Pergamon

Journal of Structural Geology, Vol. 18, Nos 2/3, pp. v to xi, 1996

S0191-8141(96)00002-8

Introduction to the Special Issue

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This Special Issue arose out of a two day meeting of the U.K. Tectonics Studies Group (part of the Geological Society of London) which was held in October 1994 at the Royal Society of Edinburgh and sponsored by Shell Research. Nineteen papers on topics related to the theme of the conference, scaling properties of fault and fracture populations, are presented in this issue. Some papers treat the collection and interpretation of fault data, whereas others discuss the origin of fault scaling relationships and the growth mechanisms of faults, fractures and veins. The aims of this Introduction are: (1) to summarize the key points of discussions that occurred at that conference, (2) to highlight the main results and conclusions of the papers presented in this volume, and (3) to draw attention to other recent publications pertaining to this theme. In so doing, we hope to provide a broad perspective on, and bibliography representative of current research on this topic. A detailed report on the conference is given by Cowie *et al.* (1995a).

The aim of the conference was to bring together results from a wide range of disciplines (field mapping, laboratory experiments, theory, modelling, and seismology) and to focus on four central questions: What are the best methods for collecting and comparing fault data sets at different scales? Are fault scaling laws reliable at predicting fault characteristics outside the range of available observations? How do fault populations evolve in space and time? What do fault scaling relationships indicate about underlying physical processes? The two papers in the first section of this volume address the problems of collecting and analysing fault data and establishing fault scaling relationships. The second section contains five papers which discuss the robustness and/or limitations of extrapolating these relationships to make predictions about faults lying below the resolution limit of a particular data set. There then follows a sequence of eight papers on the subject of fault growth and the evidence for the rates involved. This third section includes presentations of both field data and theoretical modelling. The last section concerns the mechanisms of propagation and the possible effects of differing physical processes on fault scaling relationships.

SECTION I

Collection, analysis and comparison of fault and fracture data sets

The first paper by Yielding, Needham and Jones reviews the current methods employed for deriving fault scaling relationships from seismic and core data. They utilize an idealized fractal model for a fault pattern to illustrate how sampling strategy can affect the scaling relationship inferred for faults, i.e. whether data come from cores (one-dimensional sampling), from seismic profiles (two-dimensional sampling), or from the fully three-dimensional fault population. The authors raise several key points. Firstly, after noting the difficulties in establishing the relative timing of faults in an area, they caution against analysing different fault sets together because of the artifacts that may arise. Second, they point out the biases that can arise because regions containing numerous faults or complex fault geometries are those most likely to attract the attention of the geologist. Yielding *et al.* also point out that relating one-, two- and three-dimensional samples depends on assumptions about fault clustering. In this context we note that Marrett & Allmendinger (1991) proposed simple relationships between samples collected at different dimensions but that those relationships assume that fault distributions are randomly isotropic (cf. Hatton *et al.* 1993).

Recent technological advances have increased the range of types of data now used for fault population analysis. For example, high-resolution side-scan sonar images of the sea floor have provided a wealth of information about fault formation along mid-ocean ridges where sedimentation and erosion have not obscured the structures (e.g. MacAllister *et al.* 1995, Allerton *et al.* 1995). Satellite images and aerial photography have been widely used for some time in fault pattern analysis (e.g. Kronberg 1991). De Chabalier *et al.* (1994) demonstrate the impact of remote sensing data in tectonic analysis; they use high resolution digital elevation models to determine the active crustal deformation in the Asal Rift of east Africa to a resolution of approximately 1 metre. Fault patterns on other planets, notably from Venus and Mars, are now being interpreted in detail from satellite images because of the information they can provide on crustal rheology and tectonic processes (e.g. Golombek *et al.* 1992). These types of digital data sets have not entirely superceded more traditional geologic mapping, but many field studies are now conducted using surveying techniques and photogrammetry in order to obtain quantitative data on fault displacements and lengths (e.g. Dawers *et al.* 1993).

The paper by Clark and Cox presents a new regression technique which can be used for analysing the relationship between the displacement (d) on a fault and its length (L). The power law size–frequency distribution of fault populations means there are very few large faults but a great many faults in the small-scale range so that standard linear regression is problematic. Clark & Cox conclude that faults from individual tectonic settings and rock types are most consistent with a linear relationship between d and L (cf. Cowie & Scholz 1992a). Discussion at the conference suggests that there is still disagreement as to whether the relationship is linear or non-linear for all data sets (e.g. Cowie & Scholz 1992b, Gillespie *et al.* 1992). However, the conference discussion focused more on the possible origins of the large scatter associated with these data. Rather than invoking sampling artifacts, several participants suggested that the scatter is a consequence of the mechanism of fault growth being dominated by segment linkage. Thus, the scatter itself is relevant to understanding growth processes (see discussion below). Returning to the issue of data analysing methods, a recent paper by Pickering *et al.* (1995) usefully summarises common sampling biases which can affect the analysis of power law distributions, and demonstrates how samples can be tested for bias and suitable corrections applied.

A topic that came up repeatedly in the first session of the conference was the use of fractal analysis for characterising fault and fracture populations. Although the term fractal is often used to describe any power law distribution, fractal analysis is used for measuring the spatial distributions of an object(s). Three of the most important concepts of fractal dimension are the capacity dimension, the information dimension and the correlation dimension (see Korvin 1992, p. 172 for details). Many people at the Edinburgh meeting agreed that the standard box counting method, which only yields the capacity dimension, is sensitive to the resolution limit of the data and the shape of the area being analysed (e.g. Walsh & Watterson 1993, see also Gillespie *et al.* 1993). Cowie *et al.* (1993, 1995b) recently showed how a multifractal box-counting method, which calculates the information and correlation dimensions, which may be used to obtain a better estimate of the degree of clustering and spatial variations in fault strain (see also Poliakov *et al.* 1994). Ouillon *et al.* (1995) have combined multifractal analysis with a new technique, the anisotropic wavelet coefficient method, which can be used to characterise the orientations of fault and fracture sets observed at different scales.

SECTION II

Extrapolation and interpolation of scaling relationships

Fault scaling relationships are now applied widely in practical applications to estimate the relative numbers, the position and the relative strain contribution of faults which lie below the resolution limit of a particular observational technique. A question remains, however, as to whether a purely empirical approach to fault population analysis is viable because techniques for collecting fault data vary a great deal and any single fault data set usually spans a limited scale range. This was the approach adopted by Gauthier & Lake (1993) in their development of a modelling tool for assessing the impact of faulting on hydrocarbon reservoir quality. The article by Needham, Yielding and Fox takes the view that such an approach is viable. They present an analysis of high resolution seismic and core data from hydrocarbon reservoirs, and show that the two data sets are consistent with a single size–frequency distribution ranging from faults having 100's of meters of displacements down to those with just a few millimeters. They suggest that the combination of orientation and spacing data along with the size–frequency distribution may therefore be used to characterise the true pattern of faulting in these reservoirs.

The assumption that fault and fracture populations are characterised by a few scaling exponents that are valid over a wide range of scales has been used in the calculation of 'aggregate properties', most notably the total strain due to faulting (e.g. Scholz & Cowie 1990, Walsh *et al.* 1991, Marrett & Allmendinger 1992, Westaway 1994). The paper by Marrett in this volume shows that a range of aggregate properties, including fracture surface area, fracture permeability/porosity and shear wave anisotropy, can be derived for the ideal case of a truly scale-invariant population. The principal conclusion of this study is that the magnitude of some aggregate properties, such as total strain, is mainly determined by the largest members of the population, whereas for other aggregate properties, such as fracture surface area, most of the magnitude is accounted for by the smallest members because they are more numerous.

Each of the next three papers in the volume raises issues that undermine this simple picture of scale invariance. Fossen and Rornes present data on fault populations from a hydrocarbon reservoir which show different scaling exponents for larger and smaller faults among those resolved by seismic data. By dividing their data into fault sets with limited orientations, they found that the change in scaling was no longer apparent. The scaling exponent for the different sub-populations was highly variable, however. Because the criteria on which fault sets are distinguished are always going to be subjective, two workers might derive very different conclusions from the same data set. More importantly perhaps, Fossen & Rørnes question the significance of a single regional or global scaling relationship, and even if one is defined by the data, to what extent it is representative of the fault pattern locally so that meaningful predictions may be made. The paper by Nicol, Walsh, Watterson and Gillespie also questions the degree to which fault populations follow simple power law distributions over a wide range of scale. Using a combination of seismic, coal mine and core data, these workers find that the power law exponent decreases systematically as the size of the faults decreases, i.e. that populations mapped at outcrop are characterised by lower slopes than those interpreted from seismic. They point out that populations of small faults can show a wide range of variability in a given region depending on local fault systematics and that this might explain the trend. They also suggest, however, that faulting mechanisms may vary as a function of scale (cf. Hatton *et al.* 1994); we return to this topic in more detail below.

The final paper in this section by Watterson, Walsh, Gillespie and Eaton presents a test case of prediction using a large scale range fault map derived from coal mine plans. This map includes data from faults with displacement ranging from 10 cm to 180 m and with lengths ranging from 10 m to about 10 km.

By progressively decimating the primary fault map, they illustrate the limitations of seismic data of differing resolutions. One of their main conclusions is that, for this coal field data set, a throw resolution of better than 10 m is required to provide an accurate prediction of the fault population at the metre-scale. Note that this condition is rarely satisfied by even the best quality three-dimensional seismic data.

Defining a scaling relationship assumes a continuous distribution of fault sizes, and in some cases seismic and core data support such an inference (e.g. the paper in this volume by Needham *et al.*). Field observations indicate, however, that gaps or breaks in fault and fracture size distributions can occur in some structural settings (Koestler 1994). This is another example of how site-specific observational constraints and global scaling relationships need to be reconciled when attempting prediction. The problem here is analogous to earthquake prediction in that local geological and geophysical data must be reconciled with the global Gutenberg-Richter relationship to assess seismic hazard (e.g. Wesnousky 1986).

In addressing seismic risk, hydrocarbon reservoir quality, volume change during deformation, and other significant topics, the impact of faults on rock permeability is as relevant as their size and spatial distribution. A question yet to be answered is how to combine fault population statistics with knowledge of the sealing capacity of individual faults to determine overall rock permeability. Answering this question will require detailed knowledge of the rates of dissolution and precipitation of mineral phases during deformation and the relative timing of fault slip events (e.g. Knipe 1992, Main *et al.* 1994, Ngwenya *et al.* 1995). Time-dependence of rock properties will affect fault development whether by changing effective stresses or by changing bulk rock rheology. Several research groups are tackling issues related to the role of fluids in faulting (see for example the *Journal of Geophysical Research* Special Issue, *J. Geophys. Res.* **100**, 12335–13132).

SECTION III

Growth of fault arrays and accumulation of fault displacement

The section of the volume on fault growth begins with a paper by Jackson, Norris and Youngson who use drainage patterns to infer the temporal evolution of fault and fold systems in an actively deforming region of New Zealand. Geomorphology has yielded some useful insights into a problem that is inherently difficult to address, because repeated slip along the same fault zone often destroys or modifies evidence of earlier events, and cross-cutting relationships rarely show a clear temporal sequence. The sizes and shapes of drainage basins, as well as the patterns of incision and deposition, can be used to estimate the relative ages of adjacent fault segments, the rates and direction of fault propagation and the process of fault linkage. The Jackson *et al.* paper is part of an expanding literature examining the relationship between faulting, fold growth and sedimentation (e.g. Suppe *et al.* 1992, Leeder & Jackson 1993, Jackson & Leeder 1994, Schlische & Anders 1996).

The following four papers in this section show how detailed structural analysis of fault and fracture patterns may be used to infer the mechanisms operating during fault growth. These data are derived primarily from outcrop mapping, high-resolution seismic sections and coal mine plans. The first of these papers, by Nicol, Watterson, Walsh and Childs, addresses the question of what causes the distribution of displacement on faults and shape of fault planes. Fault tip lines typically have a roughly elliptical shape that is elongated along a sub-horizontal axis with an aspect ratio greater than 2:1. These authors assess whether differences between Mode II (edge dislocation) and Mode III (screw dislocation) fracture energies can explain this observation or whether other mechanisms are more important. Their data indicate that shape is independent of the slip vector orientation and fault dip, whereas rheological layering and interaction with neighbouring faults result in irregular tip-lines and non-concentric displacement contours. A related paper (Childs *et al.* 1995) explores the temporal evolution of fault plane shape and displacement distributions in three-dimensions along kilometre-scale normal faults in sedimentary strata using a technique called structural backstripping. Anders & Schlische (1994) have analysed the linkage history and displacement accumulation on larger scale faults in the western United States.

The paper by Mansfield & Cartwright suggests that anomalous zones of reduced displacement on fault surfaces can be identified as relict linkage structures where precursory fault segments have joined together to produce a larger surface area. This evidence supports the work of Cartwright *et al.* (1995) who argue that the large scatter observed in plots of maximum fault displacement versus length could indicate that linkage is the dominant mechanism for producing longer faults. Mathematical models for fault growth have, in the past, assumed that radial tip growth is the primary process (e.g. Walsh & Watterson 1988, Cowie & Scholz 1992a). Such models lead to simple relationships between the average displacement–length ratio and rock properties, which provide a physical framework for understanding these data. In contrast, growth by linkage is likely to be a more complex process that is strongly controlled by the orientation and spatial separation of earlier generations of faults and fractures. Although this suggests a component of chance, i.e. the length of a fault depends on having neighbours to link with, the combination of stress enhancement around fault tips and stress shielding between faults means that the availability of suitable neighbours is not random. In other words an evolving fault pattern self-organises in a crust that can support finite elastic stresses over geologic time. An illustration of such a mechanism is depicted in a paper by Wu & Bruhn (1995), which shows sets of secondary faults and fractures forming beyond the tips of larger structures and growth progressing by hierarchical linkage.

The effect of fault linkage on the size–frequency of fault populations is demonstrated in the paper by Wojtal, using data collected from the southern Appalachian fold–thrust belt. Wojtal finds that in strata subject to larger amounts of strain the fault population evolves from a set of individual slip planes to a system of linked fault strands or segments. Individual strands may have a limited amount of displacement on them but overall, the linked array can represent significant strain. This paper shows that interpretations of a size–frequency distribution of fault displacements measured in a single traverse are sensitive to assumptions made about the linkage of strands out of the plane of section (cf. Walsh & Watterson 1991). Consideration of linkage in analysis of these data leads to changes in both the shape and the slope of size–frequency distributions. This has important implications for the possible origin of power law size scaling, as well as for the extrapolation of fault population data beyond the scale of observation. Note that Wojtal concludes that one-dimensional samples do not yield truly objective views of fault displacement distributions (cf. papers by Yielding *et al.* and Needham *et al.* and discussions in Sections I and II above).

In the following paper, Cladouhos & Marrett use a mathematical model to explore explicitly the competing effects of growth by tip propagation versus growth by linkage. A primary conclusion of their work is that tip propagation alone does not give rise to, and cannot maintain, power law size scaling with increased fault strain unless the slip rate and propagation rate also increase as each fault grows in size. This leads to an ever increasing moment release rate through time, which is unrealistic. These authors show that (1) fault linkage can lead to the development of power law size-scaling, even if the distribution of initial flaws is not power law, and (2) the slope of the size–frequency distribution decreases systematically as strain accumulates. Cowie *et al.* (1995b), using a numerical rupture model, reached similar conclusions. Furthermore, they found that a random distribution of faults nucleates at the onset of deformation and that a power law size distribution develops when nucleation is superceded by growth and coalescence as the dominant deformation mechanisms.

The dependence of power law slope on total strain that Cladouhos & Marrett predict, is consistent with the data presented by Wojtal in the preceding paper. However, when Cladouhos & Marrett compare their results with natural fault populations they find that the limited range and large uncertainties in the real data obscure any correlation. Nicol *et al.* (Section II this volume) also find that there is no consistent relationship in the data sets they have examined. As the size–frequency distribution is controlled by the competing effects of fault nucleation and coalescence it seems reasonable that quite a large degree of variability will be observed in nature depending on the tectonic setting and the kinematics of the deformation (e.g. Wojtal 1994). These factors affect how much of the total strain in a given area is taken up by small-scale faulting. While the total strain in a given region must converge to a finite amount, it is the rate of convergence with respect to fault size which determines the contribution from small faults. The extreme case occurs when the deformation proceeds by growth and coalescence only, then a power law exponent equal to 1.0 is predicted and the strain is strongly convergent, i.e. dominated by one major fault (Sornette & Davy 1991, Davy *et al.* 1995).

The paper by Willemse, Pollard and Aydin focuses on the mechanical interaction between the segments of linked fault arrays using a three-dimensional numerical boundary element method. They calculate cumulative displacement profiles and displacement–length ratios for faults in simple arrays, and compare their results with displacement patterns observed for real faults in analogous settings. In their numerical results, the central segments of linked fault arrays have systematically higher displacement–length ratios than distal segments. Dawers & Anders (1995) noted a similar variation in a natural fault system (see also Peacock & Sanderson 1991). Furthermore, in the numerical results, the displacement–length ratio for the whole array was comparable to that for a single isolated fault. This too conforms with the data of Dawers & Anders (1995). The fact that Willemse *et al.* are able to model these data using an entirely static model may be interpreted to mean that elastic interactions persist over geologic time and are controlling fault array development both prior to and after linkage. As these interactions occur at both short-range and long-range due to the algebraic decay of the elastic strain field, there is no such thing as a truly isolated fault. This idea is again integral to the theory of fault growth as a self-organised phenomenon, which has been proposed by A. Sornette *et al.* (1990) and D. Sornette *et al.* (1990).

The paper by Peacock and Sanderson takes a very different modelling approach in order to explain variability in fault displacement profiles. Peacock & Sanderson allow the percentage increase in fault length per slip event to be a free parameter, which can vary locally in space or time independent of the accumulated displacement. Factors which arrest tip propagation, e.g. interaction with other faults, bends in faults, or lithological variations will result in a steepening of profile shapes if displacement continues to accumulate. Peacock & Sanderson conclude that the final displacement profile may be due to the propagation history rather than the distribution of slip accrued during individual events. Note that a recent paper by Burgmann *et al.* (1994) explicitly modelled displacement profiles in the presence of lithologic layering, stress gradients, inelastic deformation, and fault interaction using elastic dislocation theory. Burgmann *et al.* (1994) are also able to model the variability described by Peacock & Sanderson even though they use a static modelling approach similar to that presented by Willemse *et al.* (this volume).

The paper by Little also discusses aspects of fault zone development. We explore this in more detail in the next section.

SECTION IV

Mechanisms of brittle deformation

This section begins with a paper by Wilson, Henderson and Main which presents a cellular automaton fracture model coupled to a lattice gas model for fluid flow. They find that variations in material properties determine where initial cracks form during a single cycle of deformation. The density of initial cracks in turn affects the onset of crack interaction and thus the subsequent evolution of the fracture array. This result is similar to the conclusions of other studies which show that complex fault and fracture topology (e.g. bends, splays, and segments) can result from local heterogeneity in the host-rock, even at the grain scale (e.g. Miltenberger *et al.* 1993, Moore & Lockner 1995, Cowie *et al.* 1995b). The impact of small-scale heterogeneity on fault pattern development is exemplified by the results of analogue modelling presented at the Edinburgh meeting. These models show many of the characteristics of real fault populations, including the scatter of the d/L ratio already mentioned (Filbrandt *et al.* 1994, Davy *et al.* 1995). Since analogue experiments use a 'uniform' aggregate of sand, the scatter can be attributed entirely to a complex interplay between random small-scale structure and the physics of fault growth under different boundary conditions.

In the following paper, Johnston and McCaffrey examine the evolution of vein arrays, and use this system to infer changes in fracture growth mechanism by documenting changes in scaling relationships. Changes in scaling, and the length scales at which they occur, may indicate as much about the physics of the processes operating as the scaling relationships in the scale invariant domains. For example, Hatton *et al.* (1994) related a break in scaling of extensional fractures in Iceland to the length scale of the preexisting cooling joint fabric; jointed lava flows act like a granular medium on the scale of metres and inhibit the lengthening of sub-metre length cracks. Likewise, the thickness of rheological layering has an impact on fault displacement profiles and size–frequency distributions (Dawers *et al.* 1993, Wojtal 1994, Marrett this volume). This is one of the issues addressed in the papers by Knott, Beach and Brockbank and Schultz and Fori. Knott *et al.* examine how sedimentary layering affects the architecture of normal faults zones, whereas Schulz & Fori show how fault patterns on Mars can be used to infer rheological properties of the planetary crust. Recently, Davy *et al.* (1995) have used analogue and numerical models to demonstrate how the statistics of an evolving fault population depends on the strength ratio between the brittle and ductile layers of the lithosphere (see also A. Sornette *et al.* 1993).

The paper by Knott *et al.* also examines the scaling of fault damage zone width with displacement. Damage zones refer to the volume of deformed rock that surrounds the main slip surface. However, the origin and timing of the damage relative to the formation of the fault itself is not clear. For example, Anders & Wiltschko (1994), have documented microcracking around faults which they relate to the propagation of the fault tip—the so called 'process zone' (see also Scholz *et al.* 1993, McGrath & Davison 1995). In contrast, the walls of a fault accommodate strain during its subsequent slip history and this signature must overprint the tip process zone and presumably intensifies with increasing fault offset. The paper by Little in Section III clearly shows that major faults, in this case the Awatere fault in New Zealand, are associated with an aureole of minor faults and fractures which apparently form as the main fault takes up displacement along the plate boundary. One of the key points here is that clustering of small faults around larger faults evolves as strain accumulates in the deforming volume. The processes which control the extent and scale of clustering need to be clarified in order to understand the origin and significance of power law size scaling in the overall fault population; it is also important in correcting fault population data which are based on one-dimensional samples.

Another aspect of brittle deformation discussed in this volume is the issue of aseismic versus seismic faulting. A yet unanswered question is: do faults which move intermittently in stick–slip events develop in a fundamentally different way to faults that slip continuously in a stable fashion? Field evidence for the recent slip history on individual faults is typically derived from palaeoseismological data (e.g. Stein 1995). However, a recent paper by Davison (1995) shows similar slip data obtained from crack-seal veins developed in extensional jogs along faults which are not necessarily seismically active. This study is particularly significant because relatively little is known about the mechanisms of slip on smaller faults (i.e. faults with lengths ≤10 km) forming at shallow crustal levels. Also the cessation of fault activity is poorly understood. Yielding *et al.* (Section I of this volume) point out the difference between the value of the seismic b-value and the power law exponent that characterises the size distribution of the faults.

Reconciling these two exponents requires that either some of the faults are seismically inactive, or that recurrence intervals vary systematically with fault size (e.g. Walsh & Watterson 1992, Marrett 1994, Cladouhos & Marrett this volume).

One important outcome of the Edinburgh meeting was the identification, via discussion, of the key areas where future research should be concentrated. To achieve more reliable assessments of fault network properties, earth scientists require a better understanding of the physics of fault population evolution, improved techniques for quantifying all fault attributes, and validation in well-constrained examples. There is a particular need for physical modelling (both theoretical and experimental) and new field measurements that bridge gaps between other data sets. It is clearly important to explore the scaling properties of orientations, intersections and linkage structures in fault populations, in addition to lengths and displacements, as these factors strongly influence connectivity in fluid saturated rocks. This is a three-dimensional problem which requires better data, especially three-dimensional seismic and field mapping, to be properly addressed. Laboratory experiments are also needed to investigate further the physical and chemical effects of fluids during fault and fracture development.

Postscript—We note with great sorrow the loss of David Johnston while conducting field work along the coast in Ireland. Dave was an active participant at the Edinburgh conference, co-authored one of the papers in this volume, and made significant contributions to the literature on fault scaling laws.

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