A METHOD FOR VISUALIZING THE STRUCTURAL EVOLUTION OF TEMPE TERRA, MARS. C. J. Orlov[1], E. K. Bramham[1], M. Thomas[1], P. K. Byrne[2], E. Mortimer[1] and S. Piazolo[1], [1]School of Earth and Environment, University of Leeds, UK (eecjo@leeds.ac.uk), [2]Department of Earth and Planetary Sciences, Washington University in St. Louis, USA.

Introduction: Investigating the structural evolution of a planetary surface is a foundational task in understanding that world's geological history. Determining both local chronology and planet-wide evolution requires us to understand the timing and relationship of events in that history. Just as maps are important for visualizing spatial variations in geological data, we need ways to visualize temporal variations. A timeline is a simple and useful tool for visualizing and communicating structural activity through time, that can support structural interpretation, make identifying patterns easier, and allow for comparison with models of regional-scale evolution. Additional classification elements, such as inferred sources of stress, types of structure, stress orientations, or scales of activity can add value to a standard timeline layout and further aid interpretation.

We recently undertook detailed mapping of faults in the Tempe Terra region of Mars, separating structures into twenty fault sets, with the aim of understanding how the fault system in Tempe Terra evolved through time and placing this evolution into context with the development of the Tharsis Rise volcanotectonic complex generally. To help achieve this goal, we created a timeline of the fault-related deformation history of Tempe Terra by placing all fault sets into relative order on the basis of absolute model ages of the geological units they cross-cut, as well as separating sets based on their being regional or local in scale. We present here the combination of qualitative and quantitative methods we used in the development of this timeline of structural evolution.

Age Determination Methods: The primary elements required for placing fault sets into a structural timeline are an age classification, either as an epoch (e.g., Middle Noachian) or absolute model age (e.g., 3.8 Ga), and the relative age of the structures.

Stratigraphic method. We established maximum ages for fault sets based on stratigraphic principles. That is, that a fault must be younger than the geological unit (or units) it intersects, and cross-cutting relationships between sets of faults, or between faults and other features, can be used to determine their relative order. Superposition relationships with the geological units of Tanaka et al. (2014) [1] provided a starting point, but were not detailed enough on their own for the complexity of faulting in Tempe Terra. We therefore used an approach similar to Scott and Dohm (1990) [2], where cross-cutting relations, fault morphology, and continuity of fault trends were also considered. When we established that a fault system is continuous across a geological boundary and the faults have consistent morphology and trend, indicating they formed in a similar time and stress field, they were grouped together and given the youngest age of the units crossed.

To establish initial relative ages, we utilized available high-resolution images to examine cross-cutting relationships between fault sets. However, in some cases determining cross-cutting relationships can be difficult, particularly for non-intersecting sets of faults, and the possibility of fault reactivation can further complicate our efforts to arrive at an internally consistent sequence of deformation.

Buffered crater counting method. To further refine the relative ages of fault sets, we determined an absolute model age for each set with the buffered crater counting (BCC) method [3, 4]. This technique allows model ages to be determined directly for linear features such as faults that are otherwise unsuited to traditional crater counting methods [4].

We used the crater catalog of Lagain et al. (2021) [5] and determined the age relationship of craters to faults through examination of high-resolution CTX (Context Camera) images [6]. Crater size–frequency distributions from BCC analysis were calculated with the *CSFD Tools* application [7], followed by statistical analysis of these data with the *Craterstats* software [8]. To determine absolute model ages we used the same system as that employed by Tanaka et al. (2014) [1] to allow for consistent comparison with stratigraphic ages. This approach utilizes the chronology function of Hartmann and Neukum (2001) [9] and the production function of Ivanov (2001) [10].

Statistical age uncertainties for BCC are the same as for other crater counting techniques [8], but as with cross-cutting relationships, BCC ages are also sensitive to fault reactivation [4]. Ages therefore represent the end of formation or reactivation of the fault sets [4].

Example Findings: Here, we illustrate an example of how we use cross-cutting relationships to establish timing by examining both the interactions between fault sets and the units that those fault sets deform. In Figure 1, fault set A2 is continuous across both the Early Hesperian (EH) and Amazonian–Hesperian (AH) unit, whereas the other five sets stop at the EH unit boundary and are buried by the AH unit. We can therefore establish that faults in set A2 are AH in age and are the youngest of those shown, whereas the other fault sets are EH. To then determine the relative age of these EH sets, we must consider their relative cross-cutting relations. Within the region shown in Figure 1, the younger set H10 cuts across older sets H6 and H9, yet set H6 cuts across set H4, such that H4 is the oldest and H10 the youngest of the these EH fault sets.

Regional Vs. Local Classification: Once the individual populations of faults were defined, it became clear there were qualitative differences in the scale of tectonic activity between them, so we looked to develop quantitative criteria to help differentiate regional fault sets from local sets. This classification was aimed at identifying structures that likely reflect local tectonic events and local sources of stress, versus regionally important events and stress regimes with implications for the wider Tharsis area. Being able to separate these groups on the structural evolution timeline allows for clearer identification of regional trends, providing a simplified way of visualizing the scale and source of tectonic activity through time.

Qualitative definition. We initially made qualitative groupings of fault sets based on investigation of the visual scale of each set relative to the size of the study area, the extent of the total fault system, and the relative scale of other sets. This process is therefore subjective as it is based on familiarity with the geological region of interest.

Quantitative definition. To develop a quantitative definition of regional and local sets, we analyzed fault set properties as a function of scale to search for any clustering in the data. We compiled the cumulative length of all faults within a given set and calculated that set's minimum bounding area—representing the size of the smallest polygon that encapsulates all faults within that set. All values were then plotted, with the clustering of the sets then used to establish cut-off values as criteria for the regional and local definitions (Figure 2). We thus considered a set as regional if it has a cumulative length >10,000 km and a minimum bounding area >100,000 km^2, criteria that resulted in four regional sets. Normalizing cumulative length to the area of exposed geological units of a given age returns the same result. Although these criteria are driven by observed separation in the data, it is worth noting there is still an interpretive element.

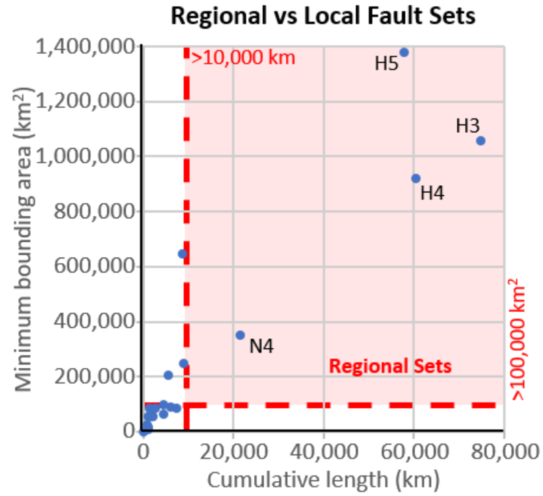

Figure 2: *Graph of cumulative length by minimum bounding area used for classifying fault sets as regional or local in scale. Red dashed lines indicate cut-off values as criteria for the regional fault set definition. Regional faults sets are labelled with their name (e.g., H1, N4).*

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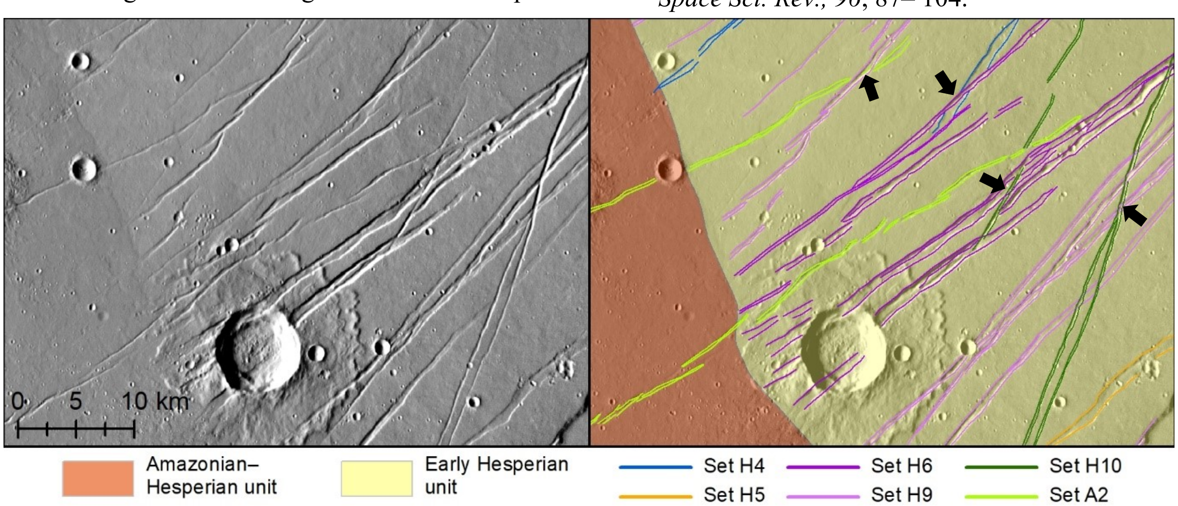

Figure 1: *An example of cross-cutting relationships between different fault sets and geological units (taken from [1]) in southwest Tempe Terra. The first panel shows uninterpreted THEMIS infrared daytime mosaic. The second panel shows geological units and interpreted fault sets, with cross-cutting locations marked by arrows.*