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Three-dimensional model and late stage warping of the Plattengneis Shear Zone in the Eastern Alps

Martin Putz [a,*], Kurt Stüwe [a], Mark Jessell [b], Philippe Calcagno [c]

[a] *Department of Earth Science, University of Graz, Heinrichstrasse 26, A-8010 Graz, Austria*
[b] *Laboratoire des Mécanismes et Transferts en Géologie, UMR 5563, 14 ave Edouard Belin, Universite Paul-Sabatier, Toulouse, France*
[c] *BRGM, 3 Avenue Claude-Guillemin, BP6009, 45060 Orleans Cedex 2, France*

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Abstract

The Plattengneis shear zone is a 250–600 m thick, flat lying, Cretaceous, eclogite facies, mylonitic shear zone, with north-over-south transport direction, that is exposed over almost 1000 km^2 in the Koralpe region along the eastern margin of the Alps. Although the shear zone is one of the largest in the Alps, its role in the Eoalpine metamorphic evolution and the subsequent exhumation of the region, remain enigmatic and its large-scale geometry is not well understood. The outcrop pattern suggests that the shear zone is made up of a single sheet that is folded into a series of open syn- and antiforms with wavelengths of about 10 km. Eclogite bodies occur above, within and below the shear zone and there is no metamorphic grade change across the shear zone. In the south, the fold axes strike east–west and plunge shallowly to the east. In the north, the fold axes are oriented in north–south direction and form a dome shaped structure of the shear zone. Total shortening during this late stage warping event was of the order of 5%. Indirect evidence constrains this folding event to have occurred between 80 and 50 Ma and the fold geometry implies that the final exhumation in the Koralpe occurred somewhat later than further north. Interestingly, the shear zone appears to strike out of the topography in the south and dip into the topography in the north, so that north of the shear zone only hanging-wall rocks are exposed and south of it only foot-wall rocks. Possibilities for the geometric relationship of the Plattengneis shear zone with the surrounding south dipping detachments are discussed.

Keywords: Three-dimensional structural modelling; Eastern Alps; Koralpe; Plattengneis shear zone; Late stage warping

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1. Introduction

The Plattengneis is a flat lying, eclogite facies shear zone that formed as part of the early evolution of the European Alps, during the Cretaceous Eoalpine tectonic event. It is exposed on the eastern side of the Koralpe range along the eastern margin of the European Alps (Fig. 1). The region is generally of poor outcrop but the distinct structural character of the shear zone suggests that the same mylonite horizon occurs over almost 1000 km^2. With this magnitude of exposure, the shear zone is probably one of the largest of its kind in the Alpine orogen. However, despite its size, many of its features remain enigmatic, including its role in burial or exhumation of

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* Corresponding author. Present address: Department of Earth Science and Engineering, Imperial College, London, Exhibition Road, SW7 2AZ, United Kingdom.

E-mail addresses: martin.putz@imperial.ac.uk (M. Putz), kurt.stuewe@uni-graz.at (K. Stüwe), mjessell@lmtg.obs-mip.fr (M. Jessell), p.calcagno@brgm.fr (P. Calcagno).

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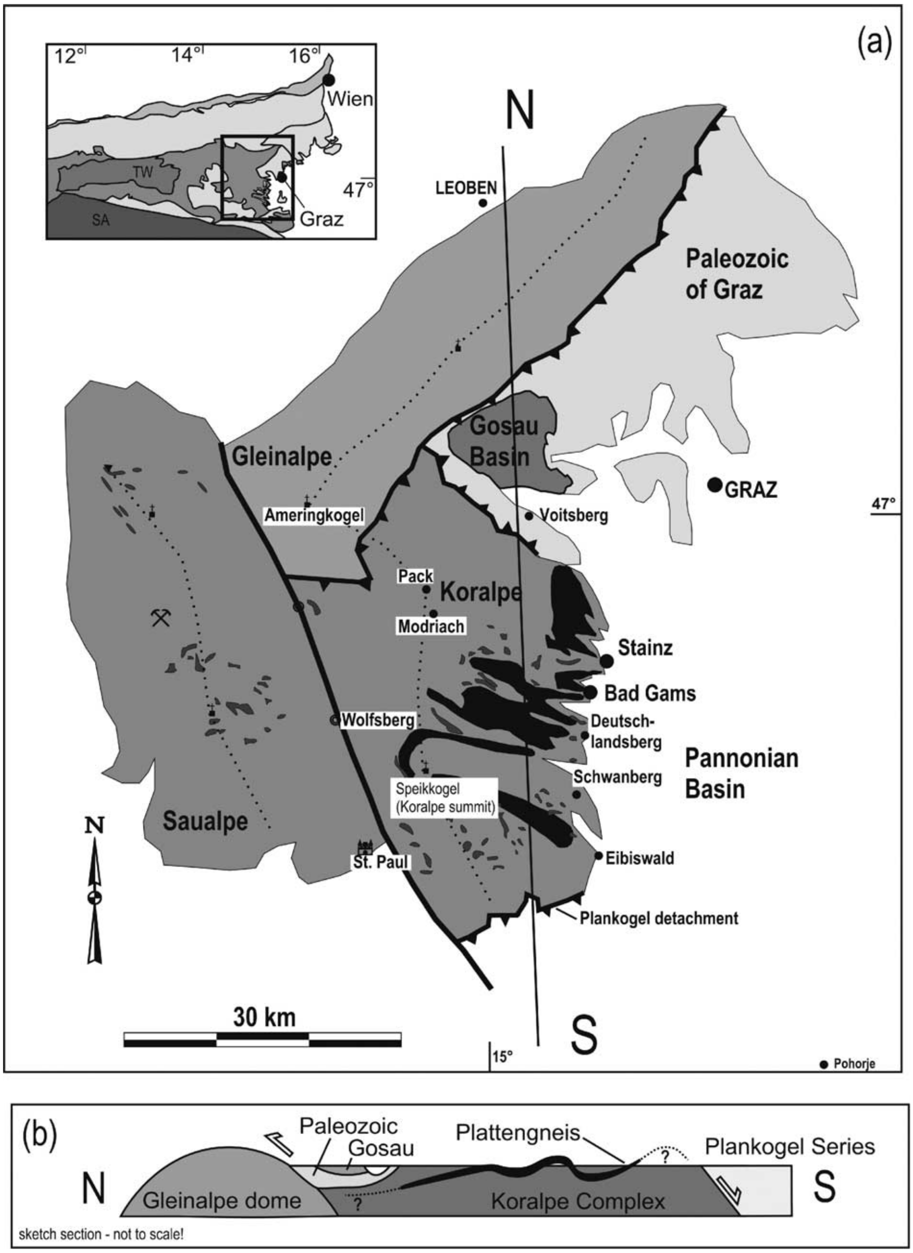

Fig. 1. (a) Simplified geological map of the investigated region along the eastern margin of the Alps (inset). On the inset TW stands for the Tauern Window and SA for the Southern Alps. The Austroalpine nappes are shown as the shaded units. On the large map, Plattengneis is shown in black and eclogite bodies are shown in dark grey. Approximate watersheds are indicated as dotted lines. (b) North–south sketch section through the investigated region.

eclogite facies rocks during the early evolution of the Alps, and its role as a contributor to the Eoalpine metamorphic heat budget. This paper defines the large scale geometry of the shear zone, with particular emphasis on interpreting a late stage event that appears to have folded the shear zone into kilometre scale open folds. Our study is motivated by the following three fundamental questions which can be constrained by our results:

1. Does the shear zone geometry allow us to infer its sense of shear? Despite an extremely strong stretching lineation, shear sense indicators are rare (Krohe, 1987) and even quartz textures are ambiguous

(Krohe, 1987; Kurz et al., 2002). Although there is now consensus that the transport direction is south over north, it is difficult to recognise this shear sense in the field. Moreover, the Plattengneis shear zone has recently been interpreted as a major detachment responsible for the Cretaceous exhumation of the underlying eclogite facies gneisses and shear sense has been suggested to be different in the south from that in the north (Kurz et al., 2002). The ill-defined shear sense could be confirmed or refuted if, for example, it could be shown that the patchy occurrence of the mylonites is due to its arrangement as a series of en echelon sheets indicating its transport direction.

2. Does the shear zone deformation contribute to the Eoalpine heat budget? The metamorphic field gradient across the Koralpe (Tenczer and Stüwe, 2003) and other features of the tectonic setting of the Austroalpine in the Cretaceous appear to indicate that heat conduction may not be the only contributor to the heat budget of the Eoalpine metamorphic event (Stüwe, 1998). In particular the remarkably heterogeneous equilibration of the rocks at 700 °C indicates that the Eoalpine event may have been extremely short lived and/or very dry (Ehlers et al., 1994; Thöni and Jagoutz, 1993). Shear heating during the Plattengneis deformation or increased radiogenic heat production have been suggested as possible contributors to the heat budget near the peak (Ehlers et al., 1994) and would provide a transient heat source causing a short lived thermal event. In order to assess such hypothesises it is important to determine the volume of the shear zone.
3. What does the geometry of the shear zone tell us about the late Cretaceous kinematic regime? The present day, large-scale geometry of the Plattengneis shear zone was established during the late Cretaceous exhumation of the region (Hejl, 1997; Willingshofer et al., 1999). This time coincides with the subsidence of the nearby Kainach Gosau basin. The evolution of this basin and exhumation of the neighbouring high pressure metamorphic rocks was subject to discussion during the last decade (e.g. Neubauer et al., 1995) and a clarification of the present day geometry of the Plattengneis may contribute to the understanding of the tectonic events during the latest Cretaceous evolution of the region. However, the topography is quite rugged, outcrop is often poor and the apparent folding is very open with a wavelength of about 10 km. These conditions make it difficult to understand the geometry of the shear zone as long as it is visualized only in plan view.

To consider these questions critically we built a three-dimensional (3D) model of the geometry of the shear zone. Our model is based on surface point data only (strike and dip of foliation) and those data were obtained by geological fieldwork. In a later section of this paper we critically assess the robustness of the model.

2. Geological setting

The Koralpe, which hosts the Plattengneis shear zone, is part of the Middle Austroalpine, which is the crystalline basement unit that constitutes much of the Eastern Alps (Fig. 1, inset). The Koralpe–and its western neighbour the Saualpe–have received some attention in the past, because they experienced the highest metamorphic grade (about 700 °C, 20 kbar; Stüwe and Powell, 1995; Thöni and Miller, 1996) of any region in the Austrian Alps during the Cretaceous Eoalpine metamorphic event (Thöni and Jagoutz, 1993; Frey et al., 1999). The region also hosts the eclogite type locality (Hauy, 1822; Miller and Thoeni, 1997; Tenczer and Stüwe, 2003). The entire region is made up of high grade pelitic gneisses containing variably sized eclogite bodies (between metres and hundreds of metres) that lie above, within and below the Plattengneis shear zone (Fig. 1). Topographically, the Koralpe and Saualpe have almost 2000 m of vertical relief with north–south striking water sheds, steep western slopes and shallower eastern slopes. The two ranges have been interpreted as two major tilt blocks that formed in response to Miocene extension of the Eastern Alps (Genser and Neubauer, 1989) and the Plattengneis lies on the eastern dip slope of the eastern of these two blocks—the Koralpe. On the eastern slope of the Saualpe similarly sheared rocks appear and are likely to present a continuation of the shear zone prior to tilting, but these will not be discussed here. To the north, the Koralpe lies structurally above the Gleinalpe dome (Neubauer et al., 1995), but metamorphic grade changes are continuous across this suture (Tenczer and Stüwe, 2003). To the south the Koralpe lies below the lower grade Plankogel series (Fig. 2). The region has been of substantial interest in the past because of the close proximity of Cretaceous eclogite facies metamorphic rocks, the Cretaceous marine Kainach Gosau basin, the Paleozoic of Graz and the Tertiary Pannonian basin (Neubauer et al., 1995).

2.1. The Plattengneis shear zone

The Plattengneis shear zone is flat-lying, it reaches several hundreds of metres in thickness and it is

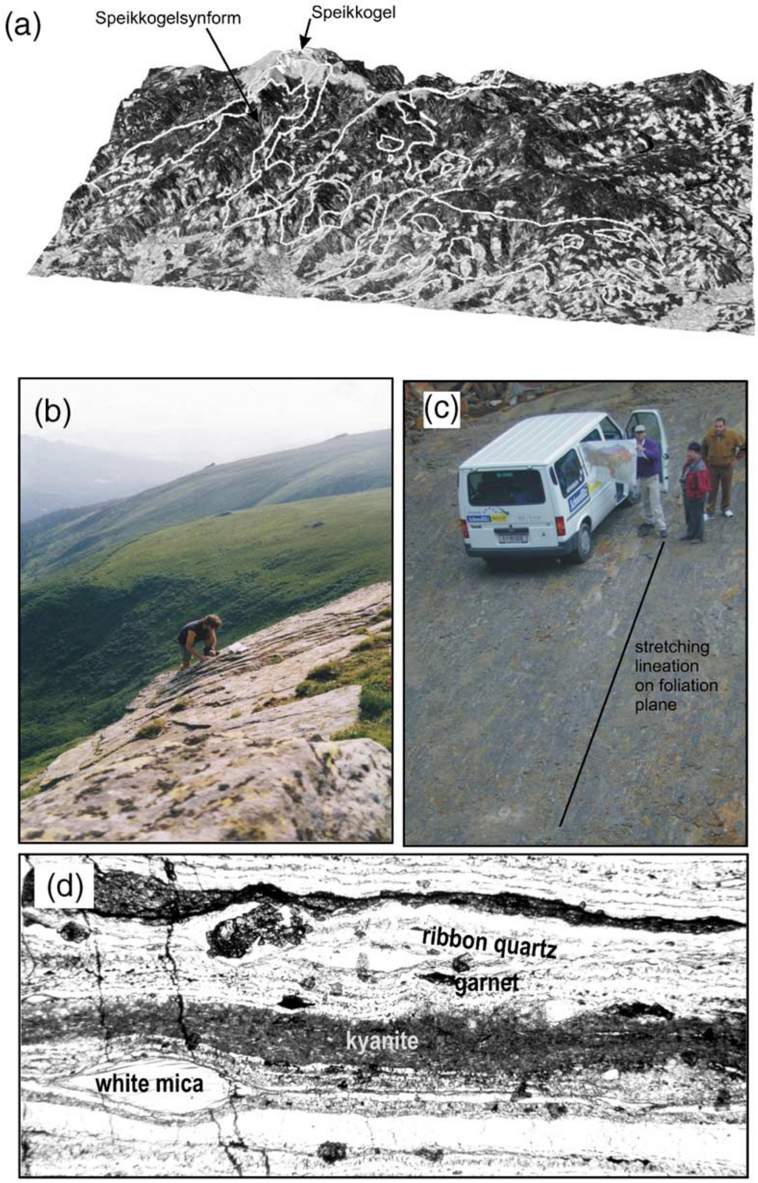

Fig. 2. (a) LandSat image of the study region draped over the digital elevation model of the Koralpe viewed from the east. The skyline forms the topographic crest of the Koralpe. The highest peak is the Speikkogel. The foreground is located in the Styrian basin. Plattengneis intersections with the topographic surface as modelled during this study are shown as white lines. (b) View of the southern limb of the Speikkogel synform viewed from the Speikkogel looking east. (c) Typical foliation surface of the Plattengneis at the type locality quarry near Stainz. (d) Photomicrograph of the Plattengneis. The length of the photo is 2 mm.

unmistakably recognised relative to the less deformed host rocks by its extreme mylonitic foliation and strong north–south oriented stretching lineation (Fig. 2) (Frank, 1987; Frank et al., 1983). Lithology and structure have been described in some detail by Krohe (1987) and Kurz et al. (2002) and their descriptions are not repeated here. The transition from the mylonitic core of the shear zone to the augengneiss textured host rocks can consist of several tens of meters of flaser textured rock (Becker, 1976). However, on the scale of our model the contacts are sharp and this transition zone can be neglected. The shear zone can therefore be mapped as a distinct unit. To the east the shear zone disappears beneath the sediments of the Styrian basin and to the west it strikes out along the topographic crest of the Koralpe range. The outcrop pattern suggests that the shear zone dips in and out of the topography and was folded about open east–west striking fold axes (Figs. 1, 2a and 3). The size of the shear zone suggests that it was one of the major transport horizons during the Eoalpine nappe stacking, but it does not separate units of significantly different metamorphic grade or lithology and its tectonic significance remains enigmatic. Kurz et al. (2002) suggested that the shear zone played a major role during the exhumation of the region. However, microstructures suggest that most of the deformation occurred near the metamorphic peak at 700 °C and 14 kbar so that its role in the exhumation history is questionable. The Plattengneis is also one of the few regions in the Eastern Alps where the transport related stretching lineation strikes north–south, although most of the Eoalpine nappe stacking occurred from east to west (Ratschbacher, 1986).

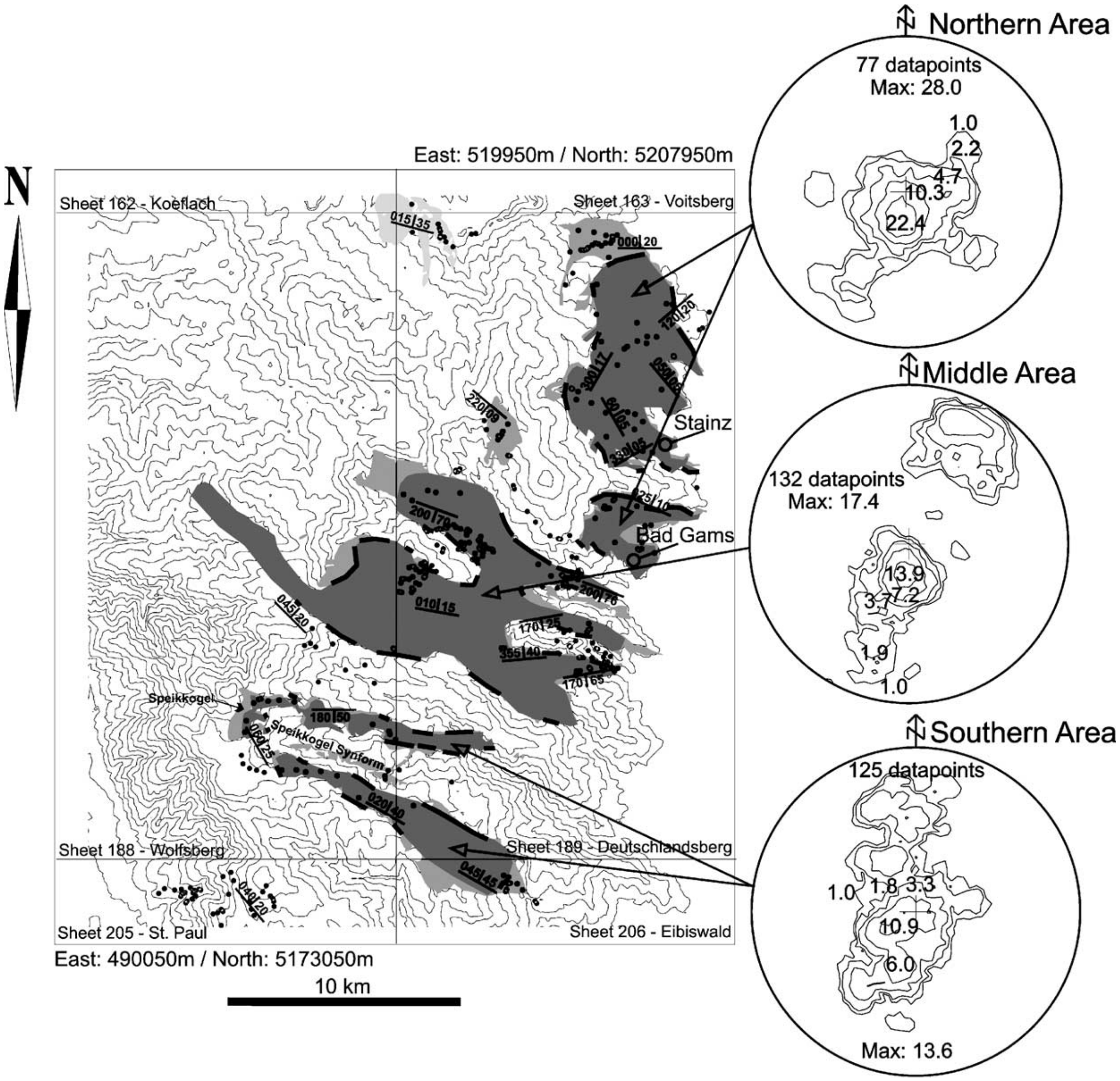

Fig. 3. Mapped distribution of Plattengneis in the Koralpe region of the Eastern Alps. Elevation contours are 100 m apart. Light grey areas: Plattengneis outcrops in existing maps. Dark grey areas: Plattengneis outcrops as mapped during this study. Because our own mapping results are shown in front, not all outlines of the previous mapping results can be seen. Black dots are mapped outcrops that were used for the modelling. Thick black polylines are upper and lower contacts of the Plattengneis as inferred in the field. The thin straight lines are the subdivision of the 1:50,000 map sheets of the Austrian mapping grid. Dip-symbols give representative values for dip-direction/dip of the Plattengneis foliation. Stereo-nets: contour lines and associated values show multiples of mean random distribution for each dataset.

3. The data

In order to identify the large-scale geometry with a 3D model, we have re-evaluated previous mapping results for the Plattengneis in the field across the entire region where the shear zone was mapped at 1:200,000 scale by Flügel and Neubauer (1984). The region has also been mapped at 1:50,000 scale on 6 map sheets of the Austrian mapping grid as shown in Fig. 3 However, the majority of the Plattengneis outcrops occur on two 1:50,000 map sheets (188 "Wolfsberg", Beck-Mannagetta, 1980 and 189 "Deutschlandsberg", Beck-Mannagetta et al., 1991). A re-evaluation of the previous mapping results was necessary for several reasons: Firstly, existing maps show little structural information on dip and strike of foliation and in particular of contacts. Secondly, the existing geological maps do not discern between observed and inferred information. Thirdly and most importantly, there are inconsistencies in the naming of units which made it impossible to correlate identical units without double-checking in the field. The published map sheets were compiled by different authors and it was necessary to compare Plattengneis mapping results across the map boundaries. For example, on the Köflach sheet (162, Becker, 1980), the highest deformed rocks within this area were defined as Plattengneis by Becker (1980), although they are not as strongly flattened as many outcrops not identified as Plattengneis by Beck-Mannagetta et al. (1991) on the adjoining Wolfsberg sheet (188). Here, we define the Plattengneis as a mylonitic rock with macroscopically perfectly flat fabric as described in detail by Becker (1976), Krohe (1987) or Tenczer and Stüwe (2003). We define the quarries at Stainz and Bad Gams as the type localities (Figs. 1 and 2c). All outcrops in which remanent SC fabrics could be identified with the naked eye were not considered as Plattengneis during the mapping (Fig. 3).

The region shows about 1800 m of vertical relief rising from about 300 m a.s.l. at the contact with the Styrian basin in the east to about 2100 m along the watershed of the Koralpe in the west. Subsidiary creeks draining the region from west to east dissect the eastern slope of the Koralpe with a relief of many hundreds of vertical metres. Outcrop conditions are good along the ridges above the timberline (about 1600 m), but poor below this elevation where exposures are largely confined to road cuts (Fig. 2a).

A total of almost 1000 locations were visited but about 20% of these proved to be without outcrop and the previously published mapping results were discarded. Nevertheless, visits to these locations are crucial to our modelling as our model is based on verified outcrops only. Of the remaining approximately 800 outcrops many were of low quality so that no decision on the occurrence of Plattengneis could be made and others were so close to each other that only a single averaged data entry was made. 333 mapped outcrops of high quality remained and are shown on Fig. 3. These outcrops were recorded in the field with latitude, longitude and elevation, as well as dip and strike of the principal foliation. As none of these outcrops exposes the contact of the shear zone itself, they were recorded with the attributes "above", "within" or "below", to indicate their position relative to the Plattengneis shear zone. A further 79 hanging-wall contacts and 72 foot-wall contacts of the shear zone could be inferred in the field and these points were mapped with the attribute "hanging-wall contact" and "foot-wall contact". These contact points were grouped into 25 foot-wall contact line segments and 24 hanging-wall contact line segments, with each line segment consisting of 2–5 contact points. The field data were organized in worksheets using Microsoft EXCEL and imported into a GIS software (MapInfo, http://www.mapinfo.com/). MapInfo allows the organisation and visualisation of virtually any spatial dataset (in the convenient form of maps) and facilitates the extraction of subsets of data with certain attributes by using queries. The data files generated with MapInfo can be imported into most 3D-visualisation and modelling programs.

The regions shown in dark grey on Fig. 3 are the areas where connected outcrops of Plattengneis can be inferred from the field data. Fig. 3 also shows the mapping results from the published 1:50,000 sheets in light grey. As our own mapping results are shown to lie above the previous mapping results, not all details of the published maps can be seen. Note that in many visited outcrops we discarded the previous mapping of Plattengneis (in particular in the north) because areas mapped as Plattengneis by previous authors showed remnant fabrics.

Fig. 3 shows that the Plattengneis outcrops may be discussed in three groups. The southern group is characterised by a kilometre scale, east plunging synform that can be directly recognised in the field without further modelling. This synform can be beautifully seen from the Speikkogel summit and is termed here the "Speikkogel synform" (see also Fig. 2b). The southern limb of the synform dips at about 20° to the north and the northern limb at 20° to the south. The fold axis plunges at about 10° to the ESE. This is somewhat steeper than the slope of the topography, so that rocks east of the Plattengneis outcrops define the hanging-wall and those west of it the foot-wall. The synformal structure is documented on Fig. 3 with the lower hemisphere stereonet data.

The central area includes a large region west of Deutschlandsberg that is apparently made up of connected Plattengneis outcrops. The distribution of foliations shows that the Plattengneis in this area dips shallowly to the NNE and SSW. The region has three distinct lobes in the east, but only two lobes in the west. Finally, the northernmost group of Plattengneis outcrops is formed by connected Plattengneis outcrops to the west and north of Bad Gams and Stainz. The foliation data suggest a vague cross girdle distribution showing that the shear zone dips in all 4 directions into the topography. This is also confirmed by direct field observations where it can be seen that the Plattengneis dips underneath its hanging-wall in all directions.

Plattengneis outcrops within each group and between the three groups can be in different geometric relationships to each other. They could–in principle–be completely separate zones of high strain forming an irregular anastomising network of high strain zones, they could be all part of a single horizon that is folded in a complicated, albeit very open manner and they could be part of an enormous en echelon set of discrete segments of the same shear zone (Fig. 4). If all outcrops are connected and are therefore part of the same sheet of mylonite, then the topology of the Plattengneis outcrops requires that the southern region is connected to the central region. However, there is no outcrop in this area and we have therefore not mapped the Plattengneis in this region on Fig. 3. It is partly the aim of the modelling to predict the occurrence or absence of Plattengneis in such regions and therefore to constrain the large scale geometry and volume of the Plattengneis mylonite horizon.

4. The model

Despite having visited about 1000 field locations, the mapped data are too sparse to permit a unique identification of the large scale geometry of the Plattengneis shear zone. This is largely because of the poor outcrop in the Koralpe region, but limited outcrop is by no means unique to the Koralpe and is a typical bane of many field areas around the world. Fig. 4 shows the danger of interpreting regions of incomplete outcrop: completely different geometries may both be consistent with the observations. Thus, we want to use 3D modelling to interpret the geometry of the Plattengneis shear zone rather than predefine it from our prejudice. As a consequence, modelling cannot be done with explicit software packages such as Surpac (http://www.surpac.com/) or GOCAD (http://gocad.ensg.inpl-nancy.fr/), which require the topology of the surfaces of the modelled units to be pre-defined.

In contrast, implicit models use three-dimensional input data to calculate a volume function that provides a description of the full geometry of a body or surface without having to prescribe data points on these surfaces (e.g. Lajaunie et al., 1997). Two interpretative 3D modelling tools have become available in recent years that can perform such implicit geometrical modelling: Earthvision (http://www.dgi.com/earthvision), and 3DGeoModeller (http://3dweg.brgm.fr/). Both software packages have been used in the geological literature for the interpretation and illustration of incomplete 3D geophysical data sets, for example with application to

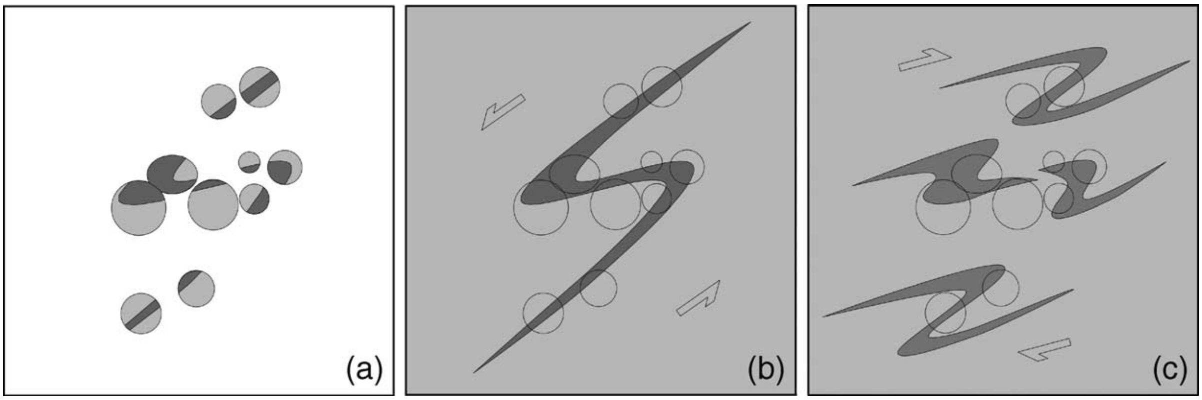

Fig. 4. Cartoon showing different possible interpretations for the structure of a region of limited outcrop. (a) Schematic geological outcrop map. Circular areas show outcrops in which two rock types (black and grey) were mapped. (b) and (c) show different possibilities how the map shown in (a) can be interpreted. Note that the two possibilities imply fundamentally different structural interpretations as indicated by the shear sense indicators.

ground water and oil reservoirs (Artimo et al., 2003; Herzog et al., 2003), or for the illustration of structures from seismic information (Courrioux et al., 2001; Martelet et al., 2004).

4.1. Modelling method

Here, we model the Plattengneis shear zone with 3DGeoModeller, developed by the French Geological Survey BRGM, and used to perform geological modelling (e.g. Maxelon, 2004; Calcagno et al., submitted for publication; Martelet et al., 2004; Sue et al., submitted for publication). It allows merging, in a single 3D space, data coming from separate sources such as geological maps and sections to formulate a 3D geometric model of the geology. The consistency of the data can be checked before interpolating them to build the model. The rapidity of the interpolation method and the geologist-oriented user interface allow easy testing and refining geological interpretations. The interpolation is based on a potential field method (Lajaunie et al., 1997). This method takes into account both (a) the observed position of the geological interfaces separating two units (interface points) and (b) the measured azimuths and dips of the units (orientation data). Orientation data can be measured on the interface or anywhere within the geological formation. Observations of the presence of a unit at a certain position within this unit are not considered by the model, but can be used to test the model results. The interpolation method is implicit, i.e. the position of the geological bodies is not explicitly known but can be inferred from the model.

3DGeoModeller was originally designed for the modelling of sedimentary units. When applying the software for the modelling of basement units, some peculiarities of the code have to be taken into account. Modelled units are dispatched into series. Note that the term "series" as used here is not consistent with its official definition by the international stratigraphic commission, but is used following the 3DGeoModeller nomenclature. In a given series, all units are considered to be part of the same layered pseudo-stratigraphy. All the units included in the same series have more or less parallel contacts, because all their data are interpolated at the same time. However, thickness variations are allowed within each unit of a series (Fig. 5a). Two relations can be set to define the behaviour of one series relative to the others: "Onlap" or "Erod". The corresponding geometries can be interpreted in terms of pinches or offsets of structurally defined units when interpreting basement terrains as done here. Fig. 5b illustrates the "Onlap" relation. It may be seen that the hanging-wall contact of the central (light grey) unit is allowed to lap onto the basal dark grey unit, which was modelled first. Fig. 5c illustrates the "Erod" relation. It may be seen that the hanging-wall contact of the light grey unit "erodes" the previously defined hanging-wall contact of the basal unit. This has the consequence that some data points previously incorporated by the model into the basal unit ultimately end up in the top unit (e.g. the two data points on the right on Fig. 5c). Clearly, these geometries are meaningless for the

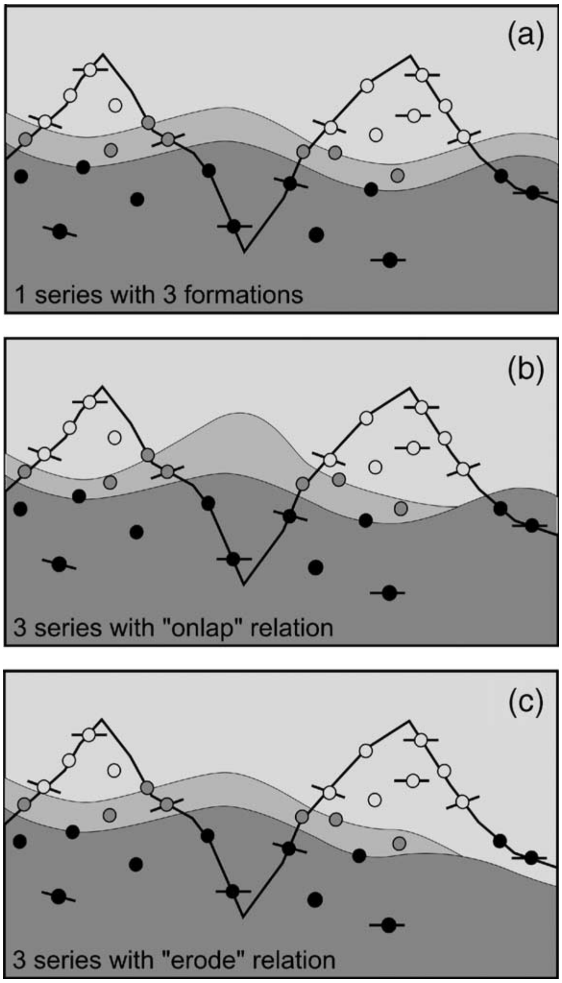

Fig. 5. Cartoon illustrating some features of the software 3DGeoModeller. The cartoon represents a schematic cross section through a mountainous topography (jagged line). There are three types of data: Orientation data (dots with dashes); interface points located on the geological contact (dots); observation of the presence of a unit (dots). White, grey and black symbols indicate that they belong to one of the three units. The shaded areas are model results for the distribution of the "white", "grey" and "dark grey" units that are consistent with the data. (a) All the units are included in one series, (b) each unit defines an "Onlap" series, (c) each unit defines an "Erod" series. See text for details.

structural interpretation of folded basement units. For more information on the possible software settings see Maxelon (2004), Martelet et al. (2004) and Calcagno et al. (submitted for publication).

The modelling was performed in a model volume that is 29.9 km by 34.9 km in size and 10 km in thickness (just over 10 000 km^3 volume). The surface topography within the model box was defined by using a digital terrain model provided by the provincial governments of Styria and Carinthia. The original resolution of a 15 × 15 m grid was resampled on a grid of 100 × 100 m to decrease the amount of data and reduce the model computation time. The model box is located in the 33°N quadrant in the WGS84 system of the UTM projection, within the east–west limits of 490 050 m and 519 950 m and the south–north limits of 5 173 050 m and 5 207 950 m, respectively. In the vertical direction the box reaches from 6000 m below to 4000 m above the reference geoid. The box dimensions were chosen so that all data points are at least 2 km from the border of the model box. Due to a software restriction the modelled bounding volume has to have north–south and east–west oriented sides. As the majority of our data define a northeast–southwest trend, there are substantial gaps in the data density in the northwest and southeast corners of the model volume. However, this is not a big problem as long as one keeps in mind that the modelling results have higher accuracies where the data density is high.

For the initial modelling, we described the hanging-wall units, the Plattengneis itself and the foot-wall units as three separate series. We used the "Onlap" relationship to allow for pinching out of the shear zone and left it open whether the shear zone was predicted to be a single sheet or is made up of several independent horizons. However, the latter did not render any outcrop patterns that related to the known distribution of the shear zone outcrops. In contrast, modelling the shear zone with combining all data of the three units in one series produces an outcrop pattern that is known from the detailed published maps of the area. We therefore continued the modelling assuming that hanging-wall, Plattengneis and foot-wall units can be described as one series as defined by the software.

5. Modelling results

The mapped distribution of Plattengneis outcrops in the Koralpe can be meaningfully reproduced assuming that the shear zone forms a single series with the bounding hanging-wall and foot-wall units. We therefore interpret the shear zone to form a single continuous sheet over the entire region. Fig. 6 shows our best fit

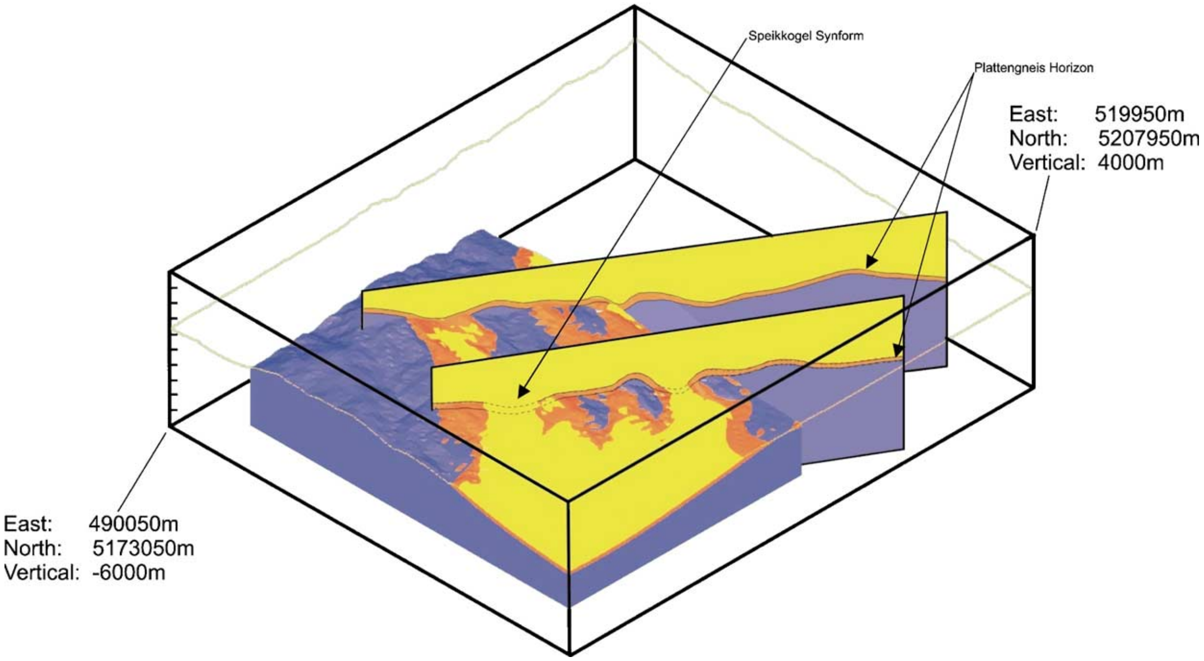

Fig. 6. Three-dimensional model output of 3DGeoModeller showing the southern half of the study region and profiles A and B (as shown in Fig. 7) as seen from the southeast. The model volume is cut off by the topography for this figure. Hanging-wall units of the Plattengneis are light shaded, Plattengneis is shown in intermediate grey and foot-wall rocks are shaded dark. The Speikkogel synform is the obvious shallow synform in the centre of the model block.

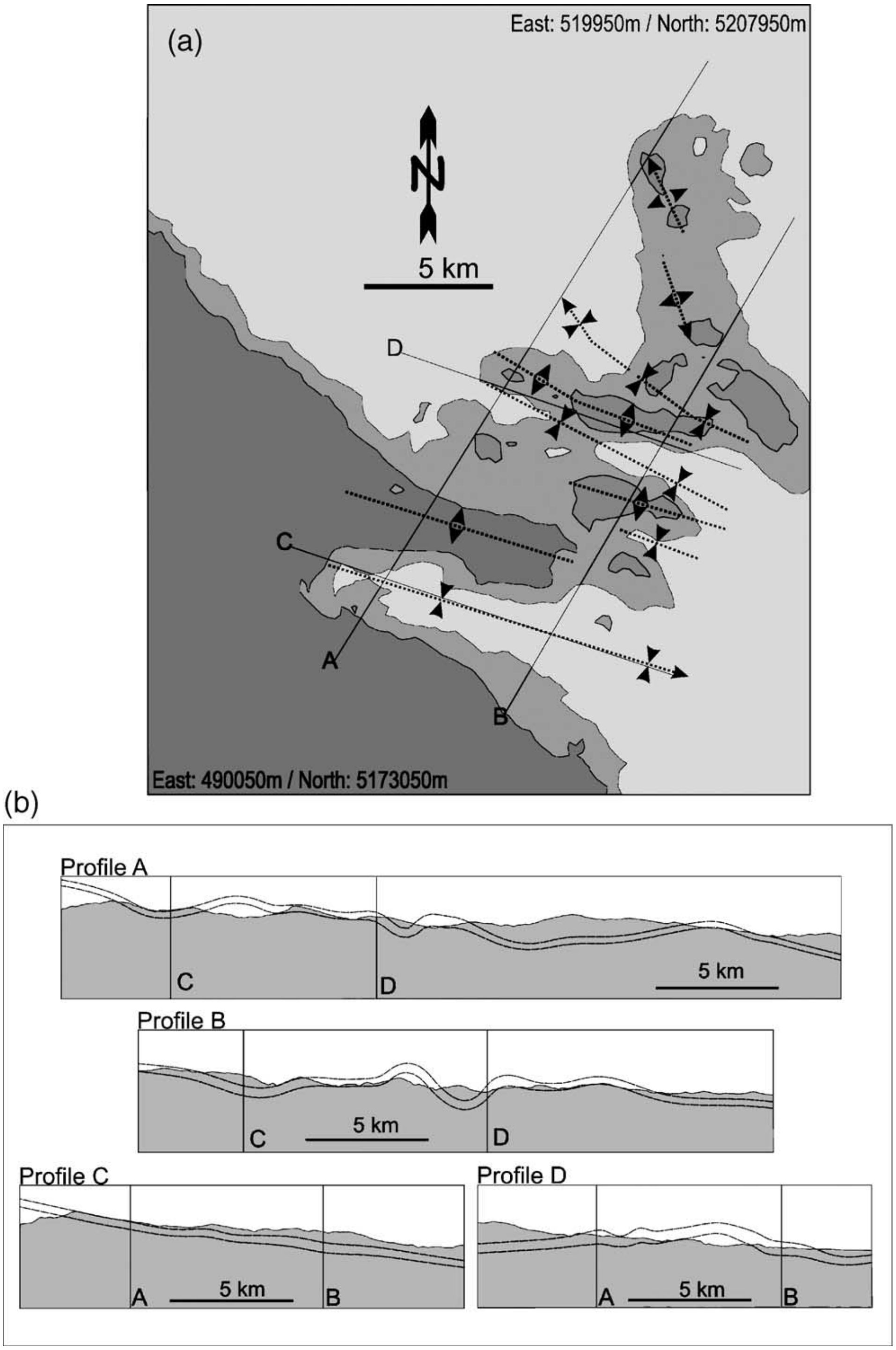

Fig. 7. Modelled distribution of Plattengneis outcrops in the study region. (a) As on Fig. 6, Plattengneis is shown by the intermediate shading, footwall units are dark and hanging-wall are light shaded. Dotted thin lines indicate inferred syn- and antiforms. Profiles shown in (b) are labelled. (b) Characteristic profiles through the study region. The topographic relief is shaded and the Plattengneis is shown by its hanging-wall and footwall contacts. Note that the Plattengneis forms a single continuous horizon of approximately constant thickness which dips into the topography in the north and strikes out in the south.

model and illustrates how the Plattengneis sheet dips in and out of the topography in a gently folded pattern. This interpretation is consistent with the observation that the gently folded overall geometry of the shear zone is also present in the surrounding host rock. This result shows that eclogite bodies occur both above and below the Plattengneis shear zone. In fact, the northern eclogite occurrences around Stainz and Bad Gams all lie in the hanging-wall units of the shear zone, as do the ones within the Speikkogel synform. The eclogite bodies south of the Speikkogel synform lie below the shear zone. This is in contrast with earlier workers (e.g. Kurz et al., 2002) who claim that eclogites generally occur structurally below the Plattengneis.

The modelled Plattengneis horizon shows a thickness that varies between 250 m and 600 m. A weak trend from greatest thickness in the central region (e.g. Fig. 7b, Profile D, region between profiles A and B) to lower thicknesses at the external parts is observed. The shear zone strikes out of the topography towards the south and west and dips into the topography in the north and east. In other words, all rocks south and west of the Speikkogel synform form the foot-wall of the Plattengneis shear zone, while all rocks in the northern part of the model region belong to the hanging-wall. This geometry requires that the shear zone strikes continuously through the model region from west to east. The southern limb of the Speikkogel synform would join the shear zone outcrops to the east of the model region but is cut off by the southern boundary of the model region or disappears beneath the Miocene sediments of the Pannonian basin (Styrian basin). In the west, the Plattengneis separates hanging-wall and foot-wall rocks by a narrow continuous extension of the shear zone towards the northwest in the centre of the model region. This continuation is in fact mapped (see Fig. 3). However, field checks showed that the Plattengneis loses its intense fabric along strike of this finger-shaped extension. As the shear zone is predicted to cover practically the entire model region, a Plattengneis volume of between 300 km^3 and 500 km^3 can be inferred from the model.

The shear zone is folded into four open synforms and five antiforms with a mean distance of about 5 km (Fig. 7a). In the south these folds strike WNW–ESE and plunge with about 10° to the east. This is consistent with the field observations at the Speikkogel synform. However, in the centre of the region the model reveals several syn- and antiforms that have not been recognized previously. There is a synform with limb angles of 90° just south of profile D on Fig. 7 which is flanked by two antiforms, all within about 3–5 km. This folding was produced by a larger shortening in the east than in the west as may be seen from a comparison of profiles A and B on Fig. 7. The overall shortening of the shear zone during this open folding event was only of the order of 5% (4.1% parallel to profile A, 5.5% parallel to profile B). The folding of the shear zone and its position more or less parallel to the topography produces a number of intersections with both hanging-wall and foot-wall of the shear zone in this central region. In the north of the study region, the Plattengneis is folded into an open doubly plunging antiform that strikes almost north–south. The change of orientation of the fold axes from south to north and the more intense folding in the east than in the west give the appearance that the shear zone has been folded in a complex stress regime or, alternatively, that the warped structure is caused by the superposition of two approximately perpendicular oriented shortening events.

5.1. Robustness of the model

The modelled outcrop pattern in Fig. 7 agrees very well with the existing maps of the region and our own field observations (Fig. 3). The Speikkogel synform is reproduced almost exactly and the apparent deviation in the western central region stem from the fact that the model has not allowed for pinching out of the shear zone within the modelled volume. The minor deviations in the northern part are the consequence of the Plattengneis being almost horizontal, so that intersections of the hanging-wall of the shear zone with the topography depend strongly on the resolution of the model and of the digital terrain model.

In order to test the model and to assess the effect of lower input data densities on the resulting model, we generated nine additional models with reduced input data, five of which are shown in Fig. 8. The original data include 333 data points plus 49 contact lines, implying a mean density of about 1 recorded field entry per every 2.6 km^2. The number of these data entries was successively reduced by 10%. That is, a random 33 foliations, 2–3 upper contact lines and 2–3 lower contact lines were taken out of the input data set and the modelling was repeated. During each deletion of contact lines, care was taken that the number of deleted contact points was also about 10% of the total number of points. That is, long or short contact lines were deleted so that this requirement remained fulfilled for each step.

The resulting outcrop patterns are striking in several ways (Fig. 8): Although the quality of the model (com-

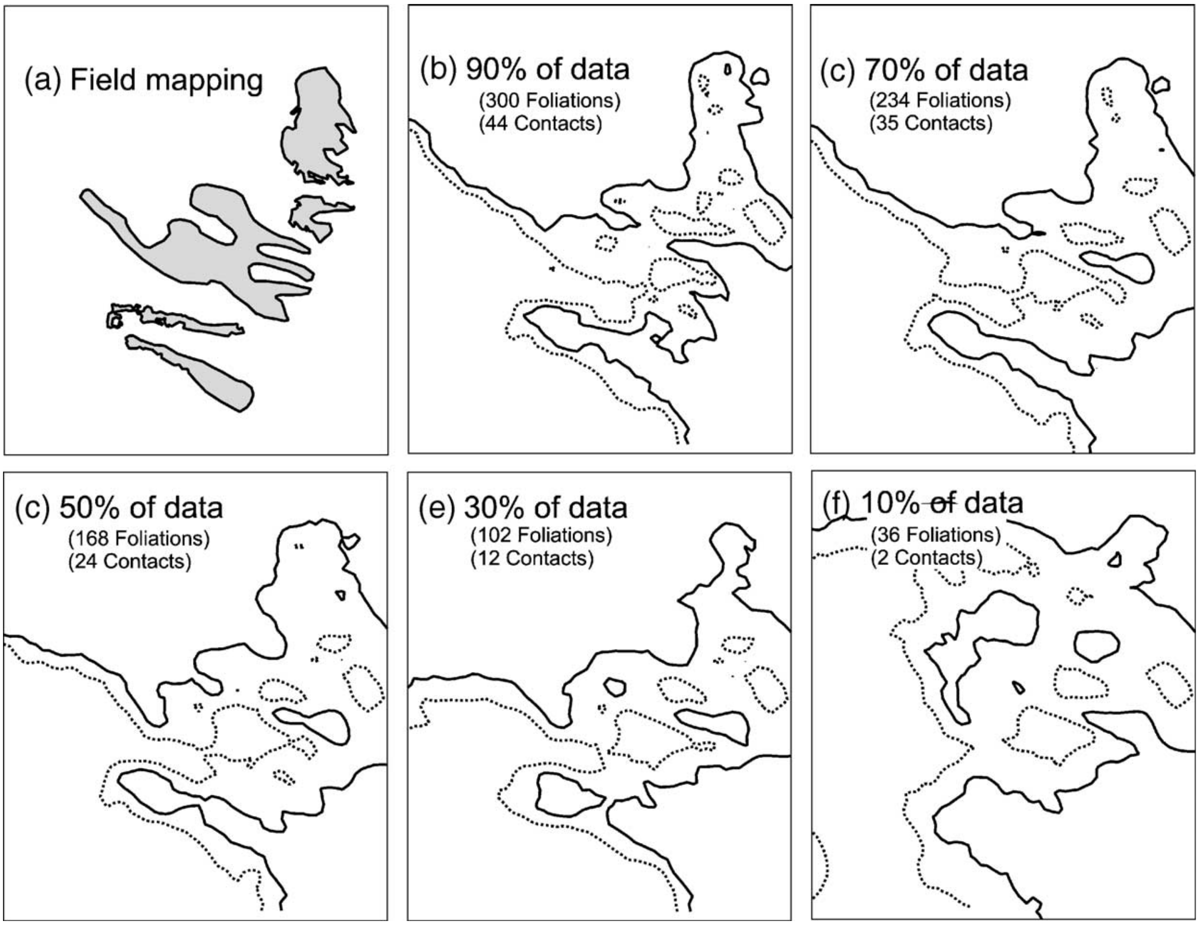

Fig. 8. Robustness of the model. (a) Distribution of Plattengneis as inferred from the mapping results. (b–f) Modelled distribution of Plattengneis with a successive reduction of data density by 10% for each modelling step. Only steps for every 20% data reduction are shown. Hanging-wall contacts are shown as continuous lines, foot-wall contacts as dashed lines. Note that there is still reasonable correspondence between modelled and mapped outcrop pattern down to a data density of 50% of the original data. The bounding box corresponds to that shown in Figs. 3, 6 and 7.

pared to the mapping results) decreases steadily with reducing the data density, a surprisingly good match of model and field observations is achieved up to a reduction to 30% of the original input data (Fig. 8e,f). The first obvious deviation occurs between 90% and 70%, where the folds in the southeast of the study area, north of the Speikkogel synform, begin to merge. However, the final cut-off point is only reached somewhere between the last two runs. Only the last model (10% of original input data) does not yield an outcrop pattern that relates to the known outcrop distribution in a meaningful way. Overall the resulting geometry tends to become flatter as the data density is reduced, which leads to slightly increased outcrop area of the Plattengneis horizon.

This experiment clearly shows that 3D structural modelling is an efficient tool for the generation of geological maps, even in areas of poor outcrop (low data densities), as the overall geometry of the region is still well represented with only few input data. However, the software does not permit an automated weighting of data and it is therefore crucial to use only high quality data as input. In our study a manual grading system for all examined outcrops was used (from 1 for perfect outcrops such as quarries, to 5 for very poor exposures such as single boulders) as a way to characterise how representative an outcrop is for the adjoining square kilometre. This allowed us to use only the most reliable data (grades 1 and 2) in regions where enough good outcrops were available while we would use data of grades 2–4 where little data was obtainable. The omission of low quality data makes the input data more homogenous which obviously improves the robustness of the model. Nevertheless, for the geometry of the Plattengneis shear zone, a data density of one field measurement every 4 km^2 appears to suffice to reproduce the large scale geometry of the shear zone.

6. Discussion

Our model suggests that the Plattengneis shear zones forms a single mylonite sheet that is openly folded about east–west striking fold axes in the south and north–south striking fold axes in the north. It disappears downwards in the north and strikes out of the topography in the south, so that all units north of the Plattengneis are structurally above the shear zone and those south of the Plattengneis structurally below it. The folding event is not associated with any fabric formation, mineral growth or brittle deformation and the event cannot be identified on the outcrop scale as there are no parasitic folds on the 1–100 m scale. All features of the folding event described here are on kilometre scale and there are no observable differences between east–west and north–south striking folds. We therefore interpret the folding of the Plattengneis shear zone as a late stage warping event following the earlier mylonitic shearing.

Late stage warping of rocks has been described in many areas (e.g. coastal Maine, Colorado Piedmont) and is generally attributed to a combination of isostatic response to differential exhumation (e.g. Leonard, 2002) and tectonic forcing. Differential thermal contraction during cooling can also cause warping (Sandwell and Fialko, 2004), but there are no major rheological discontinuities in the region and this possibility is ruled out here. Differential isostatic response is also not likely because it is difficult to conceive that this process can cause folds with limb angles of up to 90° within few kilometres (Fig. 7b). This observation also precludes other possibilities for warping, for example folding due to local differential volume change in response to retrograde metamorphic reaction. We therefore suggest that the late stage folding/warping event described here must be the response to tectonic forcing during the post-Eoalpine exhumation of the shear zone. The orientation of the fold axes suggests that the event was either two closely successive events with shortening directions perpendicular to each other or one single north–south directed event with some minor east–west component. In order to interpret this folding event in terms of its tectonic significance, it is important to constrain it as closely as possible in time.

6.1. Age of warping

As there is no mineral growth associated with the folding, the event cannot be dated directly. However, minimum and maximum constraints can be placed from other tectonometamorphic events along the eastern margin of the Alps. A maximum constraint can be derived from the geochronological information on the high grade metamorphism in the region. Peak temperature conditions in the Gleinalpe dome occurred around 94 Ma at 500 °C (Neubauer et al., 1995). Fast exhumation followed this peak during Late Cretaceous to Early Paleocene time with cooling of the rocks to about 225 °C at 61 Ma (Neubauer et al., 1995). Peak temperature conditions in the Koralpe were reached around 90 Ma with 700 °C (Thöni and Jagoutz, 1993), which is somewhat later than at the Gleinalpe. The metamorphic peak was followed by rapid exhumation until about 82 Ma (Willingshofer et al., 1999). Recent ^{40}Ar/^{39}Ar data of Wiesinger et al. (2005) from the appending Saualpe suggest rapid exhumation of the region between ca. 85.6 and 78.1 Ma. From this time on cooling/exhumation seems to have slowed down and continued at a similar rate as the Gleinalpe exhumation (Hejl, 1997). Microstructures and mineral equilibria show that the mylonitisation occurred at high grade conditions so that it can be inferred that the late stage warping described here must have occurred later than 90 Ma and probably later than 82 Ma.

A minimum constraint on the age of the folding event can be placed from its relationship with the surface topography: The fold axes mimic the slope of the topography throughout the investigated region. In the south, where the topographic slope of the Koralpe dips eastwards, fold axes also plunge shallowly to the east. Further north, where the topography disintegrates into a hilly landscape, the fold axes are also more horizontally oriented. This suggests that the surface uplift and tilting of the Koralpe postdates the folding event. Final exhumation of the Koralpe has been dated to have occurred around 50 Ma (Hejl, 1997) and surface uplift and tilting has been related to the Miocene extension (Genser and Neubauer, 1989). We therefore conclude that the folding event postdates the Eoalpine events around 90 Ma, but predates the final exhumation of the Koralpe around 50 Ma. Thus, the stress field produced by the Late Palaeogene and Neogene lateral extrusion of the orogen (Ratschbacher et al., 1991; Robl and Stüwe, 2005) is unlikely to be related to the folding event described here. The available *PTt* data are compiled in a *PTt*-path in Fig. 9(c). In summary, the folding

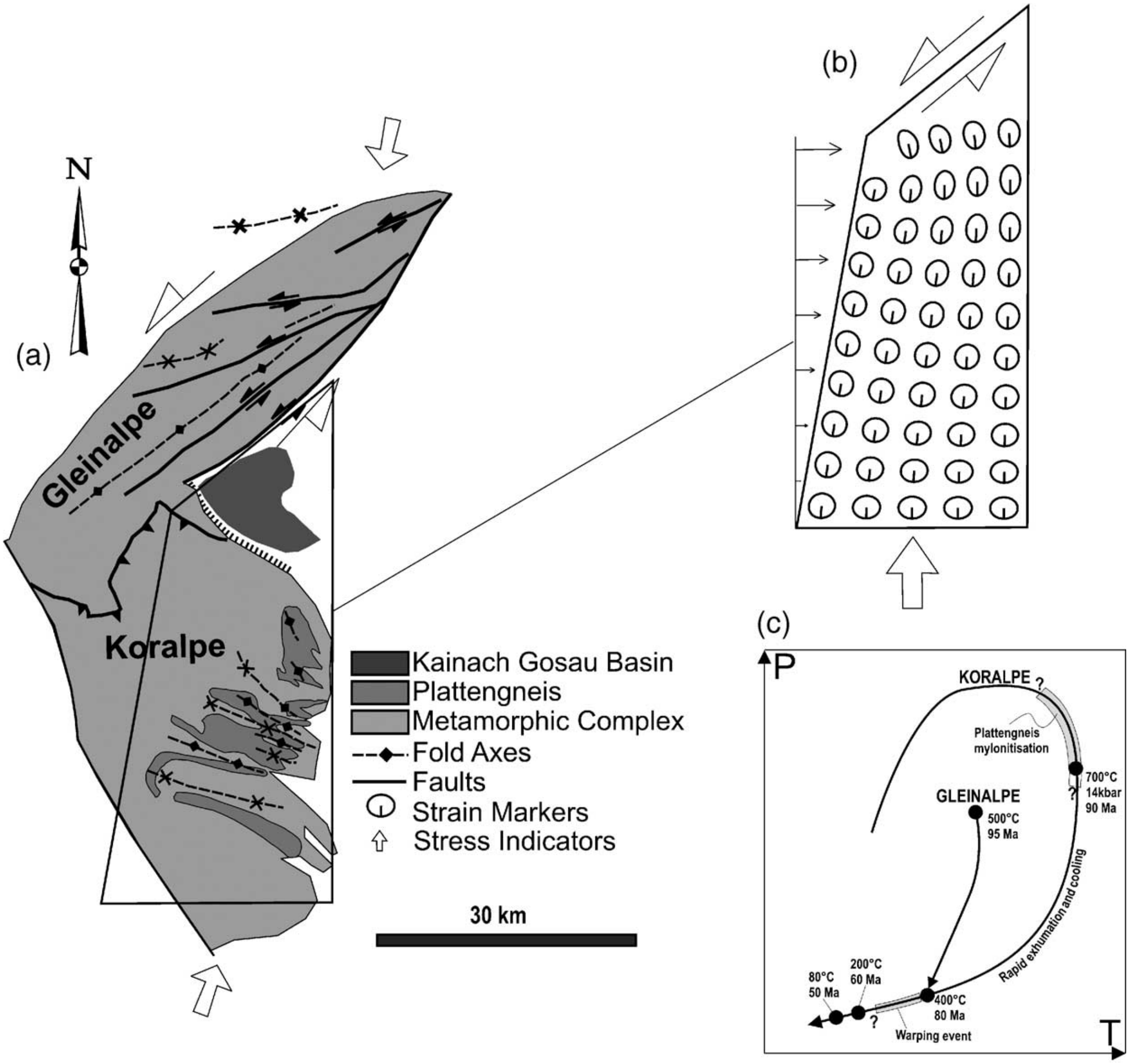

Fig. 9. (a) Tectonic interpretation of the late stage warping of the Plattengneis. For geographic orientation and naming of geological units see Fig. 1. (b) Results of a simple plane strain finite element model of the strain distribution with velocity boundary conditions as indicated by the arrows. The strain markers show that these boundary conditions result in a north–south oriented direction of maximum shortening in the south and an east–west oriented direction of maximum shortening in the north. This is consistent with the results presented on Fig. 7. (c) *PTt* paths for the Koralpe and Gleinalpe regions. The data are compiled from Thöni and Jagoutz (1993), Hejl (1997), Neubauer et al. (1995) and Willingshofer et al. (1999). The time of the mylonitisation (shaded bar near peak) is derived from microstructural observations on overprinting parageneses after, for example Stüwe and Powell (1995). The time of warping (shaded region just above fission track ages) is suggested from circumstantial evidence presented here.

event falls into an important period of the geological evolution of the region: the upper Cretaceous exhumation of the Gleinalpe dome and simultaneous subsidence of the adjacent marine Kainach Gosau basin.

6.2. Tectonic interpretation

The observed and modelled geometry of the Plattengneis shear zone can be used to constrain aspects of the late Cretaceous tectonic history of the region. This part of the tectonic evolution of the region was characterised by the simultaneous main subsidence in the Kainach Gosau basin between 85 Ma and 80 Ma (Willingshofer et al., 1999) and the rapid exhumation of the Koralpe region immediately to the west. Kurz et al. (2002) and Kurz and Froitzheim (2002) suggested that this exhumation occurred by extensional unroofing similar to that in core-complexes. More recently, the same group of authors revoked their earlier theory and explained the initial exhumation of the Austroalpine eclogites from depths up to 100 km by slab extraction from a southward dipping subduction zone (Froitzheim et al., 2003; Janak et al., 2004). The final exhumation from moderate, midcrustal depth is then interpreted to have occurred by extensional shearing and faulting (Janak et al., 2004; Froitzheim et al., 2003). Their interpretation is based on an inferred southward increase of the maximum exhumation depth along the subducted slab from the Gleinalpe in the north to ultrahigh pressure conditions (30 kbar and 800 °C) documented in Slovenian eclogites from the Pohorje range south of the Koralpe (Janak et al., 2004). This interpretation appears to be in some contrast with the metamorphic field gradient in the Koralpe documented by Tenczer and Stüwe (2003), who show a decrease in metamorphic conditions towards north and south from the central Koralpe region. However, this apparent contradiction is likely to be caused by the different scales of these studies. Nevertheless we refrain from a plate-scale tectonic interpretation of the relationship of the Plattengneis to the regions south of it and limit our tectonic interpretation to the unambiguously defined dome structure of the central Koralpe in relationship to the Gleinalpe to the north.

The fold pattern in the Koralpe region suggests a dominance of north–south directed shortening in the south but a rather east–west orientated shortening in the north. Thus, if the warping geometry was formed in a single event, the folding event was highly non-coaxial and likely to be related to an asymmetric stress regime. According to Neubauer et al. (1995) doming and exhumation of the Gleinalpe dome to the north of the investigated area, is related to shortening in the lower crust and a series of major medium to steep southeast dipping, sinistral northeast striking shear zones that separate the Koralpe from the Gleinalpe complex (Fig. 9). Following this model we suggest that folding of the Plattengneis must have occurred while these shear zones were still active, but when the Gleinalpe dome already provided a rigid backstop. Within this model, the north–south or NNE–SSW directed stress field shortens the region in north–south direction, but the slip along the sinistral shear zones bounding the Gleinalpe dome causes some shortening in east–west direction (with a minor component of NW–SE shortening due to oblige slip). This stress distribution is confirmed by the results of a simple finite element model shown in Fig. 9, the detailed description of which goes beyond the scope of this paper, but we provide some information on the boundary conditions in the figure caption. Sinistral slip along the northern margin of the Koralpe could also cause some tilting of the entire region resulting in the subsidence of the Gosau basin. Within this model, the formation of the Gosau basin is intimately related to the folding event in the Koralpe but somewhat postdates the formation of the Gleinalpe dome and is therefore not directly related to the evolution of the Gleinalpe. The Kainach Gosau basin is mainly filled by components derived from the underlying Paleozoic of Graz (Fig. 1) and the lack of clastic material derived from the adjacent crystalline units implies low relief of the region during basin formation. We infer that this suggests that the warping occurred when the Gleinalpe dome was already exhumed and the exhumation of the Koralpe was nearing its end. In summary, we suggest that the orientation of the late stage warping axes of the Plattengneis shear zone imply a southward propagation of folding and exhumation of the region during Late Cretaceous time.

The observation that the Plattengneis shear zone dips into the topography in the north and strikes out of the topography in the south is in some contrast with the south dipping Plankogel detachment and the detachment between Koralpe and Gleinalpe (Fig. 1, inset). Two possibilities offer themselves: Firstly, it is possible that the Plattengneis shear zone pinches out just after its southern and northern termination of outcrop. Within this model, less deformed rocks may form another fold to be parallel to these detachments as indicated by the dotted lines in the inset on Fig. 1. This possibility is, in fact, suggested by our modelling results which have shown that there is a slight thickness decrease of the shear zone towards the margins of the modelled region. However, it is also possible that the Plankogel and Gleinalpe detachments are unrelated to the Plattengneis and cross-cut the Plattengneis fabric at depth. The Plankogel detachment is certainly younger than the high grade deformation of the Plattengneis, so the second possibility cannot be excluded.

6.3. Other interpretations

Aside from the tectonic interpretations that our model allows, the derived volume of 300 km^3 to 500 km^3 of mylonitised rock allows us to place some constraints on the overall contribution of the shear zone to the heat budget. In simple one dimensional shear, the volumetric shear heat production is given by the production of flow stress and shear strain rate. Strain rates for other parts of the Austroalpine have been estimated to range between 10^{-13} and 10^{-14} s^{-1} (Biermeier and Stüwe, 2003). Flow stresses are much less well constrained but are likely to be of the order of tens of MPa. Thus, the volumetric shear heat production is of the order of 1–10 μW m^{-3}. For the derived volume of the shear zone between 300 km^3 and 500 km^3 the total heat production is therefore about 3×10^5 to 5×10^6 W. If the shearing duration was between 1 and 10 my, then the total heat production is between about 10^{19} and 1.5×10^{21} J. The contribution of such heat to the metamorphic temperature budget depends on the importance of heat conduction away from the site of heat production, which in turn depends on the relative time scales (e.g. Stüwe, 2002). A careful evaluation of the time scales of heat production and conduction of the Plattengneis shear zone during its Eoalpine evolution as well as a discussion of other potential heat sources, for example the unknown contribution of radioactivity of the shear zone, may form an exciting further study.

7. Conclusions

In this study, we have used three dimensional modelling of the Plattengneis shear zone to reveal the geometry of a late stage folding event that occurs on a kilometre scale in a region of little outcrop. The derived geometry can be used to interpret aspects of the late Cretaceous tectonic evolution of the region. In particular, it can be concluded that:

- The Plattengneis shear zone forms a single continuous sheet that fluctuates between 250 m and 600 m in thickness. It dips into the topography in the north and strikes out of the topography in the south and parallels largely the surface topography of the Koralpe. South of the Speikkogel synform no Plattengneis can be found which probably is due to the shear zone losing its mylonitic fabric further south.
- The shear zone crops out in several patches over an area that is about 600 km^2 in size and the mylonitised volume is between 300 km^3 and 500 km^3. Within this region it is folded into a series of open syn- and antiforms. Fold axes plunge with about 10° to the east in the south, but become shallower and successively more north–south oriented towards the north. However, folding is open and limb angles do not exceed 90° over several kilometres.
- North–south shortening of the region due to folding does not exceed a value of about 5% and east–west shortening did not exceed about 2% of its initial length. These values are good approximations for the strain of the region during Late Cretaceous–Early Paleocene as no outcrop scale parasitic folds occur in the Plattengneis horizon.
- The late stage warping of the shear zone has occurred between the high grade events in the Cretaceous (around 90 Ma) and the final exhumation of the Koralpe to the surface around 50 Ma. In our interpretation it is closely related to the subsidence of the adjacent Kainach Gosau basin between 85 Ma and 80 Ma and occurred plus/minus simultaneously to the basin formation. The orientation of the fold axes of the Plattengneis suggests that the folding occurred at a time when the wrench corridor bounding the Gleinalpe dome was still active.

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