Earth and Planetary Science Letters 431 (2015) 150–163

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Statistical mechanics and scaling of fault populations with increasing strain in the Corinth Rift

Georgios Michas [a,*], Filippos Vallianatos [a,b], Peter Sammonds [a]

[a] Institute for Risk and Disaster Reduction, University College London, Gower Street, London, WC1E 6BT, UK
[b] Laboratory of Geophysics and Seismology, Technological Educational Institute of Crete, Chania, Greece

ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 4 September 2015
Accepted 10 September 2015
Available online 1 October 2015
Editor: A. Yin

Keywords:
Corinth Rift
fault-length scaling
brittle strain
maximum entropy principle
non-extensive statistical mechanics

ABSTRACT

Scaling properties of fracture/fault systems are studied in order to characterize the mechanical properties of rocks and to provide insight into the mechanisms that govern fault growth. A comprehensive image of the fault network in the Corinth Rift, Greece, obtained through numerous field studies and marine geophysical surveys, allows for the first time such a study over the entire area of the Rift. We compile a detailed fault map of the area and analyze the scaling properties of fault trace-lengths by using a statistical mechanics model, derived in the framework of generalized statistical mechanics and associated maximum entropy principle. By using this framework, a range of asymptotic power-law to exponential-like distributions are derived that can well describe the observed scaling patterns of fault trace-lengths in the Rift. Systematic variations and in particular a transition from asymptotic power-law to exponential-like scaling are observed to be a function of increasing strain in distinct strain regimes in the Rift, providing quantitative evidence for such crustal processes in a single tectonic setting. These results indicate the organization of the fault system as a function of brittle strain in the Earth's crust and suggest there are different mechanisms for fault growth in the distinct parts of the Rift. In addition, other factors such as fault interactions and the thickness of the brittle layer affect how the fault system evolves in time. The results suggest that regional strain, fault interactions and the boundary condition of the brittle layer may control fault growth and the fault network evolution in the Corinth Rift.

1. Introduction

The formation and growth of faults is the result of deformation of the Earth's brittle crust under tectonic loading. As brittle strain increases, faults are nucleated in weaker parts of the crust and grow in length and/or displacement to accommodate strain. Crustal strain is accommodated on a system of faults and fractures that may vary in size from a few millimeters to tens or hundreds of kilometers, rather than focusing on a single fault. Fault systems are developed in geologic timescales such that present observations only represent a single frame in the tectonic history of the deforming zone. Such fault systems exhibit scaling properties that can provide insight into the underlying physical mechanism of fault growth and evolution (e.g., Cowie, 1998a). Qualitative and quantitative studies on the scaling of fracture/fault attributes have been employed in various fields of geology, geophysics and engineering in order to support models of fracturing processes and fault population evolution (Cowie et al., 1993; Cladouhos and Marrett, 1996; Berkowitz et al., 2000; Spyropoulos et al., 2002).

In many case studies, a variety of fracture and fault population attributes such as trace-lengths and displacements are approximated by fractal geometries and power-law distributions (e.g., Bonnet et al., 2001 and references therein). In other cases, exponential scaling can better describe the fault trace-length distributions (Cowie, 1998a; Vétel et al., 2005). Gupta and Scholz (2000) studied the fault trace-length distribution in the Afar Rift and provided a qualitative interpretation of their observations to indicate the transition from power-law to exponential scaling in the higher-strain zones. Furthermore, simulations on numerical models (Cowie et al., 1995; Spyropoulos et al., 2002; Hardacre and Cowie, 2003) and analogue laboratory experiments (Spyropoulos et al., 1999; Ackermann et al., 2001) indicated that the scaling properties of a fault system are associated with the total amount of strain and the rates of fault nucleation, growth and coalescence that define the main stages of fault population evolution. In these models, cracks are starting to nucleate and grow in size and number with increasing strain, exhibiting a power-law size distribution. As strain accumulates, the nucleation rate decreases, cracks are beginning to coalesce forming larger cracks, their total number decreases and

* Corresponding author.
E-mail address: georgios.michas.10@ucl.ac.uk (G. Michas).

http://dx.doi.org/10.1016/j.epsl.2015.09.014
0012-821X/

most of strain localizes along few large cracks that span the mechanical layer. At this stage, where growth and coalescence start to dominate, faults display a power-law size distribution with decreasing exponents as strain increases, indicating the increased importance of large faults in accommodating strain (Cowie et al., 1995; Ackermann et al., 2001). At later stages of deformation, the proportion of active cracks starts to decrease as stress interactions favor displacements along few cracks and lock of others, the crack population reaches saturation and the crack-length distribution turns to exponential (Spyropoulos et al., 1999, 2002; Ackermann et al., 2001; Hardacre and Cowie, 2003).

In addition, other factors such as the regional stress field, crustal rheology, boundary conditions of the brittle layer, possible heterogeneities and elastic strain interactions may all affect how the fault system evolves (e.g., Hardacre and Cowie, 2003 and references therein). The complexity of the fault network evolution is inherently related to these factors, so that in many cases simple power-law or exponential distributions may not account for the full-range of the observed fault properties (Davy, 1993; Ackermann and Schlische, 1997; Vétel et al., 2005; Vallianatos et al., 2011).

To resolve some of the limitations arising from the description of fault trace-length distributions using empirical statistical distributions, Vallianatos et al. (2011) and Vallianatos and Sammonds (2011) have recently introduced a model that incorporates the notions of statistical mechanics and maximum entropy principle (MEP) (Jaynes, 1957) to infer the least biased probability distribution that can describe the fault trace-length populations. Rather than the classic Boltzmann–Gibbs–Shannon entropy S_{BGS}, the model optimizes the non-additive entropy S_q introduced by Tsallis in the framework of non-extensive statistical mechanics (NESM) (Tsallis, 1988). S_q incorporates properties such as multifractality and/or long-range interactions (see Tsallis, 2009 and references therein), properties that are known to induce power-law size distributions in fault systems (Sornette et al., 1993; Cowie et al., 1995). The advantage of S_q is that it considers all-length scale correlations among the elements of a system leading to asymptotic power-law behavior and recovers S_{BGS} as a particular case. Recent applications on rock and earthquake physics indicated that the collective properties of fracture and earthquake populations from laboratory, to regional and planetary scale can be successfully reproduced by means of NESM (see Vallianatos et al., 2012; Vallianatos and Sammonds, 2013; Michas et al., 2013 and references therein).

In this study, we use the statistical mechanics model to study the scaling properties of fault trace-lengths in the Corinth Rift. The Corinth Rift (central Greece) is a high strain zone of active deformation in the back-arc region of the Eastern Mediterranean subduction zone. The area is known for its high earthquake activity, rapid continental extension rates and active rifting processes that have resulted in the formation and growth of an impressive en-echelon normal fault system (Armijo et al., 1996). The numerous works that study the geology and the tectonic features of the area, supplemented in the last two decades by high-resolution marine geophysical surveys, provide a rather comprehensive image of the fault network, both onshore and offshore (e.g., Taylor et al., 2011). We synthesize the results of these studies to compile a detailed fault map and study for the first time the scaling properties of the fault population over the entire area of the Rift. Based on the statistical mechanics model, we provide a qualitative and quantitative study on the scaling of fault trace-lengths and compare the results for different strain zones in the Rift. We further discuss the physical implications that arise from the analysis for fault growth processes and the fault network evolution in the Rift.

2. The Corinth Rift

2.1. Geological setting

Greece is the most seismically active area in Europe due to its location on an active tectonic plate boundary, at the convergence of the Eurasian and African lithospheric plates along the south Hellenic subduction zone (SHSZ) (Fig. 1). In the back-arc region, significant continental extension has been taking place in the Aegean Sea since the Oligocene–Miocene (e.g., Papanikolaou and Royden, 2007). Active faulting, seismicity and geodetic strain rates indicate that active extension in the Hellenic region is mainly taking place in a series of extending grabens such as the North Aegean Trough (NAT), which has significant strike-slip components and consists the prolongation of the North Anatolian Fault (NAF) to the west (Fig. 1), the Evia graben and the Corinth Rift (summary from Goldsworthy et al., 2002).

The fastest extension in these zones occurs in the Corinth Rift, a ∼130 km long × 30 km wide high strain zone that crosscuts almost perpendicular the NNW–SSE Hellenides thrust belt that forms the pre-rift basement (Doutsos et al., 1993). The currently active part of the Rift is below sea level, forming the Gulf of Corinth that separates central continental Greece to the north from the Peloponnese to the south (Fig. 1). The start of extension and rifting has been estimated to be in the Pliocene (∼5 Myr) (e.g., Armijo et al., 1996 and references therein). Throughout the Rift's history, active faulting has experienced several spatiotemporal changes, forming the present complex basin structure (Bell et al., 2009; Taylor et al., 2011). Active deformation is accommodated by a S- and N-dipping en-echelon normal fault system of an E–W general direction (Armijo et al., 1996) (Fig. 1). N-dipping faults dominate and uplift the south coast of the Gulf (Fig. 2c), however offshore seismic studies have revealed that S-dipping faults once dominated structure in some parts of the Rift (Bell et al., 2009). The Rift presents high earthquake activity, with several earthquakes of magnitude greater than 6 reported in both historic and instrumental records (Papazachos and Papazachou, 1997). Most of the computed focal mechanisms for both strong events and microearthquakes are in agreement with geodetic data and fault geometry, indicating normal faulting associated with N–S extension (Rigo et al., 1996; Hatzfeld et al., 2000).

2.2. Short and long-term strain rates in the Rift

Quaternary geology, geodetic strain rates and the earthquake activity indicate that the currently active Rift zone is confined in the narrow offshore zone of the Gulf of Corinth, extending to the east to the Alkyonides Gulf and the Perachora Peninsula (e.g., Hatzfeld et al., 2000; Briole et al., 2000; Roberts et al., 2009; Leeder et al., 2012) (area covered with faults in red in Fig. 1). Geodetic strain rates measured by Global Positioning System (GPS) data show highest rates of extension (>15 mm/yr) in a narrow zone 10–15 km wide in the west offshore part of the Rift in the area west of Aigion (Fig. 2b). GPS measured strain rates decrease gradually to the east to <5–10 mm/yr (Clarke et al., 1998; Briole et al., 2000) (Fig. 2b).

The current configuration of active faulting has been established during the Late Quaternary, between ∼0.2–0.7 Myr and present (Bell et al., 2009; Roberts et al., 2009; Leeder et al., 2012; Ford et al., 2013). The localization of active faulting offshore and along the south coast of the Gulf is evident from the footwall uplift of the syn-rift sequences of Pliocene–Quaternary sediments that are preserved in the northern Peloponnese (Armijo et al., 1996) (Fig. 1), in the hanging-walls of the normal fault system further south, that at present seems inactive (e.g., Rohais et al., 2007). This indicates that the deforming zone has been wider in the early