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Pulsation of tectonic phenomena and tectonophysical mechanisms *)

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With 5 figures

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Zusammenfassung

Heute glaubt man, daß die tektonischen Hauptphänomene aus progressiven Bewegungen einer geringen Zahl fester Platten in der Erdkruste resultieren. Wenn diese Platten sich entfernen, wird ein Expansionsgraben (von ozeanischem Typus) geöffnet; wenn die Platten sich einander nähern, wird die Kruste verkürzt und unter bestimmten Umständen ein Faltengebirge gebildet. Beide Arten von Bewegungen verursachen Erdbeben auf den Plattenrändern, und die seismische Tätigkeit soll Auskunft über die entsprechenden Bewegungen geben. Die Erdbeben weisen einen pulsierenden Charakter auf, weil anscheinend Kontraktion und Expansion mit einer Periode von 11 Jahren abwechseln. Für lange dauernde eintönige Plattenbewegungen können Thermalkonvektion oder radioaktive Undationen mögliche Ursachen sein; für die kurzperiodisch abwechselnden Phänomene jedoch ist ein Pulsieren der Gravitation vielleicht die beste Ursache. Eine pulsierende Gravitation kann eine Folgerung der allgemeinen Relativitätstheorie sein, wenn man ein angemessenes Modell des Weltalls übernimmt.

Abstract

At present, it is believed that the main tectonic phenomena result from progressive displacements of a small number of rigid plates which form the crust of the Earth. If the plates separate, a rift (of oceanic type) will open; and, if they approach, compression will shorten the crust and form eventually a mountain chain. Both rifting and compression produce earthquakes at the plate borders, and the seismic activity must depict the rate of movement of the plates. There is some indication that this seismic activity occurs in pulses with a period of about 11 years, rifting probably alternating with compression. For long lasting monotonic plate movements, thermal convection and radioactive undations could be adequate causes; but, for these short-period alternating phenomena, gravitational pulsations are considered the best available mechanism. Gravitational pulsations seem to be a necessary consequence of General Relativity, when applied to a convenient cosmological model.

Résumé

On croit, à présent, que les principaux phénomènes tectoniques résultent du déplacement progressif d'un petit nombre de plaques rigides qui forment l'écorce terrestre. Si les plaques s'éloignent, un rift (du type océanique) sera formé; et, si elles se rapprochent, la compression développée va raccourcir l'écorce et former à la longue une chaîne de montagnes. Tant l'ouverture de rifts que la compression orogénique produisent des tremblements de terre, cette activité séismique devant fournir des indications sur le mouvement des plaques. En fait, l'activité seismique montre un caractère pulsatoire avec période de 11 ans, qui semble dériver de l'alternance de contraction et d'expansion dans l'écorce. Les mouvements monotones de longue durée pourraient bien être dus aux courants de convection thermique ou aux undations radioactives; mais, pour les phénomènes pulsatoires de courte période, les pulsations de gravitation semblent être maintenant le mécanisme le plus convenable. Ces pulsations peuvent être une conséquence de la théorie de la Relativité Générale, si l'on adopte un modèle approprié pour l'Univers.

Resumo

Admite-se, presentemente, que os principais fenómenos tectónicos resultam do deslocamento progressivo dum pequeno número de placas rígidas que forman a crusta terrestre. Se estas placas se afastam, forma-se um rift (de tipo oceânico); e, se elas se aproximam, a compressão desenvolvida faz encurtar a crusta e pode vir a produzir uma cadeia de montanhas. Ambos os tipos de movimento produzem abalos de terra ao longo dos bordos das placas, a actividade sísmica devendo dar indicações sobre a variação do deslocamento daquelas placas. Esta actividade tem carácter pulsante, com período de 11 anos, parecendo que na crusta a contracção alterna com expansão. Para deslocações monótonas das placas, com longa duração, as teorias da convecção térmica ou das undações radioactivas podem oferecer mecanismos adequados; mas, para aqueles fenómenos alternantes de curto período, as pulsações de gravitação parecem constituir a explicação mais conveniente. Estas pulsações de gravitação podem ser uma consequência da Relatividade Geral, se for adoptado um modelo cosmológico apropriado.

Краткое содержание

В настоящее время распространено мнение, что основные тектонические феномены возникают в результате усиливающихся движений небольшого числа глыб земной коры. Когда эти глыбы удаляются, появляется грабен расширения (океанического типа); если же они сближаются, кора укорачивается и при некоторых условиях образуются складчатые горы. Оба типа движений на краях глыб вызывают землетрясения. Сведения об этих движениях может дать нам сейсмика. Землетрясения носят пульсирующий характер потому, что сжатие и расширение сменяются каждые 11 лет. За более продолжительные равномерные движения могут быть ответственными: тепловая конвекция, или же радиоактивные процессы. Периоды, длительность которых менее 11 лет, вызваны, наверно, пульсирующей гравитацией. Эту последнюю можно вывести из общей теории относительности.

Introduction

The new theory of global tectonics has provided a very important contribution for understanding the spatial distribution of tectonic activity.

Time of occurrence of crustal movements (and associated earthquakes) is another important aspect of the problem, which is not very thoroughly investigated yet.

This paper is an attempt to interpret the time variation of seismic and tectonic activity and the mechanism responsible for these phenomena.

Some features of Earth tectonics

According to the theory of global tectonics (Morgan, 1968), the crust of the Earth is supposed to be divided in several rigid plates (Fig. 1).

Movement of these plates produces along their borders two kinds of phenomena. When two plates separate, a fracture (or fractured belt) will develop along the common border, forming a rift of the type which is found at the middle of the oceans. Opening of the mid-oceanic rifts is accompanied by intrusion of basaltic dykes which form, in this way, new oceanic crust.

On the contrary, when two plates approach, one is forced to bend under the other, producing the so called subduction (which usually occurs at the oceanic trenches bordering some continents). Compression is now developed along the boundary between the plates (orogenic belt) and a mountain chain will be eventually formed.

The rigid plates are, therefore, growing at the midoceanic rifts and shortening at the orogenic belts. On both types of belts, conspicuous seismic activity accompanies the tectonic movements. The distribution of earthquake epicentres is indeed the best way to find the borders of the rigid plates (see Barazangi & Dorman, 1968).

The tectonic activity seems to occur in cycles, as pointed out by several authors (Bucher, 1933; Umbgrove, 1947). This pulsating character was emphasised by Beloussov (1962).

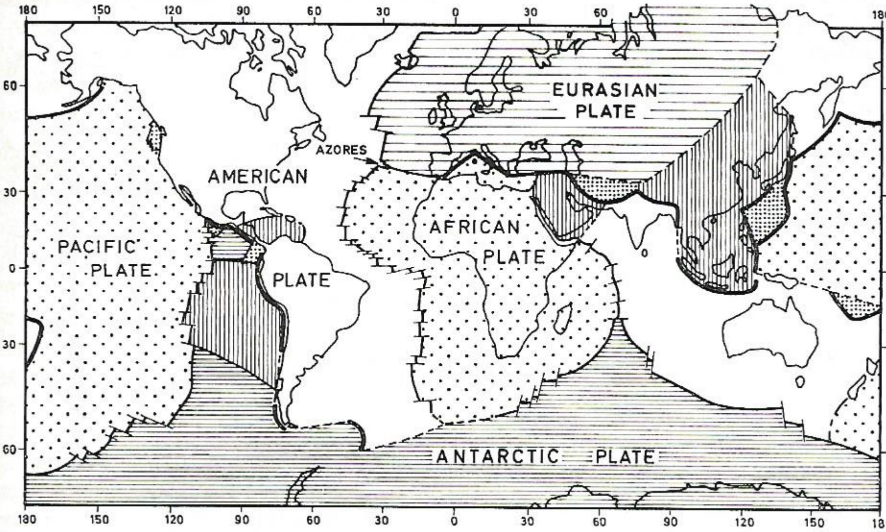

Fig. 1. Outline of the rigid crustal plates (after MORGAN, 1968).

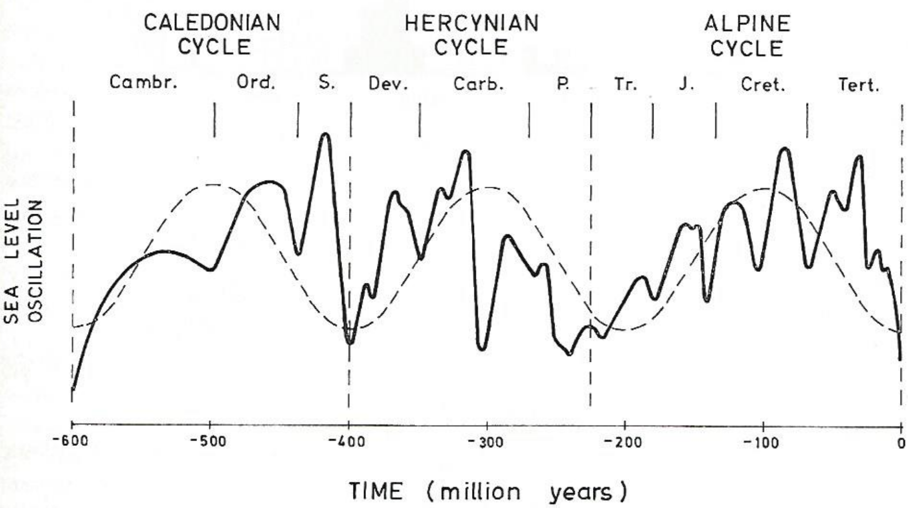

Fig. 2. World-wide sea level changes (based on data from BELOUSSOV, 1962).

Apparently, there are epochs when expansion at the rifts prevails over the orogenic shortening, and epochs when the contrary occurs. As both phenomena develop mainly in the oceans, regressions and transgressions of the sea will be associated with the tectonic cycles.

In Fig. 2 we show the changes of average sea level since the Cambrian times (based on data from BELOUSSOV, 1962). The long orogenic cycles have a period

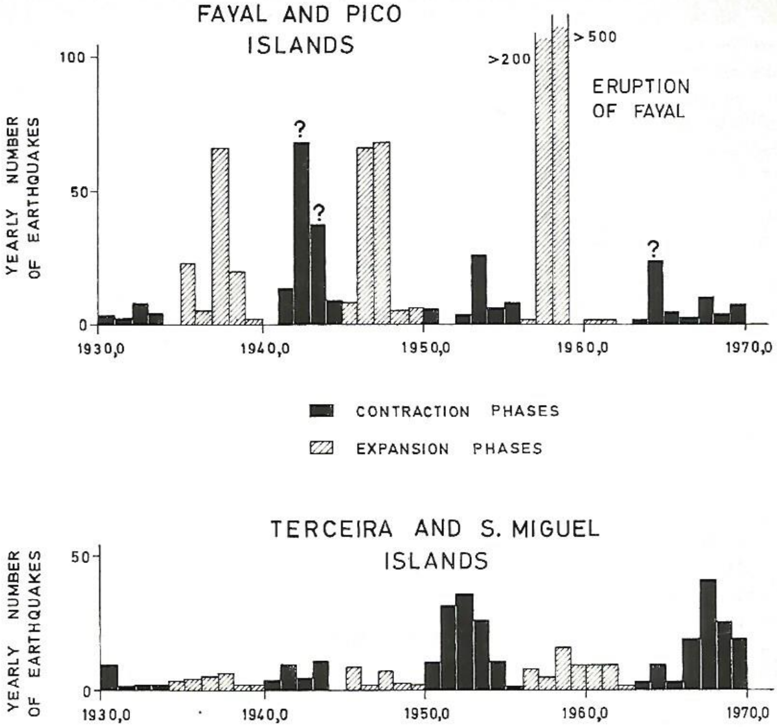

Fig. 3. Yearly frequency of earthquakes in some islands of the Azores (after Machado, 1973 a).

of about 200 million years, and on them is superimposed an irregular oscillation with intervals of, say, 30 or 40 million years.

According to Beloussov, these represent first and second order oscillations; many others, with shorter periods, would be found in a more detailed geological study.

The investigation of pulsating tectonic phenomena with very short periods is better performed on the frequency of the associated earthquakes, which will depict approximately the rate of movement of the rigid plates.

Simpson (1967; see also Machado, 1968) could find a definite seismic periodicity of 11 years, which he correlates with sunspot activity.

Much more informative is the seismicity of the Azores, which are situated at the triple junction of the American, African and Eurasian plates (Fig. 1). Here, one can expect to find earthquakes connected with the expansion of the mid-Atlantic rift and with the contraction of the Alpine belt (along the boundary between the African and Eurasian plates).

In fact, the main seismic swarms of the Islands Fayal and Pico alternate with the swarms of Terceira and San Miguel, but both exhibit a definite 11-year periodicity (Fig. 3). By studying the Earth tide effect (which acts as trigger-force), the main Fayal-Pico earthquake swarms were found to be associated with expanding phases, and the Terceira-San Miguel swarms with shortening phases (MACHADO, 1973 a).

This strongly suggests that everywhere expansion and contraction of the Earth's crust could alternate within an 11-year cycle. TAMRAZYAN (1962) also found some oscillations of the crust with that same 11-year period.

Possible mechanisms for tectonic phenomena

Within present tectonic theories, rifting and compression along the borders of the crustal plates are assumed to be a consequence of progressive displacement of those plates.

The natural tendency is to suppose that the phenomena are continuous and produced by permanent forces. Thermal convection in the Earth's mantle, which satisfies this condition, became then a popular mechanism (see, for instance, HOLMES, 1944, pp. 505—509; and RUNCORN, 1965). The convective cells would produce rifting over the ascending branches, and subduction when the subcrustal currents bend downwards; the final result would be a drift of the crust in good agreement with geological and palaeomagnetic data. Those currents could also explain the high heat flow found along the mid-oceanic rifts (cf. LEE & UYEDA, 1965).

An alternative mechanism was provided by the undation theory (see VAN BEMELEN, 1965; and also BELOUSSOV, 1962, pp. 756—765) which assumes that a portion of the Earth's mantle is subject to high radioactive heating; this "undation" would produce warping of the overlying crust, followed by gravitative sideward spreading. Rifting would then be produced at the middle of the undation and compression at the margins.

Both these mechanisms are expected to last for a long time (of the order of an orogenic cycle).

Variations of gravitation (or of the gravitational "constant") were first introduced to explain a continuous expansion of the Earth (EGYED, 1960; JORDAN, 1966). But, as the geological record suggested the presence of both contraction and expansion, pulsating mechanisms have been afterwards proposed (STEINER, 1967; MACHADO, 1967; KROPOTKIN, 1972).

Pulsations with period of 200 million years are adequate to explain the general repetition of orogenic cycles, but cannot explain so easily the apparently simultaneous activity at compression belts and mid-oceanic rifts.

An 11-year pulsation would, however, provide a mechanism capable of accumulating displacements at the right boundaries of the plates (MACHADO, 1968). Let us assume that expansion of the Earth's interior alternates with contraction (as suggested by the seismic activity of the Azores).

Then, during a phase of expansion, fractures will open at the mid-oceanic rifts and basaltic dykes will be intruded into the fractures. The dykes will solidify, at least near the surface, avoiding that the next contraction phase close the fractures again. Compression effects will, in this way, be shifted to the orogenic belts, where subduction occurs, and a net drift of the plate will therefore appear.

The following phase of expansion will open a new fracture along the previous semi-solid dyke and the process will be repeated again and again.

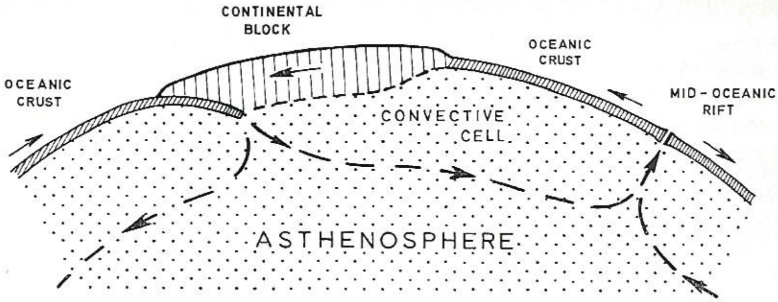

Fig. 4. Possible mantle currents produced by short-period gravitational pulsations.

Rifting and subduction will progress at different boundaries of the rigid plates. These phenomena (which alternate with intervals of 5.5 years) produce a decrease of pressure under the mid-oceanic rifts and an increase under the orogenic belts. A compensation current will be enforced at some deep level of the mantle, thus closing a convective cell (Fig. 4). This cell will explain the high heat flow at the mid-oceanic rifts, exactly as it did in the thermal convection theory.

The proposed mechanism depends on the availability of magma, at the base of the solid crust, ready to feed the assumed dykes. When magma is not available, the crustal drift will stop until magma is produced again in the upper mantle. This agrees with BRIDEN's (1967) quiescence intervals which he found in the palaeomagnetic study of the southern continents.

These short-period pulsations have a small amplitude (with a relative value of the order of 10^{-7}) and must be superimposed on the large oscillations of Fig. 2.

Gravitational pulsations

Changes of gravitation are apparently a convenient mechanism for the short-period pulsating tectonic phenomena. It is, certainly, worth to try some insight in its physical background.

EINSTEIN (1956; see also KROPOTKIN, 1971) suggested that the mass of a body could be expressed as

$$M = \mu \, m \tag{1}$$

where μ is a factor close to unity, depending on the prevailing potential due to other masses of the Universe, and m ist the mass of a body in a point where $\mu = 1$.

Considering that only the actual expanding "visible" Universe may have influence on the physical phenomena occurring in its centre, we must have (cf. MACHADO, 1972 a, 1973 b)

$$\mu = \sqrt{1 + \varkappa (\psi - \psi_0)} = \sqrt{\varkappa \psi} \tag{2}$$

with

$$\varkappa = 8 \pi f / c^2 \tag{3}$$

f being the gravitational constant and c the velocity of light; and

$$\psi = \frac{1}{4\pi} \int_{\Omega} \frac{\mu \varrho + W/c^2}{r \sqrt{1 - (r/R)^2}} \, d\Omega \tag{4}$$

where $\mu\varrho$ is the density in the infinitesimal volume $d\Omega$ at a distance r from the centre of the spherical "visible" Universe; Ω is the volume of this Universe and R the radius of its boundary; W is the total energy, per unit volume, contained in $d\Omega$ ($\mu\varrho$ and W are referred to coordinates tied to $d\Omega$). In equation (2), ψ_0 is a reference potential which, according to MACH's principle, is chosen to make μ vanish in an empty Universe (where $\psi = 0$), thus leading to the simplified form of the equation.

We assumed, as usual, that in the expanding Universe every point is receding from its centre with a velocity

$$v = Hr \tag{5}$$

which at the boundary becomes

$$c = HR \tag{6}$$

Here H is Hubble's constant.

As equation (1) must apply to both the inert and the gravitational mass, the movement of a particle (having unit mass when $\mu = 1$) in a gravitational field must satisfy the equation

$$\frac{d}{dt}\left(\mu \frac{d x_i}{dt}\right) = \frac{\varkappa c^2}{2} \mu \frac{\partial \psi}{\partial x_i} \tag{7}$$

where x_i ($i = 1, 2, 3$) are cartesian coordinates and t the time (the 4 coordinates form a local MINKOWSKI space-time).

On the other hand, according to General Relativity, the equations of movement of a particle of unit mass must be a geodesic of the Riemannian space-time which describes the Universe.

Within a fair approximation, equations (7) are the equations of a geodesic of the orthogonal Riemannian space-time whose metric (as defined by the element of arc ds) is

$$d s^2 = e^{-\mu^2 + 1} (d x^4)^2 - \frac{\mu^2}{c^2} \sum_i (d x^i)^2 \tag{8}$$

x^4 being now the time-like coordinate and x^i the space-like coordinates.

It is important to note that, within a first-order approximation, this is equivalent to the metrics proposed in other relativistic theories of gravitation (cf. FOCK, 1964; MCVITTIE, 1965). The ratio ψ / c^2 is also analogous to the scalar field introduced by BRANS & DICKE (1961).

Assuming that μ is independent of x^4, substitution of the coefficients of the metric (8) into EINSTEIN's field equations leads approximately to (MACHADO, 1972 a, 1973 b)

$$\sum_i \frac{\partial^2 \psi}{\partial x_i^2} = -(\mu\varrho + W/c^2) \tag{9}$$

$$c^2(\mu^2 - 1) = 15\,p/2\,(\mu\varrho + W/c^2) \tag{10}$$

where p is the pressure. Here we used local MINKOWSKI coordinates and assumed that the distributed gravitational energy equals the internal energy (of the fluid equivalent to the Universe, considered in a large scale); other forms of energy were neglected.

Equation (9) is POISSON's equation near the centre of a field described by the potential (4). And equation (10) describes the equilibrium of a perfect gas under adiabatic conditions

$$\varkappa\, c^2 (\psi - \psi_0) / 2 = \gamma\, p / (\gamma - 1)\,(\mu\varrho + W/c^2) \tag{11}$$

if $\varkappa\, \psi_0 = 1$, and if the ratio of specific heats under constant pressure and under constant volume is $\gamma = 15/11$. Here W/c^2 was added to the density, following the ideas of Special Relativity.

Therefore, within the used approximation, the metric (8) not only leads to the equations of motion (7), but satisfies also the field equations of General Relativity.

The above considerations show that gravitational attraction, which is represented by the right side of (7), depends on the factor μ. As $\varkappa$ is proportional to f and $\partial\psi/\partial x_i$ depends practically only on the "local" masses (which have approximately a common value of μ), we can give to the attraction its classical expression if we assume that the gravitational constant is $f\,\mu^2$. This "constant" will thus vary with the point of space, because the visible universes of the various points are likely to be slightly different (because they include different galaxies, as well as different celestial diffuse masses).

We are assuming that the local values of μ are fairly constant in time (which implies a balanced creation of matter in the expanding Universe), but, as the Sun travels along a galactic orbit, the gravitation in the solar system will depict the variation of μ^2 along that orbit (this could account easily for the relatively large oscillations shown in Fig. 2).

For explaining the fair regularity of the 11-year pulsation the following model has been proposed (MACHADO, 1972 a).

The galactic plane (corresponding to the average orbit of the Sun) is assumed to exhibit a maximum of ψ, which can be approximated by the equation

$$\psi = \psi_1 (1 - n^2 x^2) \tag{12}$$

where x is the distance of the Sun to that plane, and n is a constant, making nx small as compared with unity; ψ_1 is the maximum of ψ.

Then, the Sun, if deviated from the galactic plane, will oscillate according to the equation

$$\frac{d^2 x}{d t^2} = \frac{\varkappa\, c^2}{2} \frac{d\psi}{d x} \cong - n^2 c^2 x \tag{13}$$

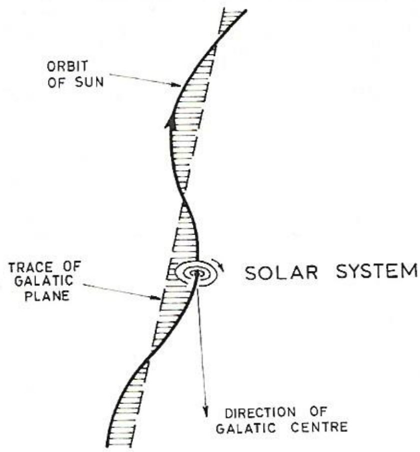

Fig. 5. Possible oscillation of the Sun along the galactic orbit (after MACHADO, 1972 b).

where the approximate value $\psi_1 \cong 1/\varkappa$ has been used [following equation (2) with $\mu \cong 1$].

The period of the oscillation is $2\,\pi/\text{nc}$, n being adjusted to give a period of 22 years (which gives two maxima of μ within each cycle). The resulting oscillation is outlined in Fig. 5.

This model implies that the Earth's movement round the Sun would act as a trigger-force for the associated seismic activity. This is in fair agreement with the monthly distribution of the Azorean earthquakes (MACHADO, 1973 b).

An 11-year pulsation, with a smaller yearly oscillation superimposed, seems also to be present in the speed of the Earth's rotation, as shown by MARKOWITZ (1970). This is easily explained by changes of the Earth's moment of inertia induced by the variation of μ.

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