Fig. 9). Faupl and Wagneich (1992) found less garnet in the Gault-Flysch of the Falknis/Tasna nappe than in the Greifenstein nappe which agrees with the idea that the Falknis/Tasna nappe represents a northern influx center for the Rhenodanubian Gault-Flysch (above). The spectra of the Gault-Flysch reflect a gradual distribution trend across the basin.

The Reiselberg Fm. (Fig. 3) is garnet-dominated with different spectra in the Greifenstein and Kahlenberg nappes (Fig. 10). They may be similar to the gradual across-basin changes as observed in the nappes of the WRF (above). However, the relevant data by Faupl and Wagneich (1992) lack the actual percentage figures (Fig. 3). The Reiselberg Fm. of the Kahlenberg nappe contains small amounts of chrome spinel (Faupl and Wagneich 1992).

The three Turonian to Campanian formations (Fig. 3), representing basin plain deposits (Faupl 1976, 1996), display gradual compositional changes across the basin (Woletz 1954 and below). The Kaumberg Fm. of the Laab nappe contains the most zircon and least garnet (Fig. 12). The relative difference in zircon and garnet content is less pronounced in the Zementmergelserie of the Greifenstein nappe. In the Kahlenberg Fm. of the Kahlenberg nappe garnet even outweighs zircon (Fig. 12). In the Kaumberg Fm. garnet may be absent (Woletz 1962) and chrome spinel may be present (Faupl and Wagneich 1992; Faupl 1996).

The mainly SE-directed paleocurrents in the Kaumberg Fm. and E-directed paleocurrents in the Zementmergelserie

Fig. 12 Heavy mineral distribution and main paleocurrent direction in the Zementmergelerde, Kaumberg, Kalkgraben, and Kahlenberg fms. The samples by Freimoser (1972) and Woletz (1950) show that fine-grained sediment tends to contain more zircon/ZTR material and less garnet than coarse-grained deposits. For legend, see Fig. 8

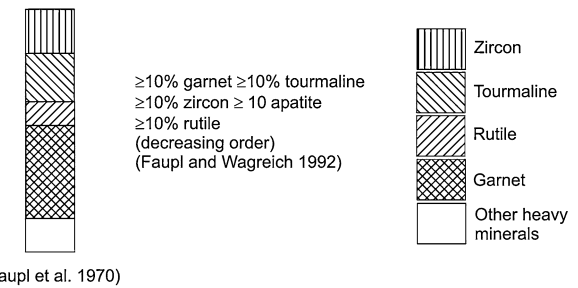


(Fig. 12) reveal a northern influx. In the garnet-rich Kahlenberg Fm., whose lithofacies is similar to that of the Zementmergelerde, paleocurrents intersect with the trend of the flysch belt in such a way that a southern source can be assessed (Fig. 12). The data suggest a northern position of the Laab nappe, a central position of the Greifenstein nappe, and a southern position of the Kahlenberg nappe in a basin with gradual compositional changes in across-basin direction.

In the Altlengbach Fm. and laterally equivalent Sievering Fm. (Fig. 3) of the respective Greifenstein and Kahlenberg nappes, garnet is the most common heavy mineral (Fig. 13). Garnet is seemingly more common in the Altlengbach Fm. than the Sievering Fm. which is contrary to the trend so far deduced for the Greifenstein and Kahlenberg nappes. A further look at the data reveals that within the Altlengbach Fm. a significant change in heavy mineral spectra exists (Woletz 1962; Schnabel 1992b; Faupl 1996); the older parts are garnet-dominated and characterized by W-directed paleocurrents (Schnabel 1992b; Egger et al. 2002) intersecting with the strike of the flysch belt from the south. Egger et al. (2002) also found Maastrichtian paleoflow directions from the north. Postmid-Danian beds are ZTR-dominated which were transported from the west and northwest (Schnabel 1992b) intersecting with the flysch zone's overall trend from the north.

The submarine fan-bearing (Faupl 1980) Sievering Fm. displays paleocurrents that are either parallel to or intersect with the trend of the flysch zone from the south (Faupl 1996, Fig. 2). In a local study of Maastrichtian sediments of the Sievering Fm., Faupl et al. (1970, Fig. 4) documented S-directed paleocurrents associated with

SIEVERING FORMATION



ALTLENGBACH FORMATION

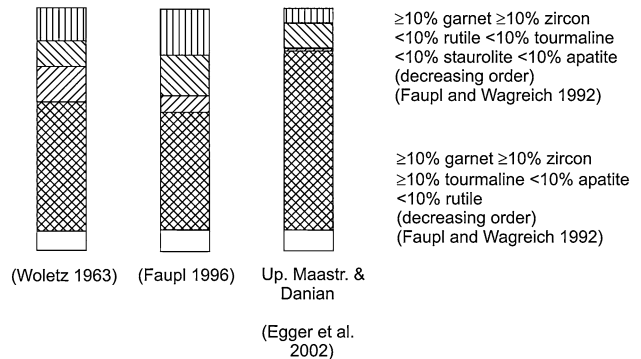


Fig. 13 Heavy mineral contents of the Sievering and Altlengbach fms

garnet-rich turbidites and WSW-, W-, and NW-directed paleocurrents intersecting with the general strike of the flysch zone from the south associated with the ZTR-dominated beds but also NW-directed currents with garnet predominance.

During the latest Cretaceous the paleogeography had changed because garnet was now being shed from the north and south to the Altlengbach and Sievering fms. It is intriguing that a similar interpretation applies to the latest Cretaceous rocks of the WRF (above). The significance of ZTR transport toward “western directions” in the Sievering Fm. is unclear, but local channel/fan channel meanders are a possible explanation (note that in the younger Altlengbach Fm. ZTR-dominated beds were transported from the west and northwest, thus, following the previous pattern).

Flute casts from the Anthering Fm. (Fig. 3), near Salzburg, indicate transport parallel to the northeast–southwest direction (Egger et al. 1997). The local heavy mineral content is characterized by ZTR dominance over garnet (31% tourmaline, 17% zircon vs. 17% garnet; 25% apatite; Egger et al. 1997).

In the Greifenstein Fm. (Fig. 3), channel fills are present (Faupl 1976). Egger (1992) interpreted this formation as a submarine fan deposit fed with sediment from the north. This is in agreement with zircon-dominated spectra (Fig. 14) and SE-directed paleocurrents (Hösch 1985, quoted in Faupl 1996). The Laab Fm. is divided into the Hois and Agsbach members (Fig. 3). The Hois Member contains lobe deposits and channel fills (Faupl 1996). Paleocurrents are SE-directed (Ringhofer 1976, quoted in Schnabel 1992b). The Agsbach Member is a basin plain deposit with NW- to W-directed paleocurrents (Ringhofer 1976, quoted in Faupl 1996). The heavy mineral contents of the Greifenstein and Laab fms. are hardly distinguishable (Fig. 14), showing that the basin was mainly fed by zircon-rich/ZTR-rich sediment during the Eocene. Evidently, the paleogeography had changed from the Cretaceous to the Eocene. Garnet had lost its importance.

Trautwein et al. (2001a, c) presented evidence related to zircon fission-track geochronology and zircon morphology for out-of-sequence thrusting in the ERF. They obtained pre-Variscan, Variscan, and Permo-Triassic fission-track ages and observed morphological characteristics in sediments of the Laab nappe linking the zircons to sources in stable Europe. The Greifenstein nappe was supplied from the evolving Eastern Alps indicated by Permian to Jurassic FT cooling ages recording increased heat fluxes during Pangea’s break-up and by Cretaceous FT cooling ages reflecting eo-Alpine metamorphism (Trautwein et al. 2001a). Moreover, the zircon morphology differs from that of the Laab nappe (Trautwein et al. 2001c). Based on their findings, Trautwein et al. (2001a, b) positioned the Laab nappe paleogeographically north of the Kahlenberg nappe and assigned the southernmost basin position to the Kahlenberg nappe. According to Trautwein et al. (2001a), a sediment transfer from the basin realm of the Laab nappe to that of the Greifenstein nappe was possible, but not vice

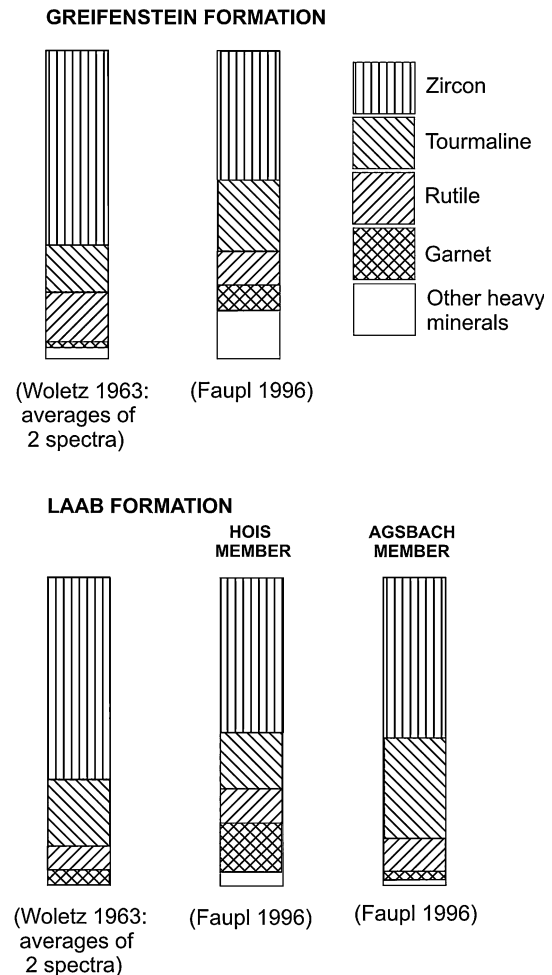


Fig. 14 Heavy mineral contents of the Greifenstein and Laab fms

versa, suggesting that sediments of the Laab nappe were deposited in shallower water than those of the Greifenstein nappe.

Out-of-sequence thrust units and thrust processes

Since the Oberstdorf and Laab nappes represent the northern basin realm but occupy the tectonically highest and southernmost positions (Figs. 1, 4, 5, 7), they were identified as out-of-sequence units by Mattern (1997, 1999) and Trautwein (2001b), respectively. The out-of-sequence position of the Laab nappe had already been envisaged by Fuchs (1985) and Oberhauser (1995).

Trautwein et al. (2001b) explained the out-of-sequence structure in the Vienna area by thrusting of Austroalpine nappes over the flysch belt. During the Eocene, the Kahlenberg nappe was overthrust first by the Austroalpine nappes (Fig. 15a). Later, but still during the Eocene, the Greifenstein, and Kahlenberg nappes were thrust over the Laab nappe which came to rest beneath the Kahlenberg

nappe. During the Late Oligocene/Early Miocene, the Laab nappe overrode the Greifenstein nappe, carrying the Kahlenberg nappe piggyback (Fig. 15a). Figure 15b explains the structure of Fig. 7b.

In the WRF, Austroalpine nappes first overrode the Sigiswang nappe. Then both overthrust the Oberstdorf nappe which came to lie beneath the Austroalpine nappes (Fig. 16). Later, the Oberstdorf nappe was thrust over the Sigiswang nappe (Fig. 16).

Discussion of method

The northern parts of the Eastern Alps were deformed by a conjugate set of northwest-trending dextral and northeast-trending sinistral strike-slip faults (e.g., Kockel et al. 1931). In addition, ENE-trending sinistral faults are regionally important in having aided the eastward tectonic extrusion of the Eastern Alps (e.g., Ratschbacher et al. 1991).

To this date there is incomplete understanding of possible vertical axis block rotations along strike-slip fault systems of the study area. Such rotations could have affected the orientation of paleocurrent indicators. The only regional study of this aspect in the Rhenodanubian Flysch by Egger et al. (2002; Fig. 2) revealed minor counterclockwise rotations between 5° and 7° between Salzburg and Steyr, where left-lateral faults of different trend dominate. ENE-trending faults which parallel the large Ennstal lateral escape fault are particularly important in this region (for overview see Tollmann 1977; Ratschbacher et al. 1991; Egger et al. 2002).

Rotations of the order of 5° – 7° have no impact on the validity of our conclusions. In the WRF and between Steyr

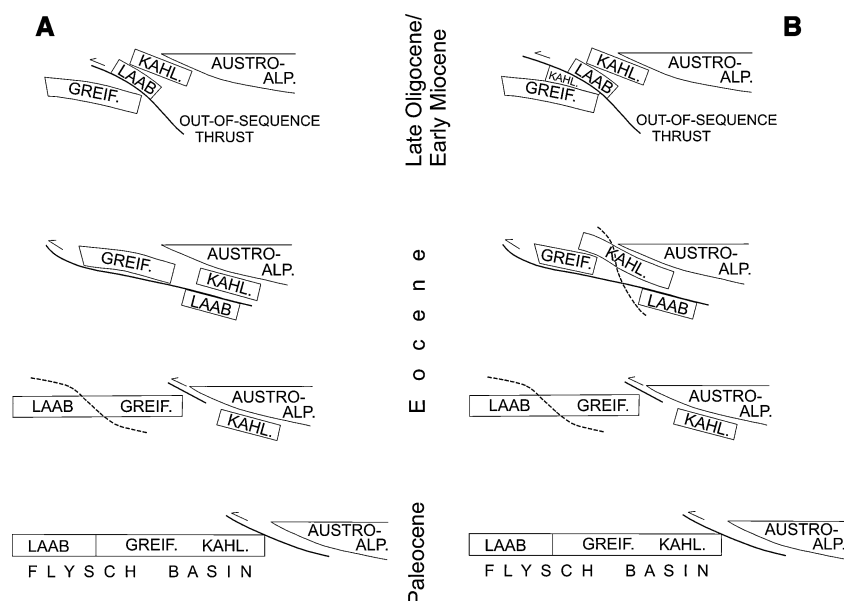
and the Vienna region, the strike-slip systems are largely characterized by the presence of the conjugate set of northwest and northeast-trending faults, fewer fault orientations, and a lesser density of faults than in the area between Salzburg and Steyr (e.g., Tollmann 1977; Ratschbacher et al. 1991). We, therefore, expect lesser strike-slip intensity and, thus, lesser block rotations in these areas. Moreover, we consider that in areas that are dominated by dextral faults (e.g., Ammer Valley, Kockel et al. 1931), possible counterclockwise rotations of paleoflow indicators may be statistically compensated by possible clockwise rotations.

It is generally known that garnet in coarse samples, and zircon in fine samples, is enriched. This also holds true for the Rhenodanubian Flysch (Fig. 12; Woletz 1950; Freimoser 1972; Von Rad 1972). Our study uses data from various scientists who unlikely would have used samples of the same grain size. However, we trust our conclusions (below) because they are not solely based on the evaluation of heavy mineral data. We tied the heavy mineral data to paleocurrent information and obtained analogous results for both, WRF and ERF.

Conclusions

The evidence from the Western and ERF is striking, mutually supportive and validates the out-of-sequence concept. The Cretaceous influx pattern “garnet from the south, zircon/ZTR from the north” is regularly observed in both areas. Both out-of-sequence nappes are rich in zircon/ZTR, whereas the other nappes are rich in garnet. Thus, both out-of-sequence nappes represent the northern basin

Fig. 15 Tectonic evolution of the ERF belt of the Vienna area resulting in out-of-sequence thrusting; **a** drawn after Trautwein et al. (2001b); **b** model to explain the complex structure of Fig. 7b



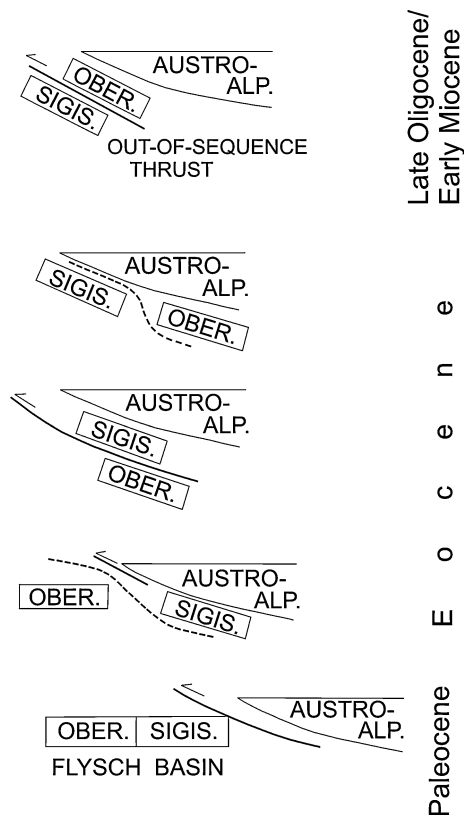


Fig. 16 Tectonic evolution of the WRF of Upper Bavaria resulting in out-of-sequence thrusting

realm. Their positions in the nappe pile, however, are not the northernmost and lowest ones. Both were thrust onto flysch nappes of a more southern origin: the Oberstdorf nappe onto the Üntschen and Sigiswang nappes; the Laab nappe onto the Greifenstein and Kahlenberg nappes.

Garnet may stem from the Central Gneiss Complex of the Tauern window (Introduction) and formerly exposed lateral equivalents, all representing the southern Mid-Penninic zone. We assign the Falknis/Tasna nappe and formerly exposed lateral equivalents to the northern Mid-Penninic zone which served as the zircon/ZTR source. Concerning a subdivided Mid-Penninic area it is of interest that Steinmann's (1994) model includes two continental blocks between the South Penninic and Helvetic realms. We assume that the northern Mid-Penninic source area was partly overthrust by the Central Gneiss Complex. Ebbing's (2002; Fig. 6.10) density section identifies the Central Gneiss Complex, the European and Adriatic plates. A block beneath the Central Gneiss Complex, however, was left unidentified ("?" in his Fig. 6.10) due to its peculiar density. Its contact to the European plate is marked by seismic reflectors; its contact to the Adriatic plate is closely paralleled by seismic reflectors (Ebbing's 2002, Fig. 6.10). We suggest that this block is Mid-Penninic and includes parts of the northern Mid-Penninic crust.

During the latest Cretaceous the influx pattern changed in both flysch sectors. Besides zircon/ZTR, garnet was now also being shed from the north. This is tentatively attributed to the presence of an accretionary wedge at the northern margin of the Mid-Penninic realm (Stampfli and Marchant 1997; Fig. 17-9). The wedge formed due to S-directed consumption of the North Penninic basin (Stampfli and Marchant 1997; Fig. 17-9) and contained garnet from the Bohemian Massif (see Faupl 1975; Fuchs et al. 1985) which was uplifted during the Late Cretaceous (Introduction).

Paleogeographic models interpreting the Rhenodanubian basin as either North or South Penninic are not viable because of contrasting heavy mineral characteristics (Introduction). We consider a Mid-Penninic basin position as best-suited. The observed gradual compositional changes in across-basin direction and the deduced basin positions of the thrust nappes render basin models with debris-shedding intrabasinal structural high(s) as unnecessarily complicated. For the Lower Cretaceous, these changes also existed between the northerly located Falknis/Tasna nappe and the flysch basin.

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References

- Burger H (1978) Arosa- und Madriser-Zone im Gebiet zwischen dem Schollberg und der Verspala (Osträtikon). *Eclogae Geol Helv* 71:255–266
- Clar E (1965) Zum Bewegungsbild des Gebirgsbaues der Ostalpen. *Zeitschr Deutsch Geol Ges* 116:267–291
- Decker K, Meschede M, Ring U (1993) Fault slip analysis along the northern margin of the Eastern Alps (Molasse, Helvetic nappes, North and South Penninic flysch, and the Northern Calcareous Alps). *Tectonophysics* 223:291–312
- Ebbing J (2002) 3-D Dichteverteilung und isostatisches Verhalten der Lithosphäre in den Ostalpen. Ph.D. thesis, Freie Universität Berlin, pp 1–143
- Egger H (1989) Zur Geologie der Flyschzone im Bundesland Salzburg. *Jahrb Geol B-A* 132:375–395
- Egger H (1992) Zur Geodynamik und Paläogeographie des Rhenodanubischen Flysches (Neokom—Eozän) der Ostalpen. *Zeitschr Deutsch Geol Ges* 143:51–65
- Egger H (1995) Zur lithostratigraphie der atllengbach-formation und der anthering-formation im Rhenodanubischen Flysch (Ostalpen, Penninikum). *N Jb Geol Pal Abh* 196:69–91
- Egger H, Bichler M, Draxler I, Homayoun M, Huber H-J, Kirchner EC, Klein P, Surenian R (1997) Mudturbidites, black shales and bentonites from the Palaeocene/Eocene boundary: the anthering formation of the Rhenodanubian Flysch (Austria). *Jahrb Geol Bundesanst* 140:29–45
- Egger H, Homayoun M, Schnabel W (2002) Tectonic and climatic control of Paleogene sedimentation in the Rhenodanubian Flysch basin (Eastern Alps, Austria). *Sediment Geol* 152:247–262
- Faupl P (1975) Schwermineralien und Strömungsrichtungen aus den Kaumberger Schichten (Oberkreide) des Wienerwald-Flysches, Niederösterreich. *N Jb Geol Pal Mh* 1975:528–540

- Faupl P (1976) Vorkommen und Bedeutung roter Pelite in den Kaumberger Schichten (Oberkreide) des Wienerwald-Flysches, Niederösterreich. *N Jb Geol Pal Mh* 1976:449–470
- Faupl P (1978) Zur räumlichen und zeitlichen Entwicklung von Breccien- und Turbiditserien in den Ostalpen. *Mitt Ges Geol Bergbaustud Österr* 25:81–110
- Faupl P (1980) Über turbiditische und nichtturbiditische Pelite in den Sieveringer Schichten (Maastricht, Wienerwald-Flyschzone). *Verh Geol B-A* 1979:285–293
- Faupl P (1996) Tiefwassersedimente und tektonischer Bau der Flyschzone des Wienerwaldes. *Exkursionsführer Sediment '96*, Wien, pp 1–32
- Faupl P, Grün W, Lauer G, Maurer R, Papp A, Schnabel W, Sturm M (1970) Zur Typisierung der Sieveringer Schichten im Flysch des Wienerwaldes. *Jahrb Geol B-A* 113:73–158
- Faupl P, Wagreich M (1992) Cretaceous flysch and pelagic sequences of the Eastern Alps: correlations, heavy minerals, and paleogeographic implications. *Cret Res* 13:387–403
- Faupl P, Wagreich M (2000) Late Jurassic to Eocene paleogeography and geodynamic evolution of the Eastern Alps. *Mitt Österr Geol Ges* 92:79–94
- Freimoser M (1972) Zur Stratigraphie, Sedimentpetrographie und Faziesentwicklung der südostbayerischen Flyschzone und des Ultrahelvetikums zwischen Bergen/Obb. und Salzburg. *Geol Bav* 66:7–91
- Frisch W (1976) Ein Modell zur alpidischen Evolution und Orogenese des Tauernfensters. *Geol Rund* 65:375–393
- Frisch W (1978) A plate tectonic model of the Eastern Alps. In: Closs H, Roeder D, Schmidt K (eds) *Alps, Apennines, Hellenides*. Schweizerbart, Stuttgart, pp 167–172
- Frisch W, Gommeringer K, Kelm U, Popp F (1987) The upper bündner Schiefer of the Tauern Window—a key to understanding Eoalpine orogenic processes in the Eastern Alps. In: Flügel HW, Faupl P (eds) *Geodynamics of the Eastern Alps*. Deuticke, Wien, pp 55–69
- Fuchs W (1985) Großtektonische Neuorientierung in den Ostalpen und Westkarpaten unter Einbeziehung plattentektonischer Gesichtspunkte. *Jb Geol B-A* 127:571–631
- Fuchs W, Wessely G, Schreiber OS (1985) Die Mittel- und Oberkreide des Molasseuntergrundes am Südsporn der Böhmisches Masse. *Österr Akad Wiss Schriften Erdwiss Komm* 7:193–220
- Gasser U (1967) Erste Resultate über die Verteilung von Schwermineralien in verschiedenen Flyschkomplexen der Schweiz. *Geol Rund* 56:300–308
- Hesse R (1965) Herkunft und Transport der Sedimente im Bayerischen Flyschtrug. *Zeitschr Deutsch Geol Ges* 116:404–426
- Hesse R (1966) Flysch-Zone. In: Stephan W, Hesse R (eds) *Erläuterungen zur Geologischen Karte von Bayern 1:25000 Blatt 8236 Tegernsee*, Bayerisches Geologisches Landesamt, Munich, pp 32–74
- Hesse R (1972) Lithostratigraphie, Petrographie und Entstehungsbedingungen des bayerischen Flysches. *Geol Bavarica* 66:148–222
- Hesse R (1973) Flysch-Gault and Falknis-Tasna-Gault (Unterkreide): Kontinuierlicher Übergang von der distalen zur proximalen Flyschfazies auf einer penninischen Trogebene der Alpen. *Geol Palaeont Sb* 2:1–90
- Hesse R (1995) Bed-by-bed correlation of trench-plain turbidite sections, Campanian Zementmergel Formation, Rhenodanubian Flysch Zone of the East Alps. In: Pickering KT, Hiscott RN, Kenyon NH, Ricci Lucchi F, Smith RDA (eds) *Atlas of deep water environments: architectural style in turbidite systems*. Chapman & Hall, London, pp 307–309
- Hösch K (1985) Zur lithofaziellen Entwicklung der Greifensteiner Schichten in der Flyschzone des Wienerwaldes. *Master's thesis*, Universität Wien, pp 1–250
- Janoschek W (1964) Geologie der Flyschzone und der helvetischen Zone zwischen Attersee und Traunsee. *Jahrb Geol B-A Wien* 107:161–214
- Kockel CW, Richter M, Steinmann HG (1931) Geologie der Bayrischen Berge zwischen Lech und Loisach. *Wiss Ver Dt Oesterr Alpenver* 10. Verlag des Deutschen und Oesterreichischen Alpenvereins, Innsbruck, pp 1–231
- Mattern F (1997) Das Sedimentationssystem des Reiselsberger Sandsteins (Cenomanium-Turonium; westlicher Rhenodanubischer Flysch; Ostalpen): tektonisch gesteuerte Progradation sandreicher, submariner Fächer. *Habilitation thesis*, Freie Universität Berlin, pp 1–239
- Mattern F (1998) Lithostratigraphie und Fazies des Reiselsberger Sandsteins: sandreiche, submarine Fächer (Cenomanium-Turonium, westlicher Rhenodanubischer Flysch, Ostalpen). *Berl geowiss Abh A* 198:1–137
- Mattern F (1999) Mid-Cretaceous basin development, paleogeography, and paleogeodynamics of the western Rhenodanubian Flysch (Alps). *Zeitschr Deutsch Geol Ges* 150:89–132
- Mattern F (2004) The main internal flysch thrust, thrust tectonic subdivision, and structure of the western Rhenodanubian Flysch Belt (eastern Alps). *Zeitschr Deutsch Geol Ges* 155:11–34
- Normark WR (1970) Growth patterns of deep-sea fans. *Am Assoc Pet Geol Bull* 54:2170–2195
- Noth R, Woletz G (1954) Zur Altersfrage der Kaumberger Schichten. *Verh Geol B-A* 1954:143–151
- Oberhauser R (1964) Zur Frage des vollständigen Zuschubs des Tauernfensters während der Kreidezeit. *Verh Geol B-A Wien* 1964:47–52
- Oberhauser R (1968) Beiträge zur Kenntnis der Tektonik und der Paläogeographie während der Oberkreide und dem Paläogen im Ostalpenraum. *Jahrb Geol B-A* 111:115–145
- Oberhauser R (1995) Zur Kenntnis der Tektonik und der Paläogeographie des Ostalpenraumes zur Kreide-, Paleozän- und Eozänzeit. *Jahrb Geol B-A* 138:369–432
- Peterek A, Rauche H, Schröder B, Franzke H-J, Bankwitz P, Bankwitz E (1997) The late- and post-Variscan tectonic evolution of the Western Border fault zone of the Bohemian massif (WBZ). *Geol Rund* 86:191–202
- Plöching B, Prey S (1974) *Der Wienerwald*. Samml Geol Führer 59. Bornträger, Berlin, pp 1–141
- Prey S (1979) Der Bau der Hauptklippenzone und der Kahlenberger Decke im Raume Purkersdorf—Wienerwaldsee (Wienerwald). *Verh Geol B-A* 1979:205–228
- Prey S (1980) Helvetikum, Flysche und Klippenzonen von Salzburg bis Wien. In: Oberhauser R (ed) *Der geologische Aufbau Österreichs*. Springer, Wien, pp 189–217
- Ratschbacher L, Frisch W, Linzer H-G (1991) Lateral extrusion in the Eastern Alps, part 2: structural analysis. *Tectonics* 10:257–271
- Richter W (1937) Sedimentpetrographische Beiträge zur Paläogeographie der ostalpinen Oberkreide. *Mitt Geol Staatsinst Hamburg* 16:59–84
- Ringhofer W (1976) Sedimentologische und stratigraphische Untersuchungen in Hinblick auf Transport und Ablagerung in den alttertiären Anteilen der Laaber Teildecke (Hois- und Aagsbachschichten). *Ph.D. thesis*, Universität Wien, pp 1–106
- Schmid SM, Fügenschuh B, Kissling E, Schuster R (2004) Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geol Helv* 97:93–117
- Schnabel W (1992a) Bericht 1989–1991 über geologische Aufnahmen im Wienerwaldflysch auf Blatt 58 Baden. *Jahrb Geol B-A* 135:686–688
- Schnabel W (1992b) New data on the Flysch Zone of the Eastern Alps in the Austrian sector and new aspects concerning the transition to the Flysch Zone of the Carpathians. *Cret Res* 13:405–419

- Schwerd K (1996) Feuerstätter Flysch, Unternoggschichten und ‘Südultrahelvetikum’. Rhenodanubischer Flysch. In: Freudenberger W, Schwerd K (eds) Erläuterungen zur Geologischen Karte von Bayern 1:500000, 4th edn. Bayerisches Geologisches Landesamt, Munich, pp 206–218
- Schwizer B (1984) Die Tristel-Formation. Vergleichende Untersuchungen in Graubünden, Liechtenstein, Vorarlberg und Bayern. Ph.D. thesis, Universität Bern, pp 1–185
- Stampfli GM, Marchant RH (1997) Geodynamic evolution of the Tethyan margins of the Western Alps. In: Pfiffner OA, Lehner P, Heitzmann P, Müller S, Steck A (eds) Deep structure of the Swiss Alps: results of NRP 20. Birkhäuser, Basel, pp 223–239
- Steinmann M (1994) Ein Beckenmodell für das Nordpenninikum der Ostschweiz. *Jahrb Geol B-A* 137:675–721
- Tollmann A (1965) Die Fortsetzung des Briançonnais in den Ostalpen. *Mitt Geol Ges Wien* 57(1964):469–478
- Tollmann A (1977) Die Bruchtektonik Österreichs im Satellitenbild. *N Jb Geol Paläont Abh* 153:1–27
- Tollmann A (1978) Plattentektonische Fragen in den Ostalpen und der plattentektonische Mechanismus des Mediterranen Orogens. *Mitt Österr Geol Ges* 69(1976):291–351
- Tollmann A (1985) Geologie von Österreich Band II Außercentralalpinen Anteil. Franz Deuticke, Wien, p 710
- Tollmann A (1990) Paleogeographic maps and profiles in the Eastern Alps and the relationship of the Eastern Alps to neighboring Terrain. *Mem Soc Géol Fr N S* 154:23–38
- Trautwein B, Dunkl I, Kuhlemann J, Frisch W (2001a) Cretaceous-Tertiary Rhenodanubian flysch wedge (Eastern Alps): clues to sediment supply and basin configuration from zircon fission-track data. *Terra Nova* 13:382–393
- Trautwein B, Dunkl I, Frisch W (2001b) Accretionary history of the Rhenodanubian Flysch zone in the Eastern Alps—evidence from apatite fission-track geochronology. *Int J Earth Sci* 90:703–713
- Trautwein B, Dunkl I, Kuhlemann J, Frisch W (2001c) Geodynamic evolution of the Rhenodanubian Flysch Zone—evidence from apatite and zircon fission-track geochronology and morphology studies on zircon. *Österr Akad Wiss Schriften Erdwiss Komm* 14:111–128
- Von Rad U (1972) Zur Sedimentologie und Fazies des Allgäuer Flysches. *Geol Bavarica* 66:92–147
- Wessely G (2006) Niederösterreich. Geologische Bundesanstalt, Wien, p 416
- Wildi W (1985) Heavy mineral distribution and dispersal pattern in penninic ligurian flysch basins (Alps, northern Apennines). *Giorn Geol Ser* 3 47:77–99
- Winkler W (1988) Mid- to early cretaceous Flysch and melange formations in the Western Part of the Eastern Alps. *Palaeotectonic Implications*. *Jb Geol B-A* 131:341–389
- Woletz G (1950) Schwermineralanalysen von klastischen Gesteinen aus dem Bereich des Wienerwaldes. *Jahrb Geol B-A* 94:167–194
- Woletz G (1954) Schwermineralanalysen von Gesteinen aus Helvetikum, Flysch und Gosau. *Verh Geol B-A* 1954:151–152
- Woletz G (1962) Zur schwermineralogischen Charakterisierung der Oberkreide- und Tertiärsedimente des Wienerwaldes. *Verh Geol B-A* 1962:268–272
- Woletz G (1963) Charakteristische Abfolgen der Schwermineralgehalte in Kreide- und Alttertiär-Schichten der nördlichen Ostalpen. *Jahrb Geol B-A* 106:89–119
- Woletz G (1967) Schwermineralvergesellschaftungen aus ostalpinen Sedimentationsbecken der Kreidezeit. *Geol Rund* 56:308–320
- Woletz G (1980) Schwerminerale in Sedimenten der Ostalpen. In: Oberhauser R (ed) *Der geologische Aufbau Österreichs*. Springer, Wien, p 43
- Wortmann UG (1996) Zur Ursache der hemipelagischen schwarz/grün Zyklen im Apt/Alb der bayerischen Flyschzone. Ph.D. thesis, Technische Universität München, pp 1–112
- Wortmann UG, Herrle JO, Weissert H (2004) Altered carbon cycling and coupled changes in Early Cretaceous weathering patterns: evidence from integrated carbon isotope sandstone records of the western Tethys. *Earth Planet Sci Lett* 220:69–82
- Zacher W (1972) Geologische Karte von Bayern 1:100000, Blatt 670 Oberstdorf, Bayerisches Geologisches Landesamt, Munich
- Ziegler PA (1987) Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland—a geodynamic model. *Tectonophysics* 137:389–420