

Characterization of Fault Zones

Yehuda Ben-Zion⁽¹⁾ and Charles G. Sammis⁽¹⁾

(1) Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740 (email: benzion@terra.usc.edu; sammis@earth.usc.edu, phone: 1-213-740-6106, fax: 1-213-740-8801)

Abstract

There are currently three major competing views on the nature of earthquake fault zones. The first is that faults are (possibly segmented and heterogeneous) Euclidean zones in a continuum solid. The second focuses on granular aspects of faults and deformation fields. The third is that faults are fundamentally rough fractal objects at all relevant scales. The existing data can not distinguish unequivocally between the three different views or determine their scale of relevance. However, in each observational category, the highest resolution results associated with mature faults are compatible with the continuum-Euclidean framework. A positive feedback mechanism associated with strain weakening attracts the long-term evolution of faults toward progressive regularization and Euclidean geometry. A negative feedback mechanism associated with strain hardening during initial deformation phases and around persisting geometrical irregularities generates renewed complexity. We conclude that long term slip accommodation may be accounted for to first order within the continuum-Euclidean framework.

Introduction

Earthquakes are *processes* associated with *objects* that are called *fault zones*. Earthquake physics is thus dictated to a very large extent by fault zone properties. Here we review conceptual frameworks and data on the character and properties of earthquake fault zones guided by the following three questions: 1) What are the geometrical properties of a fault zone? 2) What is the best theoretical framework to describe fault mechanics? 3) How do the answers depend on scale? Figure 1 illustrates the complexity involved in addressing these questions. On the global plate-tectonics scale, the entire western California may be considered as a fault zone between the Pacific and North American plates. It appears granular in the sense of having crustal blocks that translate and rotate to accommodate the deformation. It contains several strands of localized deformation that form the major sub-parallel faults in the San Andreas system, bordered by a network of subsidiary faults with complex geometry. Focusing down in scale to the main trace of the San Andreas Fault reveals a core of crushed rock containing multiple shear localizations, bordered by zones of intense fracturing and damaged rock. Numerous bends and jogs along the main strands tend to be sites of additional structural complexity. The California plate boundary may thus be viewed as a nested hierarchy of shear localizations within shear localizations, each surrounded by a granular or a continuum matrix. A fundamental question is whether this complex structure is self-similar geometrically and mechanically, or whether different frameworks are required at different scales. A related key issue is whether all components of the visible complex structure, or perhaps just a few or even one, play a dominant role in accommodating the tectonic deformation.

As suggested by the forgoing description, the three major competing views on the essential geometrical, mechanical, and mathematical (GMM) nature of faults are *continuum-Euclidean*, *granular*, and *fractal*. Each of these frameworks carries a very different set of implications. In the first standard view, faults are regular planar or tabular Euclidean zones in a continuum solid. In the *continuum-Euclidean* framework, the underlying “macroscopic” GMM structure is fundamentally smooth and continuous. This implies the possibility of stable or convergent averaging of abrupt fluctuations over smaller space-time scales that are referred to as “microscopic”, and clear separation between the microscopic and macroscopic scales. The obtained macroscopic description has gradual variations of all fields. Slip on Euclidean faults in a continuum solid can be analyzed in terms of fracture mechanics, friction, and other constitutive laws measured in laboratory rock-mechanics experiments. The constitutive laws, like all other functions, vary smoothly with the ongoing deformation. Stress transfer from a slip region falls like $1/r^3$ with r being the distance from the source. This provides an estimate for the size of expected correlation of stress and other dynamic variables in a continuum solid. In a medium governed by a *strain weakening* rheology, deformation structures and processes are expected to evolve toward the continuum-Euclidean framework. This is because strain weakening produces zones of localized deformation and strength reduction, leading to further strain localization and strength reduction. In an ideal homogeneous quasi-static case, this positive feedback mechanism cascades into deformation that is concentrated on a planar fault in a surrounding elastic continuum. In actual realistic cases, heterogeneities of geometry, material properties and applied fields, dynamic branching, etc. produce complications that prevent complete localization. Nevertheless, the long-term deformation in a brittle solid governed by strain weakening rheology will still be *dominated* by Euclidean structures of size comparable to that of the overall medium dimensions (e.g., depth of seismogenic zone), surrounded by a more-or-less continuum matrix that contains a variety lesser structures.

The second view focuses on granular aspects of fault structures and deformation fields. In the *granular* framework, the fundamental GMM structure is discrete and strongly heterogeneous. Abrupt fluctuations are present and can not be averaged out. Load is supported mostly along a few “connectivity chains” rather than the whole medium, producing strong macroscopic anisotropy of all fields. As a consequence, correlation lengths of dynamic variables exhibit strong directivity effects. For example, stress transfer along the connectivity chains can decay much slower than $1/r^3$, at the expense of much faster decay in other directions. While deformation of granular media includes strong fluctuations, it is still possible to use concepts from fracture mechanics and friction with appropriate modifications. In contrast to a continuum description, however, constitutive laws of granular material may vary abruptly at places. The *granular* framework is expected to hold in a medium governed by a *strain hardening* rheology that creates a negative feedback mechanism opposite to that associated with strain weakening. This leads to ongoing creation of new fractures, overall distributed or diffused deformation, and structures of relatively small size compared to the overall dimensions of the deforming domain.

The third view is that faults are fractal objects with rough surfaces and branching geometry. In the *fractal* framework, the fundamental GMM structure is irregular, discrete, and heterogeneous on all scales. If we take the fractal framework at face value, differential calculus and associated concepts like stress, strain, fracture, and friction are not valid. At present there are no corresponding mathematical and mechanical quantities, or effective constitutive laws, to describe deformation in a solid with truly fractal geometry. The *fractal* framework implies a *balance* between strain weakening and strain hardening processes that is *perfectly* (or *critically*) *tuned* to produce neither positive nor negative feedback mechanisms during deformation. In such a case, the long-term deformation is accommodated statistically, at all time intervals, by structures that have no preferred size scale, i.e., structures following a power law frequency-size distribution. Fractal geometry has been reported to characterize brittle deformation structures in the crust over

several bands of length scales, from regional fault networks through main traces of individual faults to the internal structure of fault zones. In this study we examine critically these observations and the mechanical significance of the fractal structures for long term accommodation of slip on faults.

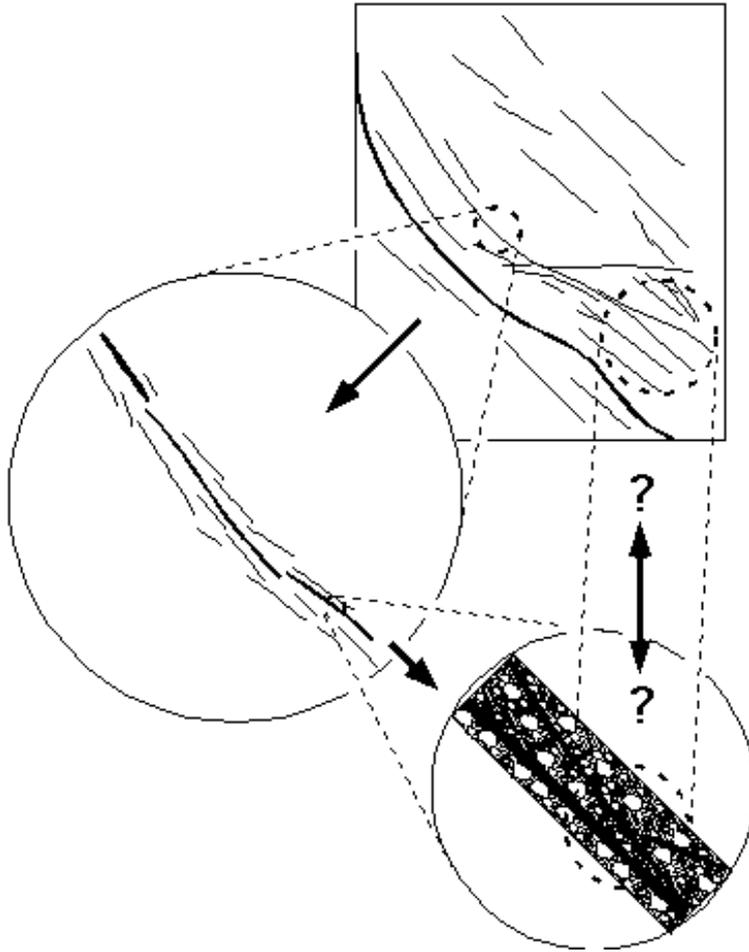


Figure 1. Schematic illustration of fault structures at different scales, each with possible Euclidean, granular, and fractal geometrical features. At the largest scale containing boundary regions of different plates, shear is distributed over a network of faults. At a plate boundary scale, individual major faults in the network are seen to consist of a quasi-linear array of sub-parallel strands. At internal fault-zone scale, each strand consists of a distributed band of intense fracturing containing one or more tabular zones of strain localization and intense fragmentation. The arrows between the different scales suggest the possibility that the key structural elements repeat at different scales.

Imaging Methods and Data Type

We consider observational evidence on the GMM character of faults from a number of different categories of imaging methods and data. For each category we discuss several classes of observations, distinguished by their imaging resolution and by whether they apply to regional or fault specific studies. The categories and classes of examined data are as follows: 1. *Surface Fault Traces and Exhumed Faults.* (a) Scaling analysis of surface traces of fault networks (e.g., [2], [14]). These studies may be considered "regional at different hierarchies" and they typically have a resolution on the order of a km. (b) Evolution of fault complexity with cumulative slip (e.g., [20], [21]). These works have various resolutions from mm

to km and they fall between those analyzing regional fault networks and those examining specific fault structures. (c) Analysis of rupture surface topography (e.g., [5], [15]). This class involves specific rupture sites and it has a resolution of sub-mm. (d) Detailed multi-disciplinary measurements on exhumed fault zone structures (e.g., [6]). The data from these works provide information on specific fault segments over a range of length scales varying from sub-mm to several km. 2. *Inversions of geophysical data for velocity models.* (a) Gravity and electro-magnetic studies (e. g., [22], [23]). These are regional studies, although they can center on specific faults, with a resolution of a few km. (b) Seismic reflection/refraction and travel time tomography (e.g., [7], [8]). These methods are lumped together here because they all use seismic travel time (and sometime also amplitude) information (as opposed to wave-form modeling). Studies in this class have a resolution of up to about 500 m, and like the previous class they are regional surveys that may center on specific faults. (c) Seismic fault zone head and trapped waves (e.g., [4], [9], [12]). These studies can have a resolution on the order of a few tens of meters and they involve specific fault segments. 3. *Patterns related to predictions of mechanical models.* (a) Rupture along a material discontinuity interface (e.g., [1], [17]). (b) Earthquake triggering and migration (e.g., [19]). (c) Earthquake statistics (e.g., [3], [11]). 4. *Hypocenter distributions.* (a) Spatial correlations among routine locations in regional and global catalogs (e.g., [10]). These are regional studies with resolution on the order of a few km. (b) Geometry and analysis of improved locations (e.g., [16], [18]). These are regional studies with resolution on the order of a few hundreds of m. (c) High-resolution relocations (e.g., [13], [17]). These studies are done on specific segments and they have a resolution from a few meters to tens of meters.

Summary of Results

The Euclidean-continuum view is supported by seismic, gravity, and electro-magnetic imaging studies; by successful modeling of observed seismic radiation, geodetic data, and changes in seismicity patterns; by many (although not all) field studies of earthquake rupture zones and exhumed faults; and by recent high resolution hypocenter distributions along several faults. The granular view is supported by observations of rock particles in fault zone gouge; by studies of block rotations and the mosaic structure of the lithosphere (which includes the overall geometry of plate tectonics); by concentration of deformation anomalies along block boundaries; by correlation of seismicity patterns on scales several times larger than those compatible with a continuum framework; and by strongly heterogeneous wave propagation effects on the earth surface. The fractal view is supported by statistical analysis of regional hypocenter locations; by long range correlation of various measurements in geophysical boreholes; by the fact that observed power law statistics of earthquakes are compatible with an underlying scale-invariant geometrical structure; by geometrical analysis of fault traces at the earth surface; and by measurements of rupture and fault surface topography. There are several overlaps between expected phenomenology in Euclidean-continuum, granular, and fractal frameworks of crustal deformation. As examples, highly heterogeneous seismic wavefields can be generated by granular medium, fractal structure, and ground motion amplification around and scattering from Euclidean fault zones. A hierarchical granular structure may have fractal geometry. Power law statistics of earthquakes can be generated by slip on one or more heterogeneous planar faults, by a fractal collection of faults, and by deformation of granular material. Each of the three frameworks can produce complex spatio-temporal patterns of earthquakes and faults.

The existing data can not distinguish at present unequivocally between the three major views on the nature of faults. However, in each observational category the highest resolution results associated with mature highly-slipped faults are compatible, in general, with the standard *contin-*

uum-Euclidean framework. The observational data, as well as modeling results, indicate that rock deformation has a short initial transient phase involving strain hardening and creation of granularity and band-limited fractal structures at several hierarchies (Figure 2A). With small increasing deformation under same applied loads, and high enough strain rate compare to the rate of healing, this is replaced by strain weakening and localization to tabular zones that become the main carriers of the following deformation (Figure 2B). At that stage, most of the complex initial structure becomes largely passive and the dominant localized fault zones evolve with continuing deformation toward Euclidean geometry and progressive simplicity and regularization (Figure 2C). Fault off-sets, kinks, and bends, as well as end regions of earthquake ruptures and faults and transition zones between different tectonic regimes, continue to produce local complexity at different scales. However, the overall structural evolution at different scales is toward progressive regularization. Global transient phases of renewed generation of complexity at different scales occur when a mature fault zone rotates away from favored orientations compatible with the motion.

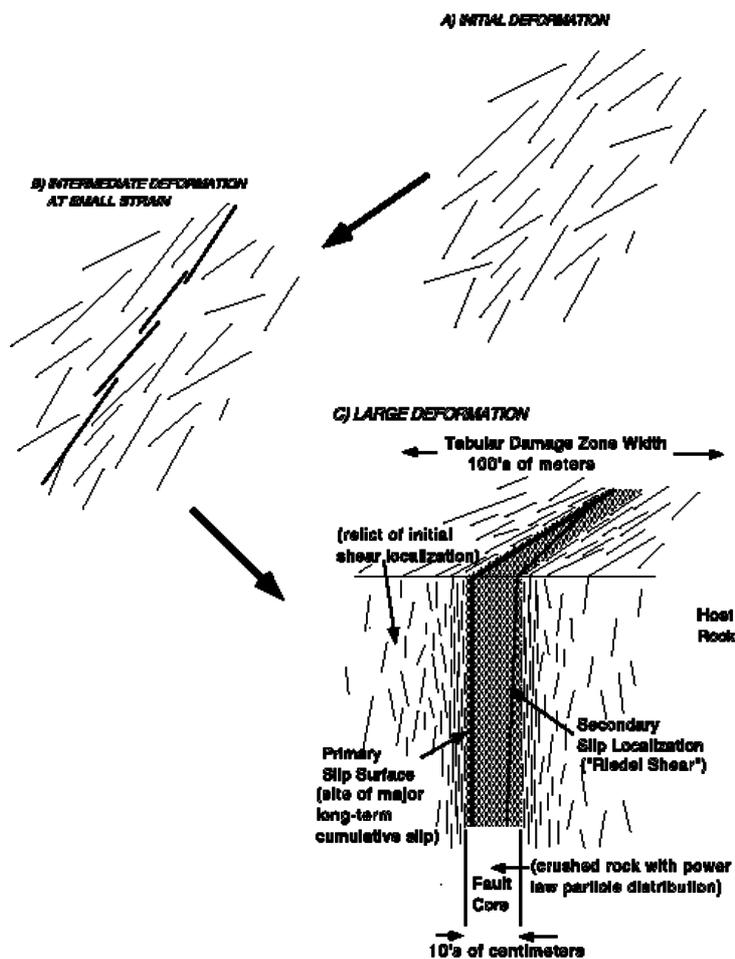


Figure 2. Schematic representation of fault structures at three main evolutionary stages. (A) Initial deformation is associated with strain hardening. At this stage there is creation of granularity and band-limited fractal structures at several hierarchies. (B) After a small initial strain there is localization to tabular primary slip zones accompanied by a transition to strain weakening. (C) Large deformation is dominated by strain weakening and overall evolution at different scales toward Euclidean geometry and progressive geometrical simplicity and regularization. The initial complex structure becomes largely passive at this stage.

Acknowledgments

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