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LITHOSPHERIC BULGE AND THICKENING OF THE LITHOSPHERE WITH AGE EXAMPLES IN THE SOUTH-WEST PACIFIC

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- INTRODUCTION :

The lithospheric bulge before its underthrusting beneath an island arc has been studied in several previous works, Gunn (1943), Lliboutry (1969-1973), Walcott (1970), Hanks (1971), Dubois et al (1973,1974,1975), Watts and Talwani (1974). Those studies have shown that the flexural parameter might be computed from the elastic plate deflection which the lithosphere is assimilated to, and therefore to derive its thickness.

That thickness has been derived to be approximately equal to the half of the lithospheric one as it can be defined from the seismic wave propagations, its basement being the upper boundary of the low velocity layer. Turcotte (1974) points out that at 25 km deep the temperature is about 300° C, from that observation he deduces that with temperatures lower than 300° C, the lithosphere would behave elastically, with respect to the given time.

In a recent work Caldwell et al (1975, in press) show up that after the elimination of the sediments, the dipping lithosphere behaves as an elastic body. Based on the study of four arcs, Aleutian, Kuril, Bonin and Mariana they show up that the thickness of the elastic lithosphere is found to vary between 20 and 29 km. The good agreement thus obtained shows that horizontal forces may be neglected and that the bending lithosphere behaves elastically in the considered cases.

The observation suggesting the outer wall of the New Hebrides trench to part from the theoretical model appears to be explained (Dubois et al, in press) through the plastic properties of the extremity of the plate at the level of its dipping with a rupture of the solid crust in surface.

The lithospheric thickness depends essentially on the criterium of definition chosen for that concept. We have seen before that the seismology and the flexure gave different values in thickness. If we consider with Schubert et al (1976) a thermal and mechanical solid state model, we can give with them a third definition of the lithospheric thickness : if u_0 is the constant lithospheric velocity in surface with regard to the deep mantle, we call lithosphere the layer where the horizontal velocity u with regard to the same referential, is such as $u \geqslant 0{,}95\ u_0$ (fig.4).

On the other hand, those authors study through that model the thus defined variation in thickness and they conclude that its thickening is a function of time. In this note, we compare some observations carried out in two subduction zones, the New Hebrides and Tonga Kermadec ones. The underthrusting lithospheres are different in age, which yields to a difference in their mechanical behaviour.

- DATA :

The North Loyalty lithosphere.

That plate deflection before its underthrusting beneath the New Hebrides has been studied through the Loyalty atoll emergences,

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as a consequence of its deformation. The previous works which have been made (Dubois et al 1973,1975) allow the computation of a flexural parameter of about 76 ± 5 km say a thickness of the elastic lithosphere of 24.2 ± 2.1 km.

The Tonga-Kermadec lithosphere.

On the Tonga-Kermadec we use bathymetric and seismic profiles carried out during the GEORSTOM III cruise. The four profiles (fig.1) from 318 to 321 cross the arc from the 35°S to the 23°S. They have been surveyed with respect to the trend perpendicular to the trench axis, the sedimentary layer is thin, 0.1 s two way travel North and 0.4 s.t.w.t. South. This is the reason why the study of the deflection has been surveyed across the bathymetric profiles and not, as Caldwell et al (1975) suggested on the acoustic basement after stripping sedimentary cover.

It seems too that the profile 318 which brings out the sediment thickness, the more important, is different enough from the others the outer wall of the trench is accretionary in type (connected with the sediments on the underthrusting plate ?) while on the three other profiles we have to deal with outer wall non-accretionary in type, as Fisher and Engel (1969) assumed through their dredging on the Tonga trench close to the profile 321 (fig.2).

One can note too that the trench dept increases from South to North from 7900 m deep on 318 to 10900 m on 321. That deepening of the trench with the increase of the distances from the rotation center of both plates underthrusting and overthrusting (here the rotation center is South of New Zealand) may be observed everywhere (Dubois et Recy, in prep.). On the outer wall a fracturation appears which has yet been mentioned previously in this study, at the level of separation from the theoretical curve. This fracturation certainly depends on the crust heterogeneity. It is as much important as the lithosphere is more heterogeneous, seamounts, fractures (see profiles 319 and 320 close to the intersection of Louisville Ridge with the subduction zone).

By means of a hand smoothing of the bathymetric profiles, we obtain a good scheme of the bulge where it is easy to measure the pseudo wavelength π/λ and the bulge amplitude (see appendix a). We can also filter the rough data with a low frequency filter which removes the short wavelengths of the topographical background superposed on to the here studied phenomenon.

The filter used here (see appendix b and fig. 3) is a symmetrical (to prevent the difference in phase) linear filter. It is a low frequency filter which we have applied with a cutoff frequency corresponding to the removal of the reliefs of less than 60 km wide. At the extremities of the profiles to prevent the removal of one wavelength, we have prolongated the profiles to 60 km more with a constant depth.

The obtained results in the measurements of the distances between two successive zeros and the corresponding values of the flexural parameter and of the elastic model thickness are noted in the Table I. For the theoretical meaning of those parameters, see Hanks (1971), Dubois et al (1974,1975). ζM corresponds to the bulge amplitude.

In spite of the inaccuracies in the reading, we can assume that a very small increase of the flexural parameter may be shown directed South to North. That increase coincides too with a small deepening of the bottom : 5880 m for the profile 318, 5940 m for the profile 319, but 5760 m for the 321.

- CORRELATIONS WITH THE AGE CRITERIUM

Let us examine those results through the previous works made about the oceanic lithosphere. It has been emphasized that an oceanic lithosphere was deepening with time and that it was thickening (Parker and Oldenburg 1973). Recently, Schubert et al (1976) proposed a coupled thermal and mechanical solid state model of the oceanic lithosphere and asthenosphere which includes vertical conduction of heat with a temperature dependant thermal conductivity, horizontal and vertical advection of heat, viscous dissipation or shear heating and linear or non linear deformation mechanisms with temperature and pressure dependant constitutive relation between shear stress and strain rate (see appendix c).

In this model, in addition to the numerical values of the medium properties, the lithospheric velocity values of the plate in surface, the temperatures at the surface and a great depth are arbitrarily chosen (to integrate the differential equation giving the temperature distribution). The model determines the depth and age dependant temperature, horizontal and vertical velocity and viscosity structure of the lithosphere and asthenosphere. Particularly we can derive the oceanic floor topography, the oceanic heat flow and the lithosphere thickness as function of the age of the ocean floor. The rate of growth of the lithosphere decreases with age.

In their theoritical work Schubert et al (1976) were arguing, on their model, about

applying or not the Newton's law on solid deformations (proportionality between the stress deviator and the velocity deformation). In laboratory on deformed olivine that behaviour has never been observed, because they are non Newtonian processes based on the dislocation movements (Weertman 1970) which are prevailing rather than diffusion between the grains under the applied stresses (Nabarro 1948). The peridotitic flexural nodules show sub-grained structures and dislocation densities equal to those of the laboratory samples. Therefore, we can expect the non Newtonian behaviour to be prevailing in the asthenosphere where the peridotitic nodules are supposed to form.

As for Schubert et al, from 1000 km towards the ridge, say at 10 M.y, (spreading rate of 10 cm/y), the dislocation mechanism is prevailing with regard to a relatively cold mantle. Thence, it is the non-Newtonian model which will be applied to the case we are studying, that of the New Hebrides and Tonga Kermadec. (fig. 5).

The empirical curve of the water depth - (age)1/2 given by Parsons and Sclater (1976) (fig.6) indicates an age of 33 M.y for the North Loyalty lithosphere and within 100 to 125 M.y for that of the Pacific basin underthrusting beneath Tonga Kermadec.

The non Newtonian models give corresponding thicknesses ranged between 61.8 and 67.5 km for the New Hebrides and 90.6 to 109.7 km for the Tonga Kermadec with regard to the chosen values of the activation volume (see Table II and fig. 5).

We can point out the derived value of the North Loyalty lithosphere thickness which is in agreement with the value derived from the study of the dispersion of Rayleigh waves (Dubois 1969).

When comparing the thickness values between Tonga Kermadec and North Loyalty, we find a ratio 1.466 to 1.578 and 1.508 to 1.625 with respect to the activation volume.

For the computation of this relation in the case of the elastic model thickness is 1.42 ± 0.12, lower than the previous values.

We can assume the relations in thickness between both cases are very similar, which would indicate that there is a proportionality between the elastic lithosphere thicknesses and those obtained from the coupled thermal and mechanical solid state model.

- Appendix a -

- Lithospheric bulge

The deflection equation of an elastic thin sheet semi infinite where a horizontal force Nb and vertical force Pb are applied on the free boundary is :

$$\zeta = \frac{-Pb}{\beta\,(\rho m - \rho w)g} \cdot \frac{2\lambda^2}{3\alpha^2 - \beta^2} \cdot e^{-\alpha x}\{2\alpha\beta \cos \beta x + (\alpha^2 - \beta^2) \sin \beta x\}$$

in which $\lambda = \{(\rho m - \rho w)g/4\,\Gamma\}^{1/4}$

$\Gamma = E\,H^3/12(1 - \sigma^2)$

$\alpha = (\lambda^2 + Nb/4\,\Gamma)^{1/2}$

$\beta = (\lambda^2 - Nb/4\,\Gamma)^{1/2}$

where σ = Poisson's ratio
E = Young's modulus
H = thickness of lithospheric plate
ρm, ρw = densities above and below the plate respectively
Pb, Nb = vertical and horizontal forces on the age of the plate respectively
Γ = flexural rigidity
g = average gravity

The distance between the two first zeros is very near of π/λ (Dubois et al 1975). If this value is known we can deduce λ and H. For the New Hebrides and Tonga Kermadec this distance is respectively of 239 ± 10 km and 312 ± 5 km.

The maximal amplitude of the simplified form of ζ is equal to :

$$\frac{\sqrt{2}\,Pb\,\lambda}{(\rho m - \rho w)\,g}\, e^{-3\pi/4}$$

, it is depending essentially of Pb, Nb and λ.

For the two considered cases :

$$\frac{\zeta M\ \text{Tonga}}{\zeta M\ \text{N.H.}} = \frac{(Pb\ \lambda)\ \text{Tonga}}{(Pb\ \lambda)\ \text{N.H.}}$$

If the forces applied on Tonga and New Hebrides plates are equal values the amplitudes ratio of the bulge will be equal to the flexural parameters ratio $1/\lambda$.

In our example ζM Tonga/ζM N.H. = 240/150 = 1.6 when the flexural parameter ratio is 1.30, this indicates that the stresses fields are different.

- Appendix b -

- Filtering

To remove the bathymetric background we computed and applied to the data a linear and symmetrical numerical filter (Behannon and Ness, 1965).

This filter consists of a series of ponderal coefficients W_k determining the transfer function W (f) of the filter which, in its most general expression, is a complex number which may be written as following :

$$W(f) = \Sigma_{k=-M}^{N} W_k(x)\, e^{i2\pi f k \Delta x}$$

The purpose being a reducing of the high frequencies without phase displacement, we use a symmetrical filter whose response in frequency is :

$$W(f) = W_o + 2\,\Sigma_{k=1}^{N} W_k(x) \cos 2\pi f k \Delta x$$

It is demonstrated that for an ideal low frequency filter (with a sharp cut off frequency) the ponderal coefficients are given by

$W_k = \frac{\sin \pi k P}{\pi k}$, where $P = \frac{f_c}{f_s}$ is the ratio of the cut off frequency to the sampling frequency.

To avoid important oscillations in the response of the filter due to the sharp cut off frequency, we extend the transfer function by a sine function which has the same value and derivative for P as the transfer function and which is, as also its derivative, equal to zero for a certain value of the frequency. The ponderal coefficients are thus given by :

$W_k = \frac{\cos \pi k h}{1-4k^2h^2} \cdot \frac{\sin \pi k (P+h)}{\pi k}$, where h is the abscissa corresponding to 1/4 period of the sine function.

To normalize the gain to the unit at the origin, we use a correction coefficient :

$\Delta = 1 - (L_o + 2\,\Sigma_{k=1}^{N} L_k)$, where L_k is the coefficient computed from the previous formula. The corrected ponderal coefficient becomes :

$W_k = L_k + \frac{\Delta}{2N+1}$, and the response is frequency of the filter is :

$$W(p) = W_o + 2\,\Sigma_{k=1}^{N} W_k \cos \pi k p, \text{ where } p = \frac{f}{f_c}$$

is the reduced abscissa.

We compute a filter with 60 coefficients. We take h = 1/60, which removes almost all the oscillations close to the cut off wavelength that we chose equal to 60 kilometers with a sampling of 1 kilometer. We are limited in the number N of coefficients of the filter for, as in a simple smoothing, the filtering is made on slipping the filter along the curve to be filtered and on applying it to 2 N + 1 points (here N = 60) of this curve whose the N first and N last points are thus eliminated. To avoid this problem we have empirically extended the curves to be filtered of 60 points on both sides to which are given the values of the extreme points of each curves. Besides before computing the filtering we smoothed handly the sea botton in removing the large montains which are surimposed to the bulge.

- Appendix c -

The thermal and mechanical model of Schubert et al rewriten from Schubert et al.

Two dimensional shear flow, viscous dissipation, variable thermal conductivity. The model includes the two dimensional flow of a medium with a Newtonian or non Newtonian temperature and pressure dependant rheology forced to deform with horizontal velocity at great depth.

Conservation of mass requires a vertical transport with velocity V to balance the variation in horizontal mass flux due to the charge in u (x) with age on distance from the ridge. The temperature equation includes advection of heat by both the horizontal and vertical notions, the viscous dissipation of the flow and variable thermal conductivity.

The conservation of mass is : $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$ (1)

The temperature equation :

$$\rho\, C_p \left(u \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y}\right) = K \frac{\partial^2 T}{\partial y^2} + \left(\frac{\partial T}{\partial y}\right)^2 \frac{\partial K}{\partial T} + \tau \frac{\partial u}{\partial y} \qquad (2)$$

ρ = density
Cp = specific heat
K = thermal conductivity
τ = shear stress parallel to a horizontal surface

The rheological law connecting shear stress and strain rate :

$$\frac{\partial u}{\partial y} = - \frac{2\ Bn}{T} \quad \tau^n \exp \{- \frac{(E^\star + pV^\star)}{RT} \} \qquad (3)$$

$E^\star$ = activation energy
$V^\star$ = activation volume
p = pressure
R = gaz constant
Bn = proportionality factor
n = 1 for Newtonian flow
n > 1 for non Newtonian flow here
n = 3 (deformation of olivine)

$$\frac{\partial \tau}{\partial y} = 0 \qquad (4)$$

The boundary conditions are :

$$u = u_o,\ T = T_o,\ V = 0 \text{ on } y = 0$$
$$u \to 0,\ \ T \to T_\infty \ \text{ as } y \to \infty \qquad (5)$$

System 1 - 5 is solved by a method of successive approximation. From temperature repartition it is deduced heat flow repartition, the sea bottom profile and the lithospheric thickness as function of time.

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Table I

		π / λ km	$1/\lambda$ km	h km	ζ M m.
New Hebrides		239 ± 10	76.0 ± 3.2	24.2 ± 1.3	150
318	smoothing	306 ± 5	97.4 ± 1.6	33.6 ± 0.8	240 ± 5
	filtering	?			
Tonga					
319	smooting	310 ± 5	98.7 ± 1.6	34.2 ± 0.8	240
	filtering	312	99.3	34.5	
Kermadec					
321	smoothing	310 ± 5	98.7 ± 1.6	34.2 ± 0.8	240 ± 5
	filtering	316	100.6	35.0	

Table II

	Sea floor depth m.	age M.y.	thickness km $V^* = 30$ cm^3/mole	thickness km $V^* = 10$ cm^3/mole
New Hebrides	4500	33	61.8	67.5
Tonga Kermadec	5800	100	90.6	101.8
	5950	125	97.5	109.7

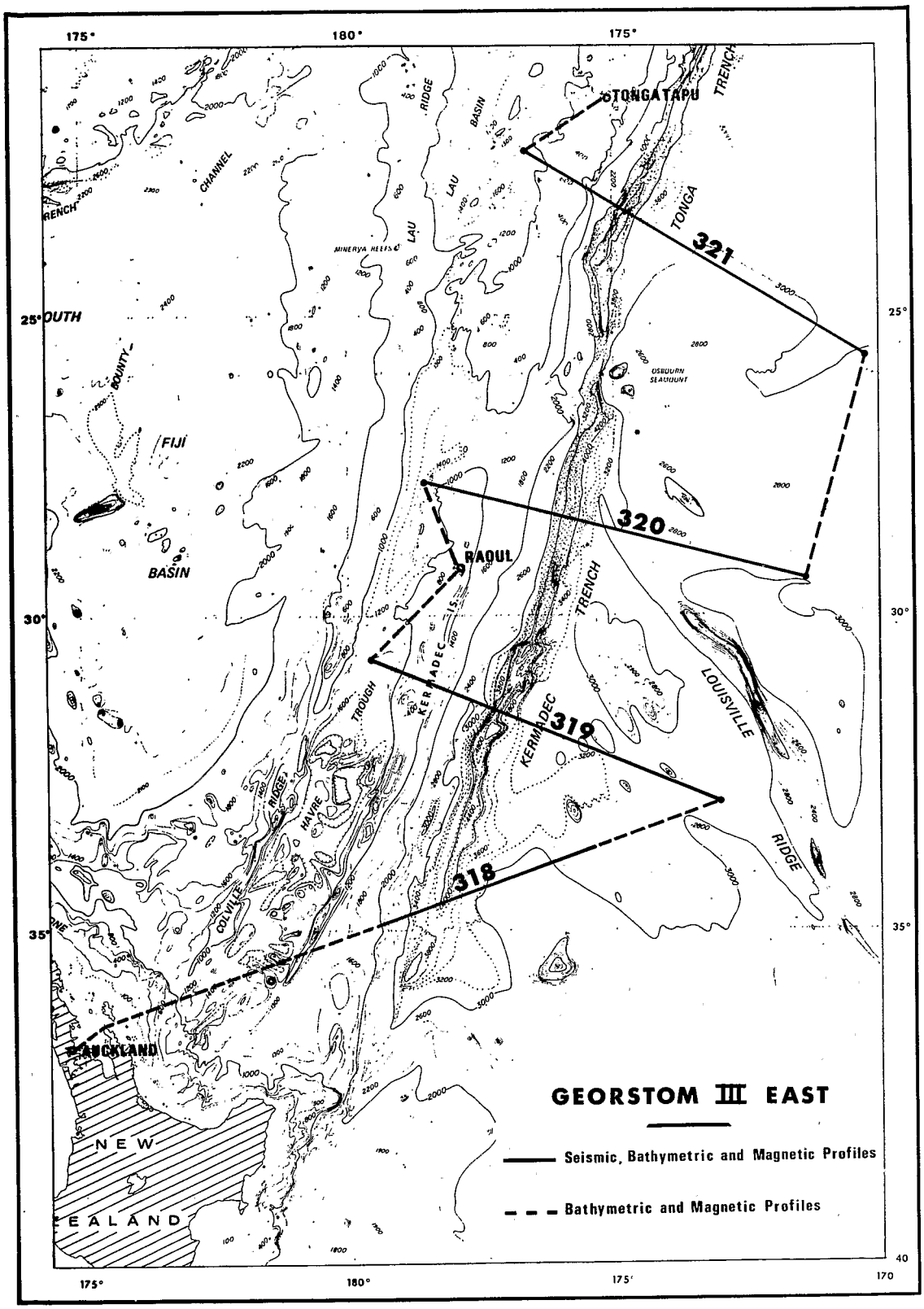

Fig. 1 - Tonga and Kermadec Trenches - Bathymetry and location of GEORSTOM III East profiles.

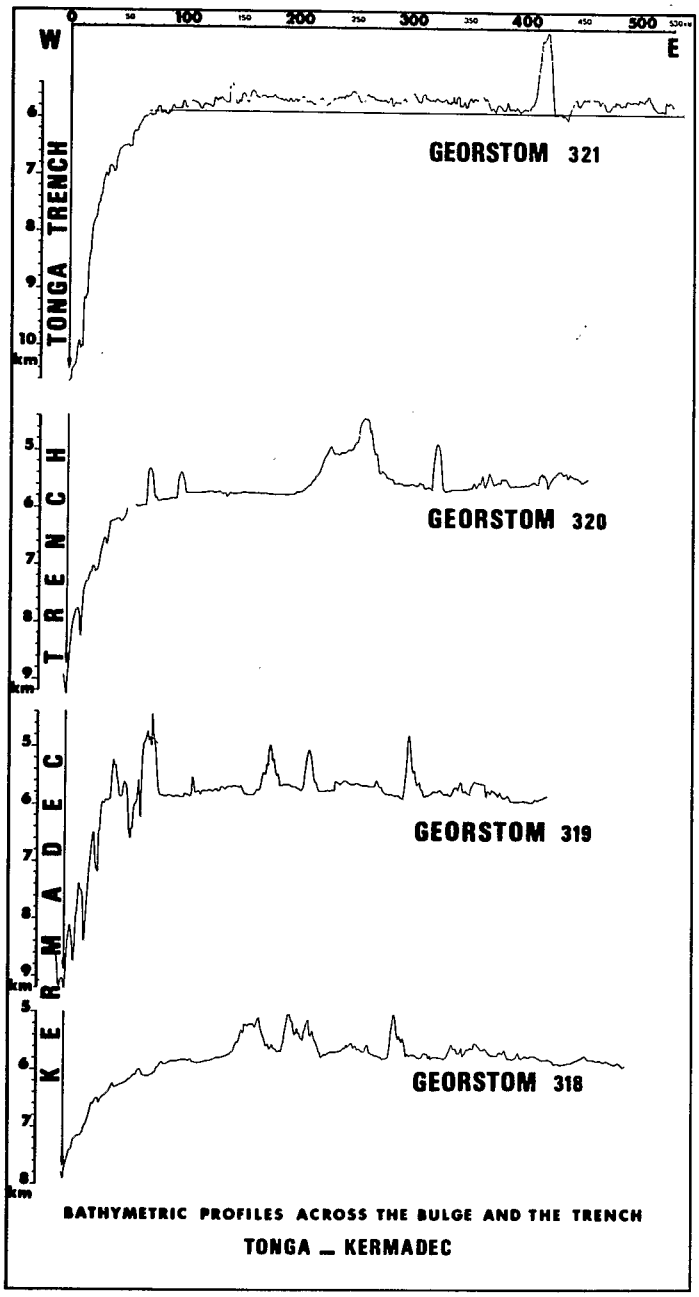

Fig. 2 - Bathymetric profiles of GEORSTOM III East cruise.

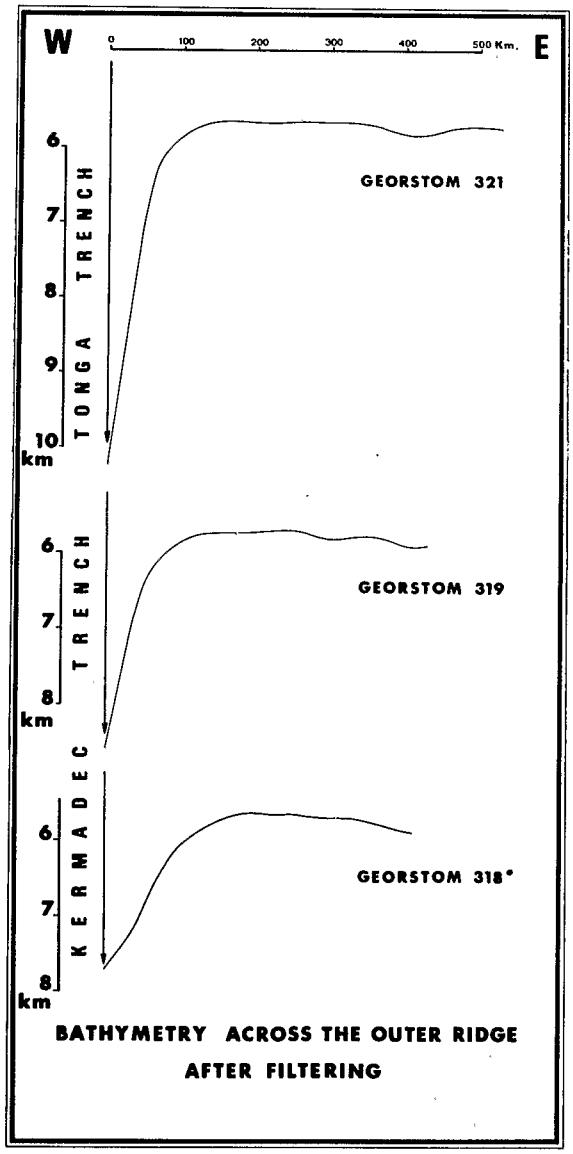

Fig. 3 - Bathymetry of GEORSTOM III East profiles after filtering. (★ Profile 318 is rabatted on a line perpendicular to the trench).

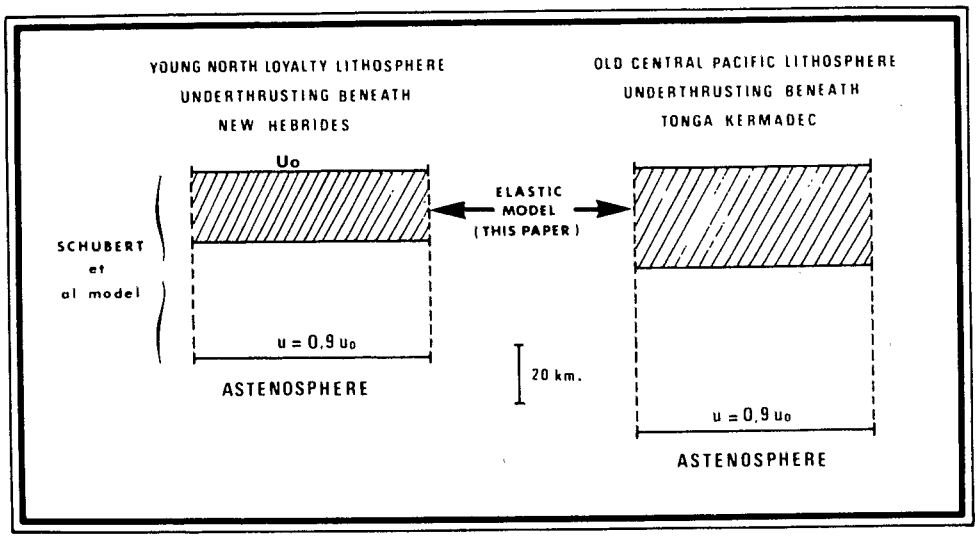

Fig. 4 - Comparison between the lithospheric thickness from Schubert et al (1976) and the elastic model (this paper).

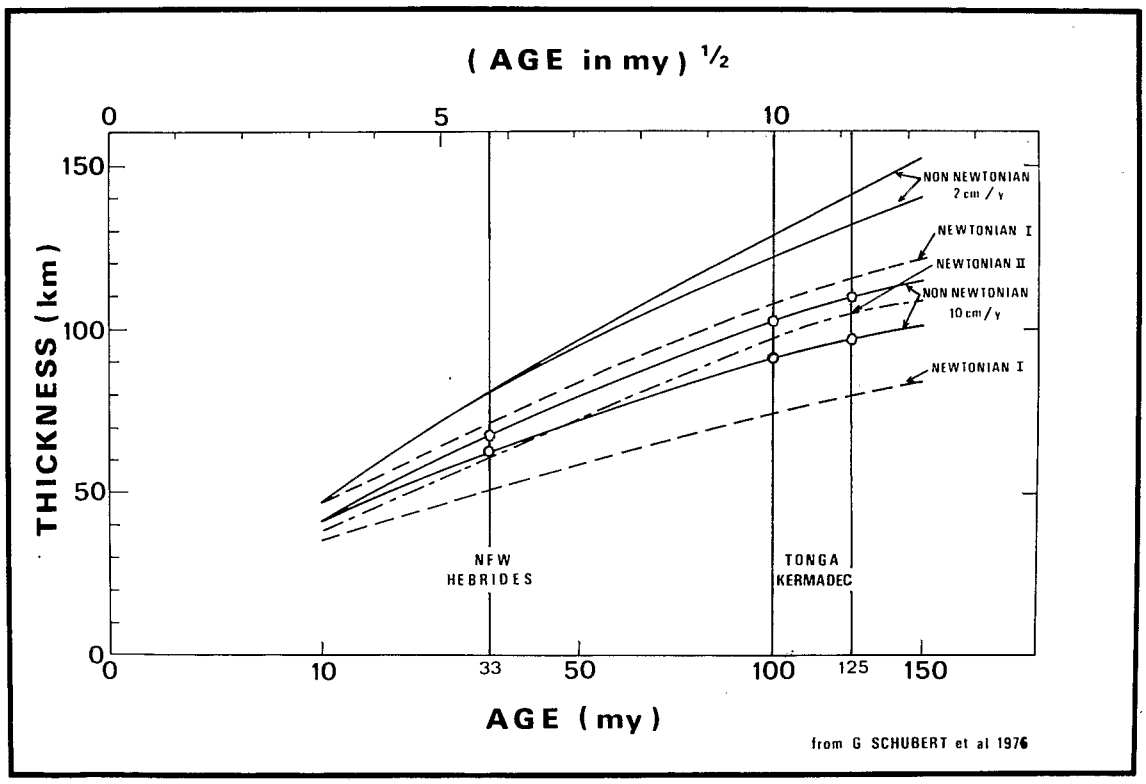

Fig. 5 - Newtonian and Non-Newtonian model curves from Schubert et al (1976).

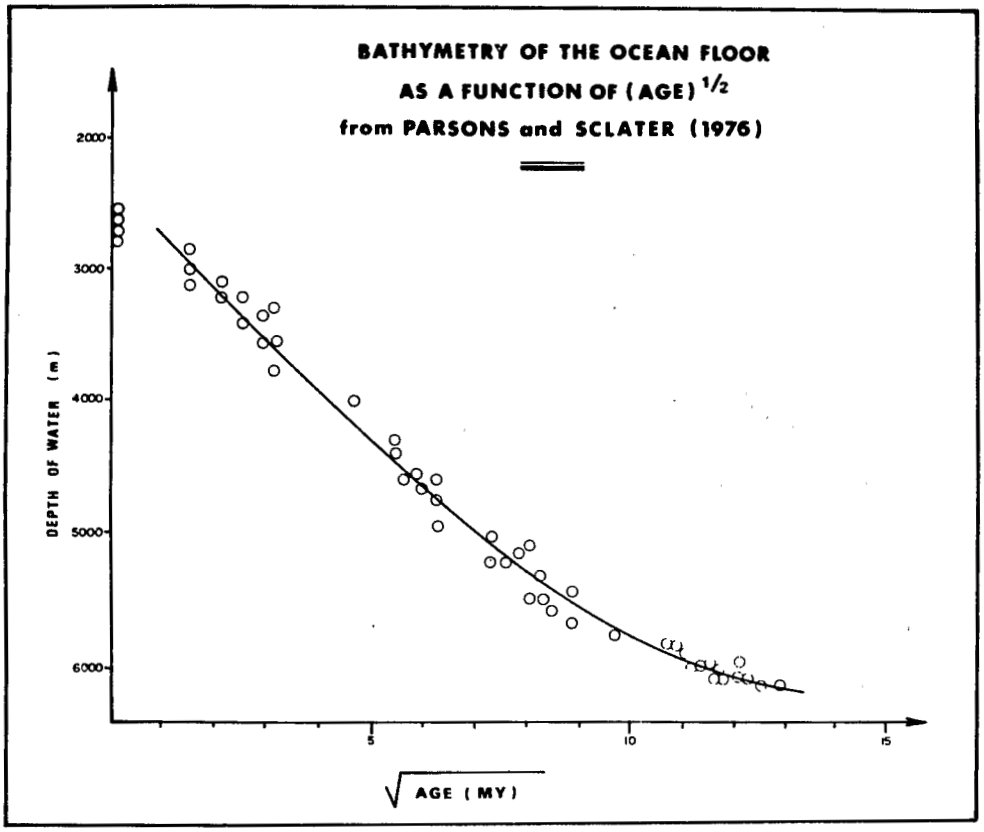

Fig. 6 - The empirical curve of the water depth - $(\text{age})^{1/2}$ from Parsons and Sclater (1976).

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