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Recumbent folds: Key structural elements in orogenic belts

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ABSTRACT

This review has two main parts. The first of them presents existing ideas and data related to recumbent folds, reviewing aspects such as the physical conditions of the development of these folds, the strain inside the folded layers, the kinematic mechanisms of their formation, the role of gravitational forces, the tectonic context of their development and the structures associated with them. In the second part, the above ideas are discussed and possible mechanisms for the development of these folds are presented. It is proposed that initial perturbations of the layers are essential to give rise to the asymmetry of recumbent folds. These perturbations may be non-planarities of the layering or may be linked to the existence of a core or basement of competent rock that hinders the normal propagation of the deformation. This could explain why many large recumbent folds have a root zone.

Deformation with an important component of simple shear is a general condition for the formation of recumbent folds. In areas with very low grade metamorphism, competent layers often play an active role during the deformation and undergo buckling with the development of an overturned fold limb, which can be stretched and thinned to finally produce a pair of recumbent folds separated by a thrust. In areas with low or medium metamorphism, buckling under a simple shear regime is probably the most important mechanism for producing large folds with gentle or moderately dipping axial surfaces; subsequent kinematic amplification by coaxial strain components with vertical maximum shortening is important for the formation of recumbent folds. These components involve a sub-horizontal stretching that can cause a problem of strain compatibility and give rise to a basal thrust. In areas deformed under high *P* and *T* conditions, recumbent folds can develop by flow perturbations and kinematic amplification of folds; this is probably a common mechanism in ductile shear zones.

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1. Introduction

The term *recumbent fold* was defined over a century ago and folds fitting this definition have been recognized on a wide variety of scales and in varied geological contexts. According to Geikie (1905, p. 137), "*Recumbent fold is the name given to a flexure, the axial plane of which approaches horizontality*". A similar definition was given by Leith (1913, p. 105) and Ries and Watson (1914, p. 154), and this is consistent with current usage by most authors. Fleuty's (1964) scheme for the classification of folds based on the attitude of the axial plane proposes an angle of 10° for the maximum dip of the axial plane of a recumbent fold and this convention has been widely accepted (e.g., Ramsay, 1967, p. 358–359; Dennis, 1972, p. 144; Ramsay and Huber, 1987, p. 322; Price and Cosgrove, 1990, p. 235; Ghosh, 1993, p. 225; van der Pluijm and Marshak, 2004; p. 244). Although this classification scheme is based on geometry rather than on the mode of origin of the folds concerned, it is evident that the formation of recumbent folds requires a different set of physical conditions than those that lead to folds with upright axial planes. In this paper we attempt to identify these specific conditions and the tectonic regime in which these conditions pertain.

Large recumbent folds were recognized in the 19th century in the Alps (Escher von der Linth, 1841; Gerlach, 1869; Renevier, 1877; Heim, 1878) and were named "recumbent-fold nappes" (Bertrand, 1884, 1887), "fold nappes" (Haug, 1900), and "first-order nappes" (Termier, 1906). Nowadays the term "fold nappe" is most commonly used, but it has a certain ambiguity. Most authors agree that a large recumbent fold is a fold nappe, but a terminological problem arises when the lower limb of the fold is cut by a thrust. Thus, for example, the Morcles Nappe (Helvetic zone of the Swiss Alps) is considered by Ramsay and Huber (1987), Price and Cosgrove (1990) and Epard and Escher (1996) to be a fold nappe, whereas it is referred to by Twiss and Moores (1992) as a thrust nappe. In agreement with most authors, and in line with Dennis et al. (1981), we prefer to define a fold nappe as a large recumbent fold whose lower limb may be cut by a thrust. Another point of contention is the length of the overturned limb, i.e. the length of the stratigraphic inversion necessary for the structure to be considered a nappe. Some authors suggest a minimum inversion of 5 km (e. g., Dennis et al., 1981; France, 1987), whereas others consider the minimum to be 10 km (e.g., Ramsay and Huber, 1987, p. 521). In any case, this decision is arbitrary and the change from 5 to 10 km is unlikely to involve a qualitative change in the kinematics of the structure.

It is interesting to consider further the common association of a large recumbent fold and a thrust cutting the lower limb. Explanation of this association may help to understand the kinematics of recumbent folds. Another additional characteristic of recumbent folds is that they are usually either close folds or isoclinal folds, and in some cases are more tightened than the non-recumbent folds found in other areas of the same orogen (e.g., Sanderson, 1979; Bastida et al., 2010).

The development of near-isoclinal large recumbent folds facing towards the foreland is common in the early phases of deformation in orogenic belts. Upright or inclined folds often appear superposed on these folds. In many cases, this superposition gives rise to interference patterns of the Type 3 of Ramsay (1967). This change in the style of folding with time must be associated with a change in the local stress regime. Consideration of the reasons for this change is key to our understanding of the kinematics and mechanics of orogenic belts.

In addition to the large recumbent folds with their corresponding parasitic folds, outcrop-scale recumbent folds are found in ductile shear zones developed commonly in the hinterland of orogens (e.g. Aller and Bastida, 1993; Yassaghi et al., 2000; Williams and Jiang, 2005). In these cases, near-isoclinal anticline–syncline fold pairs are common. Many of these folds have curved hinges and are sometimes sheath folds.

As will be seen in the examples described below, references to recumbent folds are countless and these folds have been described in a wide variety of regions: Archean cratons or terranes, greenstone belts, Proterozoic orogens, the Caledonian belt, the Northern Appalachian Mountains (Acadian deformation), the European Variscan belt, the Ural Mountains, the Moroccan Paleozoic massifs, the Central and Southern Appalachian Mountains, the Canadian Rocky Mountains, the Alps, the Himalayas, the Axial Zone of Pyrenees and the Betic Cordillera.

Recumbent folds usually develop in the internal zones or the internal/external transitional zones of orogenic belts, i.e., in a compressional tectonic regime (e.g. Hatcher, 1981; Ramsay, 1981; Dietrich and Casey, 1989; Simancas et al., 2004; Fernández et al., 2007; Ryan and Dewey, 2011). Nevertheless, they can also develop in extensional regimes (e.g., Platt, 1982; Froitzheim, 1992; Vissers et al., 1995; Orozco et al., 1998; Harris et al., 2002). Recumbent folds can occur as sedimentary structures, associated with slumps or overturned cross-bedding (e.g., McKee et al., 1962, 1971; Allen and Banks, 1972; Hendry and Stauffer, 1975; Fitches and Maltman, 1978; Doe and Dott, 1980; Plint, 1983; Owen, 1985; Farrell and Eaton, 1987; McClay, 1987; Owen, 1987; Paim, 1995; Owen, 1996; Nigro and Renda, 2004; Nichols, 2009; Pye and Tsoar, 2009; Alsop and Marco, 2011, 2012, 2013). They can occur also in glaciers of ice or salt and in the sediments associated with ice glaciers, such as push moraines or deformation tills (e.g., Hudleston, 1976, 1977; Talbot, 1979; Hudleston, 1983; Sans et al., 1996; Talbot, 1998; Hambrey and Lawson, 2000; van der Wateren, 2002; Talbot and Aftabi, 2004; Hooke, 2005; Hudec and Jackson, 2006; Evans, 2007; Hudec and Jackson, 2007; Leseman et al., 2010), or in impact structures (Price, 2001).

The fact that recumbent folds are often large and subsequently re-deformed structures makes it difficult to establish their original geometry. The isoclinal character of these large folds, together sometimes with the scarcity of outcrops and the monotony of the lithology, can even make them difficult to recognize. This complicates their kinematic and mechanical analysis. Furthermore, the wide variety of geological settings in which recumbent folds occur and their relation to other structures poses a number of additional problems.

The aim of this paper is to review the different theories for the development of recumbent folds and to consider how the analysis of the bulk strain undergone by the folded rocks can help to understand the mechanisms of formation of recumbent folds. We also seek to explain the observed relationship between recumbent folds and the other structures they are often associated with. Finally, we try to analyze the broader significance of recumbent folds in the context of orogenic belts. The analysis will be focused on the recumbent folds generated by tectonic deformation. Recumbent sheath folds have a peculiar geometry and pose specific problems that are not considered here.

2. Existing ideas and data relating to recumbent folds

Many papers make mention of recumbent folds and a variety of theories have been proposed to explain their development. For their systematization we consider in this section the descriptions and analyses made about the physical conditions, strain state, kinematics, driving forces (specifically the role of the gravitational forces), tectonic regime, and structural associations relating to recumbent folds.