F. MONGELLI

RETHICKENING OF THE LITHOSPHERE AFTER SIMPLE STRETCHING IN THE TUSCAN-LATIAL PRE-APENNINIC BELT

Abstract. A simple expression was obtained for the thickness of the lithosphere during rethickening after thinning by simple stretching. It gives a rate of rethickening of about 2-3 km/Ma. This method was applied to the Tuscan-Latial pre-Appeninic belt and the resulting current lithospheric thickness was compared to that obtained by Panza et al. (1980) using the Rayleigh wave dispersion method, with acceptable results.

INTRODUCTION

The determination of the thickness of the lithosphere is of major importance for knowledge of its physical state because the two are strictly inter-related. If one assumes that the lithosphere represents the thermal boundary layer of the Mantle then it follows that its base coincides with the depth at which the Upper Mantle reaches melting point. Thus, geothermal studies offer a method for the estimation of the lithospheric thickness by calculating this depth.

The method is based on the calculation of the temperature at depth using the observed near surface temperature and heat flow density, and employing different models according to the geodynamic history of the studied area.

Of particular interest are the areas that are, or have been, affected by passive stretching, that is, have responded passively to a field of tensional stresses. In a previous work, Mongelli et al. (1989) interpreted the heat flow density of the Tuscan-Latial pre-Apenninic belt as due to simple passive stretching, and compared the calculated lithosperic thickness at the beginning of the stretching to that obtained by Panza et al. (1980) by the Rayleigh wave dispersion method. The results were consistent, and the small difference obtained was attributed to the subsequent rethickening of the lithosphere. The scope of this work is to estimate the rate of lithosphere thickening after passive stretching in order to improve the consistency.

THE MCKENZIE MODEL OF PASSIVE STRETCHING

In the simplest quantitative model of passive stretching, McKenzie (1978) assumes that the stable lithosphere stretches uniformly, plastically, and instantaneously, whereas the asthenosphere rises up and as a result, the heat flow density increases instantaneously due to advection. The stretching is followed by cooling and rethickening of the lithosphere and a decrease of the heat flow to the surface. In this model, the heat of crustal origin is ignored and only the heat coming from the base of the lithosphere is considered.

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Dipartimento di Geologia e Geofisica, Università, Bari, Italy.

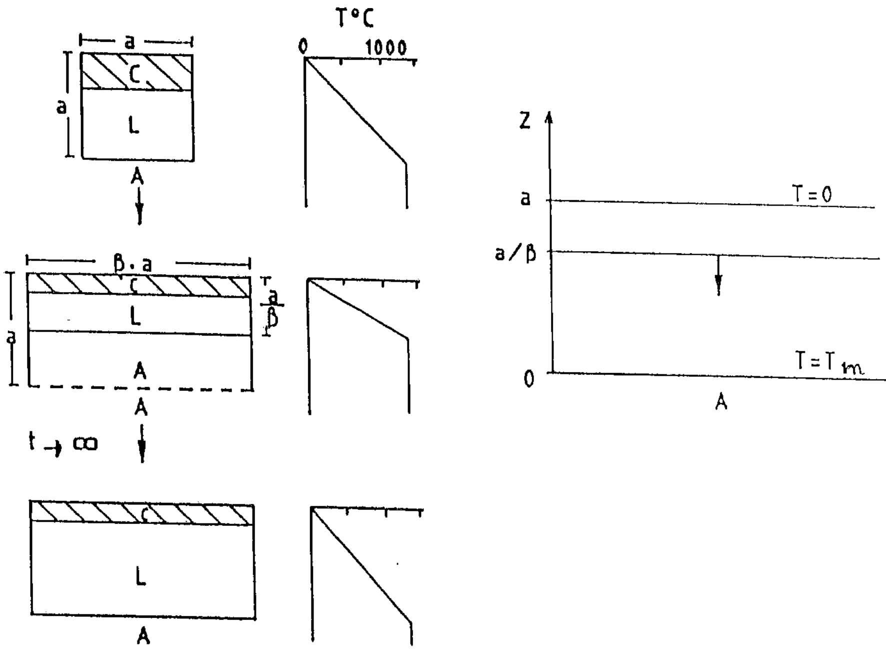

Fig. 1 - McKenzie's (1978) model of passive stretching and the reference system.

Assuming (Fig. 1)
T=0 surface temperature,
T_m temperature at the base of the lithosphere,
z measured upwards from the base of the lithosphere, before stretching,
a initial thickness of the lithosphere,
β stretching factor,
t time starting from the beginning of stretching,
$\tau = a^2/\pi^2 k$,
k thermal diffusivity,
then the temperature T after the stretching is given by (McKenzie, 1978)

$$\frac{T}{T_m} = 1 - \frac{z}{a} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{(n+1)}}{n} \left[\frac{\beta}{n\pi} \sin \frac{n\pi}{\beta} \right] \exp \left(\frac{-n^2 t}{\tau} \right) \sin \frac{n\pi z}{a} . \quad (1)$$

Subsequently, Jarvis and McKenzie (1980) demonstrated that an extension can be considered instantaneous if it lasts less than 20 Ma.

In recent years, improvements of McKenzie's model have also been proposed for continental basins, mainly in order to reconcile the stretching factors obtained from the heat flow and from the subsidence (sedimentation) data, using different stretching factors for the crust and mantle (Royden and Keen, 1980; Sclater and Cristie, 1980; Le Pichon and Sibuet, 1981; and others). In the case of the Tuscan-Latial pre-Apenninic belt, a comparison with the Rayleigh wave method results and geological evidence (Mongelli et al., 1989) suggest that it is not necessary to invoke particular stretching conditions.

Equation (1) is shown graphically in Fig. 2 assuming a=125 km, τ=62.8 Ma, and two different β values. The thickness of the lithosphere is given by $L = a - z_m$ defined from the z_m

Table - Lithospheric thickness' of the Tuscan-Latial belt by different geophysical methods.
Explanations: q_o=HFD at present; q_r=reduced HFD; Age=from the time of the stretching to the present; q_{os}=HFD of the surrounding stable area; a=thickness of the lithosphere of the surrounding stable area according Chapmann and Pollack method; q_{rs}=reduced HFD of surrounding stable area; β=stretching factor; L_0=thickness of the lithosphere at the time of the stretching; L=present thickness of the lithosphere according to this paper, and from Rayleigh waves.

q_0 mWm^{-2}	q_r mWm^{-2}	age Ma	q_{os} mWm^{-2}	a C-P km	q_{rs} mWm^{-2}	q_r/q_{rs}	β	L_o km	L H.F.D. km	L Rayl. w. km
120	98	4-6	55	120	33	3.0	2.9	41.3	60±15%	45±15

value for which $T=T_m$. Both plots show a z_m/a decrease and a corresponding increase of a-z_m with time.

The remaining problem is the quantitative estimation of the rate of increase.

RATE OF LITHOSPHERIC RETHICKENING

Assuming the condition $T=T_m$ in (1), one obtains an equation which is satisfied by z/a=0 for any t. An approximate solution of the problem can be obtained assuming that $T/T_m=\alpha$ is close to unity. Eq. (1) then becomes

$$\alpha=1-\frac{z_\alpha}{a}+\frac{2}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n}\left[\frac{\beta}{n\pi}\sin\frac{n\pi}{\beta}\right]\exp\left(\frac{-n^2t}{\tau}\right)\sin\frac{n\pi z_\alpha}{a}\ . \qquad (2)$$

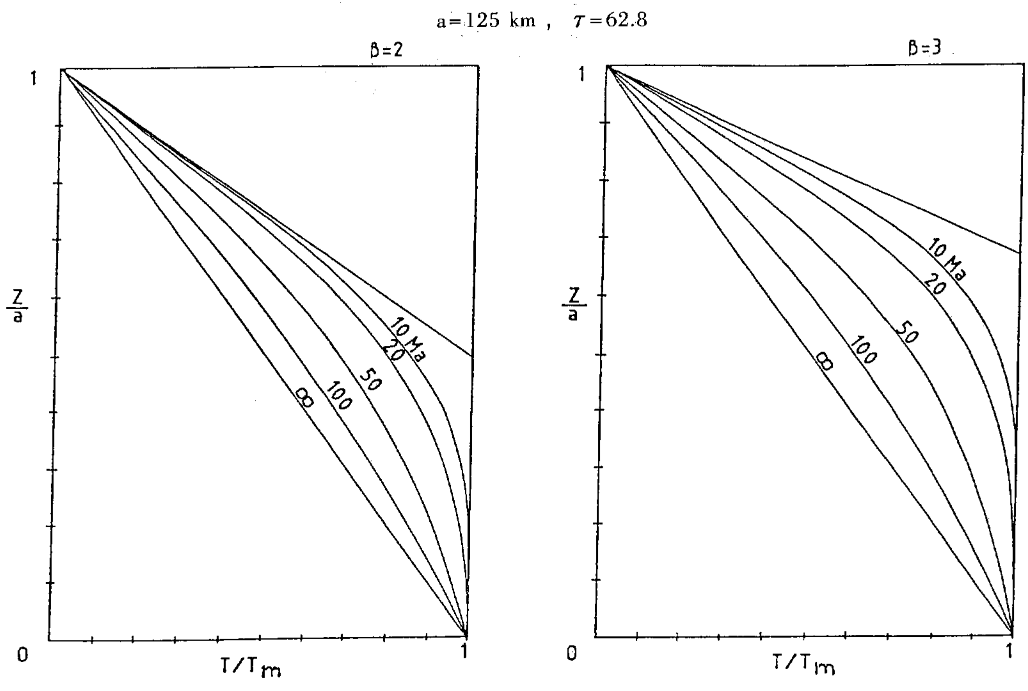

Fig. 2 - Temporal evolution of the lithospheric geotherms for two different extension values.

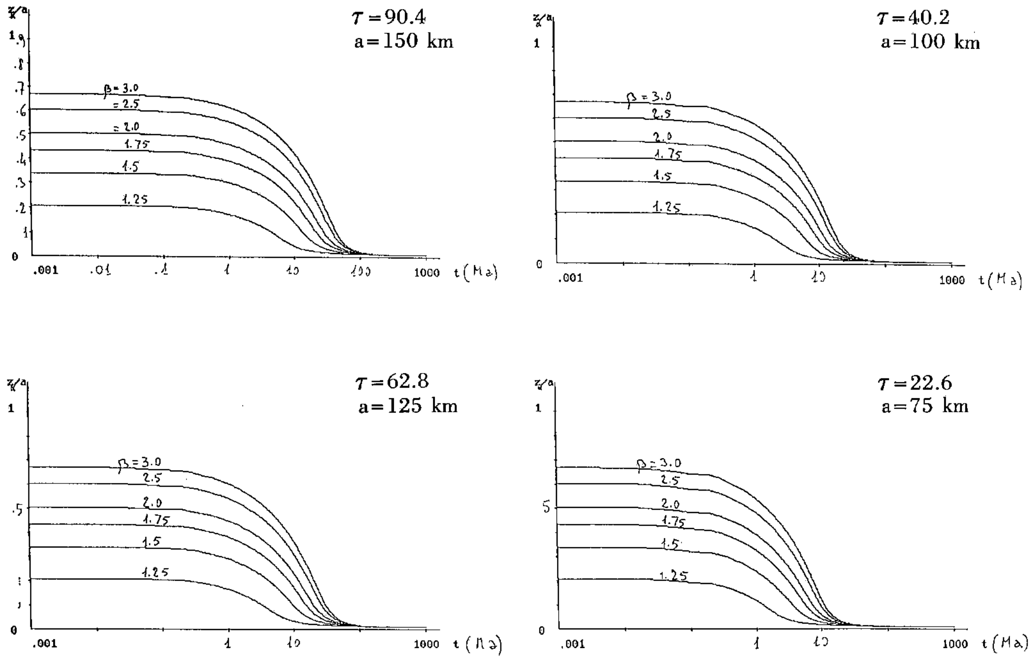

Fig. 3 - Temporal variation of z_α/a for a=75, 100, 125, 150 km. The lithosphere thickness increases following $L = a - z_\alpha$.

In choosing the value of α, one has to take into account the fact that eq. (1) is the solution of a parabolic differential equation, and thus it has a very high convergence rate. In fact, for $\alpha = 0.99$, we take into consideration a surface, which after an infinite time period is found approximately 1 km above the depth a, and is characterized by a temperature of about 10°C below that of T_m (the latter being of the order of 1000 °C).

The function z_α/a (t) was determined as follows. The t value was fixed and then from (2) the unique z_α/a value for which f (z, t) = α was obtained. The uniqueness derives from the fact that f is monotonous with respect to z; the numerical value of z_α/a was calculated by successive approximations. Fig. 3 shows the results obtained for some β values, with k=21.5 km^2/Ma, and a=75, 100, 125, 150 km. The sets of curves can be represented by a single numerical relation:

$$\frac{z_\alpha}{a} = 0.0109 + \left(1 + \frac{1}{\beta}\right) 0.99 \exp\left(-\frac{10\,t}{\beta\,\tau}\right). \qquad (3)$$

From the curves, one notes that the percentage rethickening of z_α/a depends strongly on β, and only slightly on τ (that is, a). For a lithospheric thickness of 100-120 km and $\beta = 2\text{-}3$, the rethickening rate is 2.8-3.2 km/Ma. For comparison, it should be remembered that, for the thickening of the oceanic lithosphere starting from the ridge, Parker and Oldenburg (1973) obtained the following relation:

$$L = 9.4\sqrt{t}, \qquad (4)$$

with L in km, t in Ma.

Over the time interval of 1-9 Ma, this gives an average rate of thickening of 2.2 km/Ma. A similar value is obtained from (3) for $\beta = 1.75$. In order to estimate β, one can follow the procedure indicated by McKenzie (1978). The surface heat flow density q_r as obtained from

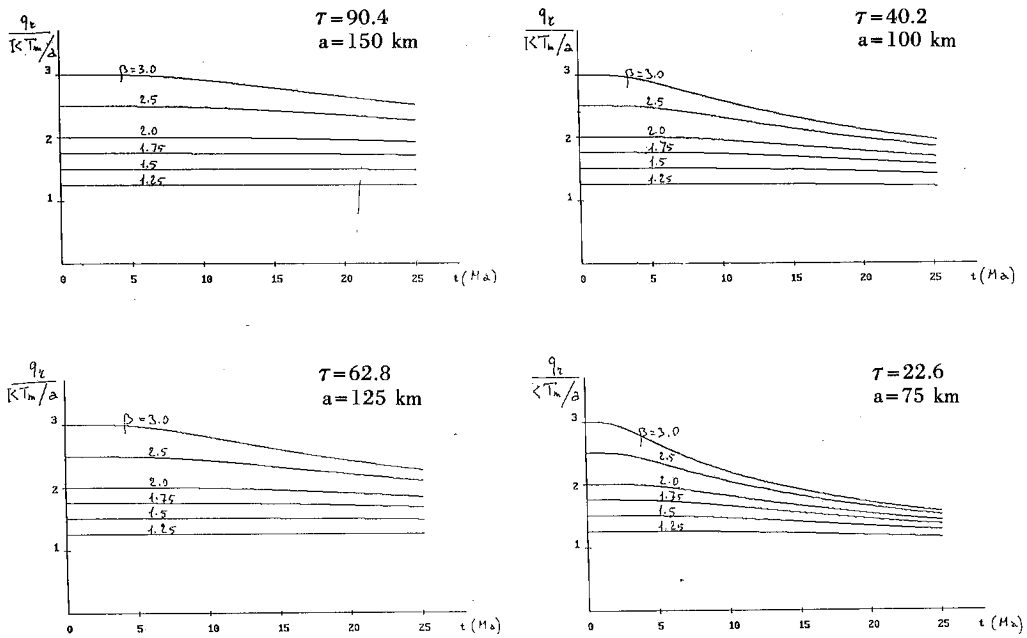

Fig. 4 - Determination of β based on the decay of heat flow density with time.

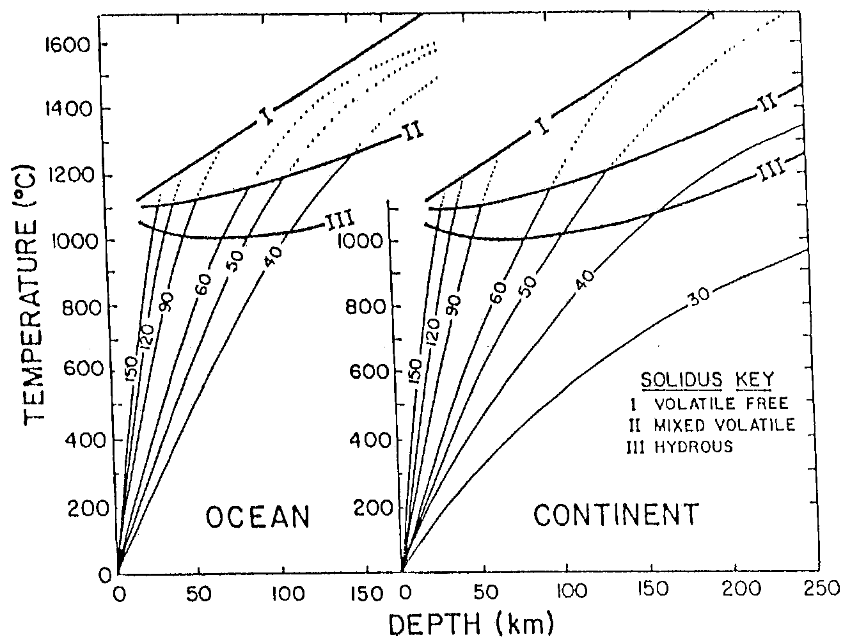

Fig. 5 - Determination of a according to the Chapman and Pollack (1977) method.

(1) (by taking the derivative with respect to z, setting z=a and multipling by K, which represents the average conductivity of the lithosphere), is

$$\frac{q_r}{KT_m/a} = 1 + 2 \sum_{n=1}^{\infty} \left[\frac{\beta}{n\pi} \sin \frac{n\pi}{\beta} \right] \exp \left(-\frac{n^2 t}{\tau} \right). \tag{5}$$

Fig. 4 gives a graphical representation of equation (5) for various a values. Then, knowing a, q_r, KT_m/a and the time t, the curves in Fig. 4 can be used to obtain β.

An experimental value of q_r is given by Birch et al. (1968) using

$$q_r = q_o - DA, \tag{6}$$

where q_o is the observed surface heat flow density, A is the radiogenic heat productivity, and D is a constant. By assuming that DA does not change significantly with the extension, the DA value can be estimated with good precision using the empirical relation proposed by Chapman and Pollack (1975):

$$q_{rs} = 0.6\ q_{os} \qquad DA = 0.4\ q_{os}, \tag{7}$$

where q_{os} is the amount of the heat flow density before extension, or observed in the surrounding stable area. Obviously $KT_m/a = q_{rs}$.

For the determination of a, we can use the curves of Chapman and Pollack (1977) which give it as a function of q_{os} (Fig. 5). It should be noted that all the q_o values used in this procedure need to be of regional significance; that is, local anomalies are to be subtracted. Taking into account the fact that the precision of q_{os} is around 10%, and that this influences the a estimate to the same degree, then the precision of z_α is of the order of 10-15%.

CONCLUSIONS

In order to apply the proposed method, the thickness of the lithosphere after stretching and the present day thickness were estimated on the basis of β determinations for Tuscany. This value was compared with that obtained using Rayleigh wave dispersion (Panza et al., 1980). The results are reported in the Table. As one can see, the thickness obtained by the Rayleigh wave method is between 30 and 60 km, and by the rethickening method after 4-6 Ma it is between 51 and 69 km. There is satisfactory agreement within the error limits, but the thermal method indicates a slightly greater thickness.

The proposed method allows the calculation of the lithosphere thickness in those regions, also of variable regime, for which only the heat flow density is known.

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REFERENCES

Birch F., Roy R.F. and Decker E.R.; 1968: *Heat flow and thermal history in New York and New England.* In: Zen E., White E., Hadley I.B. and Thompson I.B. Jr. (eds), Studies of Appalachian Geology: Northern and maritime. Interscience, New York, pp. 437-451.

Chapman D.S. and Pollack H.V.; 1975: *Global heat flow; a new look.* E.P.S.L., **28**, 23-32.

Chapman D.S and Pollack H.V.; 1977: *Regional geotherms and lithospheric thickness.* Geology, **5**, 265-268.

Jarvis G.T. and McKenzie D.; 1980: *Sedimentary basins formation with finite extension rates.* E.P.S.L., **51**, 343-361.

Le Pichon X. and Sibuet J.C.; 1981: *Passive margins: a model of formation.* J. Geophys. Res., **86**, 3708-3720.

McKenzie D.; 1978: *Some remarks on the development of sedimentary basins.* E.P.S.L., **40**, 25-32.

Mongelli F., Zito G., Ciaranfi N. and Pieri P.; 1989: *Interpretation of heat flow density on the Apennine chain -Italy.* Tectonophysics, **164**, 267-280.

Panza G.F., Calcagnile G., Scandone P. and Mueller S.; 1980: *La struttura profonda dell'area mediterranea.* Le Scienze, Maggio, 60-69.

Parker R.L. and Oldenburg D.W.; 1973: *Thermal model of Ocean ridge.* Nature Phys. Sc., **242**, 122.

Royden L. and Keen C.E.; 1980: *Rifting process and thermal evolution of the continental margin of Eastern Canada determined from subsidence curves.* E.P.S.L., **51**, 343-361.

Sclater J.G. and Cristie P.A.F.; 1980: *Continental stretching: an explanation of the post-mid-cretaceous subsidence of the Central North Sea Basin.* J. Geophys. Res., **85**, 3711-3749.