Tectonophysics 608 (2013) 530–544

Contents lists available at ScienceDirect

Tectonophysics

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

Anisotropy of fractal dimension of normal faults in northern Rocky Mountains: Implications for the kinematics of Cenozoic extension and Yellowstone hotspot's thermal expansion

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ARTICLE INFO

Article history:
Received 31 March 2013
Received in revised form 20 August 2013
Accepted 22 August 2013
Available online 30 August 2013

Keywords:
Basin and Range
Yellowstone hotspot
Cenozoic normal faulting
Anisotropy of fractal dimensions
Southwest Montana
Snake River Plain

ABSTRACT

The Basin and Range fault blocks, which were formed by an extensional event around 17 Ma, have continuously been deforming by younger, diachronous system of cross normal faults in southwest Montana and southeastern Idaho since 16.6 Ma. Reactivation of these two mid-Tertiary–Quaternary systems of normal faults, and two older, approximately N–S and E–W sets of regional normal faults, has evolved into a seismically active block faulted terrain. For both fault systems, high fractal dimensions occur in areas characterized by a large number of fault traces, high fault trace linear density, and maximum fault trace azimuthal variation. The major axis of the anisotropy ellipse of the fractal dimensions for each set of the two normal fault systems is sub-perpendicular to the linear directional mean of the faults, and gives an estimate for the direction of extension.

Indentations on the point distribution on the anisotropy ellipse of fractal dimensions indicate heterogeneities due to the presence of several fault sets and/or variation in their trend. Domains in which there is only one set of faults produce smooth, well-defined fractal anisotropy ellipses with no indentations. The axial ratio of the anisotropy ellipse provides a measure for the range of variation in the trend of the faults. The trace length, linear density, and fractal dimension of the cross normal faults, decrease, in a direction across and away from the Snake River Plain (SRP), suggesting a diminishing effect of faulting probably due to the attenuation of the Yellowstone hotspot-related thermal doming with distance from centers of eruption. The spatio-temporal distribution of the trajectories of the minor axes of the anisotropy ellipses of fractal dimensions and the linear directional mean of the cross faults define a set of asymmetric, sub-parabolic spatio-temporal pattern about the axis of the SRP, with their apices located on diachronous centers of eruption.

1. Introduction

The spatio-temporal distribution and orientation of Cenozoic normal fault systems in the northern Rocky Mountains around the Snake River Plain (SRP), in Idaho, Montana, and Wyoming, reflect a complex history of continuous deformation that started in Proterozoic and culminated in mid-Tertiary. Two major extensional events have occurred over the past 17 Ma, following the Cretaceous–Eocene Sevier–Laramide contractional event: (1) mid-Miocene Basin and Range block faulting that deformed the North American plate into large-scale horsts and grabens, and (2) diachronous normal faulting that intermittently cross faulted the Basin and Range fault blocks at high angles, apparently as the plate migrated over the Yellowstone hotspot (YHS) (Anders et al., 1989; Janecke, 2007; Janecke et al., 1998; Payne et al, 2012; Sears and Thomas, 2007; Westaway, 1994; Whitchurch and Gupta, 2007).

The reactivation of the Basin and Range (BR) and the cross fault (CF) systems defines the seismicity of a large area between northern Nevada and the present-day location of the Yellowstone hotspot (YHS) in the Wyoming–Montana area. The initiation, propagation, and reactivation of these two generations of Tertiary–Quaternary normal faults, as well as the older Late Cretaceous Laramide reverse faults, may have been locally controlled by older sets of basement normal faults that formed during at least two Proterozoic extensional events (e.g., Constenius, 1996; Giorgis et al., 2008; Janecke et al., 2001; Lowell, 1965; M'Gonigle, 1993; M'Gonigle and Hait, 1997; M'Gonigle et al., 1991; Royse et al., 1975; M'Gonigle, 1994). For example, the NE striking normal faults in southwest Montana are believed to be reactivated Laramide reverse faults, which themselves parallel Precambrian basement faults (Carney and Janecke, 2002; Janecke et al., 2000a, 2000b; Schmidt et al., 1994). NNW- to NW-striking Precambrian dikes and deformational fabrics also parallel cross normal faults in this area, for example in Ruby Mountain (Lowell, 1965; M'Gonigle, 1993; M'Gonigle and Hait, 1997; M'Gonigle et al., 1991). There are at least two other, probably Precambrian, sets of regional faults that strike approximately N–S and E–W in Idaho and SW Montana.

The spatio-temporal variation in the orientation of the cross fault system and the mechanics of its interaction with the mid-Tertiary

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0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.08.031

Basin and Range, Cretaceous Sevier–Laramide, and Precambrian faults are not well understood. Moreover, the distribution, pattern, and variability of the orientation, length, and density of the cross faults relative to the diachronous hotspot eruptive centers along the Snake River Plane are not well established. In this paper, we study the distribution and anisotropy of the fractal dimension of the traces of the two Tertiary–Quaternary normal fault systems in space and time, and investigate their kinematic and tectonic significance for normal faulting in the area around the SRP in Idaho and southwest Montana. The variations in the characteristics of the cross normal faults, such as anisotropy of fractal dimension, density, and orientation, are put in the context of the migration of the Yellowstone hotspot along the Snake River Plain, and the ensuing normal faulting due to the intermittent thermal bulging and subsidence.

2. Regional setting

The oldest exposed rocks in southwest Montana and central and southern Idaho are Archean to earliest Proterozoic gneiss and metasedimentary rocks. These basement rocks may extend beneath the thick sequence of Precambrian siliciclastic rocks of the Belt basin near the Idaho–Montana border that formed from 1450 to 1400 Ma (Foster et al., 2006; Janecke, 2007). Rifting of western North America began in the latest Proterozoic (Janecke, 2007; Karlstrom, 1999; Moores, 1991; Sears and Price, 2000). During Neoproterozoic to Ordovician time, cratonal to miogeoclinal sedimentary sequences were deposited in southwestern Montana and eastern Idaho. The Sevier thin-skinned contractional event in southwest Montana, which occurred east of the Cretaceous Idaho batholith and Bitterroot Mountains, deformed the Paleozoic and Mesozoic units into folds and thrusts, and displaced them to the northeast. During the Sevier orogeny, some SW-dipping normal faults may also have locally formed along with thrust faults (Chase et al., 1983; Janecke, 2007; Tysdal, 2002). The western part of the Sevier fold-and-thrust belt was intruded by the Idaho batholith in the Late Cretaceous (Janecke, 2007; Janecke et al., 2000a, 2000b; Skipp, 1988; Tysdal, 2002).

The contractional Sevier–Laramide orogeny ended in early Tertiary (Paleogene) and was followed by the earliest extensional event which began about 50–45 Ma before the onset of Challis volcanism (McDowell, 1992; Tysdal, 1996, 2002; Tysdal and Moye, 1996). The extension continues to the present (Janecke, 1993; Janecke, 2007; Janecke et al., 1999, 2001; Sears and Fritz, 1998; VanDenburg et al., 1998). The main, large scale continental Basin and Range extension, which occurred during late Eocene to early Miocene in the area between Salmon in eastern Idaho and Dillon in SW Montana (Janecke, 2007; Janecke et al., 2001; Silverberg, 1990), led to the formation of large horsts and full and half grabens (Anders et al., 1989; Anders and Sleep, 1992; Sears and Thomas, 2007; Whitchurch and Gupta, 2007). The extension shaped the existing NW- and NE-striking BR block-faulted mountain ranges in Idaho and southwest Montana, respectively (DuBois, 1983; Pardee, 1950; Reynolds et al., 2002). The amount of extension for these normal fault sets gradually diminishes eastward to the eastern edge of the study area. Some of these high-angle faults, especially in east-central Idaho, are still seismically active (Burchfiel and Davis, 1975; Dorobek et al., 1991). The spatial variation in the orientation of the principal strains and heterogeneity and anisotropy due to distribution of different rock types and structures, which were developed during the earlier Sevier–Laramide orogeny, led to regional variation in the orientation of the Basin and Range fault blocks (Hait and M'Gonigle, 1988; Janecke, 2007; McBride, 1988; Perry et al., 1988).

The Yellowstone hotspot was initiated by a mantle plume about 16.6 Ma near the Nevada–Oregon–Idaho border (Morgan et al., 1998; Pierce and Morgan, 1992a, 1992b, 2009). The eruptive centers of the YHS relatively migrated northeast because of the southwesterly movement of the North American plate above the fixed plume. The hotspot was at the American Falls in Idaho about 10 Ma and at the Yellowstone National Park (YNP) area around 2 Ma (Fritz and Thomas, 2011; Janecke, 2007; Sears et al, 2009; Shervais et al., 2006; Smith et al., 2007) (Fig. 1). The track of the migration of the YHS is defined by the presence of an elongate, NE-trending silicic volcanic belt along the SRP (Smith, 2000) and prominent volcanic calderas which become younger toward the present location of the YHS (Fritz and Thomas, 2011; Payne et al., 2012) (Fig. 1). The Eastern Snake River Plain (ESRP) was formed by basalt erupting from large shield volcanoes in Idaho about 13 Ma (Alt and Hyndman, 2009; Good and Pierce, 2010; Hamilton, 1960; Hamilton and Myers, 1966; Janecke, 2007; Kirkham, 2002; McQuarrie and Rodgers, 1998; Myers and Hamilton, 1964). The ESRP depression formed due to subsidence as the YHS migrated away from the centers of thermal expansion (i.e., calderas), and was filled with 1.7 to 3.1 km of volcanic rocks since 8.0 to 8.5 Ma. Volcanism mostly became caldera-forming before10 Ma (Pierce and Morgan, 1992a, 1992b; Rodgers et al., 2002; Xue and Allen, 2006, 2010).

The plume head, about 300 km in diameter, which probably was spread out at the base of the North American plate as it moved, led to a series of spatio-temporally variable extensional events that deformed the already block-faulted crust adjacent to the SRP in the Neogene time (Sears and Thomas, 2007). Over the past 17 million years, this latest, diachronous extensional deformation has formed a system of new full and half grabens and normal faults across the older BR fault blocks. The latest cross faulting is believed to be due to thermal uplift and subsequent subsidence as the North American plate migrated southwest away from the hotspot along the SRP, between northern Nevada and the present-day location of the YHS in Wyoming (Beranek et al., 2006; Dixon, 1982; Eaton, 1982; Pierce and Morgan, 1992a, 1992b; Royse et al., 1975; Sears and Thomas, 2007; Sears et al., 2009; Shiley, 2002; Stewart, 1971; Zoback and Thompson, 1978). It is likely that the intermittent, thermally-induced series of extensional events that formed the cross faults also reactivated the existing Precambrian, Sevier–Laramide, and Basin and Range faults.

The active normal faults with highest Quaternary displacement rates, and small- to moderate-magnitude earthquakes in the Idaho and northern intermountain seismic belts, are distributed in a parabolic pattern about the axis of the eastern SRP, with its apex at the Yellowstone plateau (Anders and Sleep, 1992; Anders et al., 1989; Pierce and Morgan, 1992a, 1992b; Pierce and Morgan, 2009; Smith and Braile, 1993; Smith et al., 2009). It is not known if the temporally variable sets of cross normal faults formed in a domal, ellipsoidal, or irregular pattern around the centers of eruption along the SRP, possibly due to thermally-induced, expansion–subsidence, as the YHS migrated northeast. In this paper, we investigate this problem by analyzing the distribution of the orientation, anisotropy of fractal dimension, and extension direction of each set of cross normal faults in time and space, and in relation to the trend of the Eastern Snake River Plain (ESRP) and centers of eruption.

3. Fractal geometry

In contrast to the continuous, linear, and smooth mathematical objects, natural objects, such as clouds, badland topography, river systems, mountain ranges, and fault systems are complex in shape and, as a consequence, their fine structure cannot be described by standard statistical methods or measured by Euclidian geometry (Barnett, 2004; Hassan and Kurths, 2002; Mandelbrot, 1977). Such complex one, two, or three-dimensional objects have infinite detail with a statistical self-similar or self-affine structure that occurs over a large but finite scale (Mandelbrot, 1977, 1982; Parkinson, 2002). Self-similarity means that small parts (e.g., a small fault segment) of the fractal object (fault) are similar to its larger parts (longer fault segment), which in turn are similar to the whole object (the fault itself) (Barnett, 2004; Hassan and Kurths, 2002; Hirata, 1989; La Pointe, 1988; Ozer and Ceylan, 2012). Mandelbrot (1975) referred to these complex, self-similar objects that possess an irregular and/or fragmented form, as 'fractal', and introduced the fractal dimension (D) as a measure of their 'fractality'. Because