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Thermo-Tectono-Stratigraphic Forward Modelling of the Upper Rhine Graben in reference to geometric balancing: Brittle crustal extension on a highly viscous mantle

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ABSTRACT

Four structural cross-sections through the central segment of the Upper Rhine Graben (URG) were balanced by means of Thermo-Tectono-Stratigraphic Forward Modelling (TTSF-Modelling). Results were compared to geometric retro-deformation of pre-rift reference horizons applying line length and area balancing methods. TTSF-Modelling with a deep necking level (>20 km) and/or a high effective elastic thickness (Te ≥ 15 km) yielded extension values similar to those of geometric balancing, while modelling with shallower necking depths and/or lower Te yielded unrealistic high extension values. A best fit of geometric balancing, indicating 5 km rift orthogonal extension, was reached by TTSF-Modelling with a Te of 15 km and a 'pre-rift' necking depth of 29 km coinciding with the Moho discontinuity. This is compatible with (a) the geophysically mapped Moho that does not shallow significantly beneath the central segment of the URG and its shoulders, (b) seismicity indicating brittle–elastic deformation of the entire crust and a-seismic, ductile deformation of the lithospheric mantle, (c) compensation of crustal faults and shear zones in the crust–mantle transition zone. Modelled time-extension paths imply rifting during the Middle Eocene to Early Miocene, a Late Miocene post-rift stage and renewed rifting during the Pliocene to recent. Apparent northward migration of extension in time is an effect of uplift processes, which are not related to rifting. Correcting for these, the extension history for the four cross-sections becomes very similar, suggesting plane strain deformation and rifting at very low strain rates of about 1.7×10^{-16} s^{-1} involving brittle–elastic deformation of the crust and ductile deformation of the highly viscous, high strength upper mantle that controls the position of the lithospheric necking level.

1. Introduction

The Upper Rhine Graben (URG) forms part of the European Cenozoic Rift System, a chain of kinematically linked extensional basins that stretches from the Mediterranean to the North Sea (Prodehl et al., 1995; Ziegler, 1992, 1994). The URG has been intensely studied and explored for hydrocarbons, minerals and geothermal energy. Numerous wells and a dense grid of 2D industrial reflection-seismic lines and gravity surveys document its structural configuration and stratigraphy (e.g., 1970; Bartz, 1974, Doebl, 1967; Doebl and Teichmüller, 1979; Durst, 1991; Lutz and Cleintuar, 1999; Rotstein et al., 2006; Wirth, 1962). In addition, the crustal and lithospheric configuration and graben evolution were deciphered (e.g. Berger et al., 2005a,b; Dèzes et al., 2004; Rotstein et al., 2006; Ziegler et al., 2004).

Nonetheless, there is an ongoing debate about the evolution of the URG (e.g. Bourgeois et al., 2007; Dèzes et al., 2004, 2005; Michon and Merle, 2005; Rotstein and Schaming, 2008; Ziegler, 1994). Most authors agree that the URG evolved by passive rifting in response to the build-up of far-field intraplate compressional stresses during the Alpine orogeny (Ziegler, 1994). A two-stage model, involving Paleogene more or less orthogonal extension and Neogene sinistral transtension was advocated by Illies and Greiner (1978), Buchner (1981), Michon and Merle (2000) and Dèzes et al. (2004). In contrast Schumacher (2002) proposed a five-stage model, while Behrmann et al. (2003) advanced a model of continuous sinistral transtension. Hinsken et al. (2007) showed for the southern part of the URG that its Paleogene evolution involved pure shear orthogonal rifting with a deep level of lithospheric necking.

Although numerous efforts have been made to quantify crustal extension across the URG (Table 1). This study presents for the first time the results of detailed cross-sections balancing, including back stripping of the basin fill. Pre-rift reference horizons were restored to quantify extension and combined with back stripping of the syn-rift sediments. Then the basin was retro-deformed and time-extension paths determined (e.g. Buchanan and Nieuwland, 1996; Woodward et al., 1987). Alternatively, time-extension paths can be derived from subsidence analyses of the syn-rift sediment as basin volume is related to the amount of crustal stretching (Allen and Allen, 2005; McKenzie, 1978). To address involved non-linear processes such as changes in heat flow and isostatic compensation, advanced basin restoration was

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Table 1
Extension values for the URG from previous studies.

Author	Method	Extension (△L)
Bourgeois et al. (2007)	Crustal thinning with 30 km Initial thickness	30%≈12 km
Hinsken et al. (2007)	Geometrical methods	5 km
Schwarz and Henk (2005)	3D TTSFM with 2 borderfaults soling out at 15–16 km depth	8–8.5 km rift orth. ext. 3–4 km left lat. disp.
Brun et al. (1992)	Line length balancing	5–7 km
	Crustal configuration	17 km
Meier and Eisenbacher (1991)	Area balance with detachment at 15 km	6–10 km
Villemin et al. (1986)	TTSFM	6 km
Illies (1967)	Geometrical methods	4.8 km

accomplished by forward modelling using a specially developed software for Thermo-Tectono-Stratigraphic Forward Modelling (TTSF-Modelling; Ruepke et al., 2008). This was done for four structural cross-sections through the central, continuously subsiding segment of the URG, published by Doebl and Teichmüller (1979).

2. Evolution of the Upper Rhine Graben

2.1. Pre-rift

The basement of the URG area was consolidated during the Late Paleozoic Variscan Orogeny and the latest Carboniferous–Early Permian phase of strike-slip deformation, magmatism and transtensional basin development. During the Late Permian and Mesozoic re-equilibration of the lithosphere–asthenosphere system, the area of the URG was essentially tectonically quiescent, subsided and was incorporated into an intracratonic basin that extended from the Paris Basin to the Franconian Platform (Ziegler et al., 2004). In the URG area, a 1–2 km thick sedimentary sequence accumulated during the Triassic, Jurassic and possible also the Cretaceous (Ziegler, 1990), locally affected by minor reactivation of Paleozoic crustal discontinuities (Allenbach and Wetzel, 2006; Wetzel et al., 2003). During the latest Cretaceous and Paleocene the area of the future URG was affected by an important phase of intraplate compression, causing buckling and erosion of the Mesozoic platform (Ziegler, 1990; Ziegler and Dèzes, 2007). These deformations, which controlled the Mesozoic subcrop pattern beneath the syn-rift deposits of the URG (Fig. 3), were accompanied by the intrusion of scattered dykes reflecting very low degree partial melting of the lithospheric boundary layer (Dèzes et al., 2004; Keller et al., 2002; Ziegler and Dèzes, 2007).

2.2. Syn-rift

Sedimention commenced in the URG during the early Lutetian (about 47 Ma) with local deposition of the lacustine *Bouxwiller Fm.* (Fig. 2; Berger et al., 2005b; Grimm and Hottenrott, 2005), whether these very early deposits form part of the syn-rift sequence is uncertain (Fig. 3; Schumacher, 2002; von Eller and Sittler, 1974).

During the late Lutetian-Bartonian (*Green Marls Fm.,* about 43–37 Ma), the URG started to subside rapidly and syn-rift sedimentation spread northward into the area of the investigated cross-sections where the subcrop pattern of the pre-rift series indicates that the graben had started to subside prior to the deposition of the *Green Marls Fm*. During the late Lutetian to early Rupelian (43–32 Ma), a thick succession of marls and evaporites accumulated the axial part of the URG, while conglomerates and sandstones were deposited along its margins; depositional environments fluctuated between fluvial, lacustrine, brackish and evaporitic (Fig. 2; *Green Marl Fm*, *Pechelbronn Grp.;* Derer et al., 2003; Duringer, 1988; Hinsken et al., 2007). Minor marine ingressions from the north occurred during the early Rupelian

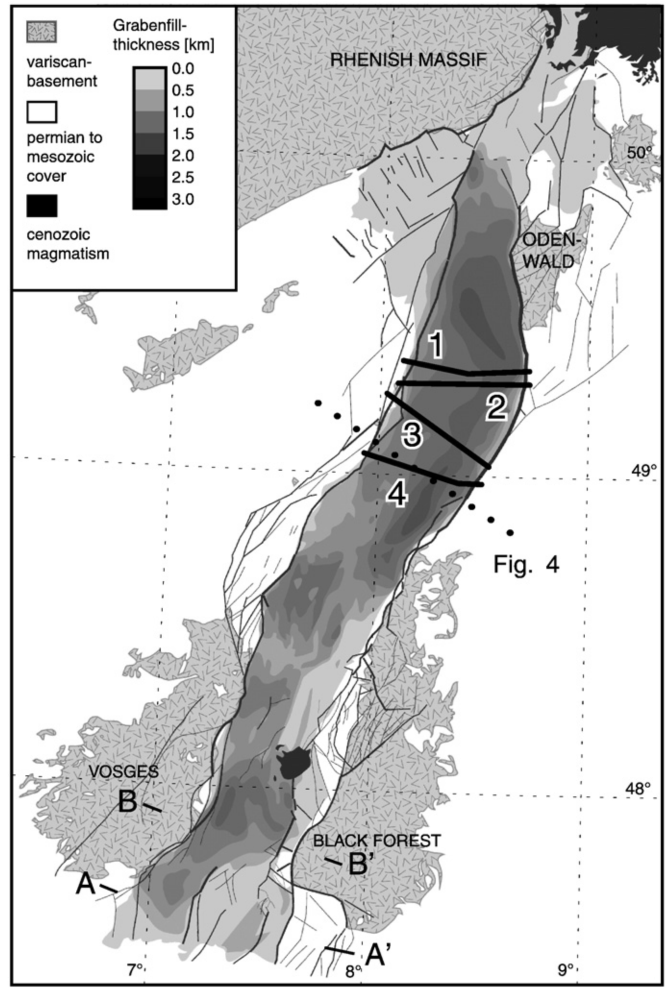

Fig. 1. Simplified geological map of the URG, showing thickness of the Cenozoic graben fill and the location of studied cross-sections in its central part.

(*Middle Pechelbronn beds*; Griessemer, 2002; Pirkenseer, 2007), preceding a late Rupelian transgression that established open marine conditions (*Grey Marls Fm.*; Pirkenseer, 2007; Rousse, 2006). Increased sediment supply caused in southern parts of the URG an early Chattian regression (e.g., Huber, 1994) and the development of brackish and finally fluvial-lacustrine conditions (*Niederröden Fm.*), while in its northern parts brackish to lacustrine conditions were established during the late Chattian (*Worms Grp*). From the middle Burdigalian onward fluvial and limnic series were deposited in the northern URG (*Ried Gp.;* Grimm and Hottenrott, 2005). Whereas the northern part of the URG subsided steadily during the Neogene (Derer et al., 2005; Haimberger et al., 2005; Roll, 1979), its southern part was uplifted during the mid-Burdigalian and subjected to profound erosion. This is evidenced by a regional angular unconformity that extends northward into the area of the investigated cross-sections and that is on-lapped by the *Ried Gp.* (Fig. 2; Berger et al., 2005a; Roll, 1979; Wirsing et al., 2007; Ziegler and Dèzes, 2007). Development of this unconformity is attributed to uplift of the Vosges–Black Forest Arch, involving lithospheric folding in response to the build-up of Alpine collision-related intraplate compressional stresses. Uplift of this arch was accompanied by the development of the Kaiserstuhl volcanic complex (18–16 Ma), deep truncation of the syn-rift series in the southern URG and erosional unroofing of the Vosges and Black Forest, stripping them of their Mesozoic cover (Bourgeois et al., 2007; Dèzes et al., 2004; Roll, 1979; Wirsing et al., 2007; Ziegler and Dèzes, 2007; Ziegler et al., 2002).