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Regional flow perturbation folding within an exhumation channel: A case study from the Cycladic Blueschists

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ABSTRACT

Kilometre-scale cylindrical folds and associated parasitic folds that trend at small angles to the transport lineation are analysed along a 100-km-long transport-normal segment of the Cycladic Blueschists in an attempt to reconstruct the 3D structural architecture within an exhumation channel. Reversals in the polarity of both fold vergence and the hinge/lineation obliquity occur in a flow-normal direction, defining transport-parallel culmination and depression surfaces that root downwards onto an underlying detachment. Fold patterns generated around culmination and depression surfaces support models of flow-perturbation folding where folds initiate at small angles or sub-parallel to transport in response to wrench-dominated differential shearing. Successive culmination and depression surfaces are separated from one another by along strike distances of ~20 km, although atypical fold geometries developed in the flanks of major culmination and depressions follow their own patterns, revealing that smaller perturbations occur within the larger scheme. Major culminations are interpreted to reflect regions of surging flow marked by increased velocity during exhumation, whilst the opposite is true for depressions. This behaviour implies that on a regional scale, differential shear varies laterally in an irregular-sinusoidal manner defining areas of relative high and relative low displacement within the exhumation channel.

1. Introduction

1.1. Deformation in exhumation channels

Analysis of the style and extent of deformation within high-pressure (HP) metamorphic terranes can provide important information about the processes occurring in subduction and exhumation channels (e.g., Godin et al., 2006; Agard et al., 2010). For example, deformation that is largely localized at the borders of a rigid and coherent exhumed slice implies that buoyancy forces are the dominant driver of exhumation (Chemenda et al., 1995; Ernst et al., 1997). Alternatively, penetrative deformation distributed throughout a strong exhumed material suggests that upwards motion in the channel is driven primarily by tectonically-induced forces (i.e. channel flow, ductile extrusion, extensional collapse) (Platt, 1993; Warren et al., 2008; Agard et al., 2009). Considerable efforts have been made over the past 20 years to produce 2D models based on vertical transport-parallel sections that show the strain distribution and the velocity fields within the subduction/exhumation channel (Grujic et al., 2002; Warren et al., 2008; Mukherjee, 2013; Butler et al., 2013). However, exhumation is a 3D process that is also characterized by transport-normal variations in the deformation parameters. To date, only a few works have focused on such 3D flow variations (e.g., Goscombe et al., 2005; Xypolias et al., 2007; Boutelier and Chemenda, 2008).

Therefore, a major aim of this study is to reconstruct the 3D structural architecture of HP rocks within an exhumation channel using the Blueschist unit of the Cycladic massif as a natural example. Several recent studies have shown that exhumation of the Cycladic Blueschists occurred by extrusion (Xypolias et al., 2003, 2012; Ring et al., 2007; Huet et al., 2009). Ductile deformation is generally distributed throughout the exhumed rock unit, indicating that extrusion was mainly triggered by external-applied stresses rather than buoyancy forces (Xypolias et al., 2010). Exhumation-related deformation is primarily expressed by the formation of outcrop- to kilometre-scale cylindrical folds with hinge lines oriented parallel or at small angles to the direction of flow (e.g., Avigad et al., 2001; Xypolias et al., 2012). This study provides a detailed structural analysis from a 100-km-long crustal segment in order to

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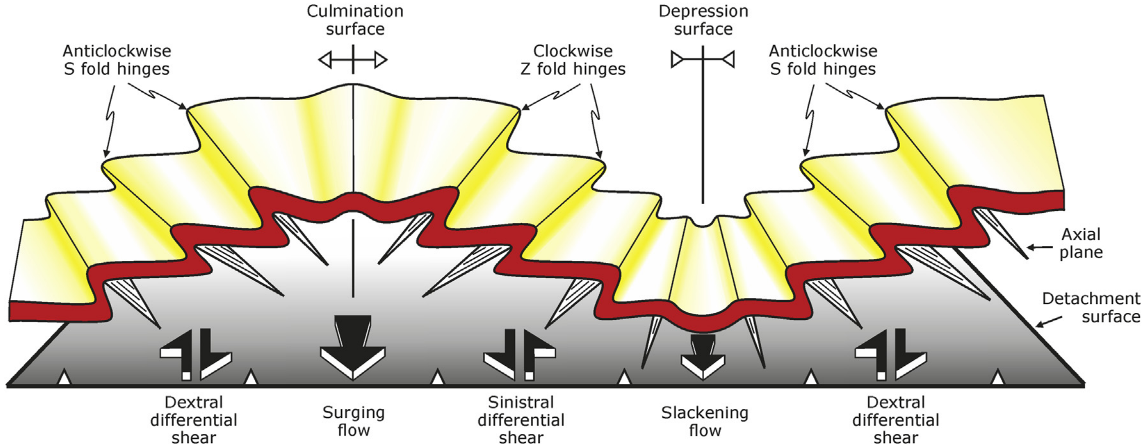

Fig. 1. Schematic 3D diagram illustrating the variable orientation and geometry of folds associated with culminations and depressions above a detachment surface (after Alsop and Holdsworth, 2002, 2007). Note the opposing dip of axial planes, the obliquity between fold hinges and the transport direction, and a switch in fold vergence associated with a reversal in the sense of differential wrench shear on either side of the vertical culmination and depression surfaces.

unravel the regional fold pattern and to elucidate the mechanism that lead to the formation of transport-parallel folds. We then interpret this pattern in terms of transport-normal variations in displacement fields within the exhumation channel.

1.2. Origin of transport-parallel folds

Cylindrical and quasi-cylindrical folds with hinges lying at small angles or sub-parallel to the dominant mineral/stretching lineation and inferred transport direction is a widespread phenomenon in metamorphic belts (Bell, 1978; Ridley, 1986; Holdsworth, 1990; Alsop, 1992). A number of controlling mechanisms have been invoked to explain such relationships. For example, co-linearity between the fold hinge and lineation may be due to regional constrictional deformation (e.g., Fletcher and Bartley, 1994; Passchier et al., 1997; Zulauf and Zulauf, 2005). Alternatively, a co-linear relationship can develop from shortening of a planar layer oriented perpendicular to the intermediate (Y) axis of the strain ellipsoid (e.g., Froitzheim, 1992; Grujic and Mancktelow, 1995). The linear anisotropy produced by an early penetrative deformation phase in a polydeformed area, may also exert control on the attitude of a subsequent fold phase that forms parallel to the pre-existing intense linear fabrics (e.g. Watkinson and Cobbold, 1981). A common interpretation invokes progressive rotation of fold hinges towards the shear direction due to intense non-coaxial shearing (Sanderson, 1973; Escher and Watterson, 1974; Bell, 1978; Williams, 1978; Alsop, 1992). For this mechanism, cylindrical folds lying sub-parallel to the lineation marking the transport direction are generated during the single clockwise or anticlockwise rotation of fold hinges initiated non-orthogonal to the transport direction (Alsop, 1992). Alternatively, original folds with axes broadly normal to the transport direction rotate progressively in opposing senses both clockwise and anticlockwise, producing curvilinear sheath fold geometries, which are characterized by a bimodal axial distribution with respect to the lineation orientation (e.g., Alsop and Holdsworth, 2004).

Variably orientated asymmetric folds with hinges that initiate at small angles or even sub-parallel to transport may also form in response to wrench-dominated differential shearing (Alsop and Holdsworth, 2007 and references therein). Such flow perturbation folds are developed in domains where velocity and shear strain rate have a large gradient in a direction normal to the slip direction (Coward and Potts, 1983; Ridley, 1986; Holdsworth, 1990; Alsop and Holdsworth, 1993). The sense of hinge/lineation obliquity and the vergence of such folds are dependent on the sense of local differential wrench shear. When viewed down plunge and from above, differential sinistral shear produces Z-folds at clockwise angles to the transport lineation, whilst dextral shear generates S-folds in an anticlockwise sense to transport (Fig. 1). According to the flow perturbation model, folds of differing vergence are therefore generated on the opposite flanks of regions characterized by increased or reduced velocity along an underlying basal detachment (Coward and Potts, 1983; Holdsworth, 1990; Alsop and Holdsworth, 1993, 2002, 2007; Holdsworth et al., 2007) (Fig. 1). Specifically, folds developed on the flanks of regions marked by increased velocity (surging flow) verge towards the outer edges, while folds generated on the flanks of regions of reduced velocity (slackening flow) verge towards the inner centre resulting in antiformal culminations and synformal depressions, respectively (Fig. 1). Along-strike reversal in both the fold vergence and the sense of differential wrench shear occurs across culmination/depression surfaces oriented orthogonal to layering and parallel with the transport direction (Alsop and Holdsworth, 2007) (Fig. 1). Within such systems, hinges of S and Z folds become sub-parallel to the transport lineation toward culmination (or depression) surfaces, while the associated axial planes display a systematic steepening as their strike becomes transport-parallel resulting in an overall 3D fanning geometry (Fig. 1).

From the above, the distinction between individual controlling mechanisms for the formation of transport-(sub) parallel folds provides critical information about the strain type, the intensity of deformation as well as potential displacement gradients. Hence, this study also tests the idea that the origin and geometry of transport-(sub) parallel cylindrical folds generated during exhumation of the Cycladic Blueschists can be explained by perturbations to the regional flow field. This structural analysis includes data from minor and map-scale folds collected from a 100-km-long traverse normal to the direction of transport. It is notable that the concepts of flow perturbation folding were developed and applied at much smaller scales within metamorphic rocks (e.g. Alsop and Holdsworth, 2007 and references therein) and also within other settings such as sedimentary slump systems (Alsop and Marco, 2011, 2013) and sub-glacial shear zones (e.g., Lesemann et al., 2010). This work therefore represents the first attempt to apply these concepts to a crustal-scale deformation zone.