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Crater–fault interactions: A metric for dating fault zones on planetary surfaces

Matthew R. Smith *, Alan R. Gillespie, David R. Montgomery, J. Batbaatar

Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195-1310, United States of America

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ABSTRACT

Constructing a tectonic history of a planetary surface requires determining precise fault ages, a task not always possible with current analytical methods. Here we introduce a new method to constrain the ages of faults, improving upon earlier methods that used cross-cutting relationships with crater-dated host surfaces, and apply it to faulted terrains by counting all craters and categorizing them into "faulted," "unfaulted" and "unclear" types to date deformation directly. Additionally, we construct a simple probabilistic model to account for regions of low fault density. This new technique is applied to the tectonically complex Thaumasia plateau, Mars, to assess the timing of regional faulting and demonstrate its usefulness and ease of application.

1. Introduction

Previous studies that have dated faulting events on planetary surfaces have relied on the geologic principle of cross-cutting relationships to constrain their range of possible ages (e.g. Wise et al., 1979, Plescia and Saunders, 1982; Dohm and Tanaka, 1999). Surfaces that are cut by faults must be older than the faults they host; if a fault encounters a surface and does not cut it, the surface age must be younger than the fault. The ages of the fault-adjacent surfaces may be determined through crater densities, from which a range of possible ages for the faulting event may be deduced. This technique has been employed successfully but requires two conditions for precise age estimates: the fault must encounter surfaces both older and younger than the faulting, and the difference in age between the two surfaces must be small. If either condition is not met, the precision of the age determination for that fault is reduced commensurately.

A technique to improve precision was devised by Tanaka (1982) based on the interaction between the age of a linear feature, or sets of linear features – such as faults, ridges, and channels – and the craters they cross. An area enveloping the linear feature is surveyed for crater density and crater–feature relationships. If the linear feature does not affect a crater, it is assumed to predate the crater. If it cuts through the crater, the crater is assumed to have formed first. The population of craters which post-date the feature can then be used to date its formation directly. This technique has been previously employed by Wichman and Schultz (1986) to study coarse-scale martian extensional tectonics and has been recently used by Fassett and Head (2008) to determine the age of martian valley networks. However, applications of this method are restricted to areas with low densities of linear features, since high densities result in overlapping survey areas between adjacent features and time-intensive surveys of several individual features.

A variation on this technique was also described by Mangold et al. (2000), which studied the interaction between craters and compressional ridges. They determined the range of ages of faulting events by counting craters not located on faults – meaning they have no relationship to the deformation – and used them to determine the upper age limit for deformation. The lower age constraint was still provided by an adjacent surface which must bury a portion of the ridge, thereby post-dating its formation.

The purpose of this paper is to extend earlier techniques to areas with high densities of linear features. We achieve this by counting all craters over a surface and categorizing them according to their relationship to the features being studied. Throughout this article, we will discuss this new technique mainly in the context of extensional fault zones, these being common high-density linear features on planetary surfaces, but this technique may also be applied to other linear features, such as dense valley networks and dike swarms. In the absence of high fault densities, we have also devised a simple probabilistic model to be applied to crater counts to compensate for

* Corresponding author. Tel.: +1 206 543 4914.
E-mail address: matthers@u.washington.edu (M.R. Smith).

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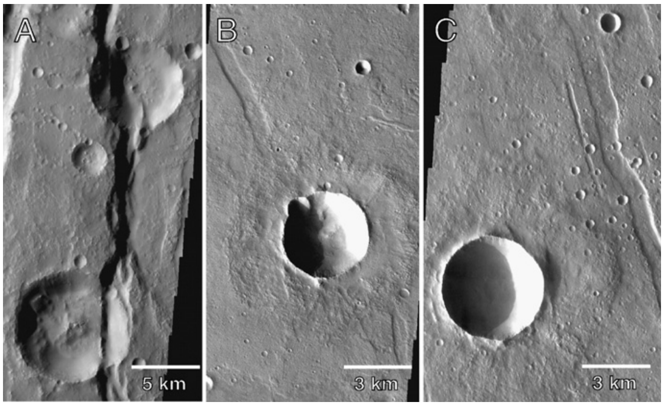

Fig. 1. Examples of crater–fault relationships. A) Craters cut by faults (V09928003); B) large crater superposing faults (V15344003). Pre-existing grabens can be seen draped by the crater ejecta; C) crater not directly on a fault, with unclear age relationship with faulting (V14820005).

few craters interacting with faults. We thus determine deformation ages for surfaces with a wide range of densities of surface features.

2. Technique

To assess the age of the faulting, we count craters on the entire faulted surface, separating the crater population into those that superpose and post-date the faults and those that are cut by them (Fig. 1). If a crater is not located on a fault, it is classified into a third category of unknown age relationship. The unfaulted crater population by itself provides the lower bound on the age determination; the combined unfaulted and unclear crater populations provide the corresponding upper bound. Fault interactions with ejecta blankets are not considered in this study, since whether ejecta are cut by or drape a fault is not easily determined in satellite images. A MOLA topographic cross-section across an ejecta-draped fault may reveal diagnostic subdued topography but is not necessarily conclusive, since MOLA footprints are often too large for narrow faults. A threshold minimum diameter for counted craters should be chosen, proportional to the average spacing of faults in order to increase the likelihood that all counted craters will encounter a fault. For regions of lower fault densities, a correction is applied as described in Section 2.1.

The population of craters that post-date fault formation is then compared to the crater-defined stratigraphic time-units as established by Tanaka (1986) to assess relative age. Numeric ages are estimated by comparing binned counts to lunar-derived isochrons, as described by Hartmann (2005). By isolating those craters which encounter faults but are unfaulted – indicating that they have formed after faulting terminated – we can calculate the amount of time passed since the cessation of faulting. The advantage of this technique is direct dating of the deformation age with crater statistics, rather than surface ages.

2.1. Data correction for low fault density

Surfaces with low fault densities make comprehensive crater counting more difficult, since a large fraction of small craters lie between the widely spaced faults, reducing the number of craters that help to constrain the timing of faulting. We have therefore constructed a simple probabilistic model to estimate the population of craters that would have had the opportunity to be faulted, had faults been more closely spaced, so that we may apply that estimate to adjust the crater counts.

The probability, P, of a single N–S trending fault, cutting through a defined survey area of size $L \times L$ that contains a single crater of diameter D and not encountering it is given as:

$$P(D) = \frac{L-D}{L}. \tag{1}$$

To define the probability P_U that the same crater is missed by all faults that cut through the same area, we must include a term, as an exponent, for the number of faults, F:

$$P_U(D) = \left(\frac{L-D}{L}\right)^F. \tag{2}$$

Therefore, the probability P_F of a single crater being faulted from a given number of parallel faults cutting through our survey area is given by:

$$P_F(D) = 1 - \left(\frac{L-D}{L}\right)^F. \tag{3}$$

The average number of faults, F, may be estimated by calculating the net fault length within a sample area and dividing it by the surveyed area to determine a number of faults per unit area. The measured crater abundances in a target area may then be divided by $P_F(D)$ to correct for the unlikelihood of a crater within a given diameter range to encounter a fault and contribute to our measurements.

3. Application: Thaumasia plateau, Mars

As a case study, we applied our technique to the Thaumasia plateau, a region with a complex faulting history. There are several heavily deformed regions that form the edges of the plateau and display a dense network of extensional faults, and areas to the south of the plateau which exhibit less dense faulting and can serve as an application of our correction for low fault densities.

3.1. Context

The Thaumasia plateau is a volcano-tectonic province located southeast of the Tharsis volcanic complex (Fig. 2). It records a tectonically active past, with several heavily faulted areas resulting from different regional stress regimes (Dohm and Tanaka, 1999). Compressional strain along the Thaumasia highlands and the Coprates rise formed a large (~1–2 km high) frontal bulge and thrust faults that border the plateau (Schultz and Tanaka, 1994). Additional minor compression is expressed in concentric wrinkle ridges oriented circumferentially to Syria Planum. These ridges occur throughout the interior of the plateau and deform Hesperian lava flows. Widespread extension is expressed in the extensive and densely packed N–S transtensional grabens in Claritas Fossae, with fewer grabens located within the Thaumasia highlands and Melas Fossae, and also in Thaumasia Fossae. Extensional faults cut through mostly Noachian-aged rocks with some minor exposures of Hesperian-aged rock units in Claritas Fossae and the Thaumasia highlands (Dohm and Tanaka, 1999). The northern border of the plateau, Valles Marineris, originated as an area of extensional strain before being subsequently widened by an array of proposed mechanisms.

The formation of the regional grabens, some of which are oriented radially to volcanic centers within the Tharsis complex, has previously been interpreted as a result of volcanic loading (e.g. Solomon and Head, 1982), Tharsis uplift (e.g. Carr, 1973; Wise et al., 1979), or some combination of both (e.g. Banerdt et al., 1982). Alternatively, Montgomery et al. (2009) recently proposed that the tectonic history of the Thaumasia plateau suggests its evolution as a gravity slide and