A NEW HYPOTHESIS FOR MARE BASALT VOLCANISM, VOLATILE DISTRIBUTION IN THE LUNAR MANTLE, AND MOONQUAKES,

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Introduction: Lunar basalt volcanism, deep moonquakes, and heterogeneities in volatile concentration (water) in the lunar mantle are distinct features of the Moon. They occur in different spatial and temporal domains. The goal of this study is to explore the possible relationship between them.

Mare basalts. Mare basalt volcanism occurred around 3.8 Ga ago and lasted for more than 1 Ga. Mare basalt volcanism is probably the most important volcanic and tectonic event in the lunar geological history after the formation of the lunar anorthositic crust that resulted from solidification of the lunar magma ocean [1]. Two characteristics of mare basalt volcanism are important for understanding the origin of the volcanism. The first is its hemispherically asymmetric distribution, that is, the volcanism predominantly occurred on the nearside of the Moon (Fig. 1) [2]. The second is that the distribution of rare earth elements of bare basalts is complementary to that of the anorthositic crust, suggesting that mare basalts were derived from remelting the melt residue that crystallized contemporaneously with the anorthositic crust [3]. There is also evidence that indicates a deep source region of mare basalts, possibly at ~500 km depth [4].

Deep Moonquakes. Moonquakes recorded by seismometers deployed in Apollo missions in 1970s display a couple of important characteristics. First, they mostly occur at large depths (~800 km) as clusters and on the nearside of the Moon (Fig. 1) [5-10]. They are correlated with mare basalt distribution [5], as recently quantified [11]. Second, the deep moonquakes show correlations with Earth-Moon tides [12-14]. Although it is possible that the occurrence of moonquakes in the nearside is partially attributed to the uneven distribution of the limited number of seismometers (i.e., all of the four seismometers were on the nearside) [8], a cluster of moonquakes, A33, from the farside were detected from the seismometers [8-10], indicating the capability of the seismometers in locating moonquakes from the farside.

Volatiles and water. Recent spacecraft studies of lunar surfaces [15-17] and laboratory analyses lunar rock samples [18] suggest that the Moon contains significant amount of water at its surface and in the lunar interiors. The water has significant effects on both elastic and viscous deformation of rocks [19,20]. Therefore, the discovery of significant amount of water in the interior of the Moon has implications for the early evolution of the Moon and as well as recent lunar tectonic activities such as moonquakes.

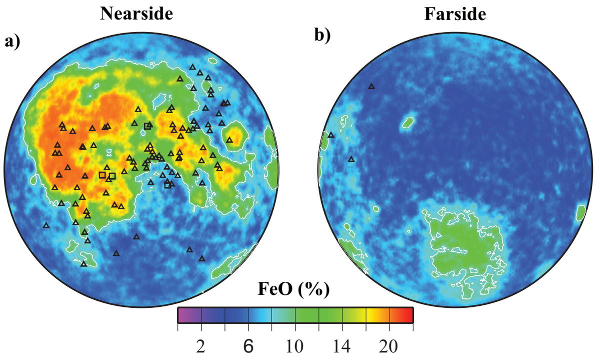

Fig. 1. The surface distribution of FeO on the (A) nearside and (B) farside of the Moon [2]. High concentration of FeO is indicative of mare basalts. Deep moonquakes are also plotted as symbols [10].

Previous Studies and Outstanding Questions: To account for the chemical characteristics and the hemispheric asymmetry of mare basalt volcanism, a number of studies have considered lunar mantle dynamics that may lead to hemispherically asymmetric structure in melt residue materials that are remelted due to temperature anomalies [21-23]. In one of the models [22], the remelting of the melt residue materials was suggested to be caused by dynamically developed upwellings in one hemisphere. While such models lead to hemispherically asymmetric distributions of not only surface volcanism but also the mantle interior structure, these studies did not explore time evolution of lunar mantle structure from the early lunar history (~3.8 Ga ago when the mare basalt volcanism occurred) to the present-day.

Moonquakes are poorly understood. Tidal deformation models have been formulated to explain the characteristics of some moonquakes [11-14]. These tidal deformation models often assume elastic parameters that vary only in the radial direction with no lateral variability which enable simple analytic solution approaches. However, three features of moonquakes present challenges to simple tidal models. First, moonquakes occur in highly localized regions and form clusters [10], while predicted tidal deformation tends to be of long-wavelength and smoothly varying. Second, tidal deformation is always symmetric, but moonquakes clearly show much higher concentration on the nearside than on the farside. Third, tidal stress tends to be small in magnitude, and it is unclear whether tidal stress is large enough to cause moonquakes at large depths [10]. Frohlich and Nakamura [10] recently suggested that fluids may play an important role in causing moonquakes in dynamic interaction with tidal stresses. However, to test this idea is beyond the current tidal deformation models.

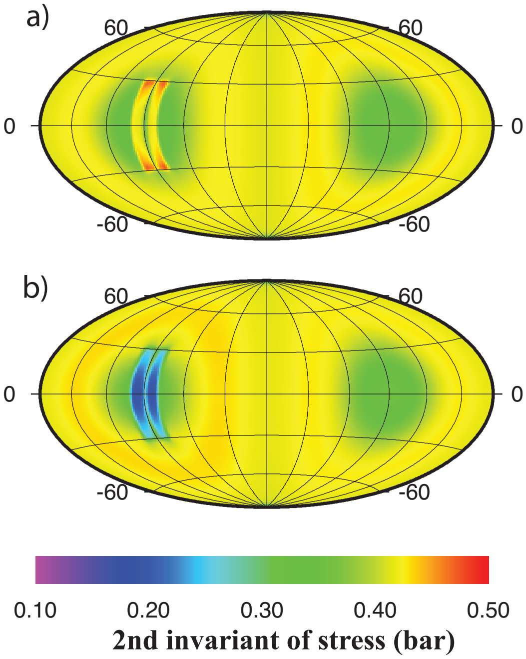

Fig. 2. Tidal stress at a depth of 1000 km from 3-dimensional tidal deformation model calculations with a) shear modulus on nearside in a 10^ox60^o region is reduced by 50% and b) increased by 50%. Notice that stress is enhanced with reduced shear modulus on the nearside.

A New Hypothesis: I propose a new hypothesis for lunar mantle structure evolution and its control on moonquake occurrence in interaction with tidal deformation. I also outline strategies to test this hypothesis and present preliminary results. I hypothesize that accompanying the mare basalt volcanism, the lunar mantle temperature, volatiles and fluids develop globally asymmetric distributions such that the nearside of the Moon has acquired a higher temperature and higher concentration of volatiles. Such distributions have been maintained throughout the lunar geological history to the present-day and are responsible for the high concentration of clusters of moonquakes on the nearside of the Moon as the asymmetric mantle structure interacts with the tidal forces.

To test this hypothesis, I have formulated preliminary tidal deformation models that differ from previous models in incorporating realistic three-dimension elastic parameters to account for the possible effects of fluids and volatiles. I use three-dimension viscoelastic finite element code CitcomSVE that was developed to study earth's post-glacial rebound [24,25]. The new models capable to include rapid variations in elastic parameters caused by fluids enable determinations of tidal stress variations over small length-scales that are comparable with those of moonquake clusters. Preliminary results (Fig. 2) show that three-dimension elastic parameters may influence tidal stress and stress rate significantly. Particularly, regions with reduced elastic parameters (e.g., shear modulus) show enhanced stresses, thus having implications for deep moonquakes.

References: [1] Ringwood A.E. & S.E. Kesson (1976) LPSC 7, 1697-1722. [2] Lawrence et al. (2002), JGR, 107, doi:10.1029/2011JE001530. [3] Taylor R.S. (1982) *A lunar perspective*, LPI, 481 pp. [4] Delano J.W. (1986) *JGR* 91, 201-213. [5] Lammlein D.R. et al. (1974) *Rev. Geophys. Space Phys*. 12, 1–21. [6] Nakamura, Y. et al. (1973) *Science* 181, 49–51. [7] Nakamura, Y. (2003) *PEPI* 139, 197–205. [8] Nakamura, Y. (2005) *JGR* 110, E0100. [9] Bulow, R.C et al. (2007) *JGR* 112, E09003. [10] Frohlich C. & Y. Nakamura (2009) *PEPI 173,* 365-374. [11] Muirhead & Zhong (2011), LPSC. [12] Latham G. et al. (1971) *Science* 174, 687-692. [13] Cheng C.H. & Toksöz M.N. (1978) *JGR* 83, 845–853. [14] Minshull, T.A. & Goulty N.R. (1988) *PEPI* 52, 41–55. [15] Pieters C. M. et al. (2009) *Science* 326, 568-572 [16] Sunshine J.M. et al. (2009) *Science* 326, 565-568. [17] Clark R.N. (2009) *Science* 326, 562-564. [18] Saal, A.E., et al. (2008) *Nature* 454, 192-195. [19] Karato S. (1986) *Nature*, 319, 309-310. [20] Hirth G. & D. L. Kohlstedt (1995) *EPSL* 144, 93-108. [21] Hess P.C. & E.M. Parmentier (1995) *EPSL* 134, 501-514. [22] Zhong S. et al. (2000) *EPSL* 177 131-140 [23] Parmentier E.M. et al. (2002) *EPSL* 201, 473-480. [24] Zhong S. et al. (2003) *GJI* 155, 679-695. [25] Paulson et al. (2005) *GJI* 163, 357-371.