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The Klagenfurt Basin in the Eastern Alps: an intra-orogenic decoupled flexural basin?

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Abstract

The Klagenfurt Basin is an E–W-trending narrow Sarmatian to Quaternary flexural basin formed by flexure of the Austro-Alpine lithosphere by loading through the southerly adjacent Karawanken Mountains in the Eastern Alps (Austria). The tectonic evolution of the basin is kinematically connected to Miocene brittle transpressive dextral strike-slip deformation along the Periadriatic Fault which separates the South Alpine unit from the Austro-Alpine unit in the Eastern Alps. The final NW-directed overthrust of the Karawanken Mountains onto the foreland is characterised by a positive flower structure, which is kinematically linked to dextral transpressive shearing along the Periadriatic Fault. Only a small part of the lithosphere appears to support the regional isostatic response to the load by the Karawanken Mountains. The area is characterised by a crustal thickness between 40 and 45 km, elevated heat flow and a strength distribution which suggests that only the upper crust elastically supports the topographic load. Ductile flow of the lower crust is also supported by the absence of a crustal root beneath the Karawanken chain. Rheologic models for this lithospheric configuration indicate a mechanical decoupling of upper crust, lower crust and mantle and generally low strengths for the lower crust and mantle.

Keywords: Periadriatic fault; Karawanken mountains; mechanical decoupling; intra-orogenic basin formation; Austro-Alpine tectonics

1. Introduction and tectonic setting

Intra-orogenic basins, like the Klagenfurt Basin in the southern part of the Eastern Alps (Fig. 1), are generally situated between strike-slip faults or depressions controlled by the topographic load of a mountain chain.

In the southeastern Alps the South Alpine unit is exposed from north to south, separated by the

Periadriatic Fault from the Austro-Alpine unit. The latter comprises a northern, flat-lying unit which is deflected towards the south at a distance of ca. 30 km towards the north of the Periadriatic Fault (Fig. 2). The resulting Klagenfurt Basin is overlain by the North Karawanken unit, which consists of the basement units and northern cover unit with Mesozoic cover sequences. S-dipping thrusts and reverse faults override minor Neogene gravel deposits ('Sattnitz conglomerate'; Kahler, 1953). These relationships indicate a piggyback thrust wedge over that overthrusting the Klagenfurt Basin. Piggyback basins in higher topographic positions can be observed in the

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Fig. 1. (a) Location of the Klagenfurt Basin within the framework of the Eastern Alps. (b) Generalised geological map of the Alpine units between East Tyrol and Slovenia adjacent to the Periadriatic Fault. Box shows location of detailed geological map in Fig. 2.

Bärental Valley (Fig. 3a) filled with Pliocene to Quaternary Bärental Conglomerate (map by van Husen, 1984).

The structure of the Klagenfurt Basin is constrained by kinematic data from surface studies

(Nemes, 1996), gravimetric investigations (Steinhauser et al., 1980; Weber et al., 1984) and data from the Vellach well (Vinzencz, 1988).

The tectonic evolution of the Klagenfurt Basin is kinematically connected to brittle transpressive

strike-slip deformation along the Periadriatic Fault. New kinematic data along the eastern part of the Periadriatic Fault in the Eastern Alps show polyphase kinematic patterns due to a succession of distinct deformation phases (Polinski and Eisbacher, 1992; Nemes, 1996). The Periadriatic Fault and related structures mark a first-order tectonic boundary between the Austro-Alpine and the South Alpine units that differ in style and timing of deformation in metamorphic conditions. Late Miocene top-to-the-NW nappe stacking north of the Periadriatic Fault (e_3 NW–SE, e_1 subhorizontal) was associated with flexure of the northern foreland (Fig. 2). The final overthrust of the Karawanken Mountains during the Pliocene and Quaternary, which form a positive flower structure, also includes flexure of the northern foreland, and formation of the narrow Sarmatian to Quaternary Klagenfurt Basin (Fig. 3). The final NNW-directed overthrust of the Karawanken Mountains onto the foreland is depicted by several NW–SE-striking dextral tear faults and NW- to NNW-directed thrust planes in Neogene sediments. Calculated palaeostress patterns from 35 stations in the Karawanken Mountains and the adjacent foreland yield for $e_3 = 170^\circ$ and $e_1 = 78^\circ$ ($e_3 > e_2 > e_1$, principal maximum stress directions). NNW–SSE-directed contraction caused transpressional structures expressed by NNW-directed thrusts and SSE-directed backthrusts, NW-striking dextral faults (R faults), and NE-trending sinistral faults (R' faults).

The Late Miocene to Pliocene sedimentary succession of the Klagenfurt Basin is strongly affected by young tectonic movements of the Karawanken mountain chain. To the south the Bärenthal Conglomerate and the underlying Rosenbach Formation are overthrust by the North Karawanken unit and folded, indicating a reverse anticline. The thrust plane dips ca. 20° to the south, and steepens towards the south (40 – 50°), indicating a minimum overthrust of ca. 2.5 km.

In this paper we present the results of a quantitative analysis of the intra-orogenic Klagenfurt Basin. The formation of this basin appears to be kinematically linked to the Periadriatic Fault (Nemes, 1996).

1.1. Stratigraphic framework

The Klagenfurt Basin comprises a more than 1000 m thick Sarmatian to Quaternary sequence. This starts with limnic, coal-bearing fine-grained sediments, the Rosenbach Formation (Kahler, 1953). This formation is divided into a lower coal-bearing part and a coarsening-upward sequence.

Lower coal-bearing sections include dark mudstones, sandstones and coarse conglomerates with interbedded carbonate and basement detritus. Palynological data indicate an early Sarmatian age (Papp, 1951; Klaus, 1956; Tollmann, 1985).

The upper sectors of the Rosenbach Formation comprise up to over 100 m thick coarse conglomerate-bearing carbonate derived from the uprising Karawanken Mountains and rocks of the Austro-Alpine metamorphic basement. Interbedded mud- and sand-bearing clastics indicate a long-distance transportation from the Karawanken thrust front. These are overlain by thick, coarse carbonate-bearing conglomerate. Large, up to 2 km long and 150 m thick carbonate blocks slipped into alluvial plain deposits and are interbedded concordantly in the Rosenbach Formation (van Husen, 1984).

The carbonate-bearing conglomerates are overlain by the Bärenthal Conglomerate (Fig. 4) with a thickness of several 100 m, and containing a Pannonian to Pontian microflora. Towards the north the Bärenthal Conglomerate grades into the coal-bearing, up to 50 m thick siltstones of the Penken Formation of Pontian age (Kahler, 1953). The Penken Formation is overlain by the up to 200 m thick Sattnitz conglomerate, which is considered to be of Pliocene to Pleistocene age (Tollmann, 1985).

Fig. 3. Two simplified geological cross-sections supporting the presence of a piggyback basin structure within and north of the Karawanken overthrust. (a) Cross-section A–A' through the Hochobir Mountain. The steep-dipping Karawanken overthrust onto the foreland indicates a positive flower structure (according to models of Harding, 1985). (b) Simplified geological map of the Bärenthal Valley (Bauer, 1982; van Husen, 1984) in the western part of the Klagenfurt Basin. Cross-section B–B' illustrates the presence of piggyback basins within the Karawanken Mountains and sedimentation of Bärenthal conglomerate (Pliocene–Quaternary) in higher topographic position.

Fig. 4. Sedimentary succession and thickness of layers recorded in the well profile 'Vellach-Müllnernbrücke' (after Vinzenz, 1988). 75% of the sedimentation consists of coarse conglomerates. These shales and siltstones, sandstones and mudstones indicate fluvial, limnic sedimentation.

1.2. Well 'Vellach Müllnernbrücke'

A commercial well near to the Vellach Müllnernbrücke south of Lake Klopein (long. 14°33'53"E, lat. 46°33'14"N; altitude, 434 m above sea level) was drilled in 1986 to explore the lithostratigraphic succession of the coal-bearing Rosenbach Formation (Vinzenz, 1988). The drilling was terminated after reaching the Rosenbach Formation at a depth of 811 m in the Miocene basin fill, providing a minimum estimate for the basin's depth.

75% of the sedimentary record is formed by coarse conglomerates, the remainder consists mainly of siltstones, sandstones and mudstones. The sedimentation can be interpreted as one of fluvial/limnic evolution, excluding a marine influence.

The main part of the well profile, however, is represented by a more than 300 m thick coarse conglomerate which lasts until a depth of 811 m, marking the end of the well. The fine-clastic sediments mostly consist of silt-, sand-, and mudstones which make up at least 8% of the whole layer.

The well profile (Fig. 4) begins with 5.9 m thick coarse-grained fluvial deposits interbedded in a sand-silt matrix. The next lithotype consists of sandy conglomerates until a depth of 39 m. The components are subrounded-angular and some carbonate, quartzite and dolomites are interbedded in these sediments. This formation belongs to the glacial sediments outcropping near to the well site (Vinzenz, 1988), which can be traced in the well profile up to a depth of 90 m.

Tertiary sedimentation begins with mudstones and siltstones continuing till a depth of 253 m. Up to 10 m thick layers of sandstones and coarse conglomerates are often interbedded, as well as metre thick black coal layers and xylites (Fig. 4). The next unit is built up by 190 m thick psephites with interbedded thin sand, silt and mud layers. In this unit an up to 2 m thick conglomerate formation with a sandy matrix can be found.

Between 441 and 464 m, mud and siltstone layers reflect a more quiet sedimentation phase, indicating a short period of limnic sedimentation. Larger pieces of woods indicate a high water level during sedimentation, interrupted by fan delta sedimentation evidenced by up to 6 m thick coarse conglomerates.

Palaeontological studies underline the early Sarmatian age of the coal-bearing Rosenbach Formation by the finding of *Carychium suevicum* (BOETTGER), indicating lower Sarmatian.

2. Gravimetry model

Gravimetry measurements were carried out in the Karawanken foreland and Sattnitz conglomerate by Steinhauser et al. (1980). The quantitative evaluation of Bouguer anomaly data was used to calculate a 2D-model which explains the E–W-trending gravity trough on the northern flank of the Karawanken Mountains. Results show that the gravity trough can be explained by the low density of the Sattnitz conglomerates which were partly overthrust by the Karawanken mountain chain (Fig. 2).

The main feature of the gravimetry model is a clearly visible, E–W-trending gravity trough north of the Karawanken overthrust. The northern edge of the gravity trough is located near Völkermarkt, to the

south the gravimetry anomaly is cut by the Periadriatic Fault. A regional increase of measured anomalies can be monitored from west to east, indicating influence of the Austro-Alpine metamorphic basement underneath the Klagenfurt Basin. No typical gravity root zone was recorded for the Karawanken Mountains.

A simple 2D-gravimetry model indicates, by considering the lower density of the Sarmatian basin fill, an overthrust in the south by the Karawanken mountain chain. Taking into consideration the density contrast of -0.47 g/cm^3 between the Austro-Alpine basement (2.67 g/cm^3) and the Sattnitz conglomerate (2.2 g/cm^3), the calculated model fits well with the measured anomalies (Fig. 5). The average basin depth is considered to reach 800–1300 m.

The calculated depth of the basin underneath the Karawanken overthrust is approx. 1250 m. Furthermore, an increase of the gravity anomalies can be seen from west to east which can be explained by the influence of the Austro-Alpine basement. The

Fig. 5. Gravimetry model of the Klagenfurt Basin showing the asymmetrical shape of the basin basement. The gravity low reflects the low density of the Sattnitz conglomerate ($\rho = 2.2 \text{ kg m}^{-3}$), partly overthrust by the Karawanken mountain chain ($\rho = 2.67 \text{ kg m}^{-3}$).

asymmetric shape of the modelled basin implies a flexure of the Austro-Alpine basement underneath the basin.

3. Constraints on the thermo-mechanical response of the lithosphere

We have carried out 2D-numerical modelling of crustal flexure and strength profile calculations in order to calculate the effective elastic thickness and shape of the Austro-Alpine crust underneath the basin. Bouguer anomaly data (Steinhauser et al., 1980; B. Meurers, pers. commun., 1996) and results from field studies, such as palaeostrain patterns and relative chronology of deformation stages in the Karawanken Mountains, were used to unravel the tectonic evolution of the basin.

To model the Klagenfurt Basin, we used a gravimetry model by Steinhauser et al. (1980), calculating the Bouguer anomaly of the basin fill and Austro-Alpine metamorphic basement. Gravimetric, geologic and topographic data from four N–S-striking cross-sections at long. 14°11', 14°20', 14°30', and 14°45'E, covering northern Slovenia and southern Austria (from lat. 46° to 47°N, distance approx. 110 km) were studied and used for the calculation of basement deflections and the controlling boundary conditions (Fig. 2).

The treatment of depth-depending rheology is based on the relation between flexural rigidity and curvature (e.g., Burov and Diamant, 1995). At the onset of bending, the flexural rigidity is only dependent on the elastic plate thickness. Upon curvature, the flexural rigidity decreases, which is calculated from the yield stress envelope.

Fig. 6. Strength profile calculated for minimum and maximum heat flow estimates (q = heat flow estimate, q_{rad} = radiogenic heat flow, q_m = mantle heat flow). (a) Heat flow estimate, $q = 50 \text{ mW m}^{-2}$, crustal thickness 40 km (20 km upper, 20 km lower crust), displaying three strong layers in the upper crust, lower crust and upper mantle. (b) Models with heat flow estimates of 50 mW m^{-2} producing strong upper crust with a significant amount of strength in the lower crust (crustal thickness 35 km). (c) For models considering heat flow estimates of 80 mW m^{-2} , the lower crust and mantle part lose nearly all their strength which is shifted into the upper crust.

Table 1

Rheological parameters: n = power; E = activation energy (kJ/mole); A = initial constant ($\text{Pa}^{-n}\text{s}^{-1}$); σ_p = plastic strength (Pa)

Power law creep: $\sigma_{\text{creep}} = \left(\frac{\dot{\epsilon}}{A}\right)^{1/n} \exp(E/nRT)$			
Quartzite (dry)	$n = 2.72$	$E = 134$	$A = 6.03 \times 10^{-24}$
Quartzite (wet)	$n = 1.9$	$E = 172.6$	$A = 1.26 \times 10^{-13}$
Diorite (wet)	$n = 2.4$	$E = 212$	$A = 1.26 \times 10^{-16}$
Dunite (wet)	$n = 4.5$	$E = 498$	$A = 3.98 \times 10^{-25}$
Dorn creep: $\sigma_{\text{creep}} = \sigma_p(l - [l - (RT/E)\ln(\dot{\epsilon}/A)]^{1/2})$			
Olivine (dry)	$\sigma_p = 8.5 \times 10^9$	$E = 535$	$A = 5.7 \times 10^{11}$ (s)

3.1. Rheological modelling

Depth-dependent rheological profiles through the lithosphere provide an important source of information on the lithosphere dynamics (e.g., McNutt et al., 1988; Burov and Diament, 1995; Cloetingh and Burov, 1996; Okaya et al., 1996; Table 1). The

strength of the lithosphere is strongly dependent on its composition and thermal structure. Strength profiles of the lithosphere underlying the Klagenfurt Basin were constructed for a comparison with estimated EET (effective elastic thickness) values derived from flexural modelling.

For our calculations the mechanical structure of

Fig. 7. Strength profile calculated for the lithosphere underlying the Klagenfurt Basin and the Karawanken Mountains. Heat flow estimates range from 50 to 80 mW m^{-2} (R. Sachsenhofer, pers. commun., 1996; Sachsenhofer et al., 1997). Also shown is the configuration of Bouguer anomalies (Steinhauser et al., 1980), topography and crustal thickness (Slejko et al., 1989) along cross-section $14^{\circ}30'$ through the western part of the Klagenfurt Basin (for locality see Fig. 2). The model adopts a quartzite upper crust, diabase lower crust, and olivine subcrustal lithosphere.

the lithosphere beneath the Klagenfurt Basin, we adopted a three-layer lithosphere with upper crust, lower crust and mantle material. The strength profiles are based on surface heat flow estimates with high overall values in the area supplemented by heat flow data in the adjacent Styrian Basin (Sachsenhofer et al., 1997). The increase of heat flow towards the east is consistent with the predominant occurrence of Neogene volcanics in the Styrian Basin.

The thermal structure adopted is a steady-state temperature profile for various basal heat flows and amounts and distributions (exponential in the upper crust, constant in the lower crust) of radiogenic heat production in the crust. The rheological configuration adapts brittle deformation according to Byerlee's law or a material-specific ductile flow law from experimental rock mechanics data (Carter and Tsenn, 1987). For the upper crust we adopted granite, for the lower crust diorite (wet) and diabase (dry), and for the mantle, dunite.

The crustal and lithospheric thicknesses in the area of the Klagenfurt Basin are about 35–45 km (Giese, 1980; Aric et al., 1987; Posgay et al., 1989), minimal surface heat flows of about 60 mW/m² (Sachsenhofer et al., 1997). The model with a surface heat flow of 60 mW/m² and a crustal thickness of 40 km gives thus an upper bound on the lithospheric strength.

Inspection of Fig. 6 shows striking differences in strength distribution for different heat flow estimates. The models predict in general a reduction of strength in the lower part of the crust and suggest that the upper crust and part of the lower crust still have limited strength. According to the rheological models the lower crust has nearly no strength, predicting an important detachment zone between the upper lower crust and the subcrustal lithosphere.

Model a (Fig. 6) with a crustal thickness of 40 km (20 km upper, 20 km lower crust) and a surface heat flow of 50 mW/m², displays three strong layers: upper crust, lower crust and upper mantle. The lower parts of the upper crust and the lower crust show low strengths, especially for wet rheologies, representing potential decollement horizons; effective elastic thickness (EET) values adapted from the formulation by Burov and Diament (1995) yield approximately 32.8 km (dry) and 22.4 km (wet).

Model b (Fig. 6) with a surface heat flow of 50 mW/m² (crustal thickness 35 km; EET 21 km, dry;

EET 15.3 km, wet) predicts a strong upper crust, whereas a significant amount of strength in the lower crust and the mantle is only retained for models with low mantle heat flows or dry rheologies.

For model c (Fig. 6) with a surface heat flow of 80 mW/m² the lower crust and upper mantle lose essentially all their strength, leaving a lithosphere with only some strength left in the upper parts of the upper crust (EET 17 km, dry; EET 8 km, wet). The upper and lower crust have still some strength, but as a result of higher temperatures the upper mantle strength is reduced effectively to zero.

From the above, the strength distribution of the lithosphere below the Klagenfurt Basin is proba-

Fig. 8. Flexural models for the response of the Austro-Alpine upper crust to thrust loading of the Karawanken mountain chain along four cross-sections (b) (locality given in (a); see also Fig. 2). Calculated deflection, including distributed surface loads and additional horizontal stress, acting on the narrow width, 10–15 km, of the weak Austro-Alpine plate. The upper crust is weakened by additional horizontal stress induced by strike-slip faulting along the Periadriatic Fault (Nemes, 1996). The inferred effective elastic thickness (EET) ranges from 1 to 2 km; density of the topographic load ($\rho = 2.67 \text{ kg m}^{-3}$). See (a) for position and total length of cross-sections.

Fig. 8 (continued).

bly characterised by a relatively strong upper crust, no strength in the lower crust, and possibly some strength in the uppermost mantle for the foreland of the Karawanken Mountains.

3.2. Flexural modelling

For our 2D-numerical modelling of crustal flexure (see e.g., van der Beek and Cloetingh, 1992; Cloetingh et al., 1992; Zoetemeijer et al., 1993), a broken plate model was adopted with the end of a plate marked by the Periadriatic Fault. The position of the Periadriatic Fault is clearly marked in small tonalite lenses (Exner, 1976; Nemes, 1996).

A stepwise-defined number of array points define the horizontal extension of the model. For the broken plate model we used 10 km and 100 points, covering approx. 100 km of the studied cross-sections. Subsurface loads were defined as a sum of load forces defined by a body with a density contrast. For the overriding mountain chain of the Karawanken Mountains and for the basin fill, densities of 2.7 g/cm³ and 2.2 g/cm³, respectively, were taken into consideration.

The northern edge of the Klagenfurt Basin is marked by the contact to the Austro-Alpine metamorphic basement. Further, the overthrust-position of the Karawanken Mountains and the calculated basin depth (Steinhauser et al., 1980) underneath the overthrust were used to constrain the deflected zone of the lower plate.

Using the broken plate model with the Periadriatic Fault as a plate boundary, a number of calculations were carried out. These models demonstrate that with only the topographic load as main vertical shear force and estimated bending moment create a too shallow deflection. The modelled deflection requires additional horizontal stress acting over the total length of the Klagenfurt Basin. The relatively narrow basin implies a steep deflection for the estimated basin shape. As a result, additional horizontal stresses forced by strike-slip deformation along the Periadriatic Fault appear to be an effective mechanism to increase the calculated bending moment, M_0 , and vertical shear force, V_0 . These horizontal forces ('horizontal load') can create a steeper deflection fitting into the estimated basin shape.

The modelled basin depth in the most western

cross-section 14°11' is approx. 1300 m underneath the Karawanken overthrust (Figs. 5 and 7). The southward extension of the basin underneath the Karawanken Mountains is uncertain, because no further data from the mountain chain are available.

The results from cross-section 14°20' yield an effective elastic thickness of 1.7 km (Fig. 8). The section runs east of the town Ferlach (see also Fig. 2). The assumed thrust angle of the Karawanken Mountains onto the foreland is relatively steep (ca. 40–50°). The calculated bending moment M_0 yields ca. 1×10^{14} N and vertical shear force $V_0 = 1.3 \times 10^{11}$ N/m, which is calculated without assumed horizontal stresses. The calculated basin depth is ca. 2200 m, and underneath the Karawanken overthrust ca. 1000 m.

Additional horizontal compression was not taken into consideration, because the shape of the deflection runs through the calculated deflection points. These points include the northern edge of the Klagenfurt Basin, the overthrust of the Karawanken Mountains and the calculated basin depth (Steinhauser et al., 1980) underneath the overthrust. The Periadriatic Fault marks the end of the 'plate', which represents the deflected Austro-Alpine metamorphic basement.

Cross-section 14°30' transects through the Hochobir and yields an effective elastic thickness of approximately 1.7 km (Fig. 8; see also Fig. 3). The calculated bending moment M_0 is 2×10^{14} N and the vertical shear force V_0 approx. 1.8×10^{11} N/m. In this cross-section no additional horizontal load was required to create the steep deflection, even the bending moment of the deflected plate is still relatively high.

The easternmost studied cross-section at 14°45' yields the lowest effective elastic thickness of 0.9 km (Fig. 8). This very low effective elastic thickness appears to be required to create very steep deflection, in conjunction with additional horizontal forces of up to 1.5 kbar. The narrow basin width and the calculated basin depth create a relative steep deflection.

The analysis showed that the flexural wavelength of the Klagenfurt Basin requires an effective elastic thickness (EET) on the order of 1–2 km which is slightly less than EET estimates obtained from the adjacent Styrian Basin (Sachsenhofer et al., 1997). The low values of EET of the Austro-Alpine base-

Fig. 9. 3D-illustration showing the position of four cross-sections 14°11', 14°20', 14°30' and 14°45' through the Klagenfurt Basin (for locality see Fig. 2).

ment underlying the Klagenfurt Basin reflect the weakening effect of elevated temperatures, indicating a heating event affecting the region before overthrust took place. The low present-day values of the EET inferred from flexural analysis might be also influenced by weakening effects by additional horizontal stresses from the adjacent Periadriatic Fault.

In Fig. 9 we provide a 3D-view based on the studied cross-section across the Klagenfurt Basin reconstructing the shape of the basin and calculated deflection of the Austro-Alpine metamorphic basement.

4. Discussion and conclusions

The results from 2D-numerical modelling of crustal flexure and strength profile calculations indicate that the shape of the Klagenfurt Basin can be explained in terms of an elastic plate model with an effective elastic thickness of 0.9–1.7 km. In addition, horizontal stresses induced by strike-slip deformation along the Periadriatic Fault appear to be invoked.

The final NW-directed overthrust of the Karawanken Mountains onto the foreland is characterised by a positive flower structure, which is kinematically linked to dextral transpressive shearing along the Periadriatic Fault. The final NNW-directed overthrust of the Karawanken Mountains onto the foreland is depicted by several NW–SE-striking dextral tear faults and NW- to NNW-directed thrust planes in upper Tertiary sediments.

The inferred low effective elastic thicknesses indicate that only a small part of the lithosphere supports the regional isostatic response to the load by the Karawanken Mountains. The lithosphere to the north of the Karawanken Mountains is characterised by crustal thicknesses of between 40 and 45 km and elevated heat flows. Rheologic models for this lithospheric configuration indicate a strong decoupling of upper crust, lower crust and mantle, and generally low strengths for the lower crust and mantle. In addition, stress-induced weakening and steep bending will probably also have promoted the development of intra-lithospheric failure. This strength distribution suggests that only the upper crust elastically supports the topographic load, and that the lower crust and perhaps mantle deformed by ductile flow.

Ductile flow of the lower crust is also supported by the absence of a crustal root beneath the Karawanken chain (Steinhauser et al., 1980).

Similar very low effective elastic thicknesses have been found in the Styrian Basin towards the east (Sachsenhofer et al., 1997). High heat flow is supported by vitrinite reflectance studies which indicated relatively high temperatures in Miocene sediments close to the Periadriatic Fault (Sachsenhofer, 1994). The effective elastic thicknesses probably also reflect a shallow position of the upper portions of the Penninic units between the Tauern and Rechnitz windows.

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