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Roberto Sabadini, Enzo Boschi

Tidal dissipation and short-term rheology of the earth

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Geofisica. — *Tidal dissipation and short-term rheology of the earth.* Nota di ROBERTO SABADINI (*) e ENZO BOSCHI (**), presentata (***) dal Corrisp. E. BOSCHI.

RIASSUNTO. — La perturbazione nel nodo ascendente del satellite Lageos può essere attribuita alla dissipazione mareale all'interno della Terra prodotta dalla marea lunare con periodo di 18.6 anni. Il numero di Love mareale corrispondente al periodo di questa marea non coincide con il valore elastico. Questo significa che un meccanismo dissipativo agisce all'interno della Terra. In questo lavoro abbiamo costruito due modelli reologici che potrebbero spiegare le variazioni osservate nel numero di Love mareale. Proponiamo un modello viscoelastico basato sulla reologia di Maxwell in cui fenomeni dissipativi avvengono in un canale a bassa viscosità sotto la litosfera e un modello del tipo Solido Lineare Standard in cui il comportamento anelastico di tutto il mantello è responsabile degli effetti osservati prodotti dalle maree.

1. INTRODUCTION

The analysis of the data obtained in the last five years during the mission of Lageos satellite for geodetic measurements, makes it possible to improve our knowledge of the short-term rheology of the Earth. The key problem in the study of the Earth's rheology is the understanding of how the material of the Earth's mantle behaves when it is subject to a shear stress. The mathematical description of this deformation process goes through the definition of a constitutive law. The constitutive law that we have to utilize in order to model a deformation process is strongly dependent on the characteristic time scale of the process itself. When the Earth is " seen " through long time scale phenomena like those characteristic of post-glacial rebound, the Maxwell viscoelastic rheology is a powerful tool to describe the relaxation of the mantle. In the steady state regime the Maxwell body behaves like a fluid. The gravity anomaly data on the Canadian shield (Peltier, 1976) and the effects of Pleistocene deglaciation on the Earth's rotation provide solid arguments to support the validity of the Maxwell rheology for the long time properties of the planet (Sabadini and Peltier, 1981; Sabadini *et al.*, 1982, Yuen *et al.*, 1982; Yuen *et al.*,

(*) Dipartimento di Fisica, Settore di Geofisica, Università di Bologna, Viale Berti Pichat, 8 - 40127 Bologna, Italy.
(**) Istituto Nazionale di Geofisica, Via Ruggero Bonghi, 11/B - 00184 Roma, Italy.
(***) Nella seduta del 24 novembre 1984.

1982). It is surprising but true that the short term rheology that is appropriate for time scales characteristic of post-seismic deformation or damping of the Chandler wobble, is less understood than the steady state one. Recently the new set of data provided by the Lageos mission came to enrich the amount of information on the short term properties of mantle rheology. The perturbation in the ascending node of Lageos satellite can be ascribed to variations in the $l = 2$ component J_2 of the Earth's gravitational potential forced by Pleistocene deglaciation and the tidal deformation of the planet due to the 18.6 yr tide (Lambeck and Nakiboglu, 1983). The effects of the tide can be observed in the variations of the tidal Love number K_2^T corresponding to the 18.6 yr tide. Basically, the Love number K_2^T is the normalized Green function of the perturbed gravitational field of the planet subject to tidal forces (Saito, 1978).

This value

$$K_2^T\,(t = 18.6 \text{ yr}) = 0.36 \tag{1}$$

differs from the elastic value evaluated at $t = 0$

$$K_2^T\,(t = 0) = 0.30\,. \tag{2}$$

The 20 per cent variation of K_2^T can be due to dissipation in the Earth's mantle induced by tidal forces (Lambeck and Nakiboglu, 1983). From the geophysical observable K_2^T we can thus extract information on the rheological properties of the Earth's mantle on the period of the tide through a comparison between the theoretical predictions of a mathematical model and observed data.

2. Tidal Love Number

The stratified, viscoelastic and self-gravitating Earth model described by Sabadini *et al.* (1982) and Yuen *et al.* (1982) can be fruitfully employed to study the behaviour of the planet under the influence of tidal forces. A short term rheological structure can be built from the model of Yuen *et al.* (1982) by means of a sharp variation in the Maxwell viscosity between a stiff mantle and a soft asthenosphere. Another rheological model appropriate for studying tidal dissipation is the Standard Linear Solid for the whole mantle. In the next paragraph we show the effects of these different rheologies on the variations of the tidal Love number. The evolution in the Laplace space of the tidal Love number is provided by the spectral decomposition

$$K_2^T\,(s) = K_0 + \sum_{i=l}^{M} k_i\,(s - s_i)^{-1} \tag{3}$$

where K^T is the elastic contribution, K_i and s_i are respectively the residue and inverse relaxation time of the i^{th} viscoelastic or anelastic deformation mode. The number M and the values of the sets $\{K_i\}$ $\{s_i\}$ depend on the stratification

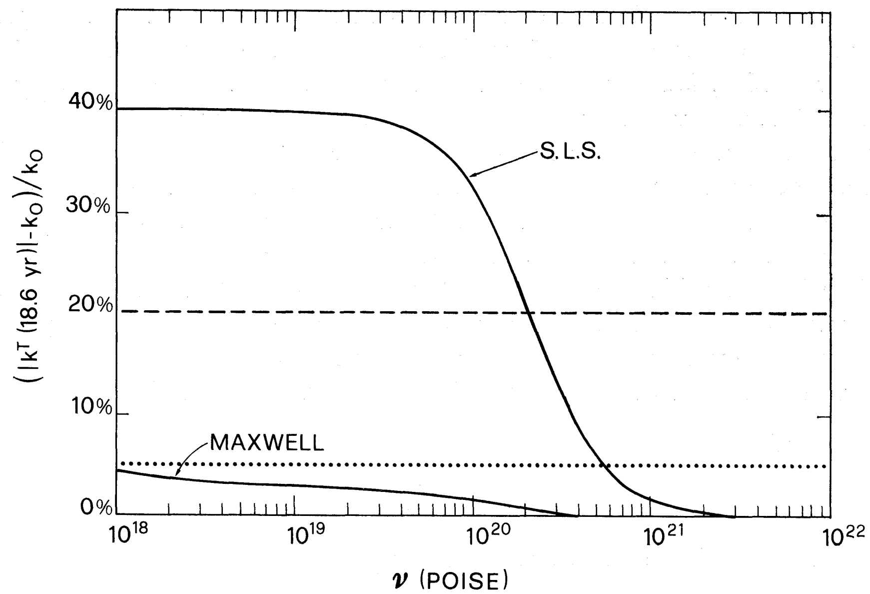

Fig. 1. – Percentual variations of tidal Love number K_2^T respect to the elastic value for the Maxwell model and Standard Linear Solid (S.L.S.). The varying viscosity refers to the asthenospheric viscosity for the Maxwell model in which the asthenosphere is 200 Km thick and to the transient viscosity for S.L.S. Dashed line denotes the datum inferred by Lambeck and Nakiboglu (1983). Dotted line takes the ocean corrections into account.

and rheology. This spectral decomposition is obtained from the solution of a boundary value problem appropriate for tidal forcing (see eq. (7) of Yuen *et al.* (1982)). The variation of K_2^T corresponding to $t = 18.6$ yr with respect to the elastic value is shown in fig. 1 for different viscosities for both Maxwell and Standard Linear Solid models. The viscosity of the Standard Linear Solid is the parameter describing the transient deformation of the whole mantle whereas the Maxwell viscosity is linked with the fluid-like behaviour of the thin low viscosity channel beneath the lithosphere. The percentual variation in fig. 1 is defined in the following way

$$P = [K_2^T(t = 18.6 \text{ yr}) - K_2^T(t = 0)]/K_2^T(t = 0) . \tag{4}$$

The asthenospheric viscosity in the Maxwell model is lowered from 10^{22} to 10^{18} Poise to emphasize the effects of tidal dissipation in the low viscosity channel. The mantle viscosity is kept fixed to 10^{22} Poise for the model with the asthenosphere, in agreement with post-glacial rebound observations. Localized creep processes in the asthenosphere are responsible for the increase of the tidal Love number when the steady state viscosity is reduced. When the Standard Linear Solid (S.L.S.) is considered, variations in K_2^T are due to dissipative effects in the anelastic mantle. The dashed line represents the 20 per cent variation as derived by Lambeck and Nakiboglu (1983). This value can be totally ascribed to dissipative phenomena only if the effects of the oceans are not included. If we take the oceans into account, assuming that the ocean tide is an equilibrium one (Smith and Dahlen, 1981), then dissipative effects can justify only 5 per cent of the total variation. The dotted line at the bottom of fig. 1 is in fact the value proposed by Lambeck and Nakiboglu (1983) corrected for the ocean tide. The most salient feature of this figure consists in the fact that dissipative mechanisms in the low viscosity channel cannot explain the total geophysical datum for realistic asthenospheric viscosity values. Comparing the curve corresponding to the Maxwell case with the dotted line, we see that only one half of the observable can be ascribed to viscoelastic relaxation in the asthenosphere when a viscosity ranging from 10^{19} to 10^{20} Poise, in agreement with post-seismic observations, is used (Cohen, 1982). We need another mechanism, besides asthenospheric creep to explain the remaining 50 per cent of the datum. This mechanism can be brought into play by transient deformation in the whole mantle, as modelled by the Standard Linear Solid. From fig. 1 we get a lower bound for the transient viscosity of the order of 10^{21} Poise. If we reduce this parameter further, we could explain the total amount of the observed variation in terms of transient deformation. In fact, with $v \simeq 5 \times 10^{20}$ P we get the 5 per cent variation that includes the equilibrium ocean tide. With $v \simeq 2 \times 10^{20}$ Poise we can explain the 20 per cent variation

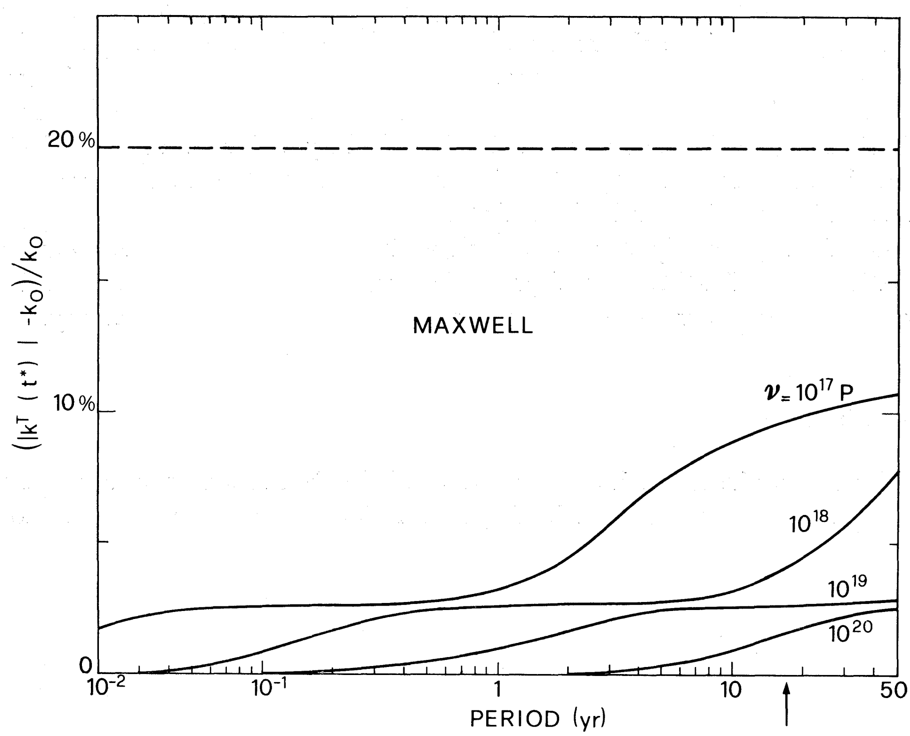

Fig. 2. – Percentual variations of K_2^T for varying period of the forcing tide and different asthenospheric viscosities. The arrow denotes the 18.6 yr tide.

without the effects of the oceans. We note that the steady state Maxwell viscosity inferred from post–glacial rebound ($\simeq 10^{22}$ Poise) can not produce any effect on the time scale of the 18.6 yr tide.

In fig. 2 we vary the period of the forcing tide and each curve corresponds to a fixed value of the Maxwell viscosity in the asthenosphere. The arrow at the bottom denotes the period of the 18.6 yr tide; if we decrease the period of the tide, we see that very low, unrealistic values of asthenospheric viscosities (lower than 10^{17} Poise) are needed in order to get a significant amount of dispersion. This means that for such short periods viscoelastic creep in the asthenosphere is not an efficient mechanism to promote tidal dissipation. A transient rheology like the Standard Linear Solid is definitely more appropriate when we want to mimic the effects of the tides with short periods like the fortnightly or the monthly ones.

3. Conclusions

From a comparison between the theoretical predictions of stratified viscoelastic or anelastic Earth models and observed variations in the tidal Love number corresponding to the 18.6 yr. lunar tide we are able to put bounds on the parameters of two short-term rheological models. We have shown that at least a portion of the observed variation in K_2^T can be due to dissipation in a soft asthenosphere when viscosity values consistent with post-seismic observations are considered. Another contribution to the increase in K_2^T comes from anelastic processes in the whole mantle, described by a Standard Linear Solid. Lower bounds, around 5×10^{20} Poise are needed for the transient viscosity characterizing the Standard Linear Solid.

Our findings clearly show how satellite observations can provide useful information on the Earth's internal properties, even if new sets of data are definitely required to derive stronger conclusions on the short-term rheology.

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