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Folding in Miocene, unconsolidated clastic sediments (Vienna basin, Austria) – gravitational versus tectonic forces

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Abstract: Spectacular folded, but virtually unconsolidated sediments in a sand pit in the Vienna basin have been used as one of the key arguments of an E-W shortening event during the Late Miocene in the eastern Alps and western Carpathians. The outcrop has been re-excavated recently and several new observations like the occurrence of refold structures, the fold shapes and the large amount of localized shortening bring into question the established tectonic interpretation. Alternatively, we propose that gravitational forces caused the folding in the frontal part of a slump along the eastern slope of the Vienna basin.

Keywords: Vienna basin, Miocene, soft sediment deformation, slump folds.

The Vienna basin, located at the junction between the eastern Alps and western Carpathians, is one of the classic examples of pull-apart basins (Royden, 1985). During extensional lateral escape tectonics of the eastern Alps (Ratschbacher *et al.*, 1991), the basin was formed as part of the Pannonian basin system along a NE-SW trending system of normal and sinistral strike-slip faults (Decker, 1996). In the Miocene, syntectonic sedimentation accumulated up to 5500 m of shallow marine and terrestrial deposits in the deepest parts of the basin (Wessely, 1983). The deformation history of the basin has been described as multistaged (Decker, 1996). An initial ESE-WNW extensional phase in the Karpatian and Badenian (~17-13 Ma) was accommodated by NNE-SSW strike-slip faults and resulted in the initiation of the rhombic pull-apart basin (Royden, 1985). An intermediate stage of Late Miocene basin inversion with E-W compressional fold structures and simultaneous dextral

reactivation of the strike-slip faults has been described (Peresson and Decker, 1997). One of the key outcrops for E-W shortening displays a SW-verging, inclined fold structure in Pannonian sands (Peresson and Decker, 1997) at the border between the Vienna basin and the south-easterly adjacent Eisenstadt-Sopron basin (Fig. 1) Pleistocene and present-day kinematics are again characterized by E-W extensional structures and the formation of local sub-basins; e.g. the Mitterndorf basin in the SW part of the Vienna basin (Hinsch *et al.*, 2005).

Structural evidence of shortening like folds –or even more likely in unconsolidated sediments–, deformation bands and faults with thrust kinematics are basically absent in this part of the Vienna and Eisenstadt-Sopron basin. Based on these considerations together with the fact that it is difficult to discriminate between tectonic and gravitational forces in deformed
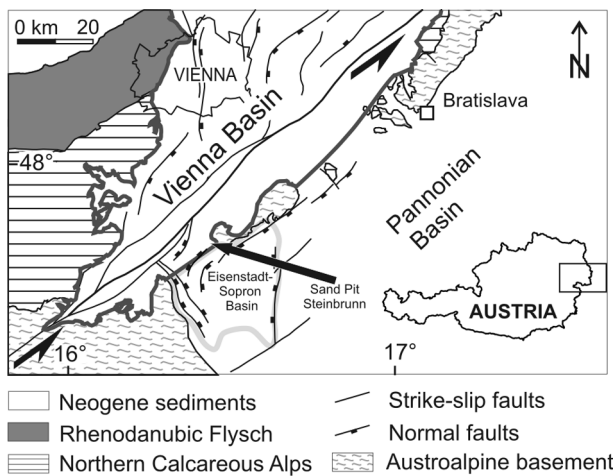
Figure 1. Location of the studied sand pit at the transition between Vienna basin and the Eisenstadt-Sopron basin. Modified after Strauss *et al.* (2006).

sediments with a low degree of lithification (Elliot and Williams, 1988), we qualitatively investigated the structures in the re-excavated sand pit.

Field observations

In a sand pit westwards of Eisenstadt, Burgenland, a spectacular example of deformed unconsolidated sediments has been described (Meyer, 1974; Sauer *et al.*, 1992). The outcrop exposes a series of SW-verging, tight folds within virtually unconsolidated sand and silt layers (Fig. 2). Regional tectonic interpretations attributed this deformation to a Late Miocene, E-W compressional phase of basin inversion which followed the main E-W extensional phase in the early and middle Miocene (Peresson and Decker, 1997).

However, due to the recent re-excavation of the outcrop, several new observations bring into question the previous interpretation.

1) In the studied outcrop, the sand layers are partly cemented only in the uppermost few decimetres exposed along the quarry walls, while the newly excavated layers –except some early diagenetic concretions– are virtually uncemented. The basal parts of the exposed sediments contain more cohesive, cm to m thick silt and silty clay layers, which form conspicuous flame-shaped geometries in the fold cores indicative of the mechanics of soft sediment deformation (Potter *et al.*, 2005). Within the fold hinges, clay-mineral rich layers develop a pronounced cleavage subparallel to the axial plane, which may have been produced by slump-straining (Farrell and Eaton, 1988).

2) Conjugate sets of normal faults (deformation bands) in the external parts of the NW-SE-striking fold hinges cut through sandy layers and terminate within silt layers. Markers within the sand layers display only few centimetres of normal offset, but the fractures are filled with a maximum 2 cm thick zone of clay fed from the overlying clay layer. This feature suggests again that the sediment was unconsolidated during the formation of these structures; its position in the external parts of fold hinges may indicate extension in the outer arcs of the folds.

3) Most of the observed folds have tight fold geometry with straight fold limbs and amplitudes of several metres. In the westernmost part of the outcrop, some fold axial planes are refolded, forming type 3 (hooks-and-crescent) interference structures with high angles between the axial surfaces and parallel fold axes. These fold shapes indicate either polyphase folding, which seems unrealistic for a short phase of basin inversion, or high strain during progressive folding and shearing. The latter has been frequently described in subaqueous slump structures (Strachan and Alsop, 2006).

4) In contrast to the observations from strike-slip faults in the Northern Calcareous Alps (Peresson and Decker, 1997), outcrops in the immediate vicinity of the described sand pit within the same stratigraphic level do not display any comparable structures with E-W shortening kinematics. In contrast, we observed exclusively E-W extensional structures (faults and deformation bands with normal offset).

5) Simple line-length restoration of the deformed succession indicates roughly 50% of ENE-WSW shortening. Clearly, an extrapolation of this estimation to a basin-wide shortening is inappropriate, as already suggested by Peresson and Decker (1997).

6) Neither analogue nor numerical modelling predicts the formation of folds or in particular localized, vergent buckle folds in the pre-existing filled part of inverted sedimentary basins (Panien *et al.*, 2006).

Conclusions

The new observations in the sand pit of Steinbrunn, enabled by the re-excavation of the outcrop, question the tectonic origin of the observed fold structures. Based on the present exposure, we propose an alternative interpretation of the deformation features as the frontal zone of a gravitational slump, where contractional strain leads to the formation of tight folds

Figure 2. Northern wall of the sand-pit, view to the north. In the right part of the picture the uppermost Pannonian sands and marls dip uniformly 20° towards east. In the left part of the picture the same sequence is folded in two WSW verging anticlines.

(Farrell, 1984). If this new interpretation of the E-W shortening structures in the Pannonian sediments is correct, the outcrop should not be incorporated into tectonic models for regional E-W compression in the late Miocene.

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