THE INFLUENCE OF A MAGMA OCEAN ON THE LUNAR GLOBAL STRESS FIELD DUE TO TIDAL INTERACTION BETWEEN THE EARTH AND MOON. R. S. Scott & L. Wilson, Planetary Science Research Group, Environmental Science Dept., Lancaster Univ., Lancaster LA1 4YQ, UK. (email: r.s.scott@lancaster.ac.uk).

Summary: We address the influence a magma ocean has on the tidally induced stress field acting on a growing lunar crust. Normal and strike-slip faulting are shown to operate to great depths within the crust.

Introduction: The mechanism by which the Moon formed imposes constraints on its orbital evolution. According to the single impact hypothesis, the Moon was initially much closer to the Earth than now [1, 2, 3]. As a consequence, the Moon was subject to tidal [4, 5], and rotational forces [5, 6], the magnitude of those forces being related to its orbital distance [2, 4, 5] and rate of spin [6]. Initially the dominant influence on the long term evolution of the Earth-Moon system was tidal exchange of angular momentum between the Earth's spin and the Moon's orbit, thus causing the semi-major axis of the lunar orbit to grow [2]. Counter-intuitively, the effect of the growth in the lunar orbit is to increase the influence of tidally induced stresses on the Moon's overall global stress field.

Both *Gash* [1978] and *Melosh* [1980] attempted to explain how a global set of NW-SE, NE-SW trending lineament system, with a less well defined N-S bisecting system, could be initiated by tidal interaction between the Earth and Moon at a time when the Moon was much closer to the Earth than now. Although *Gash* [1978] recognised that there was a need to consider intermediate degrees of restriction, both failed to take into account the presence of a viscous magma ocean sandwiched between a flotation-generated anorthositic crust and a crystallising mafic mantle. Such a magma ocean underlying the crust would behave differently from a solid substratum beneath the crust.

The effects of a magma ocean on the magnitude and subsequent orientation of the tidal stresses will not be apparent until a crust thick enough to withstand disruption and break up by large planetesimals is established. This is considered to be of the order of 10 km [6, 8]. The effects of the bombardment would have worked to weaken the crust and release any stresses that may have built up. Consequently this crust would have a low or non-existent cohesive strength and would respond to stresses by slippage.

As the Moon recedes from the Earth its ellipsoidal shape changes, becoming more spheroidal as the orbital distance increases. This change in shape produces global strain. Whilst the orientation of this tidally induced strain remains constant relative to the body of the crust, the magnitude of the strain will change as the orbital distance increases.

The orientation of the stress field can be defined in terms of polar coordinates. Due to the fixed nature of the stress field these polar coordinates are defined in relation to the sub-Earth and anti-Earth points. The small circles are similar to latitude whilst the great circles are similar to longitude. However, it is important to keep in mind that these circles are not latitude and longitude in the accepted geographic sense. Whilst the growing crust responds to the tidal forces by accumulating stress, the magma ocean below responds in a different way.

Under the influence of a tidal force, a fluid substratum will have equipotential surfaces, represented by a hydrostatic pressure, that are distorted from the spherical form they would have under gravity forces alone into the ellipsoidal form of the equilibrium tides of a fluid sphere. The underside of the growing lunar crust will intersect these ellipsoidal equipotential surfaces of the magma ocean along certain curves on which the pressure will have constant values which will increase towards the interior of the Moon [9].

Nadai [1952] derived equations for the membrane stresses σ_X and σ_Y which apply to both a fluid, such as a magma ocean, or a solid, such as a mantle. Compressive stresses are positive.

$$\sigma = [E/(32+\alpha K)]\{[K_0 y/R_c][(4-\beta K)A \pm (12+\gamma K)B]+K_1[4A \pm 6B]\}$$

where E is Young's Modulus, K_0, K and K_1 are constants that relate to the intensity of tidal forces, stiffness of the substratum and magma ocean pressures, respectively, and y and R_c are the thickness and radius of the crust. The constants α, β and γ involve Poisson's ratio whilst A and B relate to angles of sub-Earth 'latitude'. The two upper + and lower – signs refer to σ_X and σ_Y respectively.

It is not our intention to reiterate here processes that have been addressed previously [10, 11]; however, the solidification of the magma ocean has a major temporal aspect in relation to the stresses that are associated with the tidal distortion of the Moon. In particular, while the magma ocean is solidifying the Moon is receding from the Earth. Because the orbital distance between the Earth and the Moon has a direct bearing on the magnitude of the stresses [4, 5, 7], and the presence of the magma ocean will influence both the magnitude and the subsequent orientation of these stresses; then the duration of the magma ocean, the rate at which it cools, and the rate at which the orbit evolves are all interwoven.

Several workers have attempted to model the Moon's orbital growth rate using a variety of methods [2]. However, using the hafnium-tungsten (Hf-W) age of the Moon, [12] and its current mean orbital distance, the Moon's average orbital recession rate is far in excess of those that applied over the last 2.5 Ga which suggests that during the Moon's early history the rate of change of orbital distance must have been very considerably higher than the current value.

We propose a way that this problem of relating the stresses associated with the cooling of the magma ocean and the changing tidal forces to the evolution of the Moon's orbit can be addressed. *Lambeck and Pullan* [1980] and *Smith and Zuber* [1998] have suggested that there is a link between the Moon's tidal bulge and its orbital distance. For a tidal bulge to exist now, the Moon's crust must at some stage have cooled sufficiently that it was rigid enough to 'freeze in' tidal stresses. To do this the Moon must have contained an elastic zone. This is unlikely until the magma ocean has effectively solidified. Solidification will be completed 40 - 60 Ma after accretion by which time any existing tidal bulge will be 'frozen in'. *Lambeck and Pullan* [1980] argue that this tidal bulge became frozen in when the Moon was approximately 25 Earth-radii (Re) from the Earth, whereas *Smith and Zuber* [1998] suggest a much closer distance of 13 Re to 16 Re.

We have modelled four scenarios based on a solidification time of 40 Ma and 60 Ma and a 'freezing in' orbital distance of 13 and 16 Re. These orbital growth rates are similar to those proposed by other workers, [5, 15]. Models 1 and 2 are based on a Moon that evolves to an orbital distance of 13 Re and 16 Re during a crustal growth period of 40 Ma respectively, while models 3 and 4 consider the same two orbital distances but use a crustal growth period of 60 Ma. All four models predict normal faulting within 35^{o}-40^{o} of the sub and anti-Earth points, and strike-slip faulting between 40^{o} and the geographical poles.

This faulting pattern is significantly different from that proposed by *Gash* [1978] and *Melosh* [1980]. Both *Gash* [1978] and *Melosh* [1980] predict compressive faulting around the sub and anti-Earth points, strike-slip faulting in mid-latitudes and normal faulting in the geographical polar regions.

The figure below shows the maximum depth that slippage, along existing fractures, will be apparent for the four models under consideration. The figure clearly demonstrates that the deepest faulting is associated with the shorter solidification time of 40 Ma. Further inspection shows that model 1, a Moon that evolves to an orbital distance of 13 Re in 40 Ma, will have slip along existing fractures that extend from the surface down to the base of the crust.

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