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Stress inversion and basement-cover stress transmission across weak layers in the Paris basin, France

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ABSTRACT

We investigate the source of non-purely gravitational horizontal stresses in the Paris basin, a nowadays tectonically quiet intracratonic basin, in its eastern border of which outstandingly dense stress measurements are available. Based on a synthesis of published data, the stress state in the basin is first shown to be very close to the one that may be extrapolated for the underlying basement, in terms of principal stress orientations and horizontal to vertical stress ratios. This is in favour of a mechanical coupling between the basement and its sedimentary cover, which may seem contradictory to the presence of several weak rock layers in the basin fill, *e.g.* an argillite layer that was shown to bear low deviatoric stresses, and salt layers that are implicated in a major décollement elsewhere. To unravel this apparent contradiction, a 3D-numerical modelling is performed, following a rigorous inverse problem approach, to determine the long-term elastic properties of both the basement and the basin rocks. The objective is to find the set of elastic constants that provides the best fit between the calculated stress state in the basin and the *in situ* data, by assuming that the stress state in the basement is known. This methodology provides a realistic set of mechanical parameters, in agreement with previous studies, which leads to the conclusion that the horizontal stresses in the basin constitute its mechanical response to the stresses that developed in the underlying basement during and since the last tectonic event (Alpine phase). The fact that horizontal stresses could be transmitted across the weak horizons, contrary to what may be expected at first glance, is explained both by the geometry of the basin and the fact that, over the long term, the stiffnesses of the various sedimentary rocks are only slightly different from each other.

1. Introduction

The rather uniform stress pattern that prevails in intraplate areas is classically interpreted as a consequence of the far-field boundary forces that drive plate motion (Heidbach et al., 2010; Zoback and Zoback, 2007) and has been investigated by various numerical models (*e.g.* Gölke and Coblentz, 1996, for the European plate). Because sedimentary basins constitute very thin, superficial rock layers at the scale of the lithosphere, they are most of the time not considered in such large-scale models of stress sources. Furthermore, investigations of stress build-up in basins mostly focus on the mechanical behaviour of the basin fills themselves (compaction, pore pressure changes) and disregard the possible role of the underlying basement. Consequently, the mechanical relationships between basements and their sedimentary cover are still somewhat obscure when it comes to the question of stress transmission between them, especially when some “weak” rock layers, such as evaporite or shale, are present in the basin fill and may act as horizons of mechanical decoupling.

The objective of this study was to investigate the source of horizontal stresses in the Paris basin, a nowadays tectonically quiet intracratonic basin, in the eastern border of which outstandingly dense stress measurements have been obtained in the past 20 years by the ANDRA (the French radioactive waste management agency) in the framework of the feasibility study of underground nuclear waste storage. The major horizontal stress in this part of the basin was found to have a very constant NW–SE orientation (Cornet, 2010; Cornet and Röckel, 2012; Wileveau et al., 2007) that is similar to the orientation generally accepted in the underlying basement (Heidbach et al., 2010; Müller et al., 1992), which is in favour of a mechanical coupling between the basement and its sedimentary cover. Yet, several potentially decoupling weak rock layers are known to exist in the sedimentary fill, which drove Cornet and Röckel (2012) to put the attachment into question. In particular, a 140-m thick argillite formation of Jurassic age (which constitutes the target layer for waste storage) was shown to bear low deviatoric stresses, and the Triassic salt layers at the basement–basin interface are implicated in a major tectonic décollement only some 200 km away, in the Jura fold-and-thrust belt (Davis and Engelder, 1985).

In a previous study by Gunzburger and Cornet (2007), a numerical modelling of the stress build-up in the Paris basin was undertaken,

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without considering the underlying basement and assuming all sedimentary rock layers to be horizontal. It was concluded that, over the long term, the stiffness parameters of the *a priori* "strong" and of the "weak" sedimentary rocks are probably not as different as suggested by short-term laboratory tests, possibly due to the effect of pressure-solution in the (*a posteriori* not so) "strong" limestone units (Gunzburger, 2010). Based on the more complete approach described hereafter, we checked whether this conclusion holds when the bowl shape of the basin and the basement stress signature are taken into account, as well as the supposedly weak rock layers present in the basin fill.

A 3D-numerical modelling was performed under a hypothesis of elastic behaviour of both the basement and the basin rocks, and the elastic constants were determined by following a rigorous inverse problem approach. The objective was to find the set of elastic constants that provides the best fit between the calculated stress state in the basin and the *in situ* data, by assuming that the stress state in the basement is known. This methodology provided a realistic set of mechanical parameters, which led us to the conclusion that the horizontal stresses in the basin constitute its mechanical response to the far-field plate boundary forces applied to its basement during and since the Late Miocene, as a result of the ongoing Africa–Eurasia convergence. The fact that horizontal stresses could be transmitted across the *a priori* weak horizons, contrary to what may be expected at first glance, is explained both by the geometry of the basin (characterized by a very low dip angles of the bedding planes) and by the long-term mechanical behaviour of the sedimentary rocks. In fact, it appears that even a slight stiffness contrast between the various rock layers may lead to strong differences in the present stress states they bear. The next step would be to consider a time-dependant boundary loading, along with a visco-elastic rheology, but this will inevitably increase the number of unknown parameters, thus making them impossible to determine from the stress inversion only.

2. Stress state in the Eastern Paris basin and in the underlying basement

2.1. Geological setting and paleostresses

The Paris basin, which occupies most of Northern France, is an intracratonic sedimentary basin that forms a broad shallow bowl, with an almost flat topographic surface, a near circular shape of ~400 km radius on map view, and a maximal thickness of ~3 km (Fig. 1). It developed during the Meso-Cenozoic on a basement constituted of Paleozoic rocks inherited from the Hercynian orogeny, which crop out in uplifted shields: the Vosges to the E, the Central Massif to the S, the Armorican Massif to the W and the Rhenish Massif to the N. The sedimentologic history of the basin spanned a wide range of environments including continental, lagoon, littoral and open marine depositional conditions. It is described in detail by Mégnien et al. (1980) and Guillocheau et al. (2000).

The polyphase tectonic sequence in the Eastern Paris basin is well documented. An exhaustive synthesis of paleostress orientations was presented by André et al. (2010). Based on it and on their own complementary analysis of minor fault-slip data, stylolitic peaks and tension gashes, these authors concluded that the last main tectonic event recorded in the basin fill is dated from the Late Miocene and was characterized by a strike-slip regime with a major horizontal stress (*i.e.* greatest horizontal compressive stress) oriented from WNW–ESE to NNW–SSE. This paleo-stress also affected the basement at the same period, as demonstrated, for example, by the presence of numerous NW–SE oriented dykes, dated from 6–8 My, in the Central Massif (Feraud and Campredon, 1983). This so-called "Alpine" tectonic phase resulted from the indentation of the Adriatic plate, which caused the uplift of the Alps (about 23 My) and formed the Jura fold-and-thrust belt (3–5 My), but only slightly affected the Paris basin (Bergerat, 1987; Dezes et al., 2004).

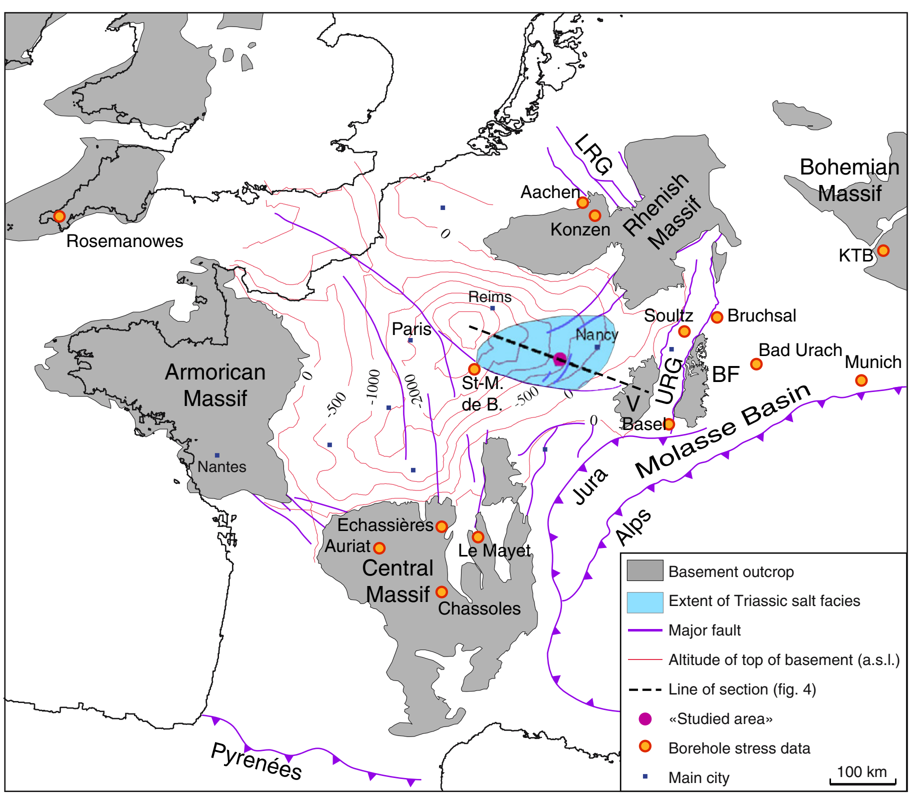

Fig. 1. Map of the Paris basin, showing the altitude a.s.l. of the basin–basement interface, as well as the areas where the basement is outcropping. The following abbreviations are used: V = Vosges, BF = Black Forest, LRG = Lower (Northern) Rhine Graben, URG = Upper (Southern) Rhine Graben. The extent of the Triassic salt formation is taken from Mégnien et al. (1980).