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Dilational fault zone architecture in a welded ignimbrite: The importance of mechanical stratigraphy

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ABSTRACT

Analysis of a population of dilational faults within a densely welded ignimbrite layer reveals fault zone geometries that vary greatly within a single fault and between faults, but does not correlate with displacement. Within an individual fault the thickness of the fault core can differ by up to an order of magnitude along dip. Similarly, joint density adjacent to faults varies along fault dip but does not increase with displacement. A correlation does exist however, between joint density and the degree of ignimbrite welding, which can vary vertically within an ignimbrite layer. Previous work has shown that welding increases ignimbrite strength: non-welded ignimbrites form deformation bands and densely welded ignimbrites form discrete fractures. We observe zones of densely welded ignimbrite with high joint density, while less-welded zones have lower joint density. In turn, high joint densities correlate with narrow fault cores and low joint densities with wide fault cores. We propose a joint based model for dilational fault initiation and growth. Faults initiate on precursory joints and grow by entraining joint bound slabs, hence the correlation between high and low joint density (thin and thick slabs) and narrow and wide fault cores respectively. Ultimately joint density and consequently fault zone architecture are controlled by subtle variations in mechanical strength within the ignimbrite layer.

1. Introduction

Detailed characterisation of fault zone structure is crucial for predicting fault permeability and developing accurate flow models for hydrocarbon production, CO_2 storage, contaminant transport and groundwater flow models (e.g. Al-Busafi et al., 2005; Dockrill and Shipton, 2010; Ferrill et al., 1999). Constraining the hydraulic characteristics of faulted ignimbrites has become increasingly important, as they are potential host lithologies for nuclear waste repositories (Millward et al., 1994; Evans and Bradbury, 2004) and CO_2 sequestration (Annunziatellis et al., 2008). Despite their importance, relatively few detailed studies of faults in ignimbrites have been carried out (Wilson et al., 2003, 2006; Evans and Bradbury, 2004; Gray et al., 2005; McGinnis et al., 2009; Riley et al., 2010).

Qualitative and quantitative characterisation of fault zone structure requires an understanding of the deformation process active during faulting in a given litho-tectonic setting. The deformation processes by which faults initiate and grow depend on a variety of factors including host rock strength (Wilson et al., 2003; van der Zee and Urai, 2005), mechanical stratigraphy (Ferrill and Morris, 2003, 2008; Schöpfer et al., 2007), tectonic setting (Acocella et al., 2003; Bastesen and Braathen, 2010) and magnitude of displacement (Power et al., 1988; Faulkner et al., 2003).

In this paper we present a detailed study of subvertical dilational normal faults and joints formed within a densely welded pyroclastic flow layer on the volcanic island of Gran Canaria, Spain. Dilational faults have a component of opening perpendicular to the fault surface as well as shear parallel to the fault surface (Mandl, 1988) and are thought to form at low confining pressures (Ferrill and Morris, 2003; Ramsey and Chester, 2004; Schöpfer et al., 2007; Ferrill et al., 2004, 2012). We develop a new conceptual model for the development of dilational faults in ignimbrites in which subtle mechanical heterogeneities within the ignimbrite layer are the predominant control on fault architecture. Our observations suggest that the faults initiated on precursory joints and that fault growth and the resultant fault zone architecture depends

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on precursory joint density, which is ultimately controlled by gradational variations in mechanical strength within the layer.

2. Geological setting

Caldera collapse initiated on Gran Canaria at 14 Ma, generating a caldera 20 km in diameter (Fig. 1a). Over a 0.6 m.y. period, 20 distinct ash- and pumice-rich ignimbrite packages known as the Mogan Group, were erupted (Fig. 2a) (Schmincke, 1998). A further 500 km^3 of volcanic material was erupted over the next 4 m.y. forming the Fataga Group. Caldera collapse generated a complex system of intra- and extra-caldera faults (Walter and Troll, 2001; Troll et al., 2002). Faults in the extra-caldera area are the focus of this study (Fig. 1a). The extracaldera area is characterised by inward-dipping normal faults concentric to the caldera margin (Troll et al., 2002). These faults accommodated extension and 'downsag' of the caldera floor on collapse (Walter and Troll, 2001; Branney, 1995) and have been reactivated during subsequent eruptive cycles of caldera inflation and deflation (Troll et al., 2002). Reactivation of the faults on Gran Canaria is evident where ignimbrite unit thicknesses change across faults (Troll et al., 2002), suggesting fault slip contemporaneous with or immediately prior to ignimbrite eruption. Such faults continue to propagate upwards through the cooled ignimbrite during later eruptions and caldera deflation.

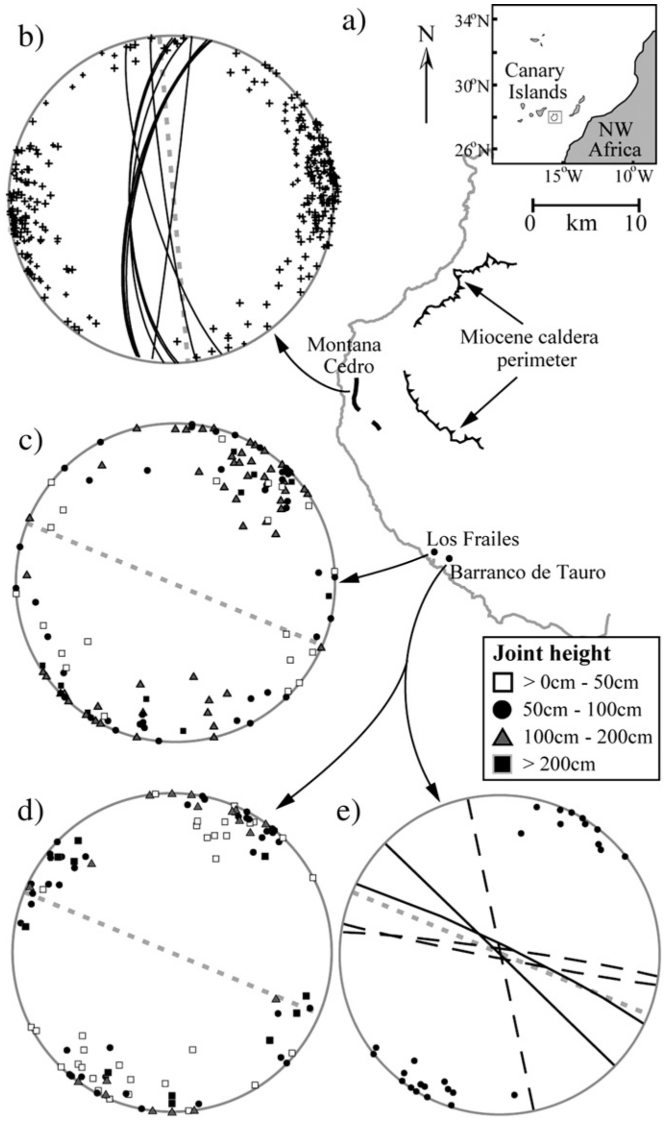

Fig. 1. a) Location of study areas and caldera perimeter. Stereonets plot b) great circles for extracaldera faults and poles to joints at Montana Cedro c) poles to joints in unfaulted rock at Los Frailes d) poles to joints in unfaulted rock at Barranco de Tauro and e) great circles for extracaldera faults at Barranco de Tauro; solid lines and poles to joints are for fault T2.5, joints adjacent to other faults at Tauro were inaccessible. Dashed grey great circle in each stereonet represents the approximate orientation of the caldera perimeter relative to each study site. Joints are grouped by height in, c) d0 and e); joint height data was not recorded at Montana Cedro (see text). Joint orientations at c) Los Frailes and d) Barranco de Tauro are concentric and radial to the caldera margin. e) Fault T2.5 and associated joints are concentric to the margin. At both Montana Cedro and Barranco de Tauro joints have similar orientations to the adjacent fault.

We have examined an exceptionally well exposed fault population within a single ignimbrite unit, called Ignimbrite B (Schmincke, 1998). Ignimbrite B was erupted during the first eruptive phase associated with initial caldera collapse and forms part of the Upper Mogan Formation (Fig. 2a).

Ignimbrite B is ash and lapilli rich, and densely welded (Schmincke, 1998). Welding is the syn- and post-depositional fusion accomplished during compaction ('flattening') of viscous glass shards, pumice and lapill, which forms fiamme (Grunder and Russell, 2005; Bull and McPhie, 2007). Welding affects rock strength as it decreases porosity and sinters particles together. Increases in welding correlate with increases in unconfined compressive strength (Moon, 1993; Schultz and Li, 1995; Quane and Russell, 2005). The degree of welding is evaluated by measuring fiamme aspect ratio. Densely welded ignimbrites have extremely flattened fiamme with high aspect ratios that form a foliation known as a eutaxitic texture (Ragan and Sheridan, 1972; Ross and Smith, 1961). Moderately to poorly welded units have lower fiamme aspect ratios and no foliation. Ignimbrite B at the sites examined in this study has a densely welded base and mid-section and less welded top.

Post-depositional cooling of welded ignimbrites forms columnar cooling joints typically with pentagonal or hexagonal patterns in plan-view (Riley et al., 2010). Dunne et al. (2003) suggested that cooling joints could be distinguished from those of tectonic origin by the presence of mineralisation on the joint surface or alteration immediately around the joint. However, mineralisation may not always be present; and orthogonal joint sets can form via rotation of the principal stress orientation during deformation (e.g. Cruikshank and Aydin, 1995).

3. Methodology

Fault populations in Ignimbrite B with displacements ranging from centimetres to 10's of metres were observed in vertical and near-vertical section at two different locations – Montana Cedro and Barranco de Tauro (Figs. 1a and 2b). An unfaulted type section used to determine background or host rock joint density was located at Los Frailes (Figs. 1a and 2c).

Faults are labelled according to their location and the amount of throw recorded at the base of Ignimbrite B. At Barranco de Tauro (T) fault T2.5 has 2.5 m throw, at Montana Cedro (C) Ignimbrite B is cut by C5 (5 m throw), C15 (15 m throw) and C22 (22 m throw) (Fig. 3). Location C22 is a sub-vertical exposure of a much larger growth fault (Troll et al., 2002). Measurements of fault properties are recorded by using vertical scanlines that extend for the height of the fault exposure (Fig. 3).

The studied faults are composed of two fault walls bounding a core of breccia. The fault walls in T2.5 (Fig. 3a) and C15 (Fig. 3c) are planar, while the ignimbrite B fault wall in faults C5 (Fig. 3b) and C22 (Fig. 3d (ii & iii)) step along dip. The T2.5 fault core is composed entirely of ignimbrite B clasts (Fig. 3a). Fault cores in C5, C15 and