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The changing role of the lithosphere in models of glacial isostasy: a historical review

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ABSTRACT

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During the last 125 years, the role of the lithosphere in models of glacial-isostatic adjustment experienced several changes. Following the postulation of glacial isostasy by Jamieson in 1865, the lithosphere was generally regarded as comparable in importance for the adjustment process to the fluid substratum. This changed with the initiation of quantitative modelling by Van Bemmelen and Berlage and by Haskell in 1935, whereupon effects due to the lithosphere were commonly *neglected* in interpretations of postglacial uplift for 30 years. After the development of a layered viscous earth model with an elastic surface layer by McConnell in 1965, the lithosphere was eventually *reintroduced* into models of glacial isostasy. Subsequent studies largely confirmed the original ideas regarding the importance of the lithosphere for the adjustment process, although the effects are pronounced only for short-wavelength deformations. Using this response characteristic of the lithosphere, estimates of its thickness have recently become available for several tectonic provinces.

1. Introduction

The concept of glacial isostasy was introduced during the second half of the nineteenth century. Its basic assertion is that the postglacial uplifts observed in North America, Fennoscandia, Scotland and elsewhere can be explained as retarded adjustment of the earth's interior to the removal of the Pleistocene ice-sheets in these regions. Whereas this view is regarded as essentially correct today, it was not universally accepted after its first proposal for several decades and a number of competing concepts were suggested (e.g. Croll, 1874). Such alternative explanations were discussed extensively at that time (e.g. Gilbert, 1890a, pp. 373–383; Upham, 1895, pp. 487–501) and have also been summarized recently (e.g. Mörner, 1979; Ekman, 1991); in the present review, they will not be considered.

Largely independent of the early studies in *glacial* isostasy was the development of the concept of *gravimetric* isostasy. This encompasses several explanations of the mass deficits indicated by gravimetric observations in mountain regions (e.g. Boscovich, 1755, p. 475; Airy, 1855; Pratt, 1859; Hayford, 1909; Love, 1911, pp. 6–37). The concepts of glacial and gravimetric isostasy are well-distinguished: Whereas the former is concerned with the *restoration* of equilibrium following the growth and decay of ice loads, the latter seeks explanations of the *maintenance* of equilibrium in the face of permanent mountain loads.

In this review, the developments in gravimetric isostasy will be mostly excluded. This is justified by the different viewpoints taken in glacial and gravimetric isostasy as indicated above. At some later stage, the question of the compatibility of the two concepts will briefly be commented on.

The history of gravimetric isostasy has been repeatedly summarized (e.g. Daly, 1940; Heiskanen and Vening Meinesz, 1958, pp. 124–146; Bialas, 1974; Garland, 1979).

In the following, glacial isostasy will be reviewed with special consideration of the role of the lithosphere taken in the conceptual models developed over the years. The term *lithosphere*, understood in the sense of a surface shell of the earth with the capacity of sustaining long-enduring stress differences without significant flow, can be traced back at least to Von Hochstetter (1880, p. 3). However, before Barrell's (1914b) formal definition of the lithosphere, the term *crust* was more common for that shell. In the present study, lithosphere and crust are regarded as synonymous and used in the above sense. We note at this point that no comprehensive review of the subject is attempted here; rather, the main lines of development will be traced.

The evolution of models in glacial isostasy can be divided into a number of distinct periods. The first period (1836–1889) is characterized by several independent formulations of the basic idea of glacial isostasy (Section 2). During the following period (1890–1934), the concepts were further elaborated. This development was largely guided by advancements in the quantity and quality of observations of postglacial uplift. At the same time, the compatibility of the concepts of glacial and gravimetric isostasy was first discussed (Section 3). A characteristic feature of the models developed before 1934 was that, normally, they were *qualitative* and that they *included* a lithosphere. On the whole, the role of the lithosphere in the process of glacial-isostatic adjustment was regarded as important during that period.

Quantitative modelling of glacial-isostatic adjustment started in 1935. During the first decades (1935–1965), effects due to the lithosphere were usually *neglected* without further comment (Section 4). This attitude changed only more recently (1966–1992), when the lithosphere was accounted for in most models and a considerable number of estimates of its thickness were proposed on the basis of observations of postglacial uplift (Section 5).

Our review concludes with a brief assessment of the varying role of the lithosphere in models of glacial isostasy over the past 125 years and with some remarks on its importance in recent studies of eustatic sea-level rise and climatic change (Section 6).

2. Emergence of glacial isostasy: 1836–1889

The concept of glacial isostasy was preceded by a closely related concept concerned with the evolution of sedimentary basins. The mechanisms proposed for the two processes are, in fact, identical, the difference being the load involved in either case. It appears that the British astronomer John Herschel was the first to speculate on effects caused by sedimentary loads. Commenting on his sketch (Fig. 1) in a letter written to the geologist Charles Lyell on February 20, 1836, he asked (Herschel, 1837):

"...What will be the effect of the enormous weight [of the sedimentary deposit C] thus added to the bed D D D...? Of course, to depress D under it, and to force it down into the yielding mass E, a portion of which will be driven laterally under the continent A, and upheave it."

Herschel's view was largely ignored by the geological community at that time. However, more than two decades later, similar ideas were discussed among a number of North American geologists concerned with the evolution of geosynclines. Prominent among them was James Hall, who noted on the origin of shallow-water deposits in sedimentary basins (Hall, 1859, p. 69):

"When these [sedimentary deposits] are spread along a belt of sea bottom, ...the first effect of this great augmentation of matter would be to produce a yielding of the earth's crust beneath,

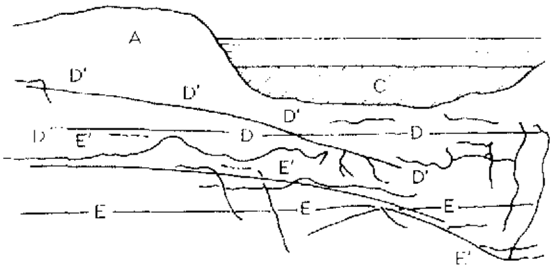

Fig. 1. Herschel's (1837) sketch of isostatic adjustment between basin loaded by sediments and neighbouring continent.

and a gradual subsidence will be the consequence."

Hall's view evidences the hypothesis on the state of the earth's interior prevailing among geologists of the nineteenth century: a molten *fluid* core surrounded by a thin *rigid* crust.

A few years after Hall's publication, the concept of glacial isostasy was first suggested by the British geologist Thomas Jamieson. Discussing field observations related to the Pleistocene glaciation of Scotland, he briefly commented on a possible cause of postglacial uplift (Jamieson, 1865):

"We don't know 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 [the weight of the ice-sheet], 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."

Later, Jamieson published a more detailed account of his hypothesis (Jamieson, 1882). In a paper on postglacial uplift in North America, he wrote (Jamieson, 1887):

"If ... the outer crust of the earth reposes at no great depth upon a stratum ... in a state of fusion, we may ... suppose that the addition of a heavy load upon the surface would cause the crust to press deeper down into this soft stratum and drive part of it away to where the pressure was less."

It is obvious from these citations that Jamieson assigned an important role to the crust in the process of glacial-isostatic adjustment. This applies also to Nathaniel Shaler, a North American geologist who advanced a model very similar to that suggested by Jamieson (Fig. 2). Discussing the role of the crust in the submergence of glaciated lands, he even proposed (Shaler, 1874):

"If this [isostatic] theory of the glacial depression be accepted we may obtain thereby a basis on which to compute the rigidity of the earth's crust ..."

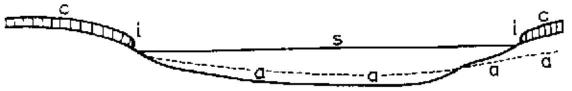

Fig. 2. Shaler's (1874) illustration of isostatic adjustment between continent loaded by ice-sheet and neighbouring sea.

In view of Shaler's suggestion, it is instructive to digress to some work done by the German physicist Heinrich Hertz, who, in a short publication, calculated the load-induced equilibrium deflection of a thin elastic plate floating on a fluid substratum (Hertz, 1884); if his solution is applied to glacial loads depressing the earth's crust, it permits first estimates of crustal rigidity. Hertz' plate model was later used by Vening Meinesz (1931) and Gunn (1949) to improve existing models of gravimetric isostasy. However, it was not employed in the context of glacial isostasy before the work of Einarsson (1953) and McGinnis (1968). Eventually, Walcott (1970a, b) applied Hertz' thin-plate theory to estimate the flexural rigidity of the earth's lithosphere as proposed by Shaler.

Incidentally, we note that hypotheses of glacial isostasy largely identical to those due to Jamieson and Shaler were postulated by several other investigators (e.g. Whittlesey, 1868; Ricketts, 1872; McGee, 1881; Chamberlin, 1884; Gilbert, 1886). In the earlier publications, usually no mutual references can be found. This suggests that the concept of glacial isostasy was arrived at independently by a number of investigators. We recall that the *term* isostasy was not used before Dutton (1889), who defined it in the sense of isostatic equilibrium (cf. also Dutton, 1925; Mayo, 1985).

3. Isostasy versus rigidity: 1890–1934

The initial period of glacial isostasy was followed by a time characterized by two important lines of development in isostatic research. Along one line, the theory of glacial isostasy was further consolidated and refined; along the other, inconsistencies between the theory of gravimetric isostasy and the geological field evidence were noted and modifications to the former suggested.

The reasonableness of gravimetric isostasy, as understood and applied by the geodetic community around the turn of the century, was soon questioned by a number of geologists. In their criticism, they discussed the main assertions of gravimetric isostasy regarding the compensation of surface inequalities, namely that isostatic equilibrium is *perfect* and *local*. Quite obviously, such claims are not easily maintained in view of the ongoing processes of orogeny, erosion and redeposition.

The North American geologist Grove Gilbert was one of the first to suggest a concept which he believed to be in better agreement with the geological evidence. Its characteristic feature is that it accounts for the *rigidity* of the crust, which supposedly counteracts *isostasy* on a more local scale. In a paper read to the Geological Society of America, he noted in particular (Gilbert, 1890b):

"There are ... two possible explanations of the inequalities of terrestrial surface, and these may be characterized... by the terms rigidity and isostasy. ... Mountains, mountain ranges, and valleys... exist generally in virtue of the rigidity of the earth's crust; continents, continental plateaus, and oceanic basins exist in virtue of isostatic equilibrium in a crust heterogeneous as to density."

Gilbert also discussed the bending of the crust due to the weight of superimposed loads. As an example, he considered the disappearance of Pleistocene Lake Bonneville, Utah, whose abandoned shoreline had been surveyed shortly before. A conspicuous feature of it is its updoming toward the centre of the former lake (Fig. 3), which Gilbert interpreted as response of the earth's crust to the desiccation of that lake. Using an engineer's formula for the rupture of a solid beam, he even estimated the thickness of the crust and suggested a value of about 50 km (Gilbert, 1890a, p. 380). On the whole, Gilbert's ideas left a positive impact on geological thinking; a more immediate effect was their use in several interpretations of postglacial uplift in North America (e.g. Upham, 1895, pp. 493–496).

About 25 years later, the North American geologist Joseph Barrell markedly extended Gilbert's concept. Barrell introduced the term *asthenosphere* for the substratum underlying the lithosphere and, in a series of thirteen papers published in the Journal of Geology during 1914 and 1915 (summarized in Barrell, 1919a, b), discussed the properties and behaviour of these two shells exhaustively.

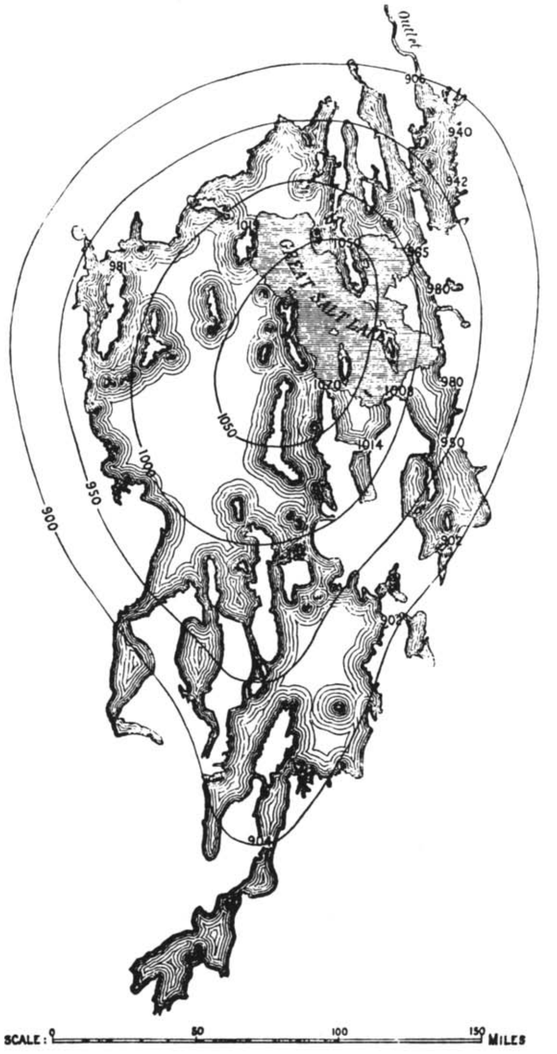

Fig. 3. Gilbert's (1890a) contour map of warped Lake Bonneville shorelines.

Very similar to Gilbert, Barrell endowed the lithosphere with rigidity, which enabled it to maintain isostatic *equilibrium* by sustaining stress differences imposed by surface irregularities and their compensating subsurface masses over geological periods (Fig. 4). Regarding the spatial scale of isostasy, he argued (Barrell, 1914b):

"Isostasy [isostatic equilibrium], then, is nearly perfect, or is very imperfect, or even non-existent, according to the size and relief of the area considered."

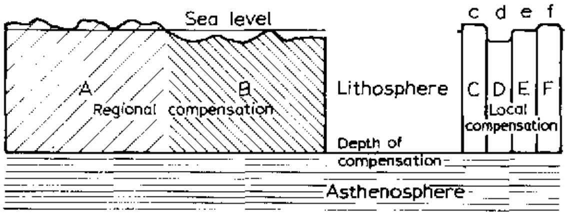

Fig. 4. Barrell's (1919b) conception of *regional* isostatic equilibrium versus conventional conception of *local* isostatic equilibrium.

On the other hand, Barrell regarded the asthenoshere as a plastic shell with the capacity to yield to long-enduring stress differences and, thus, to effect isostatic *adjustment*. Commenting on glacial isostasy, he took a more conservative view and remarked (Barrell, 1914a):

"It is not known, however, to what degree the previous [before deglaciation] downwarp compensated for the burden of the continental ice sheet and what degree of regional stress the crust was able to bear."

Notwithstanding this cautionary note, Barrell's studies seem to have been generally well-received by the proponents of glacial isostasy.

Several years later, the Norwegian oceanographer and polar researcher Fridtjof Nansen, in a comprehensive study of the glacial record preserved in Fennoscandia and elsewhere, developed a comparatively detailed model of glacial-isostatic adjustment (Nansen, 1921, pp. 290–306) and displayed its essential features in a simple illustration (Fig. 5). In another study of the properties and behaviour of the earth's crust and its substratum, he remarked (Nansen, 1928, pp. 11–12):

"The earth's crust may ...be considered as a slowly flexible sheet of solid rock floating on a viscous substratum. If loaded in one place this sheet will bend slowly under the load, and the plastic matter underneath will be displaced to the sides, where the sheet will be slightly lifted in a belt round the depressed area. If unloaded in one place the sheet will rise slowly in that area; there will be an inward flow in the substratum underneath, and a slight subsidence of the sheet in the surrounding area."

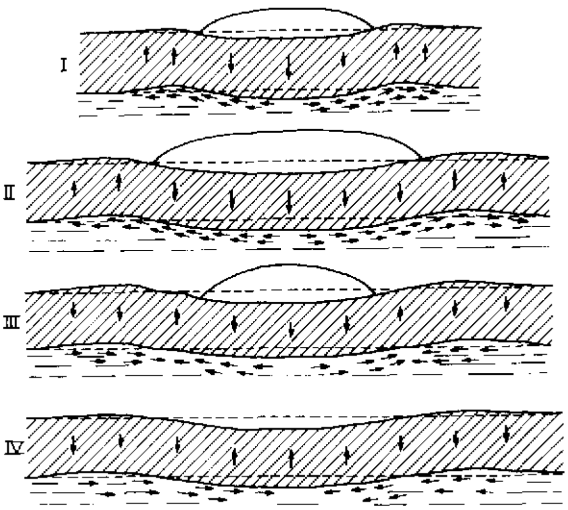

Fig. 5. Nansen's (1921) illustration of depression of crust due to ice-sheet. Note retarded response of crust and substratum.

A major proponent of Barrell's work was the North American geologist Reginald Daly, who published extensively on the Pleistocene. His views are summarized in a monograph, which also considers most of the work completed by other investigators up to that time. In particular, Daly discussed two alternative hypotheses of glacial-isostatic adjustment. To one of them he referred as *bulge hypothesis* (Fig. 6) and remarked (Daly, 1934, p. 120):

"Below it [the flexible crust] is a weak substratum... According to the bulge hypothesis, the basining [of the crust] is accompanied by outward, horizontal flow in the substratum and just beneath the crust. ...Because the substratum is

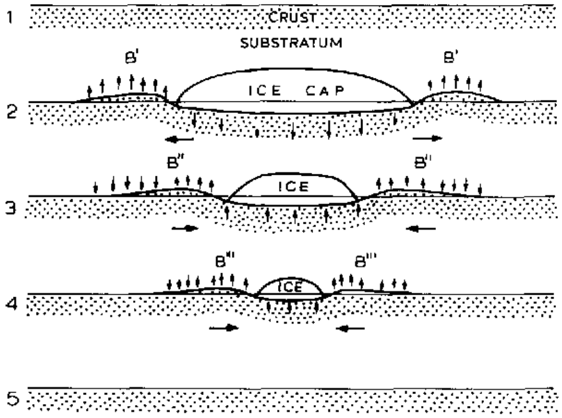

Fig. 6. Daly's (1934) illustration of *bulge hypothesis* of isostatic adjustment. Note movement of peripheral bulge.

highly viscous, its material moves but a relatively short distance away from the ice-covered region."

Although Figs. 5 and 6 look similar at first glance, a closer inspection of the direction of movement for different points at the individual stages of glaciation reveals distinct differences. Nansen and Daly discussed these special features in some detail; however, considering that their models are qualitative, not too much importance should be attached to these differences.

It is interesting to note at this point that the German geophysicist Rudzki had modelled glacial isostasy quantitatively quite early (Rudzki, 1899a, b). He chose to consider the earth as an elastic sphere, which is in line with conceptions of the earth's interior favoured by Darwin, Thomson and several other nineteenth-century physicists mainly on the basis of tidal observations. Calculating the magnitude and shape of the surface depression produced by an ice-sheet for that model, Rudzki, however, found that, for reasonable values of ice thickness and earth rigidity, the calculated depression is much smaller than the depression observed.

In a later publication (Rudzki, 1907), he elaborated the consequences of his results and suggested that the earth's response to glacial loads be more properly modelled by means of an elastic shell surrounding a viscous core. Although several physicists had completed theoretical work on perturbations of elastic shells and viscous spheres by 1900 (e.g. Lamé, 1854; Thomson, 1863; Darwin, 1879), Rudzki did not follow up these ideas and quantitative modelling of glacial isostasy was abandoned for almost three decades.

4. Quantitative models of glacial isostasy: 1935–1965

Quantitative modelling of glacial-isostatic adjustment was finally resumed in 1935. The pioneer publications usually referenced are Van Bemmelen and Berlage (1935), Haskell (1935, 1936, 1937) and Vening Meinesz (1937), which were succeeded by a considerable number of other investigations (Table 1). The models used are mainly viscous half-spaces or spheres subject to surface loads; usually, an estimate of the viscosity of the earth's interior was proposed. Since reviews of these investigations are readily available (e.g. Heiskanen and Vening Meinesz, 1958, pp. 357–370; Lliboutry, 1971; Walcott, 1973), we summarize their results only very briefly: On the supposition of a homogeneous viscous interior, the viscosity value below Fennoscandia was estimated at about 10^{21} Pa s; if a viscous channel of 100 km thickness underlain by a rigid substratum was assumed, values near 10^{19} Pa s were indicated for the channel.

TABLE 1

Quantitative models and interpretations: 1935–1965

Lithosphere neglected	Lithosphere included
Van Bemmelen and Berlage (1935)	Niskanen (1943, 1949)
Haskell (1935, 1936, 1937)	Einarsson (1953)
Vening Meinesz (1937, 1954)	McConnell (1965)
Niskanen (1939, 1948)	
Jeffreys (1952, 1959)	
Burgers and Colette (1958a, b)	
Crittenden (1963, 1967)	
McConnell (1963)	
Takeuchi (1963)	
Takeuchi and Hasegawa (1965)	

In view of the prominent role assigned to the lithosphere in the qualitative models of glacial-isostatic adjustment advanced before 1935, it surprises that the lithosphere was commonly neglected in the early quantitative models. One of the very few authors who did comment on this neglect was Gutenberg (1941), who remarked:

"Unfortunately, the assumption of a homogeneous plastic [viscous] earth without strength leads to such complicated equations that no attempt has yet been made to introduce an additional upper layer with great strength..."

Heiskanen and Vening Meinesz (1958, pp. 357–359) investigated this question in more detail. Using the thin elastic-plate model for the lithosphere, they estimated its effect quantitatively and arrived at the conclusion

"that the crust ...has played no appreciable part in the phenomenon [of glacial-isostatic adjustment]; therefore, the rising cannot provide any indication of the physical properties of the crust."

Considering Shaler's hopes of using postglacial uplift to estimate lithosphere rigidity, this result looks rather disappointing. We must note, however, that the above statement applies to a deformation wavelength of 2000 km and a plate thickness of 35 km. Since the load-induced displacement of a thin elastic plate is approximately proportional to the fourth power of the deformation wavelength and inversely proportional to the third power of the plate thickness (e.g. Wolf, 1984), smaller wavelengths or thicker plates will produce more pronounced effects.

By the time Heiskanen and Vening Meinesz published their results, a more realistic quantitative study of the role of the lithosphere in glacial isostasy by Niskanen (1943) had in fact been completed. Continuing work began by Rudzki more than 40 years earlier, Niskanen employed a thick elastic shell enclosing an inviscid core as earth model. His objective was to calculate the equilibrium displacement produced by a surface load and, in particular, to investigate the dependence of this displacement on the thickness of the shell and the radius of the load. Niskanen largely confirmed the results obtained on the basis of thin-plate theory, namely that the effect of the lithosphere increases with lithosphere thickness but decreases with load radius. Of significance for the interpretation of postglacial uplift is the "regionality" of the surface depression near the load edge (Fig. 7), a feature which proved very sensitive to lithosphere thickness and load radius. Later, Niskanen attempted to generalize this model and considered an elastic shell enclosing a viscous core (Niskanen, 1949). In consequence of a number of special assumptions introduced, the results of this theoretical study have been questioned and will not be discussed here.

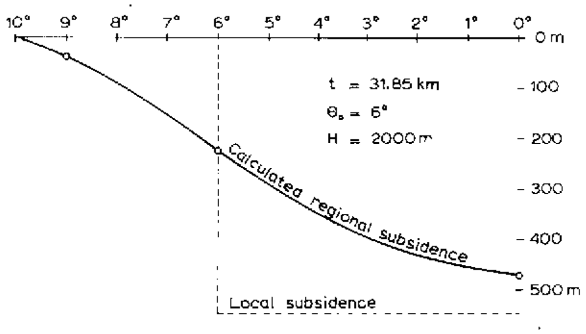

Fig. 7. Niskanen's (1943) illustration of surface displacement as a function of radial distance from load axis. Results apply to square-edged spherical ice cap of 6° radius and 2 km thickness and to lithosphere of 32 km thickness. Note *regionality* of deformation near load margin.

Apart from an elementary, semi-quantitative interpretation of postglacial uplift in Iceland employing thin-plate theory (Einarsson, 1953), the lithosphere was commonly disregarded in studies of glacial isostasy during the following years. This situation only changed after 1960, when a generalized earth model incorporating an elastic layer overlying a layered viscous half-space was developed by McConnell (1963). Of particular importance was his result that, for sufficiently short deformation wavelengths, the *relaxation time* decreases with increasing lithosphere thickness. This completed Niskanen's investigation on the effect of the lithosphere on the *equilibrium displacement* and, thus, finally set the stage for the use of glacial-isostatic adjustment to sample the lithosphere as suggested by Shaler almost 90 years before.

5. Glacial isostasy and lithosphere thickness: 1966–1992

The recent period of research in glacial isostasy is distinguished by a marked proliferation of publications on this subject. Particular emphasis has been placed on further generalizations of the theory, which has led to the development of self-gravitating, spherically symmetric, viscoelastic earth models (Peltier, 1974; Cathles, 1975, pp. 72–108). At the same time, studies of glacial-isostatic adjustment have been extended to global interpretations of relative sea-level change and related observations (e.g. Wu and Peltier, 1983; Nakada and Lambeck, 1987), allowing improved constraints on the earth's viscosity stratification. The results show that the global average of the upper-mantle viscosity is near 10^{21} Pa s; the lower-mantle viscosity tends to be higher by at least a factor of 2–10. In Fennoscandia, a low-viscosity channel below the lithosphere is indicated, where viscosity values are reduced by 1–2 orders of magnitude. Similarly low values are suggested for the uppermost mantle below tectonically active regions. The most recent lines of research include the development of laterally inhomogeneous earth models (e.g. Gasperini and Sabadini, 1989) and the study of non-linear rheologies (e.g. Wu, 1992).

In this section, we will not survey the vast literature on the theory and interpretation of glacial isostasy after 1965. Reviews of this work do exist (e.g. Peltier, 1982; Lambeck, 1990) and may be consulted for details. Instead, we will limit ourselves to publications concerned with imposing constraints on lithosphere thickness and briefly comment on the results arrived at.

The thicknesses proposed for the lithosphere using observations of glacial-isostatic adjustment are compiled in Tables 2 and 3. The globally representative maximum of 50–80 km by Nakada and Lambeck (1987) is to be understood as an average value for oceanic and continental lithospheres. This is supported by the estimates for the North American lithosphere, which are typically about 100 km and, thus, higher than the global estimate. An exceptionally large lithosphere thickness of about 200 km was claimed by Peltier (1984, 1986); according to Nakada and Lambeck (1987), it results from insufficient resolution of the load model employed in Peltier's studies. The estimates proposed by Walcott (1970a) and Wolf (1986b) are based on equilibrium models and, therefore, are to be interpreted as upper bounds.

TABLE 2

Global and continental estimates of lithosphere thickness: 1966–1992. Values followed by an asterisk are calculated from flexural rigidities using $\mu = 0.67 \times 10^{11}$ Pa and $\nu = 0.272$ as shear modulus and Poisson's number

Investigator	Lithosphere thickness
Global	
Nakada and Lambeck (1987)	≤ 50–80 km
North America	
Walcott (1970a)	58–109 km *
Peltier (1984, 1986)	200 km
Wolf (1985, 1986a)	85–110 km
Wolf (1986b)	130 ± 35 km *
Fennoscandia	
McConnell (1968)	120 km
Cathles (1975)	69 km *
Anundsen and Fjeldskaar (1983)	69 km *
Wolf (1986b)	110 ± 30 km *
Wolf (1987)	≤ 80 km
Lambeck et al. (1990)	100–150 km
Fjeldskaar and Cathles (1991)	40 km *

TABLE 3

Regional estimates of lithosphere thickness: 1966–1992. Values followed by an asterisk are calculated from flexural rigidities using $\mu = 0.67 \times 10^{11}$ Pa and $\nu = 0.272$ as shear modulus and Poisson's number.

Investigator	Lithosphere thickness
Utah and Nevada	
Walcott (1970b)	13–17 km *
Passey (1981)	≤ 19 km *
Nakiboglu and Lambeck (1982)	15–30 km
Nakiboglu and Lambeck (1983)	28–30 km
Bills and May (1987)	21–25 km
May et al. (1991)	21–25 km
Iceland	
Sigmundsson (1991)	10 km
Scotland	
Lambeck (1991)	100 km
Hokkaido	
Maeda et al. (1992)	25–40 km
Spitsbergen	
Breuer and Wolf (1992)	≤ 80–190 km (laterally variable)

The thickness of the Fennoscandian lithosphere tends to be somewhat lower and the values obtained are close to the global average. Exceptions are the estimate of 120 km by McConnell (1968), which is questionable in view of inadequacies of the data used (cf. Walcott, 1980), and that of 100–150 km by Lambeck et al. (1990). The thickness of about 110 km inferred by Wolf (1986b) is again based on an equilibrium model and represents an upper bound.

Several estimates of lithosphere thickness applying to smaller areas have been advanced. These include the tectonically active Basin and Range province in Utah and Nevada, where the lithosphere appears to be less than 25 km thick (e.g. Bills and May, 1987), the mid-Atlantic ridge location of Iceland, where even lower values are indicated (Sigmundsson, 1991), and the island of Hokkaido near the subducting Pacific plate, where thicknesses of 25–40 km have been estimated (Maeda et al., 1992). The thickness of about 100 km proposed for the lithosphere below Scotland (Lambeck, 1991) is more in line with the estimates for Fennoscandia and reflects the greater tectonic stability of these provinces. A recent study of postglacial uplift in Spitsbergen (Breuer and Wolf, 1992) suggests that the lithosphere is laterally inhomogeneous in this region: Its thickness increases from less than 80 km close to the continental margin to about twice this value below locations at greater distances from it.

6. Concluding remarks

Since the postulation of glacial-isostatic adjustment by Jamieson (1865), the role of the lithosphere in models of glacial isostasy has undergone a number of changes. Introduced originally as a rigid crust separating the earth's surface from the molten interior, its properties and behaviour soon attracted the attention of investigators. In particular, Gilbert (1890b) and Barrell (1919a, b) advanced research along these lines significantly; in result of that, the influence of the lithosphere on the process of glacial-isostatic adjustment became commonly regarded as comparable in importance to that of the substratum (e.g. Nansen, 1928; Daly, 1934).

A noteworthy change took place with the initiation of quantitative modelling by Van Bemmelen and Berlage (1935) and Haskell (1935): For the following 30 years, the influence of the lithosphere was commonly *disregarded* in models of glacial isostasy. Since the role of the lithosphere in the adjustment process had never been quantitatively assessed, this neglect was unfounded and the approach adopted therefore largely pragmatic. The main reason for ignoring the lithosphere during that period appears to be that its incorporation into the theoretical models developed was regarded as difficult.

That this was not true was demonstrated by the research of McConnell (1965), who developed a layered viscous earth model which included an elastic surface layer. After that, the lithosphere was widely *reintroduced* into models of glacial isostasy and estimates of its thickness soon became available. Recent studies have essentially confirmed the original conception of the lithosphere as a strong layer with the capacity of modifying the adjustment process. However, its importance is restricted to shorter-wavelength deformations, which renders observations from locations near the *margins* of the Pleistocene ice-sheets as crucial. The selective response characteristics of the lithosphere *retroactively* justify its neglect during the initial period of quantitative modelling: At that time, interpretations were typically concerned with explaining postglacial uplift near the *centre* of the former Fennoscandian ice-sheet, where the sensitivity to the presence of the lithosphere is only weak.

A topic beyond the scope of this review is a thorough discussion of the bearings of glacial isostasy on other fields of research. One aspect of this concerns the importance of the concept of glacial-isostatic adjustment to research on climatic change. Here, we only allude to the supposed recent episode of global warming and the concomitant eustatic sea-level rise. One of the first efforts of obtaining a value for this observable is due to Gutenberg (1941), who suggested a rise of (1.1 ± 0.8) mm/a from a global analysis of tide-gauge recordings (for brief reviews of the subject cf. Lisitzin, 1974, pp. 177–183; Emery and Aubrey, 1991, pp. 163–166). The renewed interest in eustatic sea-level rise is related to the fact that it may serve as a sensitive indicator of intensified melting of present-day glaciers and ice-sheets in response to anthropogenic heating of the atmosphere. This has recently been discussed by Peltier and Tushingham (1991), who used calculations of the ongoing glacial-isostatic adjustment to correct worldwide tide-gauge recordings of relative sea-level change. Their best estimate of eustatic sea-level rise is (2.4 ± 0.9) mm/a. However, their estimate is sensitive to the parameters of the earth model employed to filter out the glacial-isostatic component contained in the uncorrected recordings. This, in particular, applies to lithosphere thickness and sublithosphere viscosity: For values within the current ranges of uncertainty for these parameters, eustatic sea-level rises between 1.4 and 2.8 mm/a are predicted. Clearly, this sensitivity is not desired here and thus underlines the need of reliable estimates of lithosphere thickness and sublithosphere viscosity in a rather unexpected context.

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