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Review article

Polymodal faulting: Time for a new angle on shear failure

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ABSTRACT

Conjugate, or bimodal, fault patterns dominate the geological literature on shear failure. Based on Anderson's (1905) application of the Mohr-Coulomb failure criterion, these patterns have been interpreted from all tectonic regimes, including normal, strike-slip and thrust (reverse) faulting. However, a fundamental limitation of the Mohr-Coulomb failure criterion – and others that assume faults form parallel to the intermediate principal stress, σ_2 – is that only plane strain can result from slip on the conjugate faults. However, deformation in the Earth is widely accepted as being three-dimensional, with truly triaxial stresses ($\sigma_1 > \sigma_2 > \sigma_3$) and strains. Polymodal faulting, with three or more sets of faults forming and slipping simultaneously, can generate three-dimensional strains from truly triaxial stresses. Laboratory experiments and outcrop studies have verified the occurrence of polymodal fault patterns in nature. These fault patterns present a fundamental challenge to our understanding of shear failure in rocks (and other materials) and an opportunity to improve our understanding of seismic hazards and fluid flow in the subsurface. In this review, we assess the published evidence, theories and models for polymodal faulting before suggesting ways to produce a truly general and valid failure criterion for triaxial failure.

Contents

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1. Introduction

Polymodal fault patterns can be quadrimodal (i.e. four clusters of poles) or display a quasi-continuous orientation distribution of poles spanning finite arcs of strike and dip (Fig. 1; Peacock and Sanderson, 1992 – their Fig. 2). Polymodal fault patterns are therefore distinctly different from the bimodal pattern associated with the better-known case of conjugate faults.

The classical and widely accepted conceptual model for conjugate fault patterns produced by a single homogeneous stress regime dates back to Anderson and his application of the Mohr-Coulomb failure criterion to natural stress states (Anderson, 1905; Jaeger et al., 2009). In that model, two sets of faults (shear fractures) form simultaneously, with the maximum principal stress (σ_1) oriented as their acute bisector, the minimum principal stress (σ_3) bisecting their obtuse angle, and the intermediate principal stress oriented parallel to their mutual intersection (Fig. 1a). On an equal area or equal angle net, conjugate or bimodal fault patterns should appear as two clusters of poles. Allowing for inevitable natural variations in local stresses and local rock properties (such as cohesive strength or friction), one would expect noise in this bimodal orientation distribution, but the pattern should still display two clusters with evidence of central tendency about a mean direction within each of the two clusters.

However, there is significant outcrop-scale field and laboratory-scale experimental evidence for the occurrence of polymodal fault patterns, where three, four or more sets of fault planes have formed and slipped simultaneously. The first laboratory evidence came from the careful and systematic clay-cake experiments of Oertel (1965), which produced four sets of fault planes in response to the applied load. Subsequently, Reches and Dieterich (1983) conducted systematic truly triaxial experiments on small (2.2 cm) cubic samples of sandstone, limestone and granite and produced polymodal fault patterns in all rock types. Ghaffari et al. (2014) and Nasseri et al. (2014) have recently performed truly triaxial tests on larger (8 cm) cubic samples of sandstone and also produced clear evidence of polymodal fault patterns, including novel CT scans of their internal structure and the acoustic emissions produced during their propagation. The first field evidence dates back to Donath (1962) defining a rhombic map pattern in the basalts of the Basin and Range (see also Crider, 2001). Aydin and Reches (1982) reported quadrimodal fault patterns from faulted aeolian sandstones in Utah. Similar patterns have also been measured in sandstones on Arran, Scotland (Woodcock and Underhill, 1987; Underhill and Woodcock, 1987), in the Chalk of northern Germany (Koestler and Ehrmann, 1991), in carbonates of NW Australia (Miller et al., 2007) and in siliciclastics of E Australia (Carvell et al., 2014). All of these accounts describe four sets of contemporaneous faults defining rhombic map patterns or quadrimodal systems, where the poles to the measured fault planes define four clusters on an equal angle net (Fig. 1b and e).

The observation or inference that all four of the fault sets, both

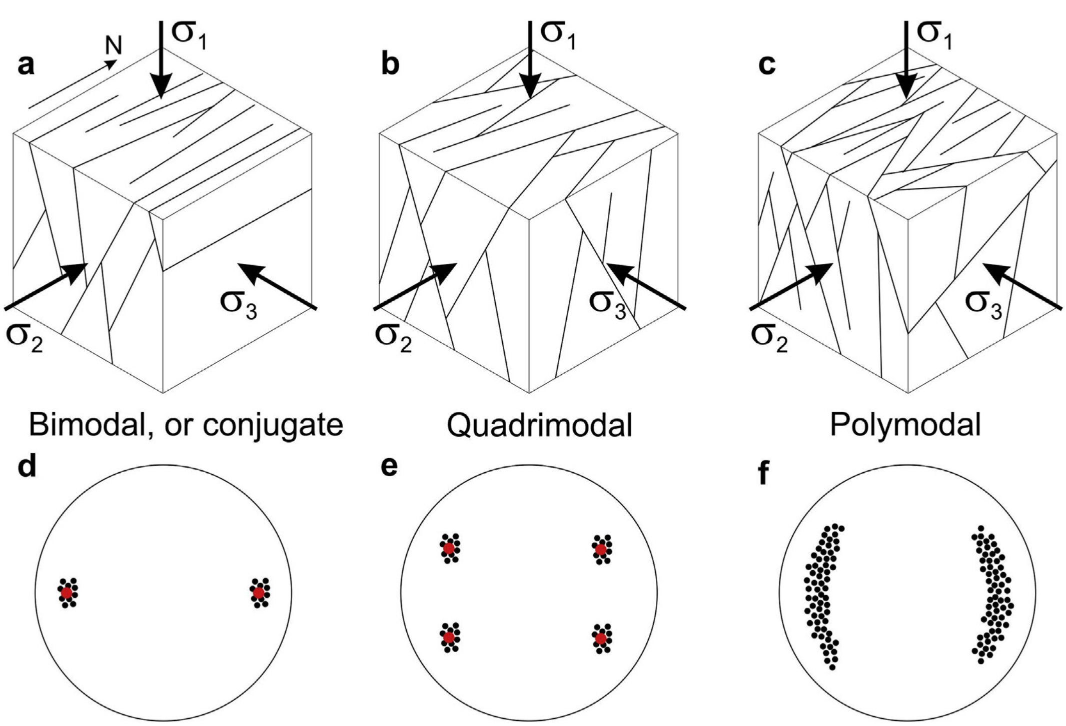

Fig. 1. Schematic block diagrams and equal angle nets showing the difference between a) bimodal (or conjugate), b) quadrimodal and c) polymodal fault patterns. Examples shown are for normal faults with σ_1 vertical. Note that polymodal fault patterns (b, c) are *apparently bimodal or conjugate* on many 2D sections (i.e. faces of the schematic block), and only an equal angle or equal area stereonet of measured 3D orientations shows the true polymodal pattern (compare d), e) and f)). Quadrimodal and polymodal faults are oblique to all three principal stresses. Black dots on the stereographic projections represent poles to faults (shear fractures), and red dots mark the average of each cluster.