Journal of Structural Geology 32 (2010) 1554–1556

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Editorial

Fault zones: A complex issue

As recognized by John Wesley Powell as early as 1870 (Fig. 1), faults are complex 4-D structures: volumes of complexly deformed rock that evolve in their structural and fluid flow properties through time. Fault zones are composed of rocks in variable degrees of deformation states, often with a lower strain fracture-dominated “damage zone” surrounding a more highly strained heterogeneous “core zone” containing one or several slip zones, gouge and breccias, and oblique Riedel shears. A zone of faults at the larger scale on the other hand, is often considered as a discrete slip plane in a volume of otherwise intact rock. However, this intact rock is rarely really intact, and studies over the last twenty or so years have shown that this depends critically upon the scale of observation: the closer you look, the smaller the faults that you can see, hence the more faults you can see. As deformation evolves, many of the smaller faults in a zone switch off leaving the larger ones to carry on getting larger (widening the core zone), often cannibalizing some of the smaller faults in the process.

Recent advances in modelling, sub-surface and field data acquisition have shed light on the spatial variability of fault structures and the time scales and length scales of changes in fault properties. Perhaps the main advances since the 1870’s have been that we appreciate much more the significance and impact of complex structure in zones of faults and fault zones. We thus arrive at a crossroads today where we understand that the complexity we see when we look closely at zones of faults at the large scale exists also at the scale of an individual fault (Fig. 2). Further, we understand that the division is really rather arbitrary and that the processes contributing to the growth and internal structural development of a single fault zone are similar to that of a zone of faults: propagation and linkage can increase the length of the fault and change the fault pattern, but can also result in brecciation and the production of a fault rock and the generation of a recognizable zone of brittley-deformed rock associated with shear. Yet we do not know how to capture this complexity in a way in which it may be used for predictive tools in the many fields in which fault zones impact us, such as seismogenesis, sealing and leaking in hydrocarbon and CO_2 systems, hydrological flow and radioactive waste management.

Although there is increasing interest in fault and fracture-related fluid flow in the Earth’s crust driven by these applications, there is a general lack of awareness of the exciting research being conducted across these traditionally diverse fields. The conference “Fault Zones: Structure, Geomechanics and Fluid Flow” was therefore convened at the Geological Society of London in September 2008 with the objective of bringing together scientists from these communities who were interested in fault growth, fault zone properties and their effects on other processes such as fluid flow and earthquake processes. The conference was attended by a wide range of scientists and was run in parallel with the meeting of the “Clay Club”.

This Journal of Structural Geology special issue presents 23 articles that stem from the conference and cover the state-of-the-art in methods and applications involved in studying fault zone structure, and its impact on geomechanical and fluid flow properties. The papers fall naturally into sections that concentrate on structure, on geomechanics, and on fluid flow properties, although there is of course a great deal of overlap and, as indeed is the point of this special issue, nearly all the papers cover more than one of these topics. An introductory review paper (Faulkner et al.) discusses

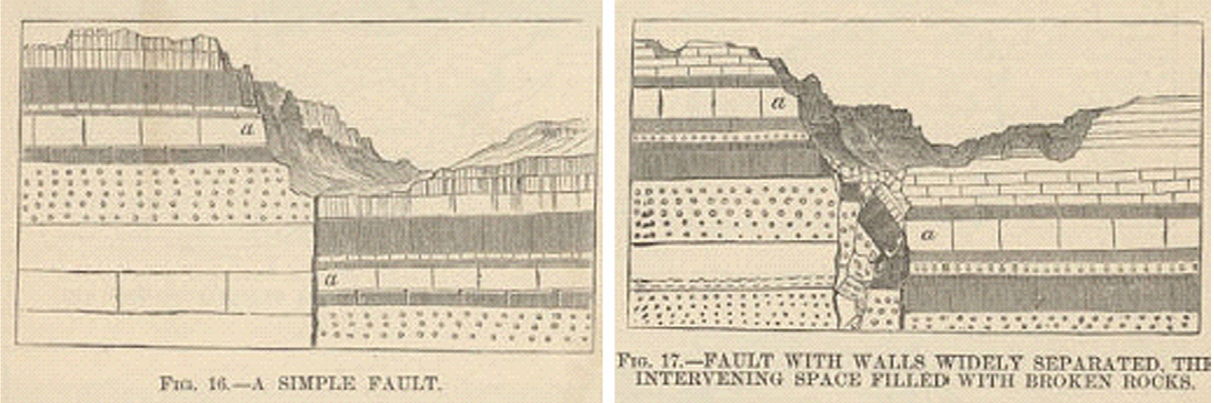

FIG. 16.—A SIMPLE FAULT.

FIG. 17.—FAULT WITH WALLS WIDELY SEPARATED, THE INTERVENING SPACE FILLED WITH BROKEN ROCKS.

Fig. 1. An example of early recognition of the 4-D complexity of fault zone structure. Excerpt from an article by William Powell “The Canyons of the Colorado” in Scientific American, v. 5, no. 124, 1878. Reprinted with kind permission from Scientific American.

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doi:10.1016/j.jsg.2010.10.006

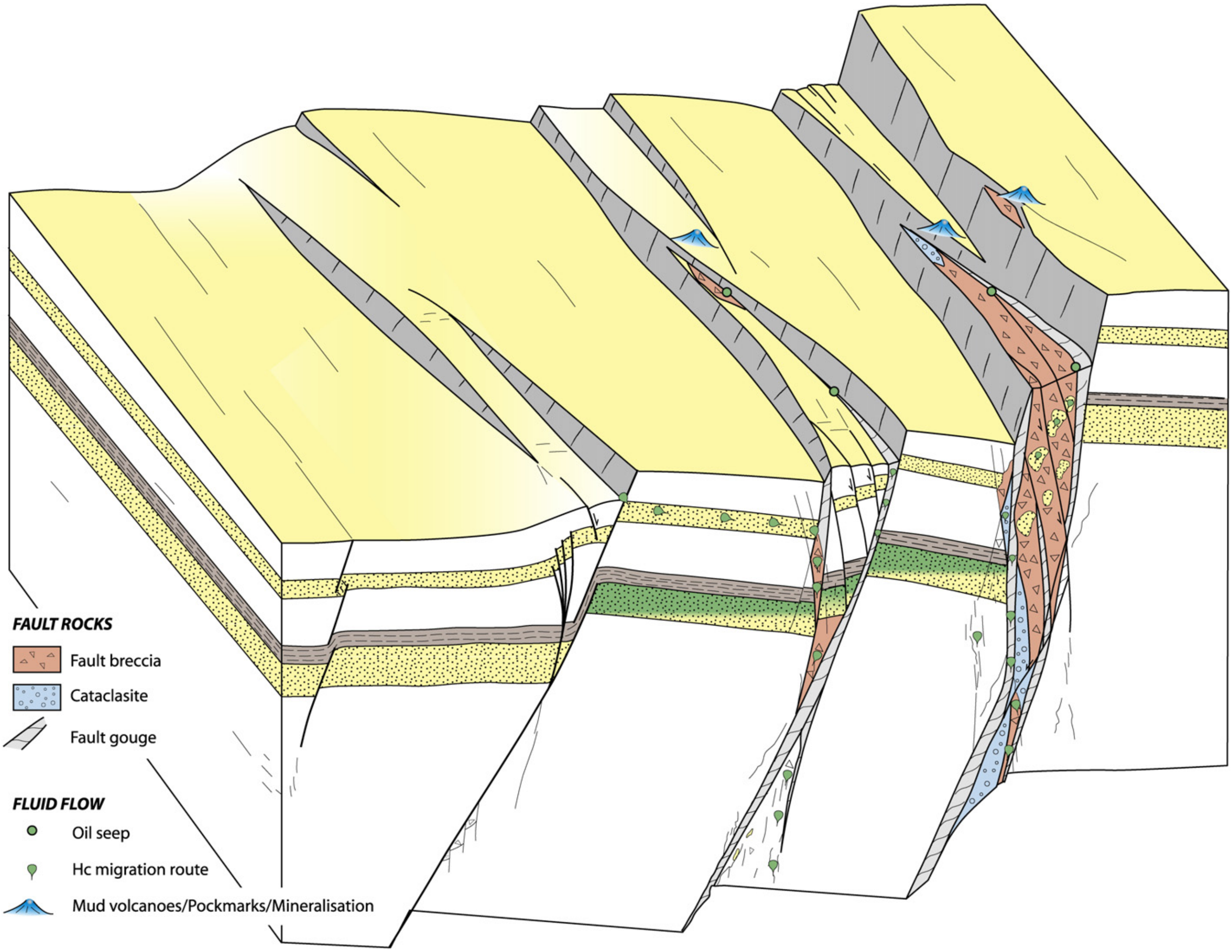

Fig. 2. Block diagram showing the evolution, from left to right, of a network of individually-nucleating faults to a single, large, complex fault zone. The fault zone grows both by the linkage of the individual faults, incorporating the slices of host rock in between as "lenses" into the fault which then get broken up, and by generating new damage around the fault which then gets "eaten up" as the fault continues to grow. A few simple fluid trapping and migration pathways are also shown for illustration.

recent work showing how fault zones and fault systems control the structure, mechanics and fluid flow properties of the Earth's upper crust. These three aspects of faults are intimately related and cannot be considered in isolation.

Some of the papers in this special issue examine the initiation and distribution of faulting and related fracturing. These studies give the emerging picture of an intimate relationship, on both the geological and co-seismic timescale, between fault propagation and fault zone fracturing and enhanced fluid flow. Fault initiation and distributions in a system, whilst strongly dependent on the intermediate principal stress (Haimson & Rudnicki) also depend on the tectonic context of shortening versus extension (Saillet & Wibberley) and presence of pre-existing oblique faults (Henza et al.). This obliquity of pre-existing structure to the new remote applied stress also controls the style of segment linkage and related fracturing (Moir et al.), as does fault friction (Soliva et al.) and the elastic modulii of wall rock and fault zone (Aydin & Berryman). Such segment linkage-related fracturing greatly increases fault permeability, and in mudstones this preferentially occurs in over-consolidated contexts, such as during exhumation (Ishii et al.). Other processes such as co-seismic rupture tip propagation may cause fracture damage, which along with radiated seismic energy, is larger when slip weakening distance is smaller due to the larger wall rock strains involved in slip pulse propagation (Savage & Cooke). Coseismic fracturing may also lead to entire brecciation of rocks by decompression boiling and precipitation as sudden hydraulic connection to geothermal reservoirs occurs (Caine et al.), and such rapid fracturing and later sealing processes can also be induced by human activity as in the case of tunneling excavations in the Boom Clay (Van Marke & Bastiaens).

The presence of "damage zones" of fractures around a highly-sheared core of fault rock is known to affect the fluid flow and mechanical behavior of the fault zone, but little quantification is available to help us predict these affects. Dockrill & Shipton show combined field and geochemical evidence for up-fault CO_2-charged groundwater flow in the fracture damage zone in multiple sporadic events, and emphasize that algorithms often used in industry for predicting across-fault flow are not appropriate to up-fault damage zone flow prediction. Medeiros et al. show how clusters of "deformation band" faults around larger faults, although causing local deviations in groundwater flow, do not seriously compartmentalize the aquifers in single-phase flow. The mechanical impact of different stiffness between host rock, fracture damage zone and a softer core zone suggests that further fractures are more likely to propagate inwards before being arrested (Gudmundsson), leading to suggestion that fault zone widening may be limited in discrete steps.

If damage zone widening may be limited by such mechanisms, then increased deformation must be accommodated by higher strains in the central part of the fault zone, the fault "core", during these periods, thus localizing further deformation in this zone. This localization is corroborated by data on carbonate fault cores by Bastesen & Braathen for normal faults with throws above around 100 m. This does not mean that these high-strain core zones become less complex as displacement increases, although structures such as lenses of host rock are perhaps in some way related to bed thickness – throw relationships. Other factors affecting "complexity" and the presence of structures such as lenses in the core zone are high competence contrast between different beds in a multilayered sequence (Schmatz et al.) and effective normal stress (Cuisiat & Skurtveit), both of which inhibit the formation of relatively simple clay smears.

Seen at the scale of a "large" fault zone, individual slip zones within it are generally assumed to be homogeneous. However, even the most localized slip zones (of sub-millimetric to centimetric widths) in granular fault zones may be heterogeneous and complex, with deformation mechanisms evolving as the properties change with strain, such as porosity reduction by progressive grain size reduction during compactional cataclastic flow (Balsamo et al.). This is argued by Hadizadeh et al. to be, in itself, a precursor to further brittle shear localization. Indeed this gets even more complex when hydrothermal fluids and temperatures are considered, with experimental work in synthetic muscovite gouges (Van Diggelen et al.) generating continuous networks of fine-grained hardening cataclastic bands anastomosting around lenses of lower strain (in some cases plastically-deformed) material. These bands gradually eat up the lenses as deformation evolves, in the same way as lenses of wall rock are incorporated into fault zones in layered sedimentary sequences and eventually get broken down with increasing strain.

Whilst many of these papers contribute to industrial applications concerning sub-surface fluid flow in the Earth's crust, correct structural interpretation – an essential foundation for reliable studies of fault sealing and fracture-related flow prediction in reservoirs – is still a primary concern. This is discussed by Freeman et al. who propose guidelines for fault interpretation from seismic using wall rock strains based on published data on fault dimensions and displacements to provide useful guidelines for structural interpretation of sub-surface data. Geomechanical applications are nicely illustrated by Cuisiat et al. (b) who describe a geomechanical study of fault stability during depletion of the Statfjord field in the North Sea. Their finding that the peak shear strength of the fault (core) material is the biggest source of uncertainty should continue to spur work on the mechanical properties of fault materials and upscaling to fault strength. Fault sealing is also addressed by Woods & Norris in terms of the migration of an exponentially decaying source migrating into a leaky seal, their numerical modelling illustrating the parameters controlling flow.

Thus beyond the direct interpretations of deformation processes contributing to fault zone growth described in this special issue, many of the descriptive observations may also serve to characterize fault zone complexity (e.g. statistical distributions of faults, fault dimensions, fault rock distributions such as the size and shape of high and/or low-permeability zones like host rock lenses, core-to-damage zone relative thicknesses) and constrain dynamic uncertainty models for fault property and fluid flow prediction. The trick will then be how to put such observational data, in quantitative form, into models for uncertainty in fault zone property prediction, and accounting for fault zone complexity.

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27 October 2010