Impact basin relaxation on Iapetus

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Introduction Crater relaxation has been used as a probe of subsurface temperature structure for over thirty years [e.g. 5]. Different craters forming at different times experience different relaxation histories. Hence, if the ages of different craters are known, the evolution of the surface heat flux with time can be determined. Conversely, craters with different degrees of relaxation can be assigned different ages if a model for the thermal evolution of the body exists. Here we follow the second approach: by coupling thermal evolution and relaxation models together, we derive model constraints on the ages of different basins. The reason for focusing on Iapetus is that it is heavily cratered [6], not tidally heated and appears to have been tectonically inactive since shortly after its formation. Thus, one might expect its thermal evolution to be simple and monotonic, which is certainly not the case for some of the other Saturnian satellites. Furthermore, its synchronous spin period and 35 km flattening [10] place some constraints on allowable thermal evolution models [2, 11].

Models To investigate the evolution of relaxation with time we coupled two codes: a convective thermal evolution code (OEDIPUS [3, 4]) and a viscoelastic relaxation code (CitcomVE [16]).
The thermal evolution model and results are described in a previous study by Robuchon et al. [11] and are summarized here. A constant temperature of 90 K was prescribed at the surface while a zero heat flux was prescribed at the inner boundary. A Newtonian viscosity was adopted partly for simplicity, but also because the low stresses associated with convection are likely to result in ice deformation via diffusion creep, which is Newtonian [8]. The model is used to compute tidal dissipation during despinning and the decay of radioactive isotopes including the short-lived nuclides ^{26}Al and ^{60}Fe. The shape evolution of Iapetus as despinning and lithospheric thickening takes place was calculated following the approach of Čadek [1] and Tobie et al. [14]. An initial amount of ^{26}Al = 72 ppb generates the correct present-day flattening and spin period.

To calculate relaxation, we model Iapetus as a self-gravitating incompressible viscoelastic (Maxwellian) sphere in a 2-D axisymmetric geometry, with a constant density. Equations (conservation of mass and momentum, and the gravitational perturbation) are solved with a finite-element method and the displacement is computed for each point of the grid mesh [16]. Null shear stress and free-surface conditions are prescribed at the surface and bottom boundaries and we set the basin center at the pole. The original code has been modified in two ways: (1) the viscosity structure evolves with time based on the thermal evolution model; (2) a topographic depression (basin) is introduced into the surface at the first time step. This depression is modeled as a negative surface load of the same density as that of the underlying mantle, i.e. a mass deficit. The initial shape of our basin is computed following a parabolic shape and we set the initial central depth to 10 km for bigger basins (400 to 800 km) and 7 km for smaller ones (100 and 200 km) following the study of Giese et al. [7].

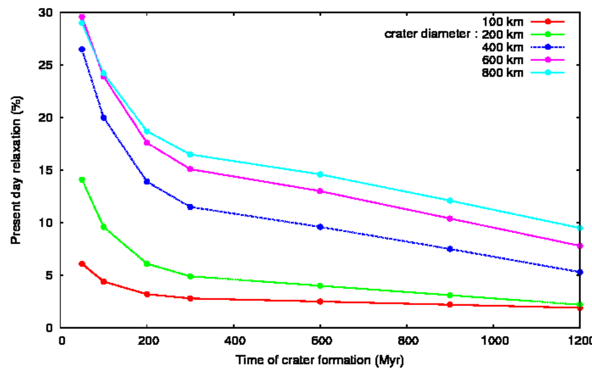

Figure 1: Present-day degree of relaxation versus time of basin formation for each different basin diameter tested. Degree of relaxation is defined by $1 - z/H$ where z is the present-day central depth and H is the initial central depth.

Results Figure 1 shows the present-day degree of relaxation f as a function of basin diameter and formation time. For the model results f is defined as $1 - (z/H)$ where z is the present-day model depth at the center. For all basins the maximum relaxation occurs for the earliest formation time, when the ice shell viscosity was low. A relaxation of 30 % is obtained for the largest basins when the formation time is 50 Myr, while the smallest relax by about 5%. Subsequently, the lithosphere thickness increases while the interior viscosity also increases due to cooling via convection. At progressively later formation times, the total degree of relaxation is correspondingly reduced. An 800 km diameter basin forming at 1200 Myr is expected to relax

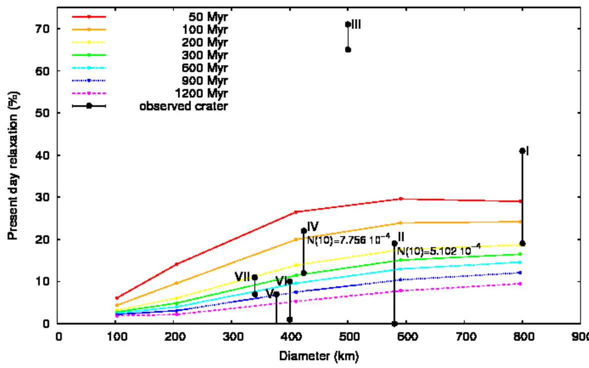

Figure 2: Basin degree of relaxation as a function of diameter. Black bars are degree of relaxations for observed basins; high and low values are derived from the two lines shown in Fig. 11c of Giese et al. [7]. Colored lines are model results for different basin formation ages. Cratering densities (in km^{-2}) for basins II and IV are from Neukum team (personal comm.).

by only 10%.

As expected, bigger basins relax more rapidly than smaller ones. This behavior is due to the fact that the inferred thickness of the ice shell of Iapetus exceeds the diameter of almost all basins considered [cf. 9].

Comparison with observations Figure 2 plots our model results compared with the observations. Despite the significant uncertainties in the observed degree of relaxation, it is not possible to fit all the basins with a single model age. In particular, basin V appears to have formed relatively late (formation time $>$ 600 Myr, age $<$ 3.96 Ga) while basins I and IV formed early (ages $>$ 4.36 Ga and $>$ 4.26 Ga, respectively).

The model basin ages that we have derived may also be compared with ages derived from crater counting. Neukum et al. (pers. comm.) found that crater densities in the inner part of basin IV exceeded those in the inner part of basin II by about 50%, suggesting a greater age for basin IV. That result is consistent with our model results. The nominal ages based on crater counts are 4.31 Ga and 4.26 Ga for basins IV and II, respectively. Although there is no agreement on how cratering rates in the outer solar system should be calibrated [15], these numbers are at least consistent with the range of model ages that we obtain.

As is immediately evident from Fig 2, the one basin which is completely inconsistent with our model results is basin III. This basin was identified by Giese et al. [7], but not by Schenk and Moore [12]. Of all the basins examined, this one has the least obviously circular outline, it sits at the edge of the stereo coverage area and is partially obscured by the later basin VI. We therefore regard its status as an impact basin as questionable.

Caveats A model with a lower initial ^{26}Al (46 ppb) results in relaxation factors f which are roughly one-third smaller for a given time and crater diameter than the values shown in Fig 2 highlighting the fact that our model results are highly sensitive to variations in ^{26}Al.

One limitation of our model is the assumption of Newtonian viscosity. Comparisons with non-Newtonian model results [13] suggest that we may be underestimating the amount of relaxation, and thus overestimating the basin ages.

Conclusion A model developed to explain the global characteristics of Iapetus (spin state and flattening) also reproduces the slightly-relaxed state of the big impact basins there. For the nominal model the basins span an age range of at least 0.5 Gyr, and our model basin relative ages are consistent with relative ages based on crater counting.

References

[1] O. Čadek. In *EGU, Nice, France, 2003*, p. 5279, 2003.
[2] J.C. Castillo-Rogez et al. *Icarus*, 190, 179–202, 2007.
[3] G. Choblet. *J. Comput. Phys.*, 205, 269–291, 2005.
[4] G. Choblet et al. *Geophys. J. Int.*, 170, 9–30, 2007.
[5] Dombard, A.J. and McKinnon, W.B. (2006). *J. Geophys. Res.*, 111, E10, 1001.
[6] Dones et al. In *Saturn from Cassini-Huygens*, p. 613–635. Springer, 2009.
[7] B. Giese et al. *Icarus*, 193, 359–371, 2008.
[8] D.L. Goldsby and D.L. Kohlstedt. *J. Geophys. Res.*, 106, 11017–11030, June 2001.
[9] E. M. Parmentier and J. W. Head. *Icarus*, 47, 100–111, 1981.
[10] Porco et al. *Science*, 307, 1237–1242, 2005.
[11] G. Robuchon et al. *Icarus*, 207, 959–971, 2010.
[12] P. M. Schenk and J. M. Moore. In *LPSC*, vol. 38, p. 2305, 2007.
[13] Thomas, P.J. and Schubert, G. (1987). *J. Geophys. Res.*, 92, B4, E749–E758.
[14] G. Tobie et al.. *Icarus*, 196, 642–652, 2008.
[15] K. Zahnle et al. *Icarus*, 163, 263–289, 2003.
[16] S. Zhong et al.. *Geophys. J. Int.*, 155, 679–695, 2003.