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Book review

Fractures, Fluid Flow and Mineralization

Geological Society Special Publication No. 155, 1999, ISBN 1-86239-034-7, 328 pp., £69.00 (UK), $115 (US), GSL price = £35.00 (UK), $58 (US), AAPG/SEPM/GSA = £40.00 (UK), $70 (US)

The Special Publication 155 entitled *Fractures, Fluid Flow and Mineralization* by the Geological Society is essentially a proceedings volume of the 1997 'Geofluids' conference in Dublin, Ireland, held in commemoration of Dave Johnston, an enthusiastic structural geologist known to me from his Ph.D thesis on the Proterozoic Pine Creek Inlier, Northern Australia. The scope of the special publication closely matches Dave's range of research interests.

The publication is divided in four subsets of articles, examining the statistical properties of fracture sets, fluid flow in fractured rock, structural controls on mineralization, and the Irish Zn–Pb deposits, respectively. These are largely review articles except for a paper by Stowell, Watson and Hudson on thickness–frequency distributions of veins in Anglesey, Wales, and an excellent paper by Everett, Wilkinson and Rye on basement infiltration of Pb–Zn mineralizing fluids in Ireland.

In the introduction the editors Lonergan, McCaffrey and Wilkinson define the purpose of the book: It shall re-assess, after 15 years of exponentially increasing research activity, the subject of fluid flow and fracturing in the context of mineralization and explore how advances made in different research communities can be applied to the understanding of the formation of economic resources. The back cover claims that the book also highlights recent advances at the interfaces of structural geology, fluid flow and mineralization research, showing the significance of the development of fracture connectivity in focusing fluid flow.

The first group of papers focuses on the scaling of the thickness and spacing fracture-hosted veins. Roberts et al. use vein thickness and frequency measurements to argue for a scale invariance of vein thickness distributions. The inferred fractal dimensionality D of the different analyzed natural datasets is interpreted as a useful indicator for vein connectivity. While D values above 1 are interpreted as indicating mainly isolated fractures, D values lower than 1 are taken as indicative of well-interconnected fracture sets. Decisive for the applicability of this interpretation, however, is the authors' assumption of a proportionality between vein-thickness and host fracture length. This assumption seems hard to defend since fracture growth is often accompanied by a change in the dilational process (Mode I to Mode II or III), and because the thickness of meter-scale veins typically is the result of repeated fracture opening and sealing (as is also pointed out in a later chapter by Cox). Are the veins perhaps self-affine as may be expected for a growth process?—The fracture length theoretically increases to infinity when the fracture percolation threshold is reached, but earthquake faulting teaches us that large 'fractures' no longer act as single mechanical entities. Roberts et al., however, attempt to explain the measured statistics by underlying mechanical processes. This makes their paper interesting and thought provoking.

In a similar study on crack–seal-textured quartz veins in Wales, Stowell et al. find a non-linear relation between (composite) vein thickness and measured vein cross-sectional length. The longer veins are disproportionately thinner than the shorter ones. This can however be related to the fact that the sampled short veins often represent splays of larger veins.

Gillespie et al. use synthetically generated thickness/spacing versus frequency plots of periodic, random, and power-law statistical distributions for comparison with 10 natural datasets. Their paper illustrates nicely how the statistics of veins measured with the scanline method can indicate either a characteristic spacing or a power-law relationship, dependent on vein scale with respect to the thickness of mechanical host units. Where power-law scaling can be inferred, measured D exponents have a fairly consistent value of 0.8.

Loriga also applies the scanline method to measure vein-thickness distributions in the Guanajuato silver mining district, Mexico. She combines her outcrop, borehole and map-scale data into a composite plot indicative of scale invariance between 1 cm and 10 m and a D exponent of 0.75. These data constrain the statistical likelihood of encountering a vein of a certain thickness. Will this be useful for the local explorationist?

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The second group of papers focuses on the characteristics of fluid flow in fracture systems. In 2D numerical experiments with the discrete element program UDEC, Sanderson and Zhang examine changes in fracture aperture when fluid pressure is increased and the differential stress is varied at a subsurface depth of 600 m. In this exciting analysis, network deformation always leads to the pronounced dilatation of a small subset of the fractures accompanied by a sudden increase in the network conductivity and its directional polarization. Assuming that all fractures are parallel, fracture-flow rates perpendicular to the 2D model are calculated and interpreted to have (multi) fractal characteristics. This model result, however, appears artificial since hydraulic conductivities of fractures rarely correlate with fracture fluxes in nature. My own numerical models indicate that, apart from the hydrological interactions among fractures, the aspect ratio of highly permeable fractures as measured parallel to the far-field fluid pressure gradient, controls fracture flow rates. Moreover, the effect of matrix permeability is not addressed by the UDEC model and a log-normal flux distribution at sub-critical stresses largely reflects the initial zero-stress aperture of 1 mm which was prescribed onto the network.

On the basis of their results, Sanderson and Zhang argue that in a critically stressed upper crust, above-lithostatic fluid pressures are not critical for the triggering of shear-failure as failure can be induced by minor variations of a sub-lithostatic fluid pressure. The authors also draw attention to the incompatibility of high fluid fluxes and inferred super-lithostatic fluid pressures in mineralized fault zones.

Jones et al. present a case study of a fractured groundwater reservoir. Their careful illustration of the critical steps in the design of a drilling strategy by means of stochastic modeling of discrete fractures using the FracMan™ software, is didactically valuable.

Connolly and Cosgrove employ a Perspex analogue model to investigate the stress distributions near dilational jogs or strike-slip fault relays. Mean-stress gradients derived from the photo-elastic effects of the deformation are interpreted to indicate fault-induced fluid-flow and fluid sources and sinks in the vicinity of the jog. These gradient patterns are discussed with reference to the positions of mineral deposits within fault relays.

While the obtained stress distributions are very well illustrated and instructive with regard to the expected mode and distribution of second order fractures, the proposed links to fluid flow are less convincing. Expected fluid-source and sink terms are not quantified nor put in perspective with permeability or storativity. Assuming, for instance, a bulk modulus of 25 GPa, a favourable porosity of 20%, and a generous mean-stress increase of 10 MPa in the rock near a fault in one year, the strain-induced non-renewable fluid-supply of $2.5 \times 10^{-12}\ m^3\ m^{-3}\ s^{-1}$ should not noticeably alter fluid pressure unless host-rock permeability is in the micro- to nano-Darcy range. Regional fluid-flow patterns near the Earth's surface, therefore, are unlikely to be affected by elastic strains which can also be seen by examination of the Coalinga (San Andreas fault) earthquake data (Yerkes et al., 1991, USGS Prof. Paper 1487, pp. 235–257).

The third group of papers examines structural controls on the localization of mineralization. Cox provides an insightful review of styles of syn-deformational lode gold deposits, estimates of time-integrated fluxes, and deformational controls of permeability. Like Sanderson and Zhang, Cox applies the percolation model to interpret the localization of flow in dilational segments of shears. He, however, argues that fluid-pressure fluctuations in the seismic cycle are important for fluid–rock interaction and ore genesis.

Blenkinsop and Sanderson interpret the earth-surface distribution of gold deposits in the Zimbabwe craton to have fractal characteristics. They present a compelling analysis why random sampling should partially mask this fractal nature of their dataset. The extracted statistics are employed to discriminate well-explored from poorly- or un-explored regions. This new technique may be free of a bias when it comes to spotting areas overlooked by past exploration.

Jolley et al. attempt to persuade the reader that thrust and injection structures filled with fine-grained 'cataclasite' which dissect the Witwatersrand gold-mineralized quartzite at the Elandsrand gold mine, played an important role in the formation of gold mineralization. The latter is interpreted as epigenetic hydrothermal.

Even though Jolley et al. document nicely the geometry of the thrusts, a convincing link to gold mineralization is not established. It is also unclear why these (still fresh) extremely fine-grained fault rocks should have been preferred fluid channel ways in the sandstone host. Annoyingly, a large body of earlier research on these fault rocks, which demonstrates that the thrusts were formed during the nearby Vredefort meteorite impact event, is dismissed because the fault rocks are different from endogenic pseudotachylites as defined by Passchier and Trouw (1996). This is precisely what the dismissed microstructural and electron-microscopic investigations of Killick et al., 1988; Roehring et al., 1989; Fletcher and Reimold, 1989 carefully establish and convincingly relate to the deformation regime imposed by the impact.

In a very interesting and well-illustrated article, Branquet et al. describe fault breccias in Columbian emerald mines. These multi-layered breccias mark thrust and oblique-reverse faults directly above earlier hydrothermal carbonate veins that enclose slightly disoriented country-rock fragments. Breccia bands often contain hydrothermal cement and are separated from hanging-wall shale by a pyrite seam. Branquet et al. propose that the breccias formed by pore fluid pressure-induced implosion of the dilated rock into fast-forming underpressured fault jogs. However, dry granular flow accompanying fragmentation during frictional sliding might be a viable alternative mechanism to explain the fluidization textures, because the breccias are commonly layered indicating laminar flow, and because, apparently, only a fraction of the brecciated rock transported in the faults is hydrothermally altered.

Brown et al. examine the Krafla fissure swarm in Iceland for its suitability as a modern analogue for the environment in which the Kambalda nickel deposits in western Australia formed. The authors show that eruption of komatiite lavas into syn-volcanic fault bounded parallel grabens would explain the inferred linear shapes and lateral fault juxtaposition of the komatiite flows at Kambalda.

Cloke et al. present an integrated study of the structural evolution of the Eocene Kutai basin, Indonesia. The interpreted evolution is well illustrated by 3D block diagrams. With the aid of synthetic-aperture radar (SAR) and gravity data, the authors highlight the important role that basement structures played in controlling the location of major igneous bodies and the development of younger fault zones in the basin.

The group of papers on the Irish Pb–Zn deposits begins with a review of the post-Devonian geological history of central and southern Ireland. Hitzman pictures an early Carboniferous shallow marine carbonate platform formed on terrestrial–fluviatile 'Old Red' sandstone deposits and broken into horsts from which turbidites are being shed into extensional minibasins bounded by growth faults. Pb–Zn mineralization forms adjacent to these faults preferably near intersections with a cross-cutting fault set and during carbonate diagenesis. Variscan compression later inverts parts of this basin, re-activating south-dipping normal faults.

Everett et al. proceed with the presentation of compelling evidence that the fluids which mineralized the normal faults also penetrated the Ordovician–Silurian basement. Through careful analysis of fluid inclusions from coeval veins in the basement, two endmember fluid compositions are identified: A moderate-salinity CO_2-bearing fluid at 150–250°C and a slightly cooler aqueous brine. Mixing of these endmembers defines systematic trends on the regional scale (> 50 km). The carefully analyzed major-element chemistry of the trapped fluid mixture indicates a seawater origin. Everett et al. further demonstrate that seawater circulation up to a depth of 3–5 km was largely restricted to the basement-penetrating mineralized growth faults. A lack of pervasive hydrothermal alteration disqualifies the 'Old Red' sandstone as a regional aquifer for a competing Mississippi-valley-type model of mineralization.

Lewis and Couples apply an impressive collection of basin-modeling software, trying to model realistically the Carboniferous basin evolution of central Ireland. Backstripping is used to constrain the growth fault-induced topography after one-dimensional decompaction of the sediments. A highly idealized cross-sectional flow model with permeable vertical faults supports the argument that water may have convected in the basin during mineralization. Oddly, while citing the above study of Everett et al., the authors rationalize the simulation of fresh water only by a lack of fluid-salinity data for central Ireland.

In the final paper of the 330-page-strong book, O'Reilly et al. use Bouguer-anomaly maps to examine the basement structure of the Irish Midlands. These gravity data indicate that the mineralized faults probably formed above existing Caledonian basement structures reactivated during lower-Carboniferous extension. Interestingly, it is also argued that many areas of low gravity are due to basement ridges of light acidic rocks rather than lower Carboniferous sediments.

The book certainly provided me with much food for thought and drove me to the library to find cited articles. Already the little graphs on the book cover highlight that the application of fractal concepts to the measurement of fault and fracture geometry constitutes a large fraction of the presented material.

I enjoyed getting an exciting new perspective of the genesis of the Irish Pb–Zn deposits. With regard to the goal of the book, many questions are left untouched, concerning the underlying processes giving rise to the observed vein-thickness/spacing statistics, and the dynamics of faulting in a wet crust producing the characteristics of fault rocks which were documented in the field. In this context, the articles by Roberts et al., Sanderson and Zhang, and Everett et al. stand out, because they critically evaluate conceptual models of geological processes employing novel tools from scientific disciplines other than the earth sciences.

Cut outs:

Rosetti and Colombo present an integrated structural, petrographical, and fluid-inclusion study of the Marmato gold deposit in central Columbia. Their analysis indicates that gold was precipitated from boiling low-salinity fluids circulating through fractured dacites near the Earth's surface.

Sevastopulo and Redmond suggest that the carbonate-dolomitization temperature of 60–150°C reached prior to Pb–Zn mineralization at the Lisheen deposit, is incompatible with the shallow burial of the Walsaurtian limestone at the time when mineralization is inferred to have formed. They therefore argue for a younger age of mineralization.

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