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GRAVITY TECTONICS: A BRIEF HISTORICAL DEVELOPMENT AND BIBLIOGRAPHY

P. K. BLAY
Earth Science Department, Faculty of Science, University of Garyounis, Benghazi, Libya

Summary

The role of gravity in the development of deformed belts has not been given the appropriate attention by geologists, particularly when plate movements seem to explain every geologic event. The lithospheric plates in plate tectonics are generated as oceanic lithosphere and move away from the mid-oceanic ridges towards trenches where they are consumed, a resultant effect is the folding and faulting of crustal rocks. The mid-oceanic ridges are areas of veritcal uplift of molten rock materials; they are zones of high gravitational potential energy. Hence, the plates are also influenced by gravity to move away from the uplifted ridge areas. This paper deals with approaches adopted in the study of gravity tectonics. The point is made that even the simple lateral compressive model should be regarded as being an essential part of the gravity model and that plate movement is a process which may also be viewed in the light of the potential gravitational energy of global masses

Introduction

Differences in height as a direct result of differential vertical movements and/or erosion and sedimentation give rise to the accumulation of potential energy. Rock masses with different relative elevations with respect to some datum, for example, sea-level have a different potential energy which causes gravitational stress fields to be set up. These stresses subject the rocks to gradients of elastic strain of different intensity in different directions. The tectonic disequilibrium which is imposed upon the rocks may be re-established in two ways, namely (i) reduction of the potential energy by erosion and/or sedimentation, and (ii) by displacement of rock masses from places with an excess of potential energy to places of relative deficit. This leads to flow of rock masses under gravity and the birth of the gravity tectonics concept. Implicit in this concept is the existence of an initial suitable slope (De Sitter, 1954). What caused the formation of the initial slope is a problem of geotectonics not yet fully resolved.

In many zones where the earth's crust has been deformed the lithological layers of rocks have taken up folded and faulted forms. For many years field geologists have studied these forms in an attempt to understand the origin of the deformed belts. As a consequence of this study numerous theories have been proposed and they may be classified into two major groups. One group considers lateral compressive stresses in the crust as the primary deformation force that cause folding and faulting in rocks. Proponents of the lateral compressive theory argue that the vertical movements which unquestionably have occurred during orogenesis are secondary to the primary compressive forces.

The other group considers vertical forces and vertical motions as primary. On this model, folding and thrusting are considered to be secondary features resulting from downslope gliding or sliding of surface strata. The downslope movement of rock masses is controlled by gravitational potential energy.

There are no clear cut field by which field geologist can differentiate folds and faults resulting from a primary lateral compression from those developed from uplift and lateral spreading of strata under gravity.

Experimental

The three types of apparatus used in the experiments are shown in Fig. 1. In A and B a section of the base of the multi-layer of gelatine was slowly raised to simulate basement uplift beneath a sedimentary pile (Blay, 1974; Blay, Cosgrove & Summers, 1977).

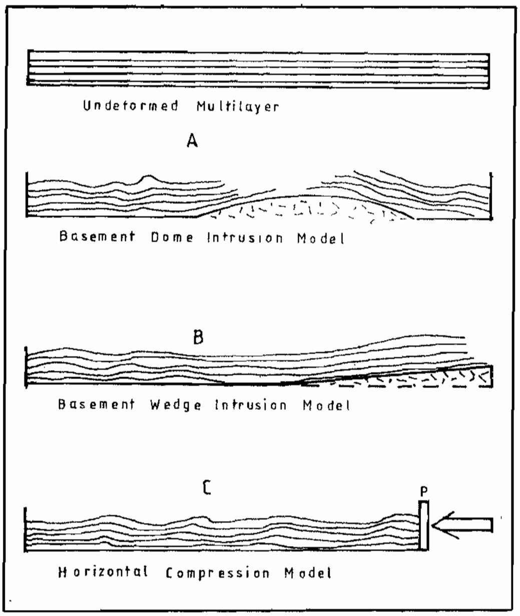

Fig. 1. Model simulated in the experiments (Blay, 1974)

As shown in A and B structures developed only as a result of downslope gravity sliding of the uplifted section of the model on a thin lubricated base layer. Also in A and B folds and thrusts developed only in the flat lying region of the model. In apparatus C, lateral compression produced by gravity sliding was simulated by the action of the vertical piston (P) driven horizontally against the end of the multi-layer by a geared electric motor. In all three types of apparatuses the structures developed were largely folds and thrusts and they were all similar. Hence, it is suggested that the lateral compression model may be regarded as being an essential part of the gravity controlled vertical uplift model.

In its widest sense all mass displacements in the earth involve gravitational forces. The contraction or the expansion of a large part of the earth, thermal convection in the mantle and plate drifting, are processes which may be viewed in the light of the potential gravitational energy of global masses.

In the restricted sense gravity tectonics implies that a regionally integrated tectonic system at the crustal level has lost potential energy during rock deformation. It is from the study of tectonic systems at the regional level that the concept of gravity tectonics has developed. Consequently, in this paper the author will first give a brief summary of the development of the gravity tectonic concept from the early part of the nineteenth century, to be followed by methods adopted in its study, and finally a bibliography on the subject of gravity tectonics.

Development of the Gravity Tectonic Concept

The idea that gravitational forces cause tectonic deformation was proposed by geologists in the first half of the nineteenth century (Scrope, 1825; Naumaan, 1849) and was firmly introduced into geology by Reyer (1888, 1892).

The phenomena of gravitational sliding date back to Schardt (1893) who envisaged the gliding of great nappes as "Sur une vertain pente determinant presque un movement spontane sous l'action de la pesa-teur". Schardt (1893) used his gravity tectonics idea to interpret the far travelled nature of the Pre-Alps and thus started the nappe theory which still dominates the concept of Alpine tectonics. Lugeon (1896, in Hubbert, 1972), following the ideas of Schardt (1893), interpreted the nappes of the Chablais region of the Western Alps in terms of gravity effects. In the Eastern Alps, Ampferer (1906), Van Bemmelen (1960) and Suess (in Hubbert, 1972) used the gravitational sliding idea to account for the Hohe Tavern deformation and the draping of folds over continental margins towards oceanic basins. It is significant to note that during the early stages attempts were made to interpret the occurrence of nappes in terms of gravity tectonics.

In the period between 1915 and 1922 the gravity tectonics concept was almost totally eclipsed by Wegener's continental drift theory, but the gravity idea resurged when Daly (1925) wrote that "the strong lateral compression of the Alpine and similar geosynclines during mountain building (can be understood) if the crust has had energy of position, large blocks of the crust sliding towards the geosynclines". Daly also used the term "sliding hypothesis", to imply gravitational gliding.

Haarman (1930) reviewed Schardt's ideas on gravitational gliding. He suggested that the process of gliding under-gravity depended upon three main factors, namely (i) a requirement for the existence of a suitable strata, for example, water-logged sediments, (ii) a requirement for an adequate inclination of the gliding surface and (iii) the time required for the gliding process corresponds to a "sudden" catastrophe, for example a landsliding, to hundreds of thousands of years corresponding to slow creep. Haarman developed, at some length, his undation theory with which he made the suggestion that folds, overthrusts and the arc-like pattern of many mountain ranges and other evidence of horizontal movement in the sedimentary cover, are secondary effects of large-scale vertical movements in the crust. Haarman's undation theory is simplified in Fig. 2. A recent account of it is given by Beloussov (1960).

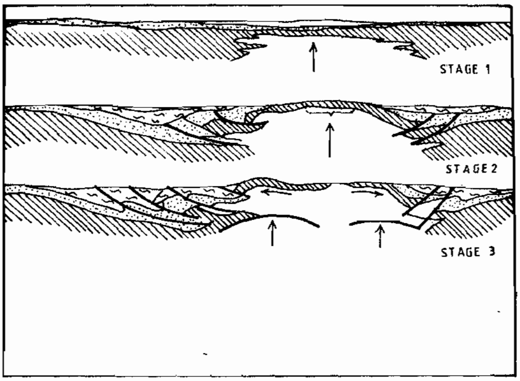

Fig. 2 Haarman's undation idea showing Zones of uplift (↑) and Zones of thrusting and folding under gravity.

Haarman's theory assumes that certain parts of the globe in the primary phase become uplifted due to oscillations which constitute the primary cause for orogenesis; and during the secondary phase, rock strata slide and glide along the slopes of the elevated parts (or geotumors) into the subsided parts (or geodepressions) under the influence of gravity producing folds and thrusts.

In principle, Haarman's theory provides a simple model for gravitational sliding. However, not only is there difficulty in finding the mechanical cause for the up and down movements outlined in the undation idea, but it is also not easy to apply the Haarman's theory to large-scale horizontal displacements.

The gravity tectonics concept after the period beginning from 1938 received a great impetus following the work of Schneegans (1938), Lugeon (1941), Gagnebin (1945) and De Sitter (1950, 1954) in the French and Swiss Alps. Migliorini (1952) from his field work in the Italian Appenines emphasized the importance of the flowage nature of the movement that occurred and which affected the entire moving mass of rock rather than "gliding" or "sliding" which is restricted to a zone.

From the general concept of gravity tectonics sprung a restricted variety in the form of "gliding" or "sliding" as defined by Dennis (1967). The idea of "gliding" or "sliding" under gravity was first used in English by Daly (1925) and was defined as "a downward movement of mobile material over a stable surface of sufficient slope". French and German geologists were first to use the concept of gliding or sliding of strata when they used terms like "glissement" (French) and "Glertung" (German). De Sitter (1952) used the phrase "gravity gliding tectonics" while Dennis (in Korn & Martin, 1959) applied "gravity tectonics" to include both flow and gliding as displayed in the Naukluft mountains of South West Africa.

The gliding tectonics idea has been elaborated into a more general theory of gravity tectonics by Van Bemmelen (1950, 1955, 1960). He pointed out that stress fields caused by accumulation of potential energy extended into deeper levels of the crust and distinguished between four major zones in which gravity influences rock deformation. These include (i) "epiderma" gravity tectonics, which is practically plastic deformation caused by gliding and diapirism of relatively large and coherent masses of the sedimentary zone, (ii) "meso-dermal" gravity tectonics which relates to plastic deformation, and faulting tectonics of the crystalline basement due to gravitational stress fields, (iii) "bathy-thermal" gravity tectonics which is also plastic deformation of the crystalline basement which has been mobilized by intrusions, migmatisation and palingenesis and (iv) "sub-crustal" gravity tectonics involving hydrodynamic mass-circuits at greater depths.

The current usage of the term "gravity tectonics" makes no distinction between "gravity tectonics", "gliding tectonics" and "sliding tectonics" and the former term is now generally adopted (King, 1960; Page, 1963; De Jong & Scholten, 1973). Gravity tectonics is also now restricted to tangential movement under gravitational forces (Dennis, 1967). It is synonymous with the general idea of decollement tectonics as outlined by Lugeon (1941) in his " gravitational decollement theory", and Laubscher's (1961) tectonic loading theory for the Jura.

Method of study

Knowledge of the role of gravity in tectonics has come about through three major sources, namely (i) field interpretation (ii) mathematical models and (iii) experimentation. The concept originated from the study of deformed belts in the field. In Europe, reference may be made to Righo de Rigli & Cortesini (1964) in Turkey, and Temple (1968) on large-scale gravity transport in the Greek Pelopponne. Maxwell (1959) also discussed gravity transport of great chaotic mass and dwelt at some length on gravity as the mechanism by which allochthons in the Italian Appennines were emplaced. Also in Italy, the works of Merla (1951), Miglorini (1952) and Page (1963) have been recognized. Julivert (1971) described a classical field example of gravity controlled decollement tectonics in the Iberian chain. The gravity tectonic model has been suggested for the evolution of the Jura deformed belt (Lugeon, 1941; Laubscher, 1961; Pierce, 1966).

In Africa, two classical examples may be cited, and these include the study of the deformed belt of the Naukluft Mountains in South West Africa (Korn & Martin, 1959)

In North America the literature on gravity tectonics is quite extensive. The development of the Appalachian Mountain Belt is interpreted in terms of gravitational tectonics (Rogers, 1963, 1964; Gwinn, 1964; Millici, 1970). In the Rocky Mountain zone, both in the United States and Canada, most field structural interpretations are based on basement uplifts and gravitational sliding. For example, Eardley (1963), Misch (1966), Sales (1968), Scholten & Ramspott (1969), Seager (1970), Mudge (1970), Price (1971) and Beutner (1972) are a few of the many geologists who have applied gravity tectonics to interpret structures (folds, thrusts and tectonic gaps) found in the Rocky Mountain Belt.

From a review of published work on orogenic belts as interpreted using the gravity model, three features are significant, namely (i) the sliding surface is generally inclined at no more than 5^0 to the horizontal (Korn & Martin, 1959; Hsu, 1969), (ii) the sliding surface lies within a soft incompetent rock unit, for example, the Lochseitenkalk at the base of the Glarus nappes (Hsu, 1969), the "unconformity Dolomite" in the Naukluft Mountain (Korn & Martin, 1959) and the black shale of the argille scagliose in the Italian Appennines (Page, 1963), and (iii) mass sliding of cover rocks under gravity is only possible if it is preceded by differential uplift of the underlying basement material.

In the Rocky Mountain zone most structural interpretations are deduced to have been associated with differential vertical uplift of basement followed by spreading of the cover material under the influence of gravity. For example, the interpretation by Foose (1960) of the structures in the Beartooth Mountain of Montana, and by Crosby (1968) on the overthrust belt in Western Wyoming in terms of vertical movement model followed by gravitational sliding for the development of the tectonic gaps in the disturbed belt of Northwest Montana.

The effects of gravity on geological processes have also been studied experimentally and by mathematical models. Most of the earlier experiments were designed to study specific structures; for example, Nettleton (1934) studied the formation of salt domes; Bucher (1956) investigated the mechanics of recumbent folding, and Ramberg (1963a) applied centrifuge methods to simulate the evolution of orogenic type diapirs and salt dome development. For large-scale structures of orogenic dimensions the experiments of Ramberg (1967a), Kerrich (1972), Blay (1974) and Blay *et al.* (1977) may be cited.

The theoretical or mathematical treatment of the effects of gravity on tectonic deformation has followed two major trends, namely (i) the buckling of idealized layers in the field of gravity by Biot (1961) and Ramberg (1961, 1968, 1970), and (ii) the mathematical analysis of Hubbert & Rubey (1959), Raleigh &Griggs (1963), Hsu (1969), Forrestall (1972) and Elliot (1973) in relation to the transportation of large overthrust sheets over long distances. The theoretical analysis of both Biot and Ramberg express mathematically the significant role played by gravity in multilayer deformation but it is difficult to extend their models to large-scale transport of rock masses under gravity. The analysis of Hubbert & Rubey (1959), Raleigh & Griggs (1963) and Forrestall (1972) on the role of pore fluid pressure, and Elliot's (1973) discussion on the motion of thrust sheets are, of course, specific to major structures.

Large overthrusts have been described, for example, the Western Wyoming Belt (Crosby, 1968). However, assuming the usual values of the coefficient of friction of rock on rock, it was obvious to early workers, for example, Smoluchowski (1909), that it was impossible for such large sheets of rocks to move more than a few kilometres for they cannot sustain the stresses which are required to move them without crushing. Hubbert & Rubey (1959) advanced the theory that overthrusts are made possible by the presence of abnormally high pore fluid pressures at the base of the thrust sheet. They showed that abnormal fluid pressure reduces the effective sliding friction and they derived the following relation for gravity sliding of a thrust plate for the case in which the thrust block is sub-aerial

$$\tan\,\theta = (1 = \lambda_1)\tan\,\phi \qquad ...1.1$$

where θ is the dip of the thrust plane and $\tan\phi$ is the coefficient of dry friction. Usually $\tan\phi = 0.577$ for rocks and λ_1 is the ratio of the fluid pressure (P) beneath the thrust plane to the normal stress (S) on that plane due to the weight of the overburden..

In neglecting shear stresses Hubbert &Rubey (1959) and Raleigh & Griggs (1963) assumed that the minimum and maximum principal stresses in the overthrust block were parallel to the faces of the block. This assumption is strongly criticised by Forestall (1972) because it leads to an overestimation of about 50 per cent in the possible length of the overthrust block. Although the criticism is valid and makes the mathematical treatment more complete, it does not alter the fact that the presence of the high pore fluid pressure does reduce friction along the sliding surface thereby facilitating gravitational sliding with only a small angle of inclination of the order of 0^0 to 5^0.

The examples cited by Hubbert & Rubey of high pore fluid pressures in oil wells, $\lambda_1 = 0.85$

to 0.95 in the Gulf Coast of America and Iran, justify the high values chosen for $\lambda_1$since the main portion of the thrust plate sliding under gravity could be assumed to be riding on a single stratigraphic horizon which is also a zone of high fluid pressures. This assumption is vitally important in decollement deformation.

Raleigh & Griggs (1963) made the point that equation 1.1 above represented the theoretical case in which the sliding block was unobstructed at the downslope end. They considered the occurrence of obstructions such as blocks of stationary rocks at the toe of the moving thrust and derived the relationship;

$$\tan\theta = (1-\lambda_1)\tan\phi + \frac{z_1}{2 \times_1 \tan\beta}\left[\frac{(1-\lambda_2)\tan\phi + \tan\beta}{1-(1-\lambda_2)\tan\phi\tan\beta}\right] \quad ...1.2$$

where θ is dip of thrust plane, $\tan\phi$ is the coefficient of dry friction, λ_1 is the ratio of the fluid pressure beneath the thrust plane to the normal stress on that plane, λ_2 is the ratio of fluid pressure beneath the toe to the normal stress on the toe, β is the angle of inclination of the toe to the horizontal, z_1 thickness of overthrust block and x_1 its length.

In the analysis presented by Hubbert & Rubey (1959) and Raleigh & Griggs (1963) the cohesive strength (τ_0) was assumed to be zero. Hsu (1969) presented arguments to show that the analysis of Hubbert & Rubey (1959) and Raleigh & Griggs (1963) were based upon faulty premises and pointed out that the cohesive strength should be omitted unless it could be proved that the moving block slid along an already existing fracture plane. Hsu (1969) distinguished between movements of cohesion bound blocks and cohesionless bound blocks.

The Glarus overthrust characterised by the presence of a ductilely deformed limestone layer (Lochseitenkalk) within the thrust zone, is considered a typical example of thrusting of cohesionless block. The former is compared with slowly creeping slices, moving at rates of the order of 1 cm or less per year, and the latter is comparable with catastrophic landslides moving at speeds of many metres per second.

Experiments show that the cohesive strength for competent sedimentary rocks is of the order of 200 bars. Incompetent rock units generally referred to as decollement beds, have low cohesive strengths of the order of 25 to 30 bars (Hsu, 1969). For example, Laubscher (1961) estimated the cohesive strength of evaporite layer under the Jura to be approximately 90 bars.

The important point is that for a cohesive strength of the order of 25 to 30 bars for weak rocks, overthrust by gravity sliding on gentle slopes of a few degrees is an extremely feasible mechanism of deformation, if pore fluid pressure is extremely high.

Hubbert & Rubey's (1959) fluid pressure theory and the cohesive theory of Hsu (1969) resolve the mechanical paradox of transporting large thrust blocks over long distances but fails to account for the problem of thrust planes riding or cross-cutting to the surface. However, Raleigh & Griggs' (1963) discussion of the effect of the toe at the front of a thrust and Elliot's (1973) theory in which the effect of perturbations on the thrust plane is considered, resolves the problem.

Price (1974) has suggested that in specific situations high pore-fluid pressures could induce hydraulic fractures which may in turn lead to instability. If the stability plane which is horizontal or inclined only a few degrees, had infinite lateral extent, the conditions of slip on this plane are given by:

$$\tau = C_0 - U\sigma_n \quad ....1.3$$

Where τ is the available shear stress, C_0 is the cohesive strength of an impervious rock unit, U is the coefficient of sliding friction and σ_n is the effective normal stress on the plane. According to Price (1974) the initiation of instability surface is due to "local" loading, although the propagation and development of such surfaces could, if conditions are favourable, be self generating. Water is squeezed more rapidly out of the stronger

Water is squeezed more rapidly out of the stronger more permeable rocks and tends to collect along bedding planes; this enhances propagation of the fracture plane and further gliding. Large-scale gliding is likely to occur if the glide plane breaks through to a free surface.

Thus, the paradox involving the transportation of large thrust sheets is resolved on the mathematical models presented by Hubbert & Rubey (1959), Raleigh & Griggs (1963), and Elliot (1973), all emphasizing the significant role gravity plays.

Gravitational instability and plate tectonics

Over the past 25 years also, the concept of global plate movements has been extensively developed (Hess, 1960; Dewey & Bird, 1970; Oliver, 1972; McCunn, 1973). According to the plate movement or tectonic theory the earth's surface is made up of a few large and several smaller plates that are generated at mid-ocean ridges and move away towards deep-sea trenches, where the moving plates dip into, and are consumed by the mantle (Isacks, Oliver & Sykes, 1968; Le Pichon, 1968; Morgan,1968).

The question of what drives the plates still remains an important intriguing problem of the new global tectonic theory. According to Jacoby (1970) it appears that it is gravity which ultimately orders and stratifies the earth with the densest materials at the greatest depths.

Also thermal expansion, chemical differentiation and mineralogical phase changes can result in strong forces capable of disturbing the gravitational equilibrium of the mass distribution within the earth. Jeesop (1970) estimates the total heat flow of about 3×10^{13} W through the earth's surface and this may be taken as an indicator of the amount of energy available from these sources. Then, if radiation and conduction cannot efficiently transfer this amount of heat, gravitational instability of the mass distribution and some mechanism of convective heat transfer will take place. The actual pattern of motions according to Jacoby (1970) will depend not only on gravity and thermal, chemical and mineralogical energy released, but also on the internal structure and the boundary conditions of the system. The present knowledge of the system of motion is restricted to those of the plates. However, the overall system must involve motion in the mantle apart from the motions of the plates.

Mantle-wide convection cells have been proposed as a mechanism (Hiskanen & Vening Meinez, 1958; Runcorn, 1962), but the assumptions upon which the mechanism is based, are still tenuous. The major difficulty involves the effective viscosity assumed for the mantle and the corresponding value of the Raleigh Number. The latter is critical in determining the nature of flow within the mantle but its value depends upon the effective viscosity (Knopoff, 1964). Considerable work has been done in an attempt to determine the viscosity of the mantle but as yet it is not known with sufficient accuracy as to make researchers determine whether convection cells are feasible.

There are geophysical evidences to suggest that inhomogeneities which inhibit mantle-wide convection occur in the mantle which is subdivided into upper and lower. According to Bullen (1954) the upper mantle is vertically homogeneous and the Raleigh number for the upper 400 km of mantle is in the range 10^3 to 10^4 which favours laminar convection. On the other hand, if convection is present in the lower mantle, it is of the turbulent type (Turcotte & Oxburgh, 1969).

Some type of thermal convection is generally accepted as the driving mechanism for plate movements (Ramberg, 1972; McCunn, 1973). The energy expended in mountain building and in volcanic activity has been related to radioactivity within the earth (Hurley, 1962). Heat from radioactivity, whether in the form of convective overturns (Holmes, 1931; Runcorn,1962) or other means, supplies most of the energy for "dynamic events". With heat as the driving force a mechanical model of vertical uplift has been proposed by Jacoby (1970), Ramberg (1972) and

McCunn (1973). These models are base on isostatic adjustment caused by gravitational forces. Ramberg (1972) visualized a solid diapir rising as a bulge from buoyant stratum deep in the asthenosphere while Jacoby (1970) suggested the process of active diapirism of the asthenosphere under the oceanic ridges.

The significant point of the above models is what the lithospheric and the crustal rock masses spread away from the vertically uplifted zones or oceanic ridges under the influence of gravity. The lithospheric plates are thus driven by gravity acting on them and probably move against drag from below due to thermal convection in the upper mantle. This gravitational instability of the lithosphere system expresses itself in active diapirism of the "fluid" low-density asthenospheric wedge into the receding and thickening dense plates of the lithosphere at the ridges and behind island arcs, and result in the gravity sliding of the plates away from the ridges (Ramberg, 1973; Seyfert, 1967; Maxwell, 1968; Wilson,1969; Hales, 1969; Jacoby,1970ab).

From the above, it is quite probable that gravity constitutes a very important source behind the movement of lithospheric plates. The experimental models of Fig. 1 strongly suggest that the horizontal compression model must be viewed as an essential part of the gravity tectonics model and that in as much as geologists associate mid-oceanic ridge areas with vertical uplifts, gravity potential energy plays an important role in the movement of lithospheric and crustal plates, and hence the influence of gravity is quite significant in the development of deformed belts.

Conclusion

An attempt has been made to put together published references on the role gravity plays in the development of deformed belts. The starting point has been the early nineteenth century. However, it is possible that ideas on gravity tectonics started at an earlier date. Even between the early part of the nineteenth century and the present many works might have been left out. The references cited in this paper, although not very extensive, may be representative of the all important subject of gravity tectonics.

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