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Review Article

Basin inversion and contractional reactivation of inherited normal faults: A review based on previous and new experimental models

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ABSTRACT

Compressional inversion of former extensional sedimentary basins is a particularly common phenomenon, given that passive margins share the same destiny of being subsequently incorporated into fold-and-thrust belts. During basin inversion pre-existing faults may concentrate stress and localise future thrust ramps, or may be reactivated recording reversal of movement from extension to reverse. This process has attracted attention largely because of its economic implications related to petroleum and ore deposit prospects, and seismic hazard assessment. Since more than two decades, analogue modelling has been used to indentify and/or test a number of parameters relevant for the inversion process. This paper aims therefore to offer a reasoned review of the analogue modelling work done on the subject, coupling such previous results with those of a new experimental series inspired to the Northern Apennines stratigraphy and evolution. Past models have explored the role of main factors governing fault reactivation susceptibility, such as fluid pressure, fault weakness, fault steepness, angle of shortening, and sediment loading. The new models have addressed the role played by geometry and strength of a basal ductile layer during inversion. Two sets of sand–silicone models were first extended orthogonally at different velocities to produce dissimilar pre-inversion internal geometries, and then shortened coaxially at different velocities to vary the brittle–ductile coupling. The experimental results confirm the selectiveness of fault inversion, and reveal strong similarities with structural styles of tectonic inversion reported from the Northern Apennines and various areas worldwide. The preferred geological model inferred from this modelling involves contribution of (1) syn-inversion rotation of pre-existing faults to shallower dip, and (2) rotation of principal stress axes, which could explain the invariable reactivation of only one of the two oppositely-dipping graben bounding faults. These factors would thus interact with the other well-established parameters controlling the fault reactivation process.

Contents

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1. Introduction and aims of the work

'Basin inversion' is a globally used term to indicate the shortening of formerly extensional basins (e.g., Bally, 1984; Buchanan and Buchanan, 1995; Cooper and Williams, 1989; Harding, 1985; Ziegler, 1982, 1987). Inversion zones are elongate structures that may stretch several tens or even hundreds of kilometres in length, and that have developed in response to compression of grabens and troughs. The compressional inversion of grabens has received great attention during the last three decades owing to its importance related to (1) the role of pre-existing faults as preferential structures accommodating the shortening of the shallow crust, (2) the role of high-angle extant faults as potential seismogenic sources (Sibson, 2009), and (3) the economic importance related to ore deposit generation (Sibson and Scott, 1998) and hydrocarbon maturation and trapping in petroliferous inverted sedimentary basins (e.g., Turner and Williams, 2004). Petroleum prospects for sedimentary basins are in fact intimately related to positive fault inversion, with this mechanism potentially controlling the thermal history of basins (by favouring uplift, erosion and exhumation of sedimentary basin), as well as the formation of new trapping structures, or the breaching and destruction of layers sealing petroleum reservoirs (e.g., Turner and Williams, 2004; Ziegler, 1987).

Even if the basin inversion concept is intuitive, the final structural outcomes observed in the field or imaged in seismic sections may be complex, and their full understanding sometimes difficult to determine. Basin shortening is in fact accommodated by typical reactivation of existing faults, but also a wide range of newly formed contractional structures (i.e., folds and faults) deforming the sedimentary basin succession may develop, thereby producing considerable changes with respect to the original tectono-sedimentary structure (e.g., Amilibia et al., 2008; Bally, 1984; Coward et al., 1991; Gillcrist et al., 1987; Turner and Williams, 2004). In addition, the extant normal faults dip habitually at high angle to the syn-inversion (sub-horizontal) σ_1 axis, and this implies that these faults can move as high-angle reverse faults only under specific and restricted conditions (Sibson, 1985). As a matter of fact, normal faults are often not reactivated and they may be commonly observed as fossil features in fold-and-thrust belts (e.g., Butler et al., 2006a; Marchegiani et al., 1999).

Given the relevance of these processes, basin inversion and fault reactivation have been the object of analytical studies (e.g. Etheridge, 1986; Nielsen and Hansen, 2000; Ranalli and Yin, 1990; Sandiford, 1999; Sibson, 1985, 1995; Tong and Yin, 2011; Yin and Ranalli, 1992), and targeted by several analogue and numerical models (Amilibia et al., 2005; Bonini, 1998; Buchanan and McClay, 1991, 1992; Buiter and Pfiffner, 2003; Buiter et al., 2009; Brun and Nalpas, 1996; Cerca et al., 2010; Del Ventisette et al., 2005, 2006; Dubois et al., 2002; Eisenstadt and Withjack, 1995; Gartrell et al., 2005: Gomes et al., 2006; Hand and Sandiford, 1999; Hansen and Nielsen, 2003; Henk and Nemčok, 2008; Jarosinski et al., 2011; Keller and McClay, 1995; Konstantinovskaya et al., 2007; Koopman et al., 1987; Letouzey et al., 1995; Lowell, 1974; Mandal and Chattopadhyay, 1995; Marques and Nogueira, 2008; McClay, 1989, 1995; McClay and Buchanan, 1992; McClay et al., 2000; Mitra, 1993; Mitra and Islam, 1994; Nalpas, 1996; Nalpas et al., 1995; Panien et al., 2005, 2006a; Pinto et al., 2010; Richard and Krantz, 1991; Sandiford et al., 2006; Sani et al., 2007; Sassi et al., 1993; Van Wees and Stephenson, 1995; Vially et al., 1994; Yagupsky et al., 2008; Yamada and McClay, 2003a,b, 2004, 2010; Ziegler et al., 1995).

This work focuses on the contribution of experimental analogue modelling for the understating of the mechanisms involved in basin inversion tectonics and the origin of associated structures, including the compressional reactivation of high-angle normal faults inherited from pre-orogenic rifting phases. In general, this experimental method aims to get insights into the complex natural geological processes by analysing the mechanical response of analogue materials simplifying the rheological properties of rocks existing in nature. Generally, the experimental results provide conceptual models that are comparable with natural examples. From one side experimental models have examined the deformation patterns resulting from basin inversion, these being of fundamental importance when looking at these structures as potential hydrocarbon structural traps (e.g., Letouzey et al., 1995; Nalpas et al., 1995). From the other side, analogue models have addressed the conditions that may allow the reactivation of high-angle normal faults under compression (e.g., Marques and Nogueira, 2008; Panien et al., 2005; Sassi et al., 1993). The experimental results can thus be used to understand the mechanisms and factors controlling fault reactivation and basin inversion, and may also have other practical aspects, as for instance they might help predicting the most likely structural configuration at depth when exploration targets for the oil industry are poorly imaged.

This paper initially reviews the deformation styles of natural inverted basins documented through fieldwork and seismic imaging during the last 2–3 decades, then it outlines the mechanical conditions of fault reactivation, and it examines and categorises the previous analogue modelling work done on the subject. Afterwards, the results of a new experimental series inspired to the Northern Apennines (Italy) are presented. The comparison of modelling results with nature will first focus on the Northern Apennines, then the deformation outcome of models is compared with settings identified