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Flexing is not stretching: An analogue study of flexure-induced fault populations

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Abstract

Flexure-induced fractures are predicted to form along the axis of maximum tensile stress within a bending brittle plate. The mechanics of this process differ from extensional fault growth in response to lithosphere stretching, where a distributed set of simultaneously growing fractures evolves through elastic interaction. To simulate extensional fault growth during lithospheric flexure, partially solidified plaster layers resting on a foam rubber substrate were depressed by a linear load and fractured in analogue models. The length- and spacing-frequency distributions of the resulting crack populations were analyzed for a series of nine thin (5 mm) and ten thick (15 mm) layer experiments. Previous analogue stretching models predict power-law length-frequency distributions and clustered spacings ($C_v > 1$) at low strains (<~ 10%), evolving toward an exponential distribution and more regular spacings ($C_v < 1$, often termed anticlusted) at larger stains. Crack populations formed at low strains during these bending experiments, however, exhibit length-frequency distributions that are not well described by either a power-law or exponential distribution model, being somewhat better fit by the exponential model in the thin layer experiments and somewhat better fit by the power-law model in the thick layer experiments. One-dimensional spacing-frequency distributions are well described by an exponential distribution model, and crack spacing can be characterized as anticlustered within both the thin and thick layer experiments. Although similar spacing patterns may develop when fracture growth is limited by mechanical layer thickness, the characteristic spacing does not scale with the layer thickness in these flexural experiments. Alternatively, the development of power-law (fractal) populations may be inhibited by the growth history of flexure-induced faults, whereby nucleation is localized spatially due to the distribution of stresses within bending plate. These analogue experiments may be relevant to the outer-rise regions of subduction zones, where the oceanic plate is flexed downward, and the abyssal flanks adjacent to fast-spreading mid-ocean ridge crests, where recent models for axial high development suggest that the plate is unbent as it rafts away from the axis.

Keywords: extensional faulting; mid-ocean ridges; subduction; analogue models; lithosphere flexure; outer-rise

1. Introduction

Extensional fault systems formed in association with the bending of an oceanic plate during subduction (e.g. [1]) or the unbending of the newly accreted lithosphere

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along a fast-spreading mid-ocean ridge crest (e.g. [2–5]) provide critical pathways for fluid circulation and mantle serpentinization. These processes alter the composition and rheological properties of oceanic lithosphere and ultimately impact many geochemical and mechanical aspects of the subduction and mid-ocean ridge systems [6]. Their influence may be most pronounced in the former environment, where the distribution of intermediate depth earthquakes (e.g. [7,8]), the strength of the bending plate (e.g. [9,10]) and the character of arc volcanism (e.g. [11]) are linked to metamorphism within the down going slab. Moreover, flexure-related outer-rise earthquakes may play an important role in transferring stress to the subduction interface [12] or in triggering devastating tsunami events [13]. The geometry and mechanics of flexure-induced fault populations therefore are topics of broad interest in the earth-science community and may have implications for earth-hazards research in subduction zone settings.

During the last decade, great effort has been expended to statistically characterize populations of extensional faults exposed in regions subjected to lithospheric stretching. In these settings, power-law distributions of fault size s (length, throw, or spacing) versus frequency are observed commonly [14,15], with the total number of faults $N(s)$ having size $\geq s$ expressed as:

$$N(s) = as^{-D} \tag{1}$$

where D is known as the power-law exponent and the constant a reflects the total number of faults. Analogue and numerical experiments of extensional fault growth have confirmed the development of a power-law fault population at low strains (e.g. [16–18]). Such scaling implies a spatial correlation between faults, with each fault interacting elastically with its neighbors [19]. Since power-law distributions exhibit a self-similar geometry with no characteristic length scale, they allow for prediction at scales smaller than those observed—a potentially powerful tool in fluid flow modeling and other applications (e.g. [20,21]).

The experiments described in this paper are designed as potential analogues for lithospheric flexure induced by vertical line loads. Although stretching- and flexing-induced normal faults may exhibit many similar traits, flexure differs fundamentally from stretching in that fault nucleation is concentrated along lines of maximum bending stress aligned parallel to and at a characteristic distance from the applied load (Fig. 1). We hypothesize that this condition may suppress the development of power-law fault size distributions, creating a fault population that exhibits a fundamentally different geometry than commonly observed in extensional stretching regimes. We are motivated largely by the need to understand fault development in two difficult to study submarine environments, the unbending abyssal flank regions at fast-spreading ridges (e.g. [2]) and the flexing outer-rise regions of subduction zones (e.g. [1]).

Abyssal hill faults on the flanks of fast-spreading mid-ocean ridges have long been thought to be the product of tectonic stretching of brittle lithosphere [22,23]. A more recent view, however, is that faults flanking axial highs are formed during the unbending of lithosphere as it

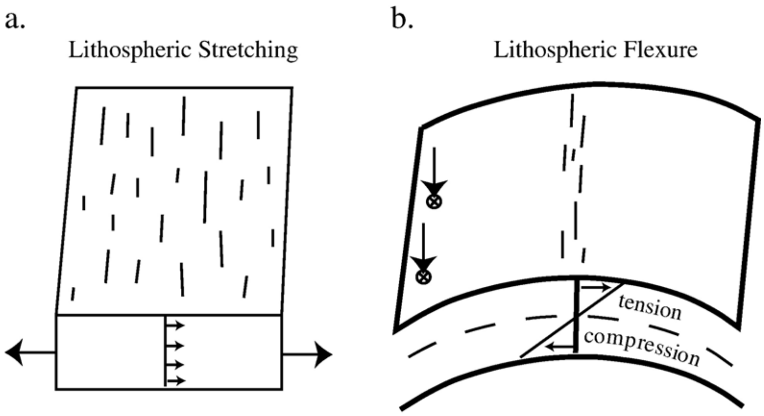

Fig. 1. Cartoon illustrating extensional fault growth in regions undergoing: a) Lithospheric stretching. The extensional component of stress is constant with depth. Faults nucleate over a broad region, and elastic interactions give rise to a power-law fault distribution. b) Lithospheric flexure. The extensional component of stress is depth dependent, with a maximum in tension at the surface and compression at greater depth. Faults preferentially nucleate and localize along lines of maximum bending stress—fundamentally different from lithospheric stretching.