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Late Pliocene–Pleistocene stress field in the Teruel and Jiloca grabens (eastern Spain): contribution of a new method of stress inversion

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Abstract

Samples of non-striated fracture surfaces within clastic materials of Late Pliocene–Pleistocene age from the Teruel grabens (eastern Spain) have been analysed using a stress inversion method based on observations of slip sense. The results obtained at 21 sites are compared with Late Miocene–Early Pliocene extensional stress tensors previously inferred from striated faults in the same area. The similarity between both sets of stress states suggests that the extensional Miocene–Pliocene stress field essentially continues (with minor changes) into Pliocene–Pleistocene times. The main changes involve (a) the dominant trend of σ_3 trajectories, which evolve from ESE to ENE; (b) the waning of the compressional component caused by Europe–Iberia–Africa convergence; and (c) the progressive trend towards a multidirectional extension regime. Stress deflection caused by large-scale extensional faults as well as switching of σ_2 and σ_3 axes induced by fracture development are common within this stress field. They produce groups of local stress ellipsoids with σ_3 axes orthogonal to each other and either orthogonal or parallel to the faults bounding the grabens. The regional consistency of the new results gives support to the new inversion method and demonstrates its utility in research on young sedimentary rocks, where 'gaps' in palaeostress records may exist due to absence of striated faults.

Keywords: Stress inversion; Iberian Chain; Neotectonics; Fault

1. Introduction

The vast majority of palaeostress inversion methods are based on the assumption that the slip direction on each fault in a rock mass is parallel to the maximum resolved shear stress on the fault plane. Bott's equation (Bott, 1959) expresses how the direction of the shear component of stress on a plane relates to the plane's orientation with respect to the stress axes and to the stress ratio. The stress ratio describes the relative values of the principal stresses and hence the overall shape of the stress ellipsoid. Many inversion methods use this equation to address the inverse problem of estimating the stress axes orientations and stress ratio given the observed shear (in the form of striations) on the fault planes (Carey and Brunier, 1974; Carey, 1976, 1979; Armijo and Cisternas, 1978; Etchecopar et al., 1981; Angelier and Bergerat, 1982; Armijo et al., 1982; Simón, 1982, 1986; Etchecopar, 1984; Angelier, 1991; Fry, 1992; Delvaux et al., 1992; Delvaux, 1994; Stapel and Moeys, 1994). There are a variety of other methods that utilise the slip direction to constrain the possible orientations of the principal stresses, e.g. Right Dihedra Method (Pegoraro, 1972; Angelier and Mechler, 1977) and Right Trihedra Method (Lisle, 1987, 1988). However, as with the methods based on the Bott equation, they all require knowledge of the slip direction.

NE Spain has been extensively investigated in terms of palaeostress during the last two decades (Simón, 1982, 1986, 1989; Amigó, 1986; Guimerà, 1988; Casas et al., 1992; Arlegui, 1996; Casas and Maestro, 1996; Arlegui and Simón, 1998; Cortés, 1999). Recently, Liesa (2000) compiled more than 1600 stress inversion results from diverse authors obtained with several methods, with affected rocks spanning from Palaeozoic to Tertiary, representing both compressive and extensional stress fields. The

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successive stages of Alpine rifting and compression have been characterised with particular detail along the Iberian Chain. However, a cursory look at the published data reveals obvious gaps in the palaeostress record, such as the lack of results from recent deposits and soft rocks. In both cases, the main problem is the paucity, due to the physical properties of the wall rocks, of striated fault surfaces over limited areas that most stress inversion methods require for analysis. Current strategies for overcoming the problems of detecting slip direction from faults in young (unlithified) sediments where striation are lacking include the use of scanning electron microscope (SEM) images of fault surfaces and stress inversions based solely on observations of dip separation (Lisle et al., 2001).

Our purpose in this paper is to explore the possibilities that the Lisle et al. (2001) method offers for stress inversion of fractures measured in recent (Upper Pliocene and Pleistocene), mainly clastic materials. The application of the method to the Teruel and Jiloca grabens allows the comparison of our results with older (Late Miocene–early Pliocene) stress tensors previously inferred in the same area.

2. Methodology of stress inversion based on fault slip sense

Lisle et al. (2001) explore the possibility of stress tensor estimation from fault slip sense alone. They show that knowledge of the sense of the dip-slip component on a fault with dip angle γ indicates the sign of gradient of normal stress $\delta\sigma/\delta\gamma$. Such information, if available for fault planes with a range of orientation, allows the orientation of principal stress axes to be constrained. Their approach involves a comparison of the levels of normal stress calculated for the observed fault with that calculated on a slightly steeper-dipping imaginary fault plane. In order to test the validity of their inversion results, they have used artificial data samples as well as natural samples in which slip lineations were not taken into account, which allows comparison with the results of conventional analysis based on striated faults. In common with other methods of stress inversion, the authors suggest that data sample size, a preferred orientation of faults or poly-phase deformation will affect the reliability of stress results.

The grid search method of inversion proposed by Lisle et al. (2001) is based on a computer search for stress tensors compatible with the observed faults and their respective slip senses. The search involves the definition of a 4-D solution space that is systematically explored by varying the orientations of σ_1, σ_2, σ_3 and the value of stress ratio Φ. The grid or mesh is the interval between two consecutive trial stress tensors. The precision of such stress inversion strategy is therefore a function of the grid search parameters. The number of observed slip senses that match the predicted slip senses is the criterion for expressing the goodness-of-fit of the trial stress tensors.

In comparison with the fault slip inversion strategies that utilise the knowledge of the orientation of slickenlines on faults, the procedure proposed by Lisle et al. (2001) produces a wider range of compatible stress tensor solutions. This increased range of compatible stress tensor solutions is a consequence of the ‘reduced information content’ of slip sense data when it is compared with slip vector data. Lisle et al. (2001) report that the precision of the method and its ability to recognise mixed data sets (potentially sourced from poly-phase deformation) are improved as sample size is increased.

Orife et al. (2002) detail a computer algorithm to implement the stress inversion procedure of Lisle et al. (2001). These authors prefer to present the inversion results using stereoplots that show modal solutions of the respective stress axes and a frequency histogram of the stress ratio values for displaying compatible stress tensors.

Lisle et al. (2001) and Orife et al. (2002), by implication, utilise the orientation of the fault plane as the reference frame for defining a normal/reverse dip-slip movement. A potential limitation of using slip sense data relates to the assumptions regarding the initial orientation of the reference markers that are used to define the sense of a displacement. However, if these reference markers are horizontal or their cut-off lines are horizontal (as they are in the present study area), the sense of separation in the down-dip line of the fault reliably indicates the sense of dip-slip movement.

3. Geological setting

The eastern sector of the Iberian Chain shows a large network of extensional faults with dominant strikes NNE–SSW and NNW–SSE (Fig. 1), which postdate the compressive structures. These faults developed during Neogene times, as the eastern margin of the Iberian Peninsula became dominated by the influence of rifting in the Valencia Trough (Álvaro et al., 1979; Vegas et al., 1979). The two main orientations of faults are inherited from late-Variscan and Mesozoic times, which moved as reverse and strike-slip faults during the Paleogene compression and were again reactivated as normal faults during Neogene and Pleistocene times. The latter gave rise to grabens that were filled with continental deposits. The NNE–SSW-trending Teruel and Maestrazgo grabens are parallel to the Valencia Trough. They represent the onshore deformation of the eastern Iberia Neogene rift (Simón, 1982; Roca and Guimerà, 1992). The Jiloca graben, located west of the former area, shows a NNW–SSE trend probably controlled by S_{Hmax} stress trajectories related to recent intraplate compression (Simón, 1989).

Extension propagated westward from the offshore Valencia Trough (where sedimentary infilling initiated by Early Miocene times), to the Maestrazgo grabens (Early–Middle Miocene), Teruel graben (Late Miocene) and Jiloca graben (Late Pliocene) (Capote et al., 2002). Local