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Predicting bulk permeability using outcrop fracture attributes: The benefits of a Maximum Likelihood Estimator

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The success of any model prediction is largely dependent on the accuracy with which its parameters are known. In characterising fracture networks in naturally fractured rocks, the main issues are related with the difficulties in accurately up- and down-scaling the parameters governing the distribution of fracture attributes. Optimal characterisation and analysis of fracture attributes (fracture lengths, apertures, orientations and densities) represents a fundamental step which can aid the estimation of permeability and fluid flow, which are of primary importance in a number of contexts ranging from hydrocarbon production in fractured reservoirs and reservoir stimulation by hydrofracturing, to geothermal energy extraction and deeper Earth systems, such as earthquakes and ocean floor hydrothermal venting. This work focuses on linking fracture data collected directly from outcrops to permeability estimation and fracture network modelling. Outcrop studies can supplement the limited data inherent to natural fractured systems in the subsurface. The study area is a highly fractured upper Miocene biosiliceous mudstone formation cropping out along the coastline north of Santa Cruz (California, USA). These unique outcrops expose a recently active bitumen-bearing formation representing a geological analogue of a fractured top seal. In order to validate field observations as useful analogues of subsurface reservoirs, we describe a methodology of statistical analysis for more accurate probability distribution of fracture attributes, using Maximum Likelihood Estimators. These procedures aim to understand whether the average permeability of a fracture network can be predicted reducing its uncertainties, and if outcrop measurements of fracture attributes can be used directly to generate statistically identical fracture network models.

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A New Kinematic Model for Polymodal Faulting: Implications for Fault Connectivity

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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 - 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 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 the polymodal fault patterns in nature. The connectivity of polymodal fault networks differs significantly from conjugate fault networks, and this presents challenges to our understanding of faulting and an opportunity to improve our understanding of seismic hazards and fluid flow. Polymodal fault patterns will, in general, have more connected nodes in 2D (and more branch lines in 3D) than comparable conjugate (bimodal) patterns. The anisotropy of permeability is therefore expected to be very different in rocks with polymodal fault patterns in comparison to conjugate fault patterns, and this has implications for the development of hydrocarbon reservoirs, the genesis of ore deposits and the management of aquifers. In this contribution, I assess the published evidence and models for polymodal faulting before presenting a novel kinematic model for general triaxial strain in the brittle field.