Arthur Holmes, 1929, *Radioactivity and Earth Movements*

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Résumé

Extraits de l'article fondateur de Holmes sur la convection interne comme moteur possible des mouvements continentaux.

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Nous présentons deux larges extraits de l'article fondateur de Holmes, *Radioactivity and Earth Movements*, de 1929 (publié en 1931), dans lequel il explique que les mouvements de convection dans le substratum peuvent être le moteur si énigmatique de la dérive des continents de Wegener. Holmes a initialement présenté son hypothèse lors d'une conférence à la Société Géologique de Glasgow le 12 janvier 1928. Un résumé fut ensuite publié dans le *Geological Magazine* en 1928. Notre travail s'appuie sur l'article de David Oldroyd, « Arthur Holmes' paper of 1929 on convection currents within the Earth as a cause of continental drift », *Episodes*, Vol 34, n° 1, mars 2011, p. 41-50.

- Holmes A., *Radioactivity and continental drift*, Geological Magazine, vol. 65, 1928, p. 236–238.
- Holmes A., « Radioactivity and earth movements », Transactions of the Geological Society of Glasgow, vol. 18 (Part 3), 1929, p. 559–606.

Les travaux géologiques d'Arthur Holmes (1890 - 1965)

Arthur Holmes est considéré comme l'un des plus grands géologues du XX$^{\text{ème}}$ siècle. Il a d'abord été professeur à l'université de Durham puis à Edimbourg, où il continue de jouir d'un très grand prestige. Ses travaux géologiques concernent essentiellement l'Afrique et la Birmanie, et il a apporté des contributions majeures en pétrologie, géomorphologie, géologie structurale et géochronologie. Mais son innovation essentielle réside dans l'application à la Terre de la découverte de la radioactivité par Becquerel en 1896. Il bouleverse ainsi radicalement le cadre pour l'estimation de l'âge de la Terre, en arrivant le premier à des âges supérieurs au milliard d'années et il apporte un mécanisme physique plausible pour expliquer les dérives continentales telles que Wegener les a imaginées. Son travail de pionnier s'est cependant heurté à une vive opposition.

Le contexte de l'article de 1929

Au moment où paraît l'article de Holmes, l'hypothèse de Wegener sur la dérive des continents a été rejetée par la majorité de la communauté scientifique. Lors du congrès de 1926 de l'American Association of Petroleum Geologists (les actes du congrès sont publiés en 1928), la plupart des intervenants s'élèvent vertement contre une idée aussi extravagante et aussi peu fondée. L'opposition majeure concerne les mécanismes de la dérive : aucune des forces invoquées par Wegener ne paraît suffisante, et de loin, pour expliquer la translation des continents. Privée d'une justification physique, l'hypothèse de Wegener n'a pas été prise au sérieux.

Holmes n'est pas un adhérent dogmatique de la dérive des continents, cherchant à trouver à tout prix un moteur aux translations. Il est plutôt concerné par le problème de la production de chaleur par les désintégrations radioactives. En 1915, puis en 1925, il a publié une série d'articles intitulés *Radioactivity and the Earth Thermal History*. Dans les premiers, il est encore partisan de la théorie contractionniste et il considère que la production radioactive de chaleur ne fait que réduire le refroidissement général de la Terre, sans l'annuler. Cette position invalide déjà les calculs de Lord Kelvin sur l'âge de la Terre et Holmes lui attribue ainsi un âge de 1,6 milliards d'années. Mais en 1925, il abandonne la théorie contractionniste car, d'après lui, elle ne permet pas d'expliquer la plupart des phénomènes de la géologie historique. Il considère alors que les désintégrations radioactives nécessitent immanquablement un processus de « décharge » pour la chaleur interne. C'est ce qui constitue la base de son article de 1929 : *« Un des objets de cet article est de discuter d'un mécanisme pour évacuer l'excès de chaleur, impliquant une circulation de matière dans le substratum par des courants de convection, et d'examiner la dérive des continents produites par de tels courants »* (p. 565). Son adhésion à la théorie de Wegener ne vient « qu'après coup », lorsqu'il se rend compte que le taux d'éléments radioactifs dans les roches internes impose l'existence de courants de convection et que pour éviter un chauffage permanent, il faut un processus pour évacuer la chaleur interne tel que la dérive des continents.

Table des matières de l'article et présentation des extraits

Le premier extrait provient de la première partie : "Tectonic Hypotheses", où Holmes présente les différentes forces pouvant agir sur les continents. Il montre qu'aucune des forces gravitationnelles ne peut expliquer la dérive des continents de Wegener, ce qui lui permet de conclure que les forces dominantes impliquées dans le mouvement de la croûte doivent nécessairement provenir de l'intérieur de la Terre. Il considère alors les hypothèses dans lesquelles les processus thermiques jouent le rôle principal et il présente son idée de la convection mantellique.

Le second extrait, pris dans la cinquième partie : "Convection Currents in the Substratum", permet de comprendre sa conception de la convection. D'une manière étonnante, la géométrie de la convection qu'il imagine résulte d'une analogie avec la circulation atmosphérique. Il suppose d'abord une circulation planétaire et, toujours par analogie avec les vents, il considère que des systèmes cycloniques et anticycloniques se superposent à la circulation générale. Ces systèmes secondaires naissent du chauffage différentiel dû aux variations dans la teneur en éléments radioactifs de la croûte.

Premier extrait : I. TECTONIC HYPOTHESES.

Both external and internal geological processes are controlled by gravity and the earth's bodily movements. The circulations of matter which constitute the external processes are maintained by energy derived from the sun, whereas the internal processes derive much of their energy from the earth's internal heat, the latter being partly an inheritance, and partly an income supplied by atomic disintegration. Hypotheses relating to the physical causes of earth movements must take all the relevant factors into consideration as fully as the data permit. At present there is a plethora of hypotheses in the field, some of which are mutually contradictory. Much of this confusion is a result of lack of data, and is temporarily unavoidable; on the other hand a good deal is unnecessary, and has been introduced by exaggerating the effects of certain factors while ignoring those of others. The most remarkable example of a neglected source of geological energy is the heat generated by the radioactive elements. Outside the British Isles there has been little recognition of the importance of this factor, and it is therefore hardly a matter for surprise that hypotheses in which it is ignored should prove to be inadequate.

Among the forces to which appeal has been made are the following:

- *Gravitational*:
  - *Cosmic* Stresses set up by
    - (a) Tides due to the sun and moon.
    - (b) Precession of the equinoxes.
  - *Terrestrial*
    - (c) Attraction between continents.
    - (d) *Pohlflucht* force.
    - Stresses set up by
    - (e) Departures from isostatic equilibrium.
    - (f) Departures from hydrostatic pressure in the crust.
    - (g) Condensation due to re-adjustments of the material of the earth.
- Thermal
    - Stresses set up by
    - (h) Contraction due to change of state and cooling by conduction.
    - (i) Expansion due to heating-up of the earth's interior.
    - (j) Contraction (h) and expansion (i) alternating in time (Joly's hypothesis of thermal cycles).
  -
    - (k) Convection currents in the substratum (the hypothesis developed in this paper).

[...]

(h) In 1915 I adopted the traditional hypothesis of a steadily cooling earth, and assumed that the effects of radioactivity were limited to slowing down the rate of cooling. Instead of calculating the age of the earth from the present thermal state of the crust, as [Lord] Kelvin had done, I took the age as a known datum and assumed that radioactivity fell away exponentially with depth, so that the present average gradient could be reached after 1,600 million years of cooling. With a known distribution of radioactivity, it was then possible to calculate the present downward variation of temperature. [...]

The consequences of this hypothesis (which reconciles all the more obvious thermal data quite satisfactorily) have been very thoroughly explored by [Harold] Jeffreys. In 1925, however, I abandoned the hypothesis because of its failure to account for the leading phenomena of geological history. The objections are:

- (1) Its inconsistency with the prevalence of vulcanism of the plateau basalt type [...]
- (2) Its quantitative inadequacy to provide the contraction necessary to produce folded and overthrust mountain structures. The calculated reduction of area is only about one sixth of the amount calling for explanation.
- (3) The distribution of orogenic periods in time is systematically different from that deduced from the hypothesis. [...]
- (4) The improbability that compression dispersed through a layer 150 km. thick could produce relatively superficial nappe structures like those of the Alps.
- (5) The failure of the hypothesis to account for marine transgressions, and particularly for the development of geosynclines.
- (6) The fact that under the hypothesis continental drift is manifestly impossible. It is of no service to say, as Jeffreys does, that continental drift is "out of the question."
- (7) No geochemical reasons are offered for the fundamental supposition that the substratum is so poor in the radioactive elements that its heat output can be ignored. [...]

From the above discussion it will be realised that the substratum should still be in a "fluid" or glassy state. One of the objects of this paper is to discuss a mechanism for discharging the excess heat, involving circulation of the material of the substratum by convection currents, and continental drift operated by such currents. Tidal friction may co-operate to a slight extent, but is not essential. The possibility that currents might be set up by differential radioactive heating was recognised by [Alfred] Bull in 1921, though in 1927 he considered that little evidence could be adduced in its support. [Otto] Ampferer has postulated unterströmungen in the substratum to explain crustal movements, and [Robert] Schwinner considers the currents to be due to convection. [Ernst] Kraus also finds it necessary to adopt magmatic currents to explain the evolution of geosynclines, orogenic belts and continents. Born has pointed out that, although such hypotheses thoroughly meet the geological requirements, they suffer from the defects that they demand extensive movements in the substratum and require a source of energy that has not been made intelligible. But one need not look far for an adequate source of energy. It is to be found in the radioactive elements.

Deuxième extrait : V. CONVECTION CURRENTS IN THE SUBSTRATUM.

THE CONDITIONS FOR CONVECTIVE CIRCULATION.

In the simple case of an extensive layer of uniformly heated viscous liquid, with rigid conducting surfaces above and below, the conditions leading to convection currents are fairly well understood. There is stability until a certain critical temperature gradient is reached, depending upon the compressibility, conductivity, and viscosity of the fluid. As the critical gradient is exceeded, the uniformly stratified distribution of material becomes unstable, and in the attempt to restore stability a system of complementary currents begins to develop, ascending in some places and descending in others. The disturbances are at first chaotic, but of all the possible systems of movement some tend to persist and to increase steadily with time at the expense of others. This leads gradually to the survival of local centres from which vertical currents ascend. Towards the top the currents spread out in all directions from each centre until they interfere with one another, turn downwards, and form sheet-like return currents. Thus irregular polygonal prisms come to be enclosed by the downward currents. Under ideally uniform conditions the polygons would ultimately become hexagonal and the diameter of the hexagons would be three or four times the depth of the convective layer. In the earth the critical gradient appears to be about 3° C. per km. So long as this is exceeded convection must go on, provided that the material has no strength, and that the viscosity is not too high.

[...]

At high temperatures the strength of materials rapidly diminishes and, as the fusion point is approached, it disappears. It is therefore to be expected that the substratum should be devoid of strength. Geologically, the abundant evidence pointing to regional isostatic compensation within a depth of 60 km. or less is the best indication that this expectation is realised. [...]

Granting the physical possibility of convection within the substratum, the effect of radioactivity would be to steepen the gradient over the critical gradient and so increase the rate of circulation until the new heat could be carried off as fast as it was generated. With the differentiation and crystallisation of the crustal materials, the interior would be able to discharge the excess heat only in so far as the crust could be fused or broken through from below. Both processes are described in the sections that follow.

The mode of circulation of the material of the substratum can be deduced from general principles. Il will depend mainly

- (a) on the varying thickness of the substratum from equator to poles;
- (b) on the varying thickness and radioactive content of the crustal cover; and
- (c) on the rotation of the earth; upward moving currents will be deflected westwards and downward currents eastwards; in the northern hemisphere horizontal movements will turn towards the right and in the southern towards the left; such deflections, however, are likely to be very slight, and they will not be further discussed at present.

THE PLANETARY CIRCULATION.

Considering the first of these we may infer by analogy with the atmosphere a circulation like that of the planetary system of winds. Within the earth the ellipticity of successive shells of increasing density gradually decreases with depth. Thus a considerable part of the difference between the polar and equatorial radii will be concentrated in the substratum. The equatorial thickness being greater than that beneath the poles, and the distribution of radioactivity being independent of latitude, the equatorial temperature gradient will be steeper than that towards the poles. Thus the general circulation from this cause should be as shown in Fig. 1.

As the equatorial ascending currents approach the base of the crust, they divide; half turning north and half south. As a result of the powerful drag thus imposed on the lower part of the crust the latter will flow with the currents but with a lower velocity, each level moving less rapidly than its underlying neighbour. The upper levels will tend to give way by fissuring or faulting as in the case of a glacier or ice-sheet. Thus the ultimate effect on continental blocks originally over the equator will be to drag them apart, leaving a depressed geosynclinal or oceanic belt along the equator.

We have already seen that the early operation of the Pohlflucht force should have left the continents distributed symmetrically about the equator. The long history of the Tethys girdling the continental half of the earth between Gondwanaland and Laurasia is a clear indication of the operation of some opposing force tending to pull the continents apart. In the planetary circulation we have a first clue to its nature. The closing up of the Tethys is referred to the subsequent action of the sub-continental circulations.

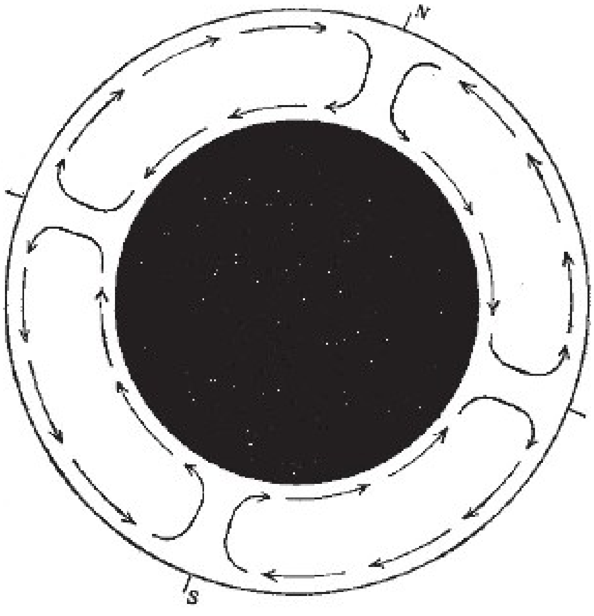

Fig. 1.

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Figure 1. Planetary circulation of the substratum (crustal effects being ignored).

Substratum, white. Metallic core, black.

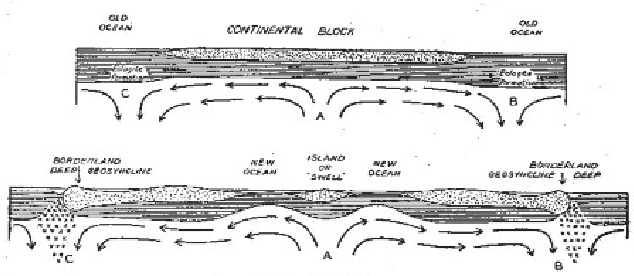
Figure 1 de A. Holmes, « Radioactivity and earth movements », Transactions of the Geological Society of Glasgow, 1929

THE SUB-CONTINENTAL CIRCULATION.

Superimposed upon the general planetary circulation there must be cyclonic and anticyclonic systems set up by the effects of regions of greater and less radioactivity in the overlying crust. Chief of these are the monsoon-like currents due to the distribution of continental blocks and ocean floors. Such evidence as we have, suggests that the radioactivity of continental rocks is generally greater than that of oceanic rocks. Thus, although the temperature at the base of the crust will be everywhere nearly the same, the continental crust should be thinner than the old or normal oceanic crust, and thus beneath the continents the temperature should be higher than at the same level beneath the oceans. The circulation due to this unequal heating of the substratum would be a system of ascending currents somewhere within a continental region, spreading out at the top in all directions towards the cooler peripheral regions. The downward currents would become strongest beyond the continental edges where weaker currents from the oceanic regions would be encountered (Fig. 2).

In the simplest case the drag on the base of the continental crust would be radially outwards, but in reality the circulation would necessarily be more complex. Ascending currents would not generally be localised about a single centre, but rather about several centres and along previously thickened belts such as those of mountain ranges. In the peripheral regions, however, the currents would be everywhere directed towards the oceans.

In Fig. 3 an attempt has been made to represent the effects on a continental profile under ideally simple conditions. Where the ascending currents turn over, the opposing shears and the resulting flowage in the crust would produce a stretched region or a disruptive basin which would subside between the main blocks. If the latter could be carried apart on the backs of the currents, the intervening geosyncline would develop into a new oceanic region. The formation of a new ocean floor would involve the discharge of a great deal of excess heat. It will be shown later that the new crust will be more nearly basaltic in composition and more richly radioactive than the normal material of the substratum.



Figs. 2 and 3.

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Figure 2. Sub-continental circulation / Distension of the continent on each side of A leaving an island or "swell" in the "deal" area above A.

Fig. 2 : Sub-continental circulation. Upper or sial layer, dotted. Intermediate layer (amphibolite, gabbro, etc) line shaded. Substratum, unshaded.

Fig. 3 : Distension of the continent on each side of A leaving an island or "swell" in the "deal" area above A. Above B and C eclogite formation results from the crystallisation of the material of the intermediate layer, and oceanic deeps are produced. The front part of the sial is thickened and o borderland results. Behind this, one effect of the heat transport from A to B or from A to C is the development in each case of a geosyncline.

Figures 2 et 3 de A. Holmes, « Radioactivity and earth movements », Transactions of the Geological Society of Glasgow, 1929

We must next consider what will happen at the continental margins, or generally, where two currents meet and turn downwards. The crust above the zone of contact will be thrown into powerful compression and the amphibolite layer will tend to be thickened by accumulation of material flowing in from two directions. The observed effects of dynamic metamorphism at high temperature and differential pressure on such material lead us to expect that recrystallisation into the high-pressure facies, eclogite, will here take place on a large scale. The change of density from 2.9 or 3.0 to 3.4 or more, combined with the simultaneous operation of isostasy would lead to marked subsidence. [...] Such foundering would effectually speed up the downward current for two reasons: the greater density of the sinking blocks, and the cooling of the substratum material in their vicinity.

Other possible consequences of eclogite formation will be suggested later; meanwhile we may notice that it provides a mechanism for "engineering" continental drift, and at the same time for discharging some of the excess heat generated in the substratum. Each part of the continental block would be enabled to move forward, partly by the fracturing and foundering of the belt of ocean floor weighed down with eclogite immediately in front, and partly by over-riding the ocean floor along thrust planes lubricated by magmatic injections from below.

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