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MARTIAN SEISMICITY THROUGH TIME FROM SURFACE FAULTING

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An objective of future Mars missions involves emplacing a seismic network on Mars to determine the internal structure of the planet. An argument based on the relative geologic histories of the terrestrial planets suggests that Mars should be seismically more active than the Moon, but less active than the Earth (e.g., 1). Although the Viking 2 seismometer failed to detect a marsquake, the poor sensitivity of the instrument (on the lander) does not preclude Mars from being a seismically active planet (2). In addition, calculations (1) indicate that stresses induced by cooling of the martian lithosphere through time should give rise to marsquakes that exceed the occurrence of high-frequency teleseisms on the Moon (28 events in 5 years) thought to be similar to tectonic earthquakes (3). The seismic moment M_o, is defined as, $M_o=\mu SA$, for slip (S) over a fault of area A, and rigidity μ. Therefore measuring the slip across a fault of known or estimated area allows a determination of the seismic moment, which can be related to the magnitude of an equivalent earthquake, assuming an appropriate moment-magnitude relationship. In this abstract, we estimate the seismicity expected on Mars through time from slip on faults visible on the planet's surface. These estimates of martian seismicity must be considered a lower limit as only structures produced by shear faulting visible at the surface today are included (i.e., no provision is made for buried structures or non-shear structures); in addition, the estimate does not include seismic events that do not produce surface displacement (e.g., activity associated with hidden faults, deep lithospheric processes or volcanism) or events produced by tidal triggering or meteorite impacts. Calibration of these estimates suggests that Mars may be many times more seismically active than the Moon.

Tectonic features on Mars are preferentially found around the Tharsis region, which covers the entire western hemisphere of Mars. Tharsis faults formed mainly during two tectonic periods (4, 5), one during Late Noachian/Early Hesperian and the other during Late Hesperian/Early Amazonian. A recent review of martian structures (6) defines a number of tectonic features that formed by shear faulting. The most common tectonic feature is the simple graben, which is bounded by two inward dipping normal faults with dips of about 60° (7). The widths of the structures and geometrical considerations indicate that on average the bounding faults extend down dip about 2.5 km, and have experienced 150 m of slip (8). We have estimated the faulting on narrow grabens from a data set (9) that includes the locations and lengths of all visible grabens (about 7000), about half of which formed during each of the two tectonic periods. Larger grabens and rifts that involve more of the lithosphere (proportional to their width) also are found on Mars, principally in Valles Marineris, Thaumasia, Tempe Terra, and Alba. Faults bounding the Thaumasia graben, which formed during the Late Hesperian/Early Amazonian period and canyons in Valles Marineris, which formed during both periods are likely to extend through the entire brittle lithosphere, which is about 40 km thick (6); slip was estimated from the observed topographic relief (4-8 km for Valles Marineris; 1.5 km for the Thaumasia graben). Grabens at Alba and Tempe Terra are narrower, probably involving the upper 5-10 km of the lithosphere. Grabens at Alba formed mostly during the Early Amazonian and have experienced 0.2-0.5 km of slip. Tempe Terra rifts are about 0.5 km deep and formed in the Late Noachian. Lengths of the faults were measured directly from surface maps.

Abundant compressional wrinkle ridges around Tharsis formed during the Early Hesperian. Interpretations of the subsurface structure of ridges include folds above reverse faults that extend a couple of kilometers deep (10). We applied a recent model (11) that infers subsurface thrust faults dipping about 30° that extend 5 km down dip with about 150 m of slip to the lengths of about 2000 ridges around Tharsis (9). In addition, we measured the length and average width (inferred depth) of Middle and Late Amazonian grabens, to derive fault areas and slips for these two youngest time periods. Caldera collapse also was included in the measurements of Late Amazonian activity, because a detailed seismologic study (12) on Earth shows that it occurs by an equivalent shear process, producing fairly large earthquakes. We measured the length of circular caldera faults on the tops of Olympus, Ascraeus, Pavonis and Arsia Mons, assumed the faults extend 10 km deep (13) and estimated slip from present relief (14). We assumed a μ of 10^{11} dyne/cm^2, based on likely properties of the outer layers of Mars (4), to calculate the total accumulated moment for each of the 4 time periods discussed above.

The total moment in each time period was divided by its duration, based on two crater/absolute age time scales (e.g., 15) to produce a plot of seismic moment release per year (M_0/yr) through time. M_0/yr was greatest during Late Noachian/Early Hesperian period of Tharsis deformation at 1.5-3.7x10^{23} dyne-cm/yr, decreasing to 1x10^{23}-5.1x10^{22} dyne-cm/yr during the Late Hesperian/Early Amazonian Tharsis deformation period, and to 1.7x10^{22}-4.7x10^{21} dyne-cm/yr during the Middle and Late Amazonian periods. M_0/yr during the first two periods is dominated by that contributed from Valles Marineris faults, which have large slip, depth and length. The decrease in M_0/yr appears to follow an exponential decay toward the present, which argues that Mars is nearly as seismically active today as it has been for the entire Late Amazonian. The best estimate for the present, inferred for the Late Amazonian, or the past 250 m.y. is 1.3x10^{22} dyne-cm/yr. Assuming a moment-frequency distribution (16) similar to oceanic intraplate earthquakes allows determination of the number of marsquakes of a given moment per year. Results suggest hundreds of marsquakes of moment 10^{16} dyne-cm per year, about 1 marsquake of moment 10^{20} dyne-cm per year, and thousands of years between marsquakes of moment 10^{26} dyne-cm.

On the Earth, seismic activity is distributed over a range of earthquake magnitudes, described by the empirical relation log N = a-bm, where N is the number of earthquakes larger than magnitude (m). The slope of the curve b is 0.9 for intraplate oceanic earthquakes (16). If we assume the largest marsquake is equivalent to a magnitude 6 earthquake, based on the largest shallow moonquake (17), the largest intraplate oceanic earthquake (18), and the smallest teleseismic marsquake likely to have been detected by Viking 2 (2), and we assume b = 0.9, we can calculate a distribution of marsquakes per year from M_o/yr, assuming a moment-magnitude relationship of the form log M_o=A+Bm (B=2.35; A=11.71 [body-wave] for intraplate oceanic earthquakes; 18). The most likely present seismic moment release rate of 1.3×10^{22} dyne-cm/yr results in recurrence intervals of 435, 55, 7, and 1 yrs for equivalent body-wave magnitude 5-6, 4-5, 3-4, and 2-3 earthquakes on Mars, respectively. (A number of factors argue that an equivalent magnitude 4 earthquake on Mars would be similar in detectability to a magnitude 5 earthquake on the Earth [1].) Whereas, 7 years might be considered a long time to wait for an equivalent body-wave magnitude 3-4 earthquake on Mars, it must be remembered that these estimates are likely minima. For example on Earth, substantially more earthquakes occur without surface breaks than those that do produce faulting at the surface. If there are 100 earthquakes of a given magnitude without surface breakage for each earthquake with surface breakage, then these estimates predict about 2, 15, and 115 equivalent body-wave magnitude 4-5, 3-4, and 2-3 per year, respectively, on Mars at present. By way of calibration, we extrapolated the total moment release on the Moon at present from all observed grabens, which formed from 3.8-3.6 b.y. and mare wrinkle ridges, which formed from 3.6-3.0 b.y.; results predict a rate of moment release about 1000 times below that observed (10^{22} dyne-cm/yr [17, 20]). If our estimates for Mars are similarly low, then Mars could have of order 100 marsquakes of equivalent 3-6 Earth magnitude per year (about 2 per year of magnitude 5-6), which presents a promising prospect for future missions to Mars. These calculations predict a present day moment release for Mars of about 10^{25} dyne-cm/yr, which agrees with theoretical lithospheric cooling calculations for Mars (1, 19) and is midway between the total moment release (20) for the Moon (10^{22} dyne-cm/yr) and the Earth (10^{29} dyne-cm/yr) as would be expected.

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