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ORIGINAL PAPER

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Tectonics and sedimentation in the Fohnsdorf-Seckau Basin (Miocene, Austria): from a pull-apart basin to a half-graben

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Abstract The Miocene intramontane Fohnsdorf-Seckau Basin is situated at the junction of the sinistral Mur-Mürz-fault system and the dextral Pöls-Lavanttal fault system. The basin comprises a 2,400-m-thick coal-bearing fluviodeltaic–lacustrine succession (Lower to Middle Miocene, Upper Karpatian?/Lower Badenian) which is overlain by a 1,000-m-thick alluvio-deltaic conglomeratic succession (Apfelberg Formation, ?Middle/Upper Badenian) in the south. A three-stage model for the basin evolution has been reconstructed from structural analysis and basin fill geometries. During a first pull-apart phase, subsidence occurred along ENE-trending, sinistral strike-slip faults of the Mur-Mürz fault system and NE-SW to N-S-trending normal faults, forming a composite pull-apart basin between overstepping en-echelon strike-slip faults. The Seckau and Fohnsdorf sub-basins are considered as two adjacent pull-aparts which merged into one basin. During the second phase, N-S to NNW-SSE extension and normal faulting along the southern basin margin fault formed a half-graben, filled by wedge-shaped alluvial strata (Apfelberg Formation). During the third phase, after the end of basin sedimentation, the dextral Pöls-Lavanttal fault system reshaped the western basin margin into a positive flower structure.

Keywords Miocene · Eastern Alps · Pull-apart basin · Half-graben · Syntectonic sedimentation · Intramontane basin

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Introduction

The formation of intramontane basins is a very peculiar feature in the late-stage evolution of the Eastern Alpine orogen, generally interpreted as the result of extension of previously thickened crust. Miocene subsidence of small fault-bounded intramontane basins is interpreted as a result of orogen-parallel extension and eastward lateral extrusion of central parts of the Eastern Alps between major sinistral and dextral wrench faults (Fig. 1; e.g. Ratschbacher et al. 1989, 1991; Decker and Peresson 1996; Frisch et al. 1998). Along the Mur-Mürz fault (MMF) system several small-scale en-echelon basins such as the Fohnsdorf-Seckau Basin, the Trofaiach Basin, the Kapfenberg Basin and the Krieglach Basin formed probably during the Miocene (Steininger et al. 1989) between left-stepping ENE-striking faults. The Fohnsdorf-Seckau Basin is the largest of these basins. It is situated at the junction of the sinistral ENE-trending MMF and the dextral NW-trending Pöls-Lavanttal fault (PLF) system (Polesny 1970; Metz 1973; Gnjezda 1988), which were active during Miocene lateral extrusion (Decker and Peresson 1996; Linzer et al. 1997; Reinecker 2000). To the NE, the MMF continues into the Vienna pull-apart basin (Mur-Mürz-Semmering-Vienna basin fault system; Nievoll 1985; Decker 1996). This fault array and the PLF are considered to delimit one of the major wedges extruding out of the Alpine collision zone to the E or NE (Fig. 1). The timing of extrusion may be inferred from the sedimentation ages of the basins which formed along the faults, i.e. the Vienna Basin, the basins along the MMF including the Fohnsdorf-Seckau Basin, and the Lavanttal Basin (Ratschbacher et al. 1991). However, high-quality stratigraphic, sedimentological and tectonic data have only been available for the Vienna Basin so far, leaving much room for speculations on the exact timing of faulting and lateral extrusion, and modes of basin subsidence.

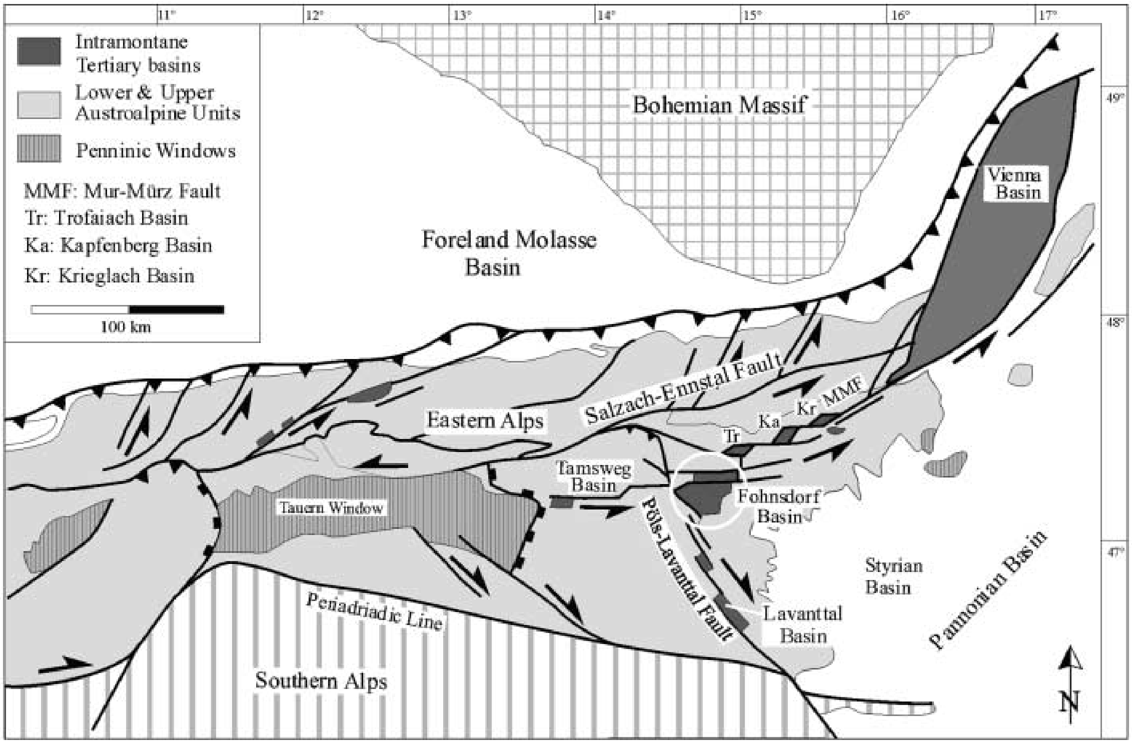


Fig. 1 Schematic sketch map of the Eastern Alps showing major Neogene faults and intramontane basins (after Neubauer 1988; Decker and Peresson 1996)

Consequently, fault-related intramontane basins have been interpreted as pull-apart basins (Neubauer 1988; Decker and Peresson 1996; Wang and Neubauer 1998), extensional half-grabens (Neubauer et al. 2000) or basins due to compressional flexure loading (Nemes et al. 1997).

Based on (micro)tectonic analysis, including fault-striae data, the interpretation of mesoscale deformational structures, and facies and sedimentation patterns of the syntectonic basin fill, a tectono-sedimentary model for the Fohnsdorf-Seckau Basin is given. This model takes into account seismic and borehole data which have been published by Sachsenhofer et al. (2000a, 2000b). Based on the reconstruction of the Miocene basin evolution, we present new interpretations of the age and sequential movements along the MMF and PLF.

Geological setting and basin stratigraphy

The Fohnsdorf-Seckau Basin comprises an area of about 120 km^2 (Fig. 2) and a preserved maximum thickness of Tertiary deposits of about 2,000 m according to deep mining, borehole data and seismic sections (Figs. 3, 4; Sachsenhofer et al. 2000a), overlying variscan-alpine metamorphic basement rocks of the Austroalpine unit (Neubauer 1988; Schuster et al. 1999). Tertiary strata of the basin fill are largely covered by Quaternary deposits and only a few outcrops of Miocene sediments, mainly along the basin margins, are accessible (Polesny 1970).

The lithostratigraphic subdivision of the Fohnsdorf-Seckau Basin is based on Petrascheck (1924) and Polesny (1970). Three main lithostratigraphic units can be identified (Fig. 3): the lower complex with breccias, sandstones and a coal seam at the top ("Liegendserie": Polesny 1970; Fohnsdorf Formation, Sachsenhofer et al. 2000b); the middle coarsening-upward complex with lacustrine-deltaic fine-to-coarse grained deposits ("Hangendserie": Polesny 1970; Ingering Formation, Sachsenhofer et al. 2000b); and the upper complex of conglomerates, including boulder beds ("Blockschotter": Polesny 1970; Apfelberg Formation, Sachsenhofer et al. 2000b). The Apfelberg Formation is unconformably overlying both the lower formations and metamorphic basement.

Chronostratigraphic correlations of the basin fill of the Fohnsdorf-Seckau Basin are still under discussion, therefore exact ages for sediments and tectonic phases cannot be given. The lower part of the deposits including the coal seam was attributed formerly to the Karpatian stage of the central Paratethyan subdivision (Steininger et al. 1989; Rögl 1996; Vakarcs et al. 1998), and the Apfelberg Formation to the Lower Badenian (e.g. Polesny 1970; Tollmann 1985; Steininger et al. 1989). New fission track data from a tuff within the Ingering Formation point to an early to middle Badenian age (14.9 Ma; Dunkl, in Sachsenhofer et al. 2000a). Precise biostratigraphic age datings of the formations are still lacking. At present a Late

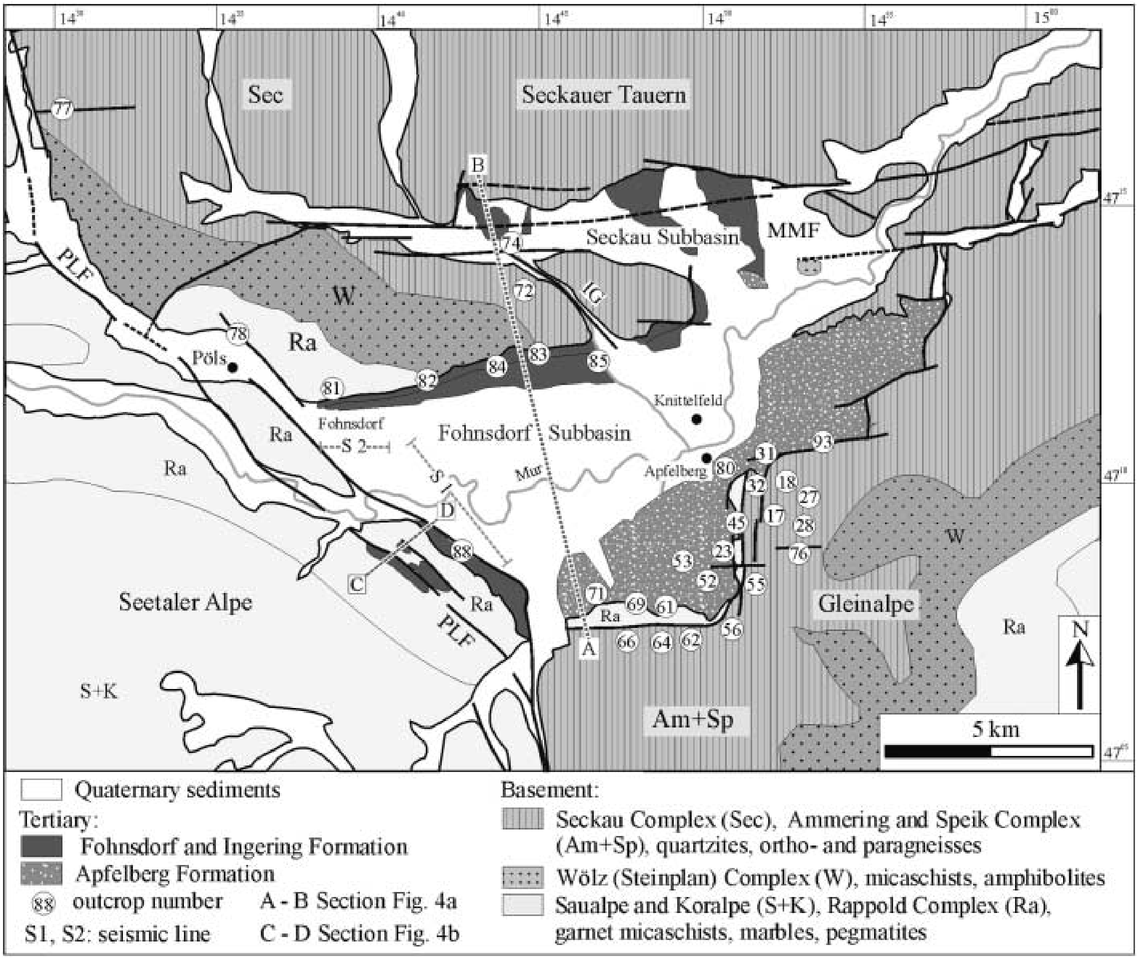


Fig. 2 Geological map of the Fohnsdorf-Seckau Basin and the surrounding basement. *Numbers* refer to outcrops used for tectonic analysis. Note repetition of Rappold complex (*Ra*) due to normal faulting along the SE basin margin. Synthesized from maps by Polesny (1970), Flügel and Neubauer (1984), Schuster et al. (1999) *PLF* Pöls-Lavanttal fault system, *MMF* Mur-Mürz fault system, *IG* Ingering fault

Karpatian to Early Badenian age is assumed for the Fohnsdorf and Ingering Formations. Mammal biostratigraphic data (Polesny 1970, Daxner-Höck, personal communication) suggest a Middle to Late Badenian age for the Apfelberg Formation.

Basin tectonics and sedimentation

Brittle tectonics of the Fohnsdorf-Seckau Basin and its surroundings are analyzed using mesoscale deformational structures such as faults, folds, extension gashes, stylolites and joints. The results from 31 outcrops are included in the present paper (Fig. 2; Table 1). Tectonic mapping is centered on the kinematic analyses of major faults in order to assess the nature of the basin boundary faults and the faulting mechanisms causing basement subsidence. No paleostress analyses, which are regarded as inadequate for the analysis of complex wrench fault settings, are performed. According to our data, regional tectonics are divided into pre-Miocene events not affecting the basin, and three major Miocene events which are reflected by distinct steps in the sedimentary evolution of the Fohnsdorf-Seckau Basin. Older brittle structures within the basement, which are cut by Miocene sinistral strike-slip faults, include dextral NW-SE trending strike-slip faults (e.g. the Ingering Fault, Fig. 2). Similar NW-SE trending strike-slip faults of Late Eocene to Oligocene age are known from the Northern Calcareous Alps (e.g. Decker and Peresson 1996; Linzer et al. 1997). The Miocene basin evolution is divided into (1) a pull-apart phase due to sinistral strike-slip faulting, (2) subsequent fault reactivation and half-graben formation, and (3) a post-sedimentary compressional event. Relative timing of these phases is based on cross-cutting relationships and the geometry of the basin fill.

Pull-apart basin formation

Evidence for sinistral strike-slip faulting comes from microstructural data obtained at the southern boun-

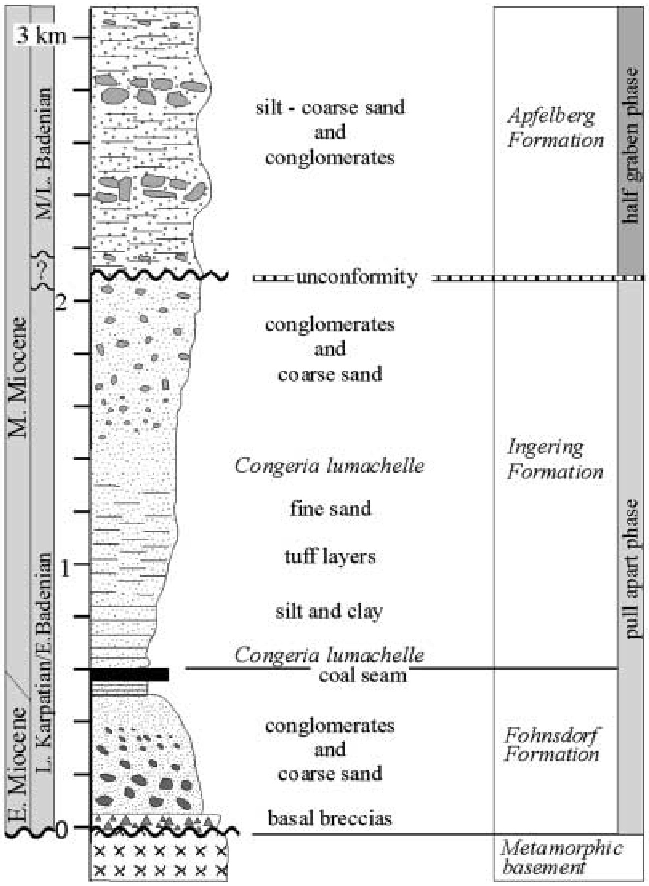
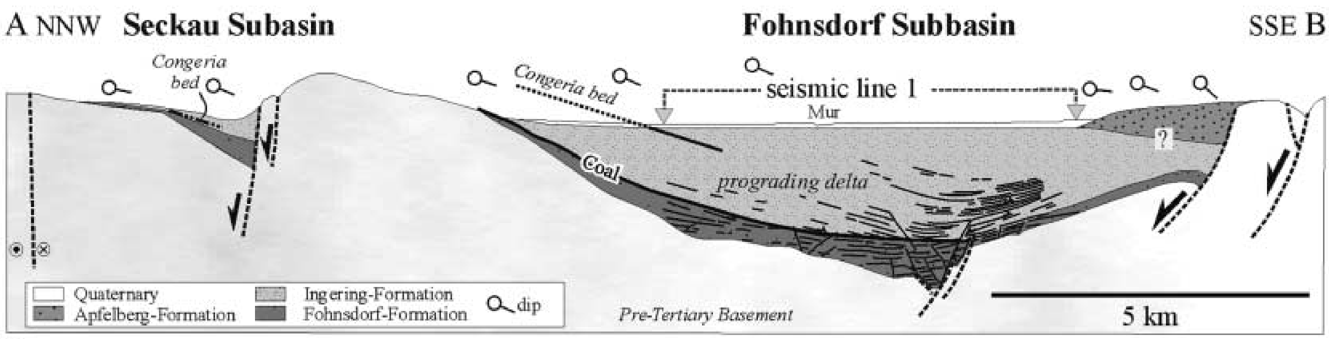


Fig. 3 Lithostratigraphic section (after Polesny 1970; Sachsenhofer et al. 2000a, 2000b), chronostratigraphic correlation and major Miocene tectonic phases recorded in the Fohnsdorf-Seckau Basin

dary fault of the Fohnsdorf sub-basin (plots 62, 66, 71) and the northern boundary fault of the Seckau sub-basin (plot 74), where a displaced subvertically dipping amphibolite marker indicates 4-km sinistral horizontal displacement (Fig. 5). Thick cataclastic fault rocks are conspicuous features of both basin boundary faults. The kinematic connection of the en-echelon strike-slip faults to several west-dipping normal faults is preserved at the eastern margin of the Fohnsdorf sub-basin (plots 17, 45, Fig. 5). A vertical displacement of more than 500 m along one of these west-dipping faults can be reconstructed from displaced metamorphic rocks of the Rappold Complex of the Gleinalpe unit (Fig. 5). Corresponding rocks crop out E and W of the fault at elevations of about 1,400 and 900 m respectively. East-dipping extension gashes in the coal of the Fohnsdorf Formation (plot 81, Fig. 5) are cut by S-dipping normal faults (plot 81, Fig. 6), which are assigned to the second Miocene deformational event (half-graben phase). These structures prove an Early to Middle Miocene age for E-W extension during pull-apart formation.

Deposition during the pull-apart phase is characterized by thick alluvial, lacustrine and brackish succes-



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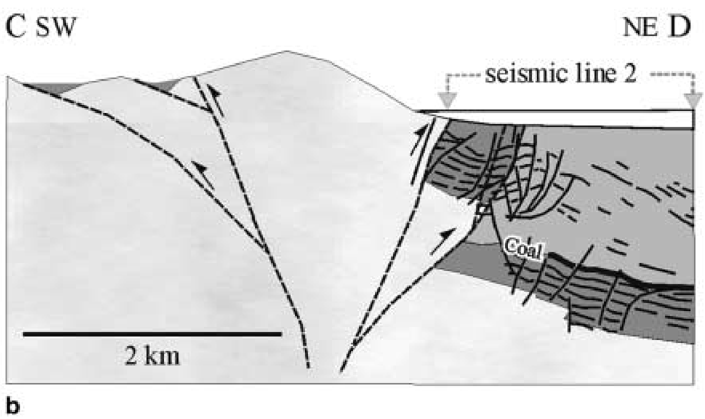

b

Fig. 4a,b Cross sections through the Seckau and Fohnsdorf sub-basin including interpreted reflectors from **a** seismic line 1 (*section A–B*) and **b** seismic line 2 (*section C–D*) through the flower structure along the Pöls-Lavanttal fault system. Data and seismic interpretation from Sachsenhofer et al. (2000a). For locations see Fig. 2

Table 1 List of outcrops used for tectonic analyses including coordinates (Easting: XGKM, Northing: YGKM, Austrian map 1:50.000), lithostratigraphic units, and ages (*b* metamorphic basement, *m* Miocene). For locations see Fig. 2

Outcrop number	X GKM BMN 31	Y GKM BMN 31	Unit	Age
17	637904	228111	Speik Complex	b
18	637618	228601	Rappold Complex	b
23	637094	225981	Apfelberg Fm.	m
27	638053	228681	Speik Complex	b
28	638524	228446	Speik Complex	b
31	638253	229391	Speik Complex	b
32	638528	229431	Speik Complex	b
45	637019	227311	Speik Complex	b
52	637034	225906	Apfelberg Fm.	m
53	636724	225796	Apfelberg Fm.	m
55	639354	228611	Speik Complex	b
56	636342	223126	Speik Complex	b
61	562358	223041	Speik Complex	b
62	563226	223620	Rappold Complex	b
64	562919	223078	Speik Complex	b
66	562239	222877	Speik Complex	b
69	562184	222875	Speik Complex	b
71	558608	221656	Speik Complex	b
72	557718	235503	Seckau Complex	b
74	556389	236597	Seckau Complex	b
76	638979	227469	Speik complex	b
77	537527	240813	Wölz Complex	b
78	543951	233357	Wölz Complex	b
80	636968	229796	Apfelberg Fm.	m
81	550214	231080	Fohnsdorf Fm.	m
82	553654	232133	Fohnsdorf Fm.	m
83	554138	232182	Fohnsdorf Fm.	m
84	557004	232009	Fohnsdorf Fm.	m
85	559736	232641	Fohnsdorf Fm.	m
88	559736	232641	Fohnsdorf Fm.?	m
93	641199	203149	Speik Complex	b

sions. The Fohnsdorf Formation comprises up to 500-m-thick breccias, conglomerates and sandstones overlain by a coal seam with a maximum thickness of 15 m. Coarse-grained sedimentation is attributed to deposition on alluvial fans from both the northern and the southern basin margin during rapid initial basin subsidence. After the deposition of the coal seam in a rheotrophic environment (Gruber and Sachsenhofer 2000) subsidence increased significantly and a moderately deep lake formed with deposition of sapropelites and pelitic pro-delta strata. This lacustrine-deltaic succession forms a more than 1,000-m-thick coarsening-upward cycle (Fig. 3), indicating decreasing subsidence rates and/or increasing sediment supply. According to seismic data the lake was filled by a large delta from the north (Fig. 4a and Sachsenhofer et al. 2000a). The occurrence of the bivalves *Congeria cf antecroatica* and *Theodoxodus crenulatus* ssp. (Mandic, personal communication 1999) and low organic carbon/sulphur ratios of both coals and overlying shales (Sachsenhofer et al. 2000b) indicate brackish influx. Heavy mineral spectra rich in garnet, dominating quartz and micaschist pebbles, as well as paleocurrent data indicate a northern provenance from the basement north of the Seckau sub-basin (Polesny 1970). The delta prograded from the northern margin of the Seckau sub-basin into the Fohnsdorf sub-basin, indicating that both basins were filled by the same depositional system during the pull-apart phase. Further evidence for a connection of the sub-basins comes from the correlation of *Congeria* beds (Polesny 1970) which occur at similar stratigraphic positions (Fig. 4a).

High subsidence rates, coarse lateral sediment input, sedimentation on small alluvial fans and the formation of a deep-water lake are typical features of pull-apart basins (comp. Christie-Blick and Biddle 1985; Ryang and Chough 1999). The reconstructed basin geometry and strong lateral thickness changes of the Fohnsdorf Formation suggest that the evolution of the Fohnsdorf-Seckau Basin started by the formation of smaller pull-apart basins between en-echelon left-stepping ENE-striking segments of the sinistral MMF. Coalescence of these basins resulted in the formation of a composite pull-apart basin in the Seckau-Fohnsdorf area of the MMF.

Half-graben formation

The second major synsedimentary tectonic event reconstructed in the Fohnsdorf-Seckau Basin area includes the reactivation of the basin boundary faults as normal faults (plot 61, 64, 76, 93, Fig. 6a). Structural evidence for this event is found in Miocene sediments as well as in the surrounding basement units, and includes cross-cutting faults and overprinted former sinistral strike-slip faults along the basin mar-

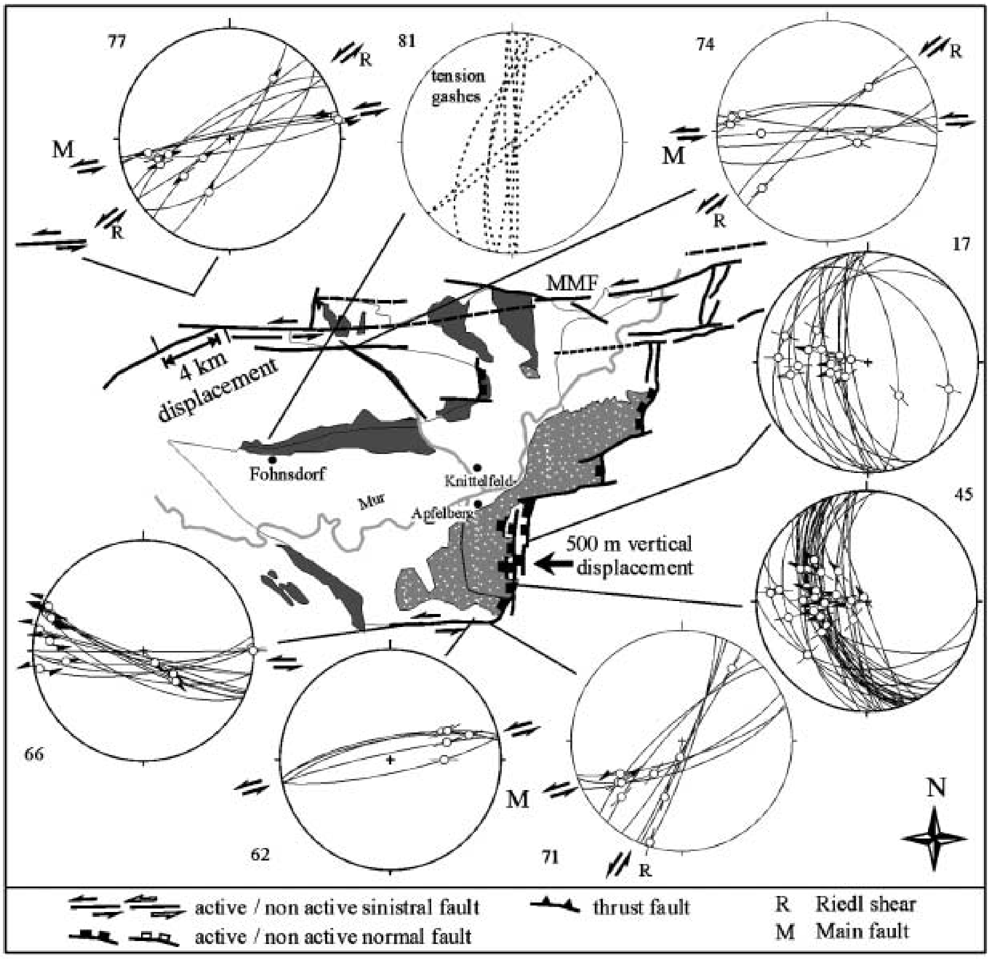

Fig. 5 Selected tectonic data and map interpretation for the pull-apart phase (Late Karpatian/Early Badenian) of the Fohnsdorf-Seckau Basin. Fault planes are plotted in *Schmid net, lower hemisphere projection*. *Large circles* and *points* denote fault planes and slicken lines, respectively. *Double arrows* indicate sense of shear. Tectonic map interpretation based on Fig. 2

gins of both the Seckau and Fohnsdorf sub-basins (Fig. 6c). Further evidence for a Middle to Late Miocene age of the deformation comes from S-dipping normal faults in the Fohnsdorf Formation (plot 81 Fig. 6a) and boulders of the Apfelberg Formation, which are fractured and displaced by small-scale en-echelon normal faults (Fig. 6b). Calcite-filled tension gashes and small-scale faults indicate NNW-SSE-directed extension. Measured extension gashes in fractured pebbles (outcrop 52) give a range of 9–16% for minimum finite extension.

A strong asymmetry of the resulting extensional basin is proved by the wedge-shaped geometry of the syntectonic Apfelberg Formation described below. Its coarse-grained facies and the restriction to the southern part of the Fohnsdorf sub-basin suggest syntectonic deposition adjacent to an active fault scarp. The Apfelberg Formation unconformably overlies both the Ingering Formation and crystalline basement (Polesny 1970). It comprises very poorly sorted, often matrix-supported conglomerates with boulder beds and well-sorted fine-grained sands and silts including thin coal seams. Boulders up to a maximum size of 30 m^3 are found adjacent to southern basin margin faults, suggesting a tectonically enhanced relief in the hinterland. Coarse debris flow deposits and gravelly to sandy channel fills predominate. Minor facies types include well-sorted fine sands, muds and thin coal seams of delta-plain origin. Heavy mineral spectra rich in hornblende and garnet, and the polymict clast composition, including amphibolites, gneisses and marbles, point to a southeastern source area within the Gleinalpe units. A general fining and thinning trend from the southern basin margin towards the center is observed. Depositional systems are interpreted as coarse-grained alluvial fans and fan deltas or braid deltas (Leeder and Gawthorpe 1987; Ryang and Chough 1999) prograding into a lacustrine half-graben from the south. The fans were controlled by active fault scarps, which formed by N-directed normal faulting at the southern basin margin during the Middle to Late Badenian.

The large-scale geometry of the half-grabens is constrained by seismic data, boreholes and the southward dip of strata in both sub-basins (Fig. 4a). These data suggest that the former composite Fohnsdorf-Seckau pull-apart basin became separated by asymmetric block tilting, which caused the exhumation of a base-

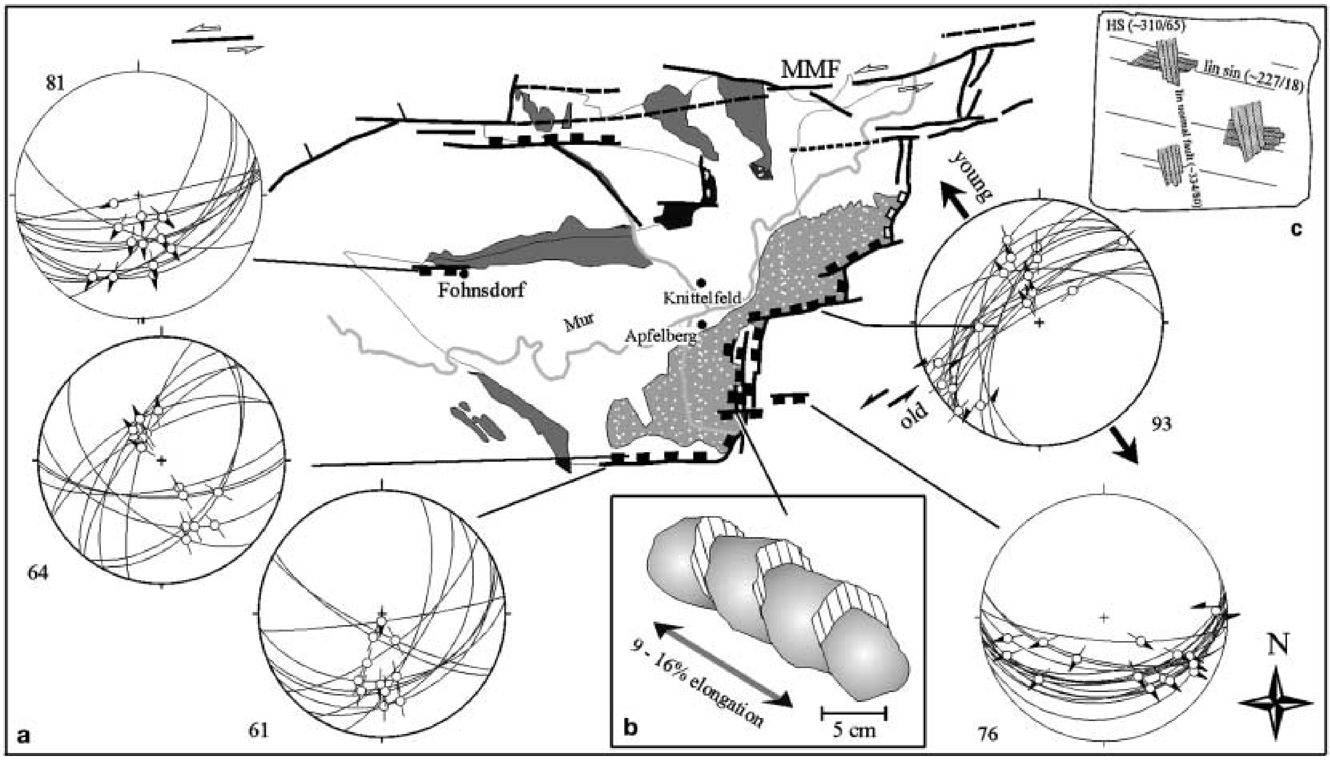

Fig. 6 **a** Selected tectonic data and map interpretation for the half-graben phase (Middle/Late Badenian) of the Fohnsdorf-Seckau Basin (legend in Fig. 4). **b** Deformed pebble of the Apfelberg Formation indicative of 9–16% finite extension by extension gashes and normal faults. **c** NE-striking fault plane with older sinistral strike-slip lineation attributed to the pull-apart phase overgrown by younger fibrous calcite indicating normal slip reactivation during half-graben phase (cf. plot 93)

ment ridge between the sub-basins (Fig. 4b). A minimum of 1.5 km of erosion of Miocene sediments is estimated from vitrinite reflectance data obtained from coal seams cropping out along the northern margin of the Fohnsdorf sub-basin (Sachsenhofer et al. 2000a).

Strike-slip faulting along the Pöls-Lavanttal Fault

The third major Miocene tectonic phase reconstructed in the Fohnsdorf-Seckau Basin and the basement units to the west is related to dextral strike-slip movement of the NNW-striking PLF system (Fig. 7). Based on seismic sections along the present-day southwestern basin margin (Fig. 4b), Sachsenhofer et al. (2000a) interpreted this margin as a positive flower structure resulting from dextral strike-slip along the PLF. The SE- to SSE-trending folds within sediments of the pull-apart phase (Metz 1973) are probably related to shorting and thrusting adjacent to this flower structure. The flower structure is restricted to the area between the southern and northern sinistral strike-slip basin margin faults. Structures within the Apfelberg Formation (plot 80, Fig. 7) give evidence for a post-Middle Miocene age for this deformation.

Discussion and conclusion

The tectonic history of the Fohnsdorf-Seckau Basin includes three Miocene tectonic phases (Fig. 8). Data suggest (1) the formation of an Early to Middle Miocene pull-apart basin between overstepping en-echelon segments of the MMF, (2) block tilting and asymmetric half-graben subsidence during the Middle Miocene and (3) dextral movement along the PLF system (post-Middle Badenian).

1. Pull-apart basin formation initiated during Late Karpatian to Early Badenian. The basin subsided between overstepping en-echelon segments of the sinistral E(NE)-striking MMF system, which were kinematically linked to connecting E- and W-directed normal faults. The rapidly subsiding pull-apart basin was filled with more than 2,000-m-thick alluvial and lacustrine breccias, conglomerates, sandstones and pelites (Fohnsdorf and Ingering Formation). High subsidence rates in the order of several hundred meters per Ma conform with rates which are commonly observed in pull-apart basins (Christie-Blick and Biddle 1985). The onset of pull-apart subsidence in the Fohnsdorf-Seckau Basin is tentatively correlated to the Late Karpatian initiation of the Vienna pull-apart basin at the NE continuation of the MMF (e.g. Sauer et al. 1992; Fodor

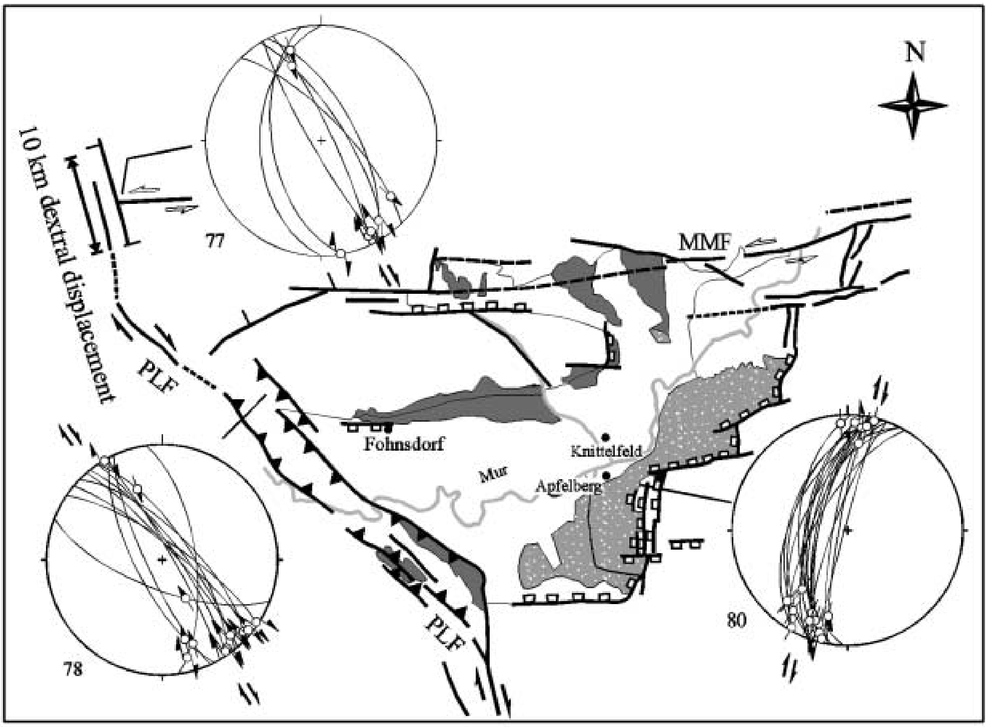

Fig. 7 Selected tectonic data and map interpretation for strike-slip faulting along the Pöls-Lavanttal Fault (legend in Fig. 4). The formation of a positive flower structure is indicated by upthrust basement and Fohnsdorf Formation along a restraining bend of the PLF in the western Fohnsdorf-Seckau Basin (cf. cross section Fig. 4b)

1995; Decker 1996). Fission track data (Dunkl, in Sachsenhofer et al. 2000a) indicate that the sedimentation during the pull-apart phase continued into the Early/Middle? Badenian. Movement of the MMF also caused the formation of several other basins such as the Trofaiach Basin (Nievoll 1985), the Kapfenberg Basin, the Krieglach Basin and the Tamsweg Basin (Zeilinger et al. 1999) along its eastern and western continuation, respectively (Fig. 1). For these basins, an Early to Middle Miocene age is commonly assumed by correlation to the Fohnsdorf-Seckau Basin (e.g. Steininger et al. 1989; Zeilinger et al. 1999).

Several lines of evidence suggest a complex evolution of the Fohnsdorf-Seckau Basin during the Early to Middle Miocene. Both the sinistral, ENE-striking MMF and the dextral NNW-striking PLF bordering the Fohnsdorf-Seckau Basin were active during the Miocene (Ratschbacher et al. 1991). This is indicated by sedimentary ages from the Lavanttal Basin along the PLF containing Middle Miocene (Lower Badenian) marine sediments (Beck-Mannagetta 1952; Schmid 1974; Tollmann 1985; Steininger et al. 1989). Miocene movement on both fault systems, which intersect at the Fohnsdorf-Seckau Basin, can only be achieved by sequential movements along the faults in order to avoid strain incompatibility at the intersection point (Fig. 9a). Sedimentological data suggest a marked break in the pull-apart evolution evidenced by a significant decrease in subsidence rates during the formation of a thick coal seam (Sachsenhofer et al. 2000a). This event could be caused by an interruption of sinistral movement along the MMF and related pull-apart subsidence by a short-term dextral strike-slip event along the PLF in the Early Badenian (Fig. 9b). Our model is supported by temporal brackish influx into the basin during sedimentation of the coal peat and the overlying lacustrine sediments, which could be related to faulting and subsidence along the PLF establishing a marine connection between the Fohnsdorf-Seckau Basin and the Lavanttal Basin. The tentative correlation of the brackish sediments in the Fohnsdorf-Seckau Basin with Early Badenian marine strata in the Lavanttal Basin is in agreement with the fission track age from a tuff within the Ingering Formation. Renewed sinistral slip along the MMF (Fig. 9c) and increased pull-apart subsidence led to the flooding of the coal peat and the formation of a deep lake (Sachsenhofer et al. 2000a).

2. During the Middle to Late Badenian, NNW-SSE directed extension caused the formation of asymmetric half-grabens and the dissection of the former pull-apart basin. Normal slip reactivation of the southern basin margin faults resulted in the formation of tilted fault blocks, partial erosion of the pull-apart basin fill, and the separation of the Seckau sub-basin by an intervening basement ridge (Fig. 8b). This tectonic event is correlated to the deposition of the Apfelberg Formation in the southern part of the Fohnsdorf-Seckau Basin. Mammal biostratigraphic data suggest a Middle to Late Badenian age (Daxner-Höck, personal communication) for tilting and half-graben sedimentation. The reconstructed half-graben geometry

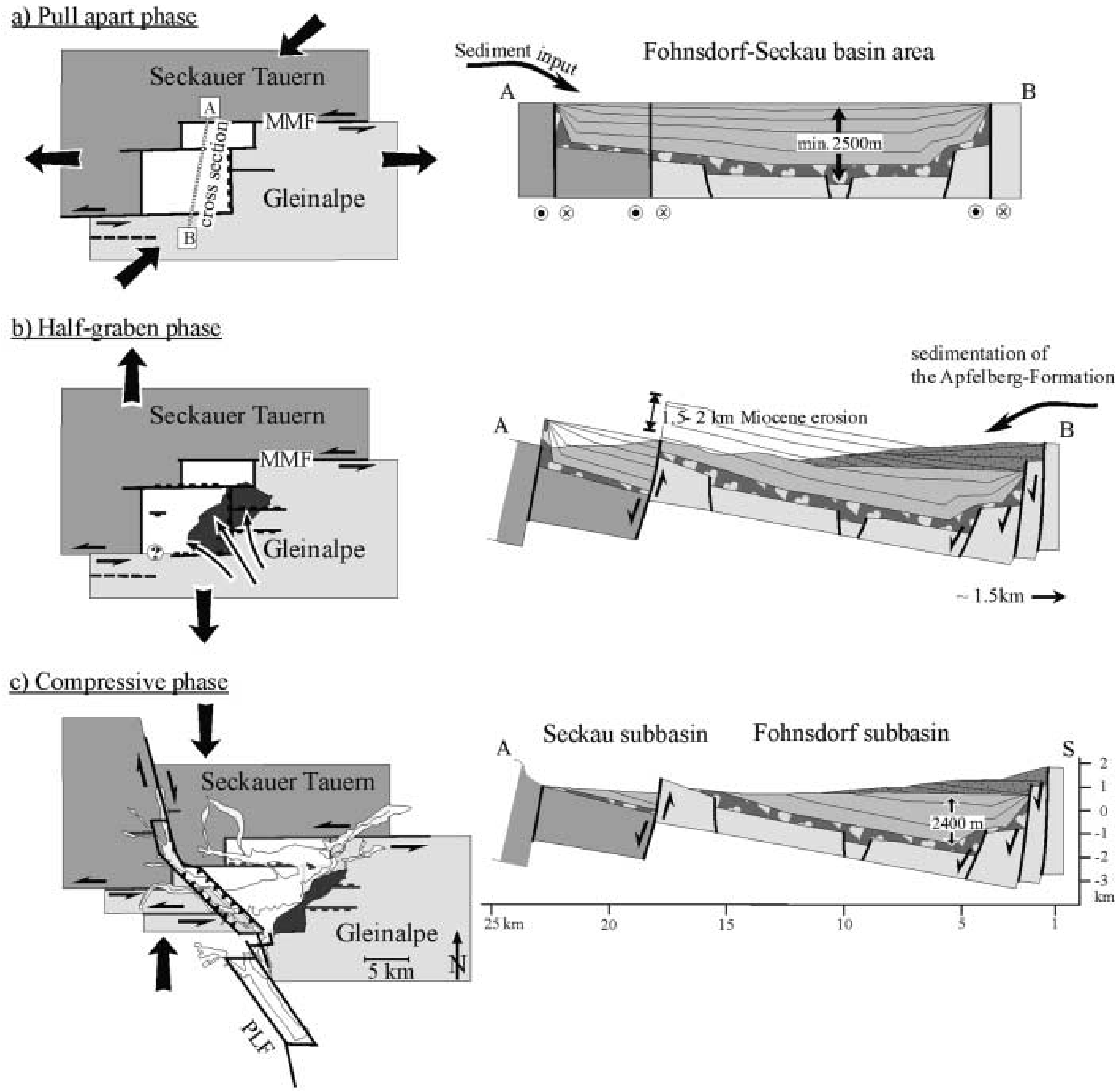

Fig. 8a–c Cartoons of the three major steps in the evolution of the Fohnsdorf-Seckau Basin based on tectonic and sedimentary data. **a** Pull-apart basin formation between overstepping sinistral strike-slip faults of the Mur-Mürz fault (*MMF*) system during the Late Karpatian/Early Badenian. **b** N-S to NNW-SSE extension, block tilting and half-graben formation (Middle/Late Badenian). **c** Dextral movement along the Pöls-Lavanttal fault (*PLF*) system and formation of a flower structure at the western basin margin (post-Middle Badenian)

(Fig. 8b) indicates about 10% extension compared with the initial width of the Fohnsdorf-Seckau pull-apart basin.

3. Post-Middle Badenian to recent NNW-SSE directed shortening induced dextral strike-slip along the PLF and caused the formation of a positive flower structure at the western boundary of the Fohnsdorf-Seckau Basin (Fig. 4b). A striking feature of this structure is its location between the basin boundary faults of the former pull-apart basin. We interpret the formation of the restraining bend at this position as a consequence of alternating movements along two intersecting strike-slip fault systems. During faulting along the PLF in the Early Badenian, the western margin of the Fohnsdorf-Seckau Basin probably had a strike-slip fault or releasing bend geometry (Fig. 9b). Renewed sinistral strike-slip along the MMF displaced the PLF and changed its geometry into a restraining bend in the Fohnsdorf-Seckau Basin (Fig. 9c). This may have resulted in the formation of a positive flower structure during renewed dextral slip of the PLF (Fig. 9d).

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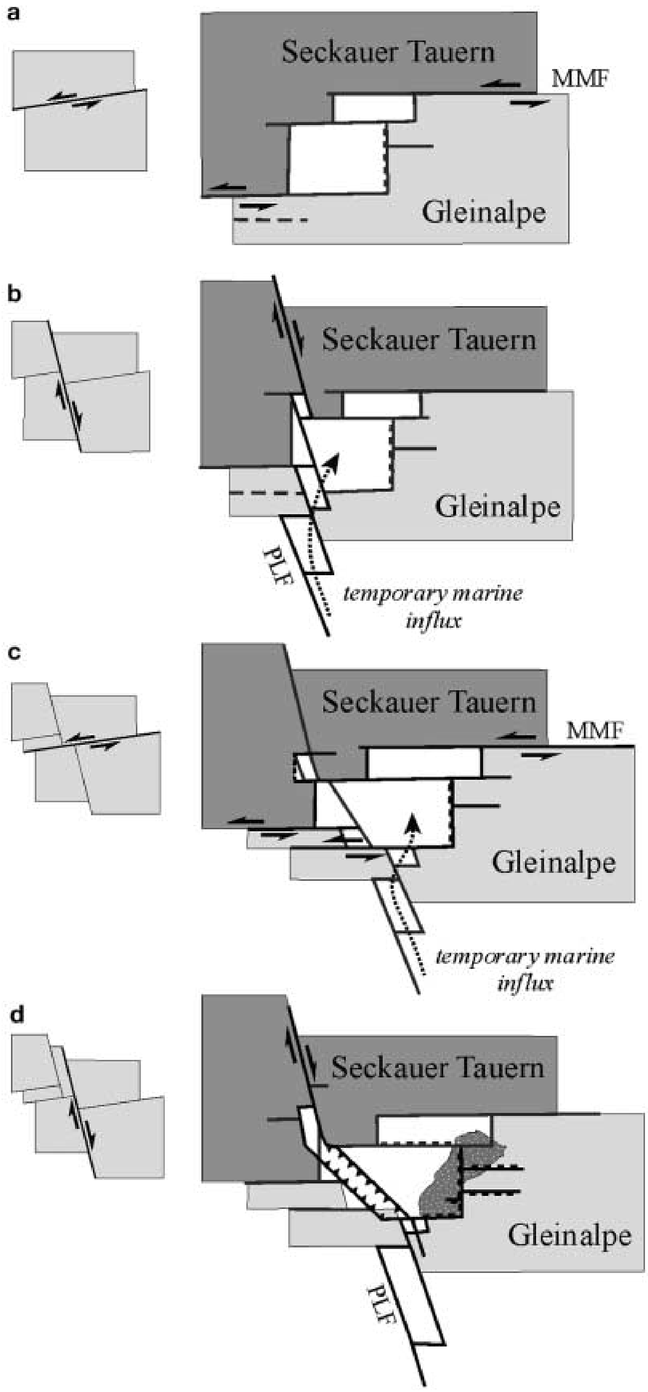

Fig. 9a–d Model of sequential strike-slip movements along intersecting Pöls-Lavanttal fault (*PLF*) and Mur-Mürz fault (*MMF*). **a** Formation of pull-apart basins between overstepping segments of the MMF (Late Karpatian/Early Badenian). **b** Offset of the MMF by formation of the dextral PLF during the Early Badenian, correlated to a decrease in pull-apart subsidence and brackish influx from the Lavanttal Basin along the southern continuation of the PLF. **c** Renewed sinistral faulting along the MMF and offset of the PLF, forming a restraining bend geometry in the Fohnsdorf-Seckau Basin (Early Badenian). **d** Dextral slip and formation of a flower structure along the restraining bend of the PLF (post-Middle Badenian)

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