**CONSTRAINTS ON THE LARGEST MARSQUAKE**

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A recent estimate of martian seismicity through time has been made from the observed surface faulting on Mars (1), based on the definition of seismic moment, $M_o = \mu S A_f$, where $\mu$ is uniform rigidity and S is average slip over fault area $A_f$. In this study, information on the extent and history of faulting on Mars was compiled to estimate the total moment release per year, which was then apportioned into different sized events based on likely moment-frequency relationships. One of the critical parameters needed to estimate the frequency of marsquakes is the size of the largest event. In this abstract, a number of arguments are made beyond those in Golombek et al. (1) that better constrain the largest marsquake. These arguments suggest the largest marsquake likely is limited to seismic moment of order $10^{27}$ dyne-cm, which is roughly equivalent to a body-wave magnitude 7 event on Earth (2); events larger than this are unlikely without subduction or plate tectonics. As in the earlier paper, the size of an event will be discussed primarily in terms of seismic moment, which is a more fundamental measure of seismic energy release than magnitude, and can be compared between planets without concern for specific seismic wave propagation characteristics or seismometer response.

The seismic events on Earth most likely to be analogous to events on Mars are intraplate oceanic earthquakes (2). These events make up a class of earthquakes that are due to lithospheric cooling and are relatively free from plate boundary effects. The largest intraplate oceanic earthquake since 1977 is under $10^{27}$ dyne-cm (actually $5.4 \times 10^{26}$ dyne-cm, 3), excluding the Chagos Bank earthquake ($1.8 \times 10^{27}$ dyne-cm), which is believed to have occurred on a diffuse plate boundary (4). As a result, Golombek et al. (1) assumed the largest marsquake was $10^{26.5}$ dyne-cm. Note that even if the Chagos Bank event were included as an intraplate event the maximum moment would be limited to less than $2 \times 10^{27}$ dyne-cm.

On Earth, seismic events of a particular moment typically have a limited range of fault areas and slips. Earthquakes of moment $10^{27}$ dyne-cm typically involve fault areas of a few hundred to a few thousand km$^2$ and slips of 1-10 m, for the nominal $\mu$ of $3 \times 10^{11}$ dyne/cm$^2$. As examples, slip of 1 m on a fault a few hundred km long by 10 km wide would produce a $10^{27}$ dyne-cm moment event as would slip of 10 m on a fault a few tens of km long by 10 km wide. To further quantify these types of characteristics, earthquakes with well documented fault length (from field observations of surface breaks), width (from hypocenter distributions), slip (from field and geodetic observations of surface breaks) and moment (from waveform analysis) were extracted from the literature (these requirements purposefully excluded subduction related events). A couple of dozen examples show that in addition to the slip-area relationships just described, earthquakes with different focal mechanisms have different characteristic aspect ratios. Specifically, normal and thrust events typically occur on more equant shaped fault surfaces than strike-slip faults. Tabulation of about 8 normal fault earthquakes with well documented slip and fault plane information (5, 6, 7, 8) shows that they have an average aspect ratio of 2.3 (that is their fault length is on average 2.3 times greater than their width).

The size of a structure effectively limits the size of the quake that it could generate. Most grabens and wrinkle ridges on Mars are bounded by faults with widths that are <5 km (1). For fault rupture lengths of up to 10 km and slips of order 10 cm, the maximum moment event is $\sim 10^{24}$ dyne-cm. Larger grabens and faults bounding collapsed summit calderas of martian volcanoes probably extend up to 10 km deep (9 and refs. in 1). Fault rupture lengths of roughly 50 km with slip of about 50 cm could generate marquakes with moments of $\sim 10^{26}$ dyne-cm. Larger marsquakes require larger faults that cut the entire brittle lithosphere on Mars. Such faults bound rifts such as Valles Marineris and the Thaumasia rift on Mars (9). The brittle lithosphere on Mars has been estimated to be no more than 40 km thick based on assumed present-day heat flow and lithospheric strength envelopes (e.g., 9). For a normal fault with a width of about 40 km, the average length that would rupture during an individual marsquake is roughly 100 km, assuming an average aspect ratio for normal fault earthquakes. Geologic mapping of Valles Marineris, which

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has been active over most of martian geologic time, also indicates characteristic individual normal fault strands at the base of canyon wall scarps of about 100 km length (10). Slip of 1 m on a fault 100 km by 40 km would produce an event of moment $\sim 10^{27}$ dyne-cm. Slip of 10 m, which is possible for a fault of this size on Earth, would produce a moment release an order of magnitude greater than this (although a 40 km fault width is an upper limit). As a result, slip on large normal faults bounding canyons of Valles Marineris could reasonably be expected to generate marsquakes of moment $\sim 10^{27}$ dyne-cm.

Given that the largest marsquakes are generated on normal faults, a potential bound to such events on Mars could be the largest continental normal fault events on Earth. The largest continental normal earthquakes (excluding plate boundary or subduction-related plate bending events) release about $10^{27}$ dyne-cm (11). Among these is the particularly well documented 1959 Hebgen Lake, Montana (near Yellowstone) event (e.g., 5, 6). This event ruptured a 30 km long by 15 km wide fault plane, with a slip of about 10 m, for a moment release of $1\text{-}2 \times 10^{27}$ dyne-cm. Note that the Chagos Bank event that occurred in oceanic lithosphere, which is typically stronger than continental lithosphere (particularly when it is older than 10 Ma, 12), released about the same moment ($1.8 \times 10^{27}$ dyne-cm). These examples indicate that non-plate boundary normal fault events can be as large as about $2 \times 10^{27}$ dyne-cm, but not much larger.

The arguments discussed above suggest that the largest moment marsquake that could be generated is about $2 \times 10^{27}$ dyne-cm. This is the moment release of the largest intraplate oceanic earthquake as well as the largest intraplate continental normal fault earthquake. These two classes of earthquakes are relatively free of plate boundary effects and the oceanic events are primarily due to lithospheric cooling, both of which are likely attributes of the processes that generate marsquakes (2). Considerations of the largest faults on Mars, which bound Valles Marineris canyons, and typical aspect ratios and slips for normal events on Earth, also allow marsquakes of about this size. Using the moment-magnitude relationship derived earlier for purposes of illustration (1), suggests that an event of seismic moment $10^{27}$ dyne-cm is roughly equivalent to a body-wave magnitude 7 earthquake. This comparison and analysis clearly show that events equivalent to magnitude 8 or larger earthquakes, with moment release of order $10^{30}$ dyne-cm (which only occur between subducting plates on Earth, 11), are not possible on Mars. Subduction related events on Earth involve fault planes with widths of a few hundred km, lengths up to a thousand km and slips of 10-30 m, conditions that only can be met at subducting plate boundaries. For reference, note that large strike-slip events along transform faults on Earth only generate events of moment $\sim 10^{28}$ dyne-cm. It is interesting to note that an event of moment $10^{30}$ dyne-cm exceeds the total annual moment release of the Earth by 1 order of magnitude ($\sim 10^{29}$ dyne-cm/yr). The maximum moment release marquake derived herein ($10^{27}$ dyne-cm) exceeds our best estimate for the total annual moment release on Mars (1) by 2 orders of magnitude ($10^{25}$ dyne-cm/yr). Finally, if the largest moment release event on Mars is $10^{27}$ dyne-cm, then the recurrence interval for marsquakes is 1.6 times longer than estimated in Golombek et al. (1). The recurrence interval for $10^{27}$ dyne-cm moment events, using the same assumptions for the entire seismogenic lithosphere (1) is 112 years (note that the recurrence interval for $10^{26.5}$ dyne-cm events, if these are the largest events for the entire seismogenic lithosphere, is really 35.6 years, rather than the 365 years mistakenly reported in Golombek et al., 1).

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