Contemporary and recent vertical crustal movements and their interpretation

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Summary. — The available evidence on contemporary and recent (i.e. postglacial) vertical crustal movements was collated and is presented on composite maps showing isobases. It was found that movements in continental platform areas are on the average ± 4 to 5 mm/year, maximum rates of uplift occur in the recently glaciated shield areas of Fennoscandia and North America (up to 10 mm/year; this rate was even higher right at the end of the last ice age) and in the Krivoy Rog Region of the Soviet Union. The maximum rates of subsidence are in Czechoslovakia (13 mm/year) and in France (26 mm/year).

The possible theories of the mechanics of the vertical crustal movements are reviewed. A detailed evaluation thereof leads to the conclusion that there is little doubt that tectonic forces and isostasy are the two main factors that are responsible for the vertical crustal movements.

Riassunto. — Le testimonianze disponibili concernenti i movimenti verticali crostali contemporanei e recenti (cioè post-graciali) sono state riunite e rappresentate su carte indicanti le isobate. È stato rilevato che nelle zone continentali a piattaforma i movimenti oscillano intorno ad una media di ± 4-5 mm all'anno, che i valori massimi di sollevamento si hanno nelle zone a scudo recentemente coperte da ghiacciai, cioè nella Fennoscandia e nel Nord America (fino a 10 mm annui; questo valore era ancora più alto alla fine dell'ultimo periodo glaciale) e nella zona di Krivoy Rog nell'Unione Sovietica, e che i valori massimi di abbassamento si hanno in Cecoslovacchia (13 mm annui) ed in Francia (26 mm annui).

Da una rassegna delle possibili teorie sul meccanismo dei movimenti verticali crostali, si può concludere che pochi dubbi esistono sul fatto che le forze tettoniche e l'isostasia sono i due principali fattori responsabili dei movimenti su citati.

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I – Introduction.

The geological history of the Earth shows that there have been large crustal movements on all parts of its surface. Modern history also records upward and downward movements of the land at various points. The contemporary and recent movements are considered to be small, but it is believed that they are of the same kind as past movements. As to terminology, we define as contemporary vertical movements those which are taking place at the present time, before our eyes, or have occurred in historic times. Recent movements are those which have occurred during the Quaternary period (72). We shall discuss the data pertaining to these two time intervals separately.

Because of great practical and theoretical importance, the study of vertical movements has received much attention since the beginning of the last decade. Two international symposia on this subject have been conducted, in 1962 at Leipzig (1), G. D. R., and in 1966 at Aulanko, Finland (2).

The purpose of this paper is two-fold: first, it is to investigate the presence of recent and contemporary crustal movements in all parts of the world and to present the rates of these movements; second, it is to discuss the possible causes of these movements in the light of existing theories, and to evaluate the latter.

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II – Contemporary movements.

A – *Europe*.

Hiersemann (27) compiled a preliminary map of contemporary crustal movements in Europe, but he could not present the nature of the movements of some countries like Romania, France, etc.; thus, an attempt has been made to complete Hiersemann's map as far as information is available. This has been done in Fig. 1. The data in addition to Hiersemann's have been collected from papers by:

Tryggvason (79) for Iceland; Jakubovsky (32) and Lennon (44) for the European waters; Valentin (80), Edge (15), Halliday (24), and Janes (35) for Great Britain; Kvale (43) and Jelstrup (34) for Norway; Bergsten (7) for Sweden; Simonsen (74) and Egedal (16) for Denmark; Kääriainen (37), Lisitzin (49), and Hyyppa (31) for Finland; Sinyagina (75), Gerasimov (19), Gorelov (21), Beloussov (6), Zhelnin (88,89), Orviku (66), Kääriainen (36), Nikonov(65), Ramsay(67), Kozanchyan(39), Nikolayev(64), and Nelidov(69) for the U.S.S.R.; Lees (44) for the Middle East; Constantinescu (12) and Ciocardel (10,11) and others for Romania; Hristov and Galabov (30) and Kanev (33) for Bulgaria; Krnis (42) and Svoboda (75) for Czechoslovakia; Niewiarowski and Wyrzykowski (63) and Wyrzykowski (86,88) for Poland; Wernthaler (85) for West Germany; Waalewijn (82,83) for the Netherlands; Keyzer and Jones (40) for Belgium; Beloussov (6) for France; Lilienberg and Mescherikov (47) for Yugoslavia; and Vening Meinesz (81) for the Alpine Regions.

The map shown in Fig. 1 significantly establishes the uplift of the Fennoscandian countries. This uplift has given Fennoscandia an appearance of a shield with its center rising in the Gulf of Bothnia. In the center of the shield, crustal movements have reached a magnitude of up to 10 mm/year whereas towards its edge they gradually decrease to zero. The tendency of this uplift is also continued in the western part of the U.S.S.R. and it follows up to the margin of the Carpathians and the Balkans. Velocities of + 10 mm/year are also reached in this region. The other parts of the U.S.S.R. have been subjected to both uplifts and subsidences. The Ukrainian Shield consisting of Precambrian rocks rises and the same behavior continues near Krivoy Rog. The regions of wide depressions of the plain sediments (syneclise of Moscow) exhibit subsidences whereas those of wide up-vaultings of the plain sediments (Voronesh anteclise) show uplifts.

The gradual decrease in the magnitude of vertical movements from the Northern towards the Southern part of Fennoscandia is continued up to the areas of the north-German and Polish Plain. The movements attain negative values (subsidences) after following a relatively very small stable region of Copenhagen in Denmark. The sinking velocities, extending from Gdansk (Poland) to the Netherlands, reach values of 1 to 2 mm/year. Around the North Sea and the southern parts of the Baltic Sea with their great thickness of sediments there is a rising area of old folded complexes which extends from Scotland, England, Belgium to Germany and which is interrupted only by the subsidence of the British Channel (27).

The isobases drawn for Romania make it clear that the tendency of uplift in the south-western part of the U.S.S.R. is continued up to the northern part of Romania where the uplifts have shown the magnitudes of the order of 2 to 7.5 mm/year. The central part of Romania is relatively stable whereas in the southern part of this territory, the movements are more differentiated and are between — 1 to + 2 mm/year. However, the same differentiated pattern is extended into Bulgaria and other neighbouring areas.

Fig. 1 – Map of contemporary movements in Europe and in the Asian part of the U.S.S.R.

France has been subjected to very intensive subsidence varying from 37 to 5 mm/year extending from its northern part towards the southern one. Since no reliable data of precise levellings are available for this country, it is very difficult to confirm this pattern of movements. The disagreement between the movements of France and those of the neighbouring countries have further increased our doubts regarding the reliability of the nature of movements presented on the map.

In the regions of Alpidic folding, too, the vertical crustal movements are much more differentiated,a lthough it is significantly recognised that the very thick sedimentary layers are sinking here.

A tendency of rising at the present time is recognised for the Precambrian and the Pre-Alpidic folding complexes, even though they are covered by younger, thinner, sediments. On the other hand, a tendency of sinking is recognised for the regions with a thickness of sedimentary layers of more than 5 km.

B – *North America.*

Work on vertical movements on the North American Continent has been reported by MacLean (33), Gutenberg (23), Clark and Persoage(11) Hodgson et al. (28), Milne et al. (58), Lilly et al. (48), Mathews et al. (56), Andrews (3), Barnett(5), Blake (8), Lewis (46), Grant (22), and Small (77). A composite picture of the results obtained from the cited papers is shown in Figure 2.

Accordingly, Small (77) summarized that, in North America, the velocity of movement in the eastern (platform) part is $\pm$ 3 to 5 mm/year (the Gulf Coast basin is subsiding while the Appalachian Mountains, the Ozarks, and the Canadian Shield are in the process of uplifting). In the western part, which is orogenic in character, the rate of movement is as great as 10-15 mm/year (the Rocky Mountains, Great basin, Coast Ranges). The most interesting conditions occur in that part of North America which has recently been deglaciated after the end of the most recent ice age. In this region, one has observed the existence of three post-glacial uplift centers; one located over southeastern Hudson Bay, another located in northern Keewatin, and finally a small center situated over the northern Queen Elizabeth Islands.

In the Great Lakes region, results indicate a tilting of the land upward in a northerly direction, by about one millimeter per kilometer per century or by about 10 cm per 100 km per century. In other words, to understand the effect of these movements, we can say that two points 100 kilometers apart in the direction of maximum tilt would change their relative elevation by 10 cm in one hundred years. Despite the fact that the results revealed by the records of precise water level gauges are quite reliable and accurate, they have proved to be of very limited use by revealing only relative movements and failing to indicate movements relative to sea level. However, in some parts of Canada, vertical movements are indicated based on the records of precise levelling. There are pretty strong indications which have proved that the crust in the region of Lake St. John is rising relative to Quebec City at the rate of about 5 mm/year. On the other hand, there are very few and less conclusive indications that have led to the speculation that the high ground in Laurentides Park between Lake St. John and Quebec City is subsiding at about the same rate of 5 mm/year. While this subsidence is definitely indicated by two

Fig. 2 – Contemporary crustal movements in North America.

levellings separated by an interval of some 30 years, Lilly [18] and others do not exclude the possibility that some systematic errors could have occurred in the levelling. However, we are very much optimistic that a further relevelling after 10 or 20 years would give a much clearer picture of the situation. So far there has been no evidence of pronounced movement along the St. Lawrence River from Quebec City to St. Simeon, and as the tidal records at Father Point indicate stability, it is safe to assume that the whole region is stable. This assumption makes us say that the indicated movement (5 mm/year) at Lake St. John is in fact an actual upheaval relative to sea level rather than relative to Quebec City.

Precise levelling in British Columbia has indicated some vertical movements in the area between Prince Rupert and Prince George, the indication being that the higher ground is subsiding relative to sea level. Since no evidence other than a single line of levels, run in 1920-21 and repeated in 1963-64, is available, this investigation cannot be regarded as conclusive. Another set of levellings in British Columbia (carried on in 1931 and 1940) has indicated a subsidence of 6 cm for Bridesville with respect to Midway. Relevelling along the same line in 1960 has indicated an additional subsidence of about 9 cm. While on the one hand, Bridesville is sinking at a rate of 5 mm/year with respect to Midway, on the other hand it is sinking at a rate of 3 mm/year with respect to Osoyoos.

Evidence of relative crustal movements has been found in Manitoba also. Relevelling in 1962 from Winnipeg to Great Falls indicated an upheaval of bench marks in the Great Falls area by an amount of 12 cm with respect to Winnipeg. However, because the bench marks at Great Falls are situated in bedrock and because of the nature of the sediments in old Lake Agassiz in the Winnipeg area, it will be more appropriate to assume that the Winnipeg area is subsiding and the Great Falls bench marks are stable. Subsequent levelling in 1963 by a different route confirmed relative movements between Winnipeg and Great Falls. However, this levelling could not reveal any movements between Winnipeg, Emerson, Portage la Prairie and other points in the Red River Valley; and therefore it is assumed that either the entire area of the Red River Valley is slowly subsiding or that the rock area at Great Falls is rising. If the latter assumption is true, then it may be connected (or tied in) with the general relative movements of the Great Lakes area.

Though there is definite evidence that Halifax and Charlottetown are subsiding relative to sea level at the rate of about 1.5 mm/year, some more investigations are required to be carried on before establishing this fact. On similar terms, the speculation of an uplift at a slower rate on the Pacific Coast of Canada is yet to be confirmed.

Regarding the remaining parts of North America, we note that the U.S. Coast and Geodetic Survey has been assigned the responsibility of establishing a first — and second — order vertical control net over the United States. The areas of known vertical change in which the

Coast and Geodetic Survey has undertaken concentrated relevellings are as follows: 1. San Jose, California; 2. Delta Area, California; 3. Dixie Valley, Nevada; 4. San Joaquin Valley, California; 5. Eight Crossings of Fault Lines, California; 6. Long Beach and Terminal Island, California; 7. El Centro, California; 8. Hoover Dam, Arizona and Nevada; 9. Hebgen Lake Earthquake, Montana; and 10. Galveston-Houston, Texas.

The values of vertical movements obtained by the U.S. Coast and Geodetic Survey are very large and may be doubtful. The rates of vertical movements in the U.S. are many times greater than those of other parts of the globe. If we consider them to be true and reliable, then we can expect that the San Jaoquin Valley will be deepened further by about 18 meters in one human lifetime (60 years) itself.

C – *Remaining areas of the world*

Investigations of vertical crustal movements have not been carried out in the remaining parts of the world to the same extent as in Europe and North America, except in Japan. However, while on the one hand we have succeeded in obtaining some information about Argentina, Australia, Burma, India, Japan, and the Philippine Islands, on the other hand we have nothing to report about the whole of Africa and South America. The results thus obtained are collated in Figure 3.

Accordingly, Japan is subject to large crustal movements. The vertical movements of the Earth's crust in that country for the period from 1900 to 1928 were measured by Miyabe (57). His results were based upon many assumptions; the most fundamental of them was that the movements of bench marks are uniform during the periods between successive levellings. Although his assumptions were subject to criticism by Dambara and Hirose (14), Miyabe's (59) calculations at that time seemed to be the only authentic uniform material for the compilation of a map of the recent vertical crustal movements covering the whole territory of Japan. Since his work was published in tabular form with no map representation, it did not prove to be of wide importance. However, in 1965, Miyabe, Miyamura and Mizoue(60) joined together to prepare a map using the same data on the scale of 1:2,000,000 and presented it to the public as a tentative compilation map of the secular vertical movements of the Earth's crust in Japan. These results are incorporated into our Figure 3. The map shows the magnitude of the movements in mm during the period of 28 years.

Many of these movements are believed to have some direct connection with the seismic and volcanic activities of Japan. The subsidence of the tips of the Kii Peninsula and the Muroto Promontory are considered as a pre-seismic crustal movement of the big earthquakes in 1944 and 1946 in the Pacific Ocean near the coast. An intensive

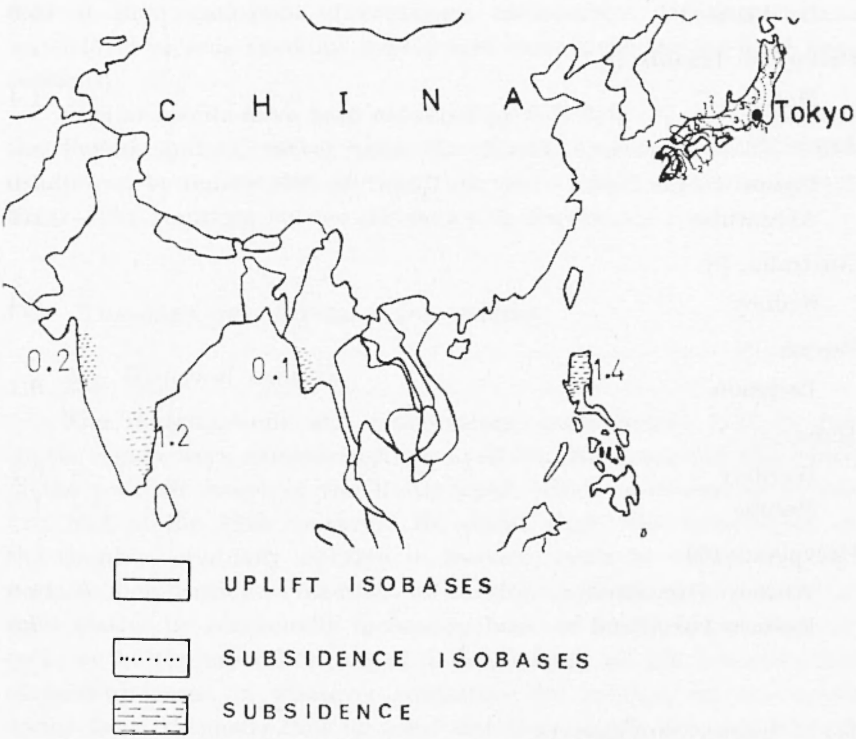

Fig. 3 – Contemporary crustal movements in Asia.

concentration of the contour lines (isobases) in the southern part of Kyusyu is due to the crustal movement accompanying the eruption of the Volcano Sakurazima in 1914.

As noted, not much work on crustal movements has been done in other remaining areas of the world. However, the assumed rates of contemporary crustal movement at certain points of the remaining areas are shown in Table I.

Table I

Rate of uplift (+) or subsidence (—)
mm/year for various countries

Locality	Rate
Argentina: [6]	
Buenos Aires	— 1.1
La Plata	— 10.0
Philippine Islands: [6]	
Manila	— 1.4
Japan: [6]	
Isyoro	— 1.0
Abaratubo	— 1.4
Australia: [6]	
Sydney	+ 0.4
Burma: [6]	
Rangoon	— 0.1
India: [6]	
Bombay	— 0.2
Madras	— 1.2
Greenland: [68]	
Western Greenland	+ 14.0
Eastern Greenland	+ 7.0

III – Recent movements.

It is much more difficult to determine past (so-called " recent ", i.e. post-glacial) rates of uplift than contemporary ones. Usually, recourse has to be taken to radiocarbon dating, pollen analysis, etc. Thus, Farrand [17], and, later, Andrews [9] have computed postglacial rates of uplift for northern North America. Average rates of postglacial uplift reach a maximum value of nearly 4 cm/year over the southeastern Hudson Bay; another high area with a rate of about 2.5 cm/year lies between Bathurst Inlet and Southampton Island. Contemporary rates of uplift have a maximum value of about 1.3 cm/year in the southeastern Hudson Bay and a minimum value of

0.2 cm/year. The estimated rate of uplift over the last 1000 years of the Melville Peninsula was about 0.7 cm/year, based on the radiocarbon age of a shell sample, whereas the present rate of uplift amounts to 0.75 cm/year. Thus, the observations indicate that rates of uplift declined from a maximum of 10 to 12 cm/year, immediately following deglaciation, to a current maximum of about 1.3 cm/year. Agreement is satisfactory when one compares these rates of uplift with those derived from geological observations, radiocarbon dates, and from water-level records (making appropriate corrections for sea-level fluctuations).

Similar results have been obtained by Schofield (71) when studying the Fennoscandian, rather than the North American, Shield. The results can be represented as "uplift curves": Uplift is plotted against time. The resulting curves are shown in Figure 4.

IV – Theories of vertical land motion.

A – *Historical remarks.*

The investigations and observations made before 1837 in the Baltic region were summarized by Lyell (50). He expressed the views of the possible causes of the Baltic uplift which were current in the first half of the 19th century. He stated that "the foundations of the country, gradually uplifted in Sweden, must be undergoing important modification. Whether we ascribe these to an expansion of solid matter by continually increasing heat, or to the liquefaction of rock, or to the crystallization of a dense fluid, or the accumulation of pent-up gases, in whatever conjecture we indulge, we can never doubt for a moment, that at some unknown depth the structure of the globe is in our own times becoming changed from day to day, throughout a space probably more than a thousand miles in length and several hundred in breadth".

B – *Glacial isostasy.*

Ice unloading and subsequent isostatic adjustment, proposed by Jamieson in 1865, was considered to be the modern theory of the cause of crustal movement in Fennoscandia and North America. In Scandinavia and North America, as well as in Scotland, there is evidence of a great ice-cover; and interesting to say, the height to which marine fossils have been found in all three countries is very nearly the same. It is possible that the enormous weight of the ice thrown upon the land may have had something to do with this depression. Sometimes it is considered that the ice might have been a mile thick in some parts of America; and everything points to a great thickness in Scandinavia and North Britain. It is not known what is the state of the matter on which the solid crust of the earth reposes. If it is in a state of fusion, a depression might take place from a cause of this kind, and then the melting of the ice would account for the rising of the land, which seems to have followed upon the decrease of the glaciers.

The tendency of portions of the earth's crust to approach a condition of balance leads to the establishment of a state of equilibrium in the crust known as " isostasy ". The upwarping of strandlines in former glaciated areas has been cited by many geologists and geophysicists as one of the most convincing proofs of the principle of isostasy.

Gutenberg ([23]) felt that it is very probable that the tilt in the Great Lakes region is due to forces which tend to restore isostatic equilibrium, disturbed by the melting of ice after the Ice Age. On similar terms, most geologists as well as ourselves believe that the differential uplift of the Earth's crust in the Great Lakes region is caused by recovery of the crust after depression by the load of the glacial ice.

Krass and Ushakov ([41]) made a detailed study on some effects of the dynamics of glacial isostasy of the upper mantle in the peripheral zone of the regions of continental glaciation. They concluded that a considerable uncompensated uplift in the peripheral part of Antarctica (for example, the Gamburtsev Mountains) could have been caused by the glacio-isostatic dynamics of the upper mantle only under conditions of an appreciable rheological inhomogeneity and the effects of its hardening.

Gutenberg ([23]) and Flint ([18]) have made numerous comparisons of the postglacial land uplift of Fennoscandia and the Great Lakes region of North America which stressed the overall similarity of uplift in the two areas but did not compare in detail the relationships between the maximum depressions, the distances from their respective ice centers, and the rates of contemporary uplift. MacLean ([53]) attempted to establish a comparison between these relationships.

If the two regions are analogous, it would seem that an examination of the rate and extent of contemporary land uplift in Fennoscandia would aid in locating, at least approximately, the zero isobase of contemporary land uplift in the region which had been covered by the Laurentide ice sheet. Although the Fennoscandian ice sheet was smaller than the Laurentide sheet, both areas had approximately the same thickness of ice, above 2,500 meters, and consequently about the same depth of depression of the crust. Therefore the distance from the ice center to the zero isobase in the Great Lakes-Hudson Bay area should be roughly equal to the distance from the Fennoscandian ice center to the zero isobase at Leningrad, U.S.S.R.

The information in the following paragraphs regarding the Fennoscandian-Great Lakes analogy is from MacLean ([53]).

A plot of the uplift of the Finnish tide gage stations, determined by precise levelling (in feet per 100 years), against their distances (in miles) from the Fennoscandian axis of maximum ice thickness reveals that the distribution of points lies almost in a straight line; the slope of the line fitted by the method of least squares gives a contemporary rate of uplift of 3.36 feet/450 miles/100 years or 14 cm/ 100 km/ 100 years. This rate might then be assumed to be of the proper order of magnitude for the contemporary Laurentide land uplift.

If the analogy with Fennoscandia holds, the zero isobase of the land uplift would follow along a line extending down from the western fifth of Hudson Bay to the south-western shore of James Bay (just southwest of Moosonee, Ontario), then to the vicinity of Kempt Lake, Quebec, crossing the St. Lawrence River about 32 km northeast of Quebec, Quebec. The relationship of Churchill, Manitoba, to the zero isobase, i.e., Churchill is about 100 km farther away from the ice center than the presumed zero isobase, may support those investigators who deny the existence of land uplift at Churchill as opposed to those who claim that up to about 2 meters of uplift per century is taking place at Churchill.

It is possible that the ice which covered Churchill came from the ice divide to the west of Hudson Bay; if this were the case, Churchill, being about 456 km from the western ice divide, would have a contemporary uplift of about 30 cm per century (again applying the modern Fennoscandian rate of uplift).

C – *Tectonic theory.*

Scientists who explain the upwarping by isostatic rebound are opposed by those who believe that contemporary uplift is a continuation of movements which have characterized shield areas (the Baltic Shield and the Canadian Shield) since Precambrian times. One of the adherents of the tectonic (endogenetic) theory of land uplift in these areas summarized this concept by stating that both the Canadian and the Baltic Shields were being elevated, clearly by tectonic forces, prior to the glaciated period; and that there are no grounds for maintaining that the very same forces did not play an important role in the recent movement of the Shields ([51]). According to Tryggvason ([79]) also, the subsidence in south-west Iceland is due to elastic deformation of the upper crustal layer: no movements were detected on the faults. He feels that since there is no relevant isostatic anomaly, the subsidence is probably due to horizontal tension, or to plastic flow away from the graben.

According to a comparison made by Hiersemann ([25]) between geophysical maps and the map of recent crustal movements, there are relations between the recent movements and the deep structure of the G. D. R. in such a way that the isostatic equilibrium which had been disturbed in earlier geological epochs by orogenic forces is reestablished, the regions of mass abundance remaining relatively at rest. The attempt to find a similar relation between the Pleistocene covering of ice and the recent crustal movements is obviated in the territory of the G. D. R. An uplift as a consequence of the unloading of the ice is found neither at the coast nor inland. Even if we take a general displacement of the level in consideration, there will be no regions of uplift which at any place have been drawn from the melting ice border. In the G. D. R. the post-glacial uplift is subordinated to older tendencies of movements, which are still maintained by deep-seated structure, or it is completely absent.

Walcott ([81]) has suggested an isostatic-tectonic origin for basement uplifts. He declares that the tectonics involved in the structural development of uplifts in the stable platforms are suggested to be a natural consequence of loading the platform by sedimentary rocks. Any original compensated topography on the platform will cause differential loading with sediments thicker and the load greater in the valleys than over the hills. If the wavelength of topography is large, differential vertical movements can occur causing an amplification of the original topography and the growth of an arch. If the wavelength lies in a critical region defined by the flexural rigidity of the lithosphere, stress differences within the lithosphere caused by the loading may exceed the elastic limit producing faulting and the development of horsts. The Boothia uplift, the Early and Middle Paleozoic development of the Peace River Uplift and other structures in Canada, are suggested to be examples of such a process. Similarly, the subsidence of the Williston and Michigan Basins are also examples of such a process. In other words, the structural development of some of the above features is attributed to isostatic processes, the rise of positive areas being balanced by sinking of negative areas.

Walcott (84) summarized his observations by saying that " The basic idea for the origin of basement uplifts is, therefore, that any compensated topography on a surface that is depressed below sea level and progressively loaded with sediment will tend to be amplified. The greater sedimentary load in the valley will cause a relative depression of the valley floor and, as with modern deltas, a migration of mantle material from beneath the growing basin ".

Lyustikh and Magnitsky (52) have discussed relations of the gravity field to the vertical movements of the crust and to the transfer of matter along the Earth's surface. They inferred that vertical movements of the crust are accompanied by the displacement of subcrustal material in the direction suitable to the establishment of the equilibrium of the crust. However, it seems that the dominating cause of vertical movements is the change of volume of the subcrustal material. Only in the course of time can the disturbances of the gravity field due to this process be eliminated by the trasnfer of material in the subcrustal weak layer (probably the low-velocity layer). The results of Lyustikh and Magnitsky (52) are in fair agreement with results obtained by the other geophysical investigations and with data from investigations of mineral transformations due to the temperature and pressure changes.

Besides the above theory, Magnitsky (54) came up with the suggestion that phase transformations in the upper mantle could be considered as the cause of recent vertical crustal movements. However, at the same time, he maintained his earlier theory by declaring that the larger part of the Earth's crustal displacement is caused not by phase transition but by the flow of the material into the asthenosphere (approximately 80%). This is in good agreement with the conclusions drawn earlier on the basis of consideration of the gravity field of the platform (52).

Sleigh and others (76) have discovered that the imposition of a large mass of water can also cause crustal deformation. Levelling results have made clear that the crust has subsided under the lake created by damming the Zambezi River at Kariba Gorge (Zambia, Africa) in 1958. The subsidence is measurable to a distance of 36 km from the lake. Movement has been unequal at different points. One bench mark appears to have been uplifted; this may be due to fault movement during one or more of the later shocks of the heavy seismic activity of 1963. From available information it is difficult to estimate the mechanism of the crustal movements, but it is suggested that it may be primarily one of elastic bending of strata under the loading, possibly associated with lubrification of existing faults.

D – *Glacial Crustal Flexure Theory.*

Silvester and Brotchie ([73]) feel that the deformation of the Earth's crust under superposed loads is considered as a problem in structural mechanics. The crust is treated as a uniform, elastic, thin, spherical shell, and the mantle is treated as an enclosed viscous liquid. Crustal deformation is expressed in terms of a parameter known as "radius of relative stiffness", and expressed by l. Crustal stiffness, curvature, and mantle density combine to form the parameter l, and the average continental value of l is about 58 km. The corresponding value for the oceanic crust is 20 km, including the effect of immersion.

For concentrated loads such as volcanic cones and reservoirs, the zone of downward displacement extends to approximately $4l$ from the load center, i.e. to 230 km on the continent and 80 km beneath the sea. For uniform loading, the zone of downward displacement extends approximately to form 2 to $3l$ beyond the edge of the load. Isostatic equilibrium is obtained at the center only when the loaded radius is greater than $3l$. The deformed zone as a whole is essentially in isostatic equilibrium under constant loads but areas within the zone are in flexural equilibrium only, allowing isostatic gravity anomalies, both positive and negative.

A global effect of deglaciation is flow of the melted ice into the oceans, which causes a rise in sea level, and a compensating flow of the mantle from beneath the ocean to beneath the zone deformed by the ice, which lowers the ocean bottom. The flow of the mantle lags behind the flow of the water. Various types of crustal deformation may be predicted. Under a distributed load of radius A, the zone of downward displacement has a radius greater than A. Under loading of other types than homogeneously distributed (e.g., circumferential loads) or under combined bending and compression, the crust will tend to deform into ridges and troughs with wavelengths of the order of $2\pi l$. For concentrated loading such as volcanic cones, troughs of widths less than $4l$ may surround the cone. The width of the troughs decreases with increasing width of load. Creep in the crust due to flexure or compression will tend to deepen these troughs and reduce their width.

E – *Ocean Plate Theory.*

Regarding the movements of the oceanic crust, the following observations can be established. According to Menard ([57]), a moving oceanic crustal plate is elevated where it is created at the trailing edge and it subsides as it grows older. The subsidence continues far beyond the obvious topographic boundaries of midocean ridges. The rate of subsidence averages 9 cm per thousand years for the first ten million years, 3.3 cm per thousand years for the next thirty million years, and is estimated at 2 cm per thousand years for the next thirty million years. Even the older crust in the Pacific subsided at a slower rate for an additional 25 million years. In the Atlantic, however, the rate was much faster during the same period. Subsidence is related to the interaction of mantle degassing, erosion, sedimentation, mantle counterflow, and sea floor spreading. "Midplate rises" exist in all the major ocean basins. Many are broad elevations characterized by thick pelagic center phenomena. They probably mark the locus of small transient convection cells which act under rather than at the edges of large crustal plates.

V – Evaluation of theories of vertical land motion.

Glacial isostasy seems to be a logical and practicable phenomenon that can cause vertical movements of the Earth's crust. One has found evidence of great ice-covers in Scandinavia, North America and Scotland. At the same time, observations have revealed that all these places were subsiding until the melting of the ice. Hence it is obvious that the enormous weight of the ice thrown upon the land might have played an important role in the depression of the land. As a matter of fact, the similarity in the heights to which marine fossils have been found in Scandinavia, North America and Scotland, makes us feel that the depression of land in these countries also could have been similar to one another. Now the question arises as to how this phenomenon holds good in cases of land uplift. Let us assume that the material on which the solid crust of the Earth reposes is in a rheologically " soft " state of fusion. Therefore, a depression of the crust might take place when it is loaded with an enormous weight of ice; the removal of the load by the melting of the ice would account for the rising of the land. On the basis of this simple logical thought, we feel that the depression of the Earth's crust is caused by the enormous load of the glacial ice on the land and its uplift is caused by the recovery of the crust after depression. We quote the following argument of Daly (13) to those scientists who claim that glacial isostasy has nothing to do with crustal movements:

" This hypothesis, that there is no connection between the upwarping and the deglaciation, shows its full weakness when confronted with field statistics. We might conceive that the observed systematic warping in one or two tracts might be explained by independent epeirogenic movements, but it seems incredible that in a dozen regions the same type of warping should appear as mere accidental products of a stress system that has no vital connection with ice-loads. Yet basining and recoil have been demonstrated in as many widely separated tracts, each having been covered with heavy masses of ice recently melted away. In some, if not all, of the cases the melting and warping began less than 50,000 years ago. With few exceptions, there are no signs that the lithosphere outside these tracts was simultaneously disturbed by anything like the same amount ".

Furthermore, inspecting Schofield's (71) (Fig. 4) uplift curves for localities on the Baltic and Canadian shields, one observes that the curves obtained for all localities belong to one family, indicating that similar forces were at work at precisely the same times within both shields. This similarity, together with the high rate of uplift, particularly in early Postglacial time, makes it almost certain that isostatic rebound, following melting of the ice, has been real and not illusory.

We do not believe that glacial isostasy is the sole cause of crustal movements, because if it were so, then we would not have been able to observe crustal movements at places where there never was any ice-cover. This leads us to the belief that some other processes also might be responsible for the causes of crustal movements. In the act of crustal movements, we feel that the theory of tectonic isostasy plays a role similar to that of glacial isostasy. There is no doubt that both the Canadian Shield and the Baltic Shield were being elevated prior to the glaciated period, and hence some cause other than glacial isostasy must have been responsible for this uplift. Secondly, observations at many places have proved that contemporary uplift is a continuation of movements which have characterized Shield areas since Pre-cambrian times. Therefore, we believe that tectonic forces also have been playing a role in the crustal movements.

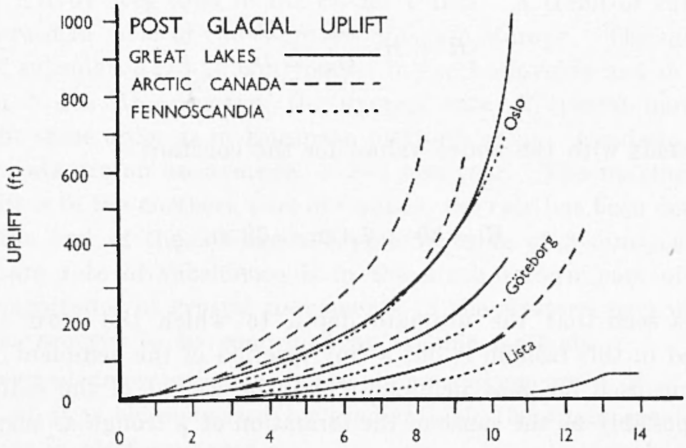

Fig. 4 – Family of post-glacial uplift curves (after Schofield [71]).

Walcott's [84] theory of an isostatic-tectonic origin for basement uplifts, however, does not seem to be appealing to us. It is absolutely impossible for any compensated topography on a surface that is depressed below sea level and progressively loaded with sediment, to be amplified. In other words, Walcott [84] thinks that the weight of the deposition of the sediments whose density is 2.4 can cause the depression of the crust into the mantle whose density is 3.4. This phenomenon sounds to be in conflict with the fact that it is impossible for a heavier material to be depressed by the weight of lighter material on it, except if this lighter material is piled to great heights (like the ice). Holmes [29] and Scheidegger [69,70] have strongly argued that the weight of the sediments piled to sea level cannot possibly be the cause of the formation of a trough. This fact has been established by them on the basis of the following derivation: Let the deposition of sediments (density $D_s = 2.4$) take place in a water (density $D_w = 1$) depth of $H_w + 30$ meters, and proceed until the water depth is completely filled in. If the maximum thickness of sediments deposited in this manner be H meters, then the ultimate amount of the depression of the crust into the mantle (density $D_m = 3.4$) is $(H - H_u)$. Isostasy then requires

$$H\,D_s = H_w\,D_w + D_m\,(H - H_w)$$

or

$$H = H_w \frac{D_n - D_u}{D_m - D_s}$$

which yields with the above values for the constant

$$H = 30 \times 2.4 \text{ m} = 72 \text{ m}.$$

It is seen that the ultimate depth to which the crust can be depressed in this fashion is but a tiny fraction of the sediment thicknesses surmised for geosynclines. Thus, the weight of the sediments cannot possibly be the cause of the formation of a trough as suggested by Walcott (84).

It is quite possible that vertical movements of the crust are accompanied by the displacement of subcrustal material in the direction suitable to the establishment of the equilibrium of the crust. Therefore, we think that Lyustikh anf Magnitsky (52) have reached the right conclusion that the Earth's crustal displacement is sometimes caused by the flow of subcrustal material into the asthenosphere.

So far, sufficient evidence has not been found to prove the validity of the glacial crustal flexure theory suggested by Silvester and Brotchie (73). Once it is proved that the flow of the mantle lags behind the flow of the water in the process of the flow of the melted ice into the oceans, which causes a rise in sea level, and a compensating flow of the mantle from beneath the ocean to beneath the zone deformed by the ice, then we can say that the glacial crustal flexure theory is validated as one of the causes of crustal movements.

The ocean plate theory recommended by Menard (57) is in good agreement with the general observations of the movements of the oceanic crust. Also, " midplate rises " are presumed to exist in all the major ocean basins.

VI. – Conclusion.

In summary, we may state that in continental platform areas such as eastern and northern Europe the rate of contemporary geodetic vertical movements are on an average ± 4 to 5 mm/year. The maximum rate of uplift (10 mm/year) is in the central part of Fennoscandia (this rate was higher right at the end of the last ice age) and in the Krivoy Rog area in the Soviet Union. A trend of subsidence is observed in most of the countries of South Europe. The maximum rate of subsidence (13-26 mm/year) is in Czechoslovakia and in France.

In North America too, the average rate of crustal movements is of the same order as in European platform areas. Geodetic vertical movements are on an average + 3–4 mm/year. The maximum rate or uplift is in the northern part of Canada, the rate has been decreasing since the end of the ice age to a present value of 8 mm/year. The maximum rate of subsidence is in the north-eastern part of U.S.A. The magnitudes of crustal movements in the western part of North America are yet to be confirmed by reliable methods.

Vertical deformation in Japan shows average rates of ± 4 mm/year, but it is characterized by gradients 10–100 times greater than gradients in platform areas.

A detailed evaluation of the various theories of land uplift leads to the conclusion that there is little doubt regarding the proposition that tectonic forces and isostasy are the two main factors that are responsible for the slow but regular vertical movements of the Earth's crust. However, we do not rule out the possibility of other factors that also contribute to vertical crustal movements all over the world. ¡Some of these factors are: physico-chemical processes in the Earth's nterior, frost action, varying moisture content of the soil, removal of underground water, removal of oil and gas, mining activities, fault lines, earthquakes, etc. There are some indications that crustal movements caused by these factors are not of similarly slow but regular character as those caused by tectonic forces and isostasy.

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