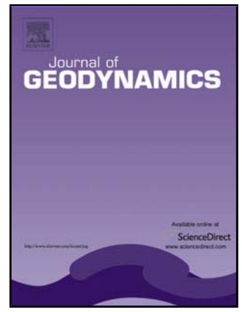
Lithospheric Thickness Recovery from Horizontal and Vertical Land Uplift Rates

Martin Vermeer, Karin Kollo

Accepted Manuscript



Title: Lithospheric Thickness Recovery from Horizontal and Vertical Land Uplift Rates

Authors: Martin Vermeer, Karin Kollo

PII:	S0264-3707(09)00162-8
DOI:	doi:10.1016/j.jog.2009.11.006
Reference:	GEOD 955

To appear in: *Journal of Geodynamics*

Received date:	28-11-2008
Revised date:	9-9-2009
Accepted date:	16-11-2009

Please cite this article as: Vermeer, M., Kollo, K., Lithospheric Thickness Recovery from Horizontal and Vertical Land Uplift Rates, *Journal of Geodynamics* (2008), doi:10.1016/j.jog.2009.11.006

Author affiliations:

Martin Vermeer
Helsinki University of Technology, Department of Surveying (Otakaari 1, FIN-02150 Espoo, FINLAND
e-mail: martin.vermeer@tkk.fi)

Karin Kollo
primary affiliation:
Chief Specialist, Dept. of Geodesy, Estonian Land Board (Mustamäe tee 51, 10621, Tallinn, ESTONIA
e-mail: Karin.Kollo@maaamet.ee)
secondary affiliation:
Helsinki University of Technology, Department of Surveying (Otakaari 1, FIN-02150 Espoo, FINLAND)

Please let me know if this os enough.

Lithospheric Thickness Recovery from Horizontal and Vertical Land Uplift Rates

Karin Kollo and Martin Vermeer

Abstract

As a result of the BIFROST studies of the Fennoscandian postglacial rebound, it is known that in addition to uplift, there also exists a horizontal movement of the Earth's surface, so that points on it move away from the uplift centre at a rate of about 10% of that of the uplift.

We aim to study the vertical and horizontal postglacial motion in order to determine the lithospheric thickness from observed rates.

We conjecture that the cause of the radial movement is that, while a thin lithosphere will move up radially from the Earth's centre, in the case of a thick lithosphere, the mantle blocks may slightly rotate due to the land uplift gradient. This phenomenon is investigated and modelled for further analysis.

In the computations, the BIFROST dataset for Fennoscandia is used to test our hypothesis. Unfortunately for the North-American land uplift area our method did not produce reasonable results; we suspect one reason is the fragmented nature of the lithosphere in this area.

Key words: Lithospheric thickness; Glacial Isostatic Adjustment; BIFROST; Fennoscandia

1. Introduction

Postglacial rebound, or the glacial isostatic adjustment (GIA) phenomenon, has been widely investigated, both in Fennoscandia and in North America.

The advent of space geodesy, in particular GPS, has led to a change in monitoring technology: its costs compared to first order leveling are very much lower, and it provides a three-dimensional measurement capability, obtaining crustal velocities with accuracies of better than a few mm/a. GIA motions were successfully observed using space geodesy in Fennoscandia, and in the much larger area affected by GIA in North America (Sella et al., 2007, and references therein).

Already in 1921 Norwegian oceanographer Fridtjof Nansen showed that the uplift of the crust should be accompanied by a horizontal viscous inflow of subcrustal material, see Fig. 1(Ekman, 2009).

Our interest is in deriving lithospheric thickness from the patterns of vertical and horizontal movements, i.e., the mechanical lithosphere. Lithosphere thickness has been studied so far from the geological point of view, using such data sources as seismics and magnetotelluric measurements. In our computations we use the geodetic data acquired from GPS measurements. We show that vertical and horizontal uplift rates can be used for lithosphere thickness determination.

Our method is purely geometric and, as such, orthogonal to physical modelling of GIA. We assume the effect to be first order in tilt, but it also depends on lithosphere thickness, which we thus can estimate is twice the ratio between horizontal radial movement and land uplift horizontal gradient. In the Fennoscandian and Canadian shield areas, the lithosphere tends to be

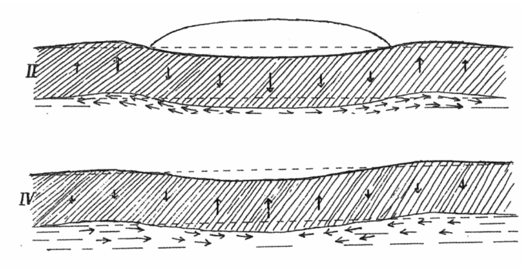


Figure 1: Changing ice load and viscous flow of subcrustal material by Nansen (1921) [reproduction from Ekman (2009)]

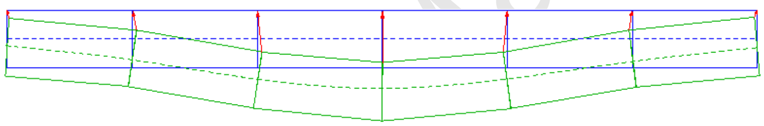


Figure 2: Land uplift producing outward horizontal motion

thick, and during land uplift, blocks of it rotate rigidly. This means that points on the bottom surface of the block have to move inward, and points on the top surface, outward. The "midline" of the lithosphere, i.e., the surface half-way between top and bottom, will move strictly vertically upward, away from the geocentre. This phenomenon is illustrated in Fig. 2.

The Fennoscandian uplift picture clearly shows the horizontal radially outward motion pattern (Fig. 4). In North America however, no such pattern is visible (Sella et al., 2007).

The horizontal movement should be referred to a zero point, for which one may take the center of the uplift area. This means that horizontal motions must be reduced for plate motion in a way that makes this zero point motionless.

2. Theoretical background

2.1. Post-glacial rebound

The oldest written documents on the land uplift, or "decrease of the water", in Fennoscandia date from the 15th century. The phenomenon has been subject of scientific investigations since the 17th century (Mäkinen, 2000). In 1865 Thomas Jamieson presented the theory that the rise of the land is connected with the ice age, which had been discovered in 1837. The theory was accepted after investigations by Gerard De Geer of old shorelines in Scandinavia published in 1890 (Sella et al., 2007) and in North America in 1892 (Ekman, 2009).

At glacial maximum, the Earth is depressed under the weight of ice. When the ice sheet disintegrates, this process reverses and the land rises with respect to sea level in places that were once ice covered. On the forebulges of the ancient Laurentian and Fennoscandian ice sheets sea level will appear to be rising as a consequence of the sinking of the land with respect to the geoid that accompanies the isostatic readjustment of the surface following deglaciation (Peltier, 1990).

The phenomenon of GIA has its roots to the last glacial period, when much of northern Europe, Asia, North America, Greenland and Antarctica were covered by thick continental glaciers. The weight of this ice caused the Earth's crust to flex downward under the load. At the end of the ice age when the glaciers retreated, the removal of the weight from the depressed land led to uplift or rebound of the surface. Due to the extreme viscosity of the mantle, it will take many thousands of years for equilibrium to be re-established (Anon., 2008).

The glacial and postglacial readjustment process of the Earth depends on both the space-time history of the large ice-sheets and the rheology of the Earth's lithosphere and mantle (Wu et al., 1998). Post-glacial rebound produces the following measurable effects (Ekman, 2009; Anon., 2008):

1. vertical crustal motion;
2. global sea level change;
3. horizontal crustal motion,
4. gravity field change;
5. Earth's rotational motion change, and
6. a state of stress leading to multiple small earthquakes.

Rebound rates for Fennoscandia were studied in the BIFROST project using GPS. It showed a horizontal motion diverging from the centre of the uplift area. The largest vertical velocity values are about 11 mm/a, the largest horizontal velocity is found to be about 2 mm/a near the former ice margin (Ekman, 2009; Lidberg, 2007; Mäkinen, 2000; Anon., 2008).

The situation in North America is less certain; however the vertical velocities show fast rebound (ca 10 mm/a) near Hudson Bay, which changes to slower rate (1-2 mm/a) at the south of the Great Lakes. The horizontal velocities are more scattered than in Fennoscandia and show no comparable radial pattern, see Sella et al. (2007). However, a more careful analysis (Sella et al., 2007) based on what seems to be a larger data set, appears to show motions directed outward from Hudson Bay uplift maximum, as expected; but with substantial uncertainty.

2.2. Lithospheric thickness

The lithosphere is defined as the outermost layer of rigid rock which includes the crust (7-100 km thick) and the uppermost solid mantle. The lithosphere is broken into a dozen or more large and small rigid parts, and these plates slowly move relative to one another (Anon., 2009). Many references state that lithosphere thickness is in the range of 80 to 200-250 km (see Artemieva (2002); Jaupart et al. (2002); Artemieva and Mooney (2002), etc).

A thicker lithosphere spreads the deformation farther from the load center, a thinner lithosphere generally results in a smaller horizontal displacement although the node of zero horizontal motion shifts closer to the center of the load (Wu et al., 1998).

Different models and investigation techniques show that lithospheric thickness could be in the range of 100-300 km in both Fennoscandia and North America. E.g., in Fennoscandia, thermal models show that lithospheric thickness is greater than 330 km, but constraints from geophysics again give lithospheric thicknesses of 200-250 km (Jaupart et al., 2002). From seismic and thermal data the thickness of the lithosphere may be estimated to be in the range of 140 to 350 km (Artemieva and Mooney, 2002).

Note that rigidity will also depend on time scale of deformation: material rigid on the time scale of seismic propagation may not be on that of GIA. Thus, there are several possible ways to define the lithosphere, and the boundary between it and the underlying asthenosphere, not always giving the same result (Jaupart et al., 2002; Artemieva and Mooney, 2002; Jaupart et al., 1998; Van der Lee, 2002; Artemieva, 2002, and references therein).

2.3. Reference frame

One of the main tasks of modern geodesy is to define and maintain a global terrestrial reference frame in order to measure and map the Earth's surface. How well the reference frame can be realized has important implications for our ability to study both regional and global properties of the Earth, including post-glacial rebound, sea level change, plate tectonics, regional subsidence and loading, plate boundary deformation, and Earth orientation excitation (Altamimi et al., 2008). A geodetic reference frame may be considered as a consistent set of geodetic stations with assigned coordinate values, possibly velocities, and an epoch of validity (Altamimi et al., 2007).

The vertical datum is a theoretical reference surface for height measurements. Since post-glacial rebound continuously deforms the crustal surface (as well as changes the gravitational field), a vertical datum for practical use needs to be redefined repeatedly through time. (Anon., 2008)

Land uplift values and horizontal motion vectors are referred to some reference frame. All components are GPS-derived, i.e., geometric. However, lithospheric plates move horizontally, and these velocities are added to the motions that we are trying to study. The derivation given assumes that these non-postglacial motions have already been reduced out. However, doing so correctly is non-trivial. Also intra-plate proper motions unrelated to postglacial processes may be superimposed on the postglacial pattern, even in a fragmented fashion.

3. Mathematical background

We derive our formula for modelling lithosphere thickness using ideas presented in the Fig. 1 and Fig. 2. Our idea is geometrical in nature, i.e., a geometric description of the lithosphere's behaviour while the GIA process is going on.

Firstly, as the given dataset contained geodetic coordinates, we computed plane, i.e., map projection, co-ordinates. The procedure is described in Kollo and Vermeer (2008).

Next, the postglacial motion values (north, east and upward) are used, either directly from the BIFROST project or computed from geocentrical velocities by using the inverse of the following rotation matrix (Torge, 2001):

$$\mathbf{A} = \begin{pmatrix} -\sin\varphi\cos\lambda & -\sin\lambda & \cos\varphi\cos\lambda \\ -\sin\varphi\sin\lambda & \cos\lambda & \cos\varphi\sin\lambda \\ \cos\varphi & 0 & \sin\varphi \end{pmatrix},$$

where the first column signifies the north, the second the east and the third the upward velocity unit vector, all expressed in geocentric coordinates.

Our method requires as input maps of both the uplift rate $\dot{h}(x,y)$ and the horizontal velocity vector field $\dot{\mathbf{x}} = \begin{bmatrix} \dot{x}(x,y) & \dot{y}(x,y) \end{bmatrix}^T$. The relationship between the horizontal rate $\dot{\mathbf{x}}$ and the horizontal gradient of the uplift rate $\nabla\dot{h}$ is given by:

$$\dot{\mathbf{x}} = \frac{D}{2}\nabla\dot{h}, \tag{1}$$

where D is lithospheric thickness, (x,y) map projection coordinates and ∇ is the horizontal (x,y) gradient operator. The technique produces a quasi-

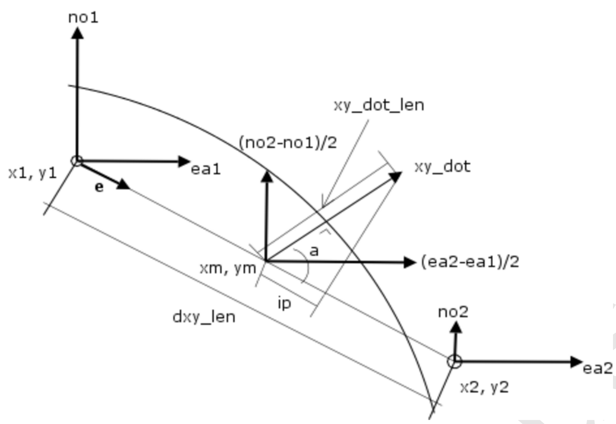


Figure 3: Graphical representation of the computation process.

local value for D. Given a set of point values x_i, y_i, $\dot{h}_i$, $\dot{x}_i$, $\dot{y}_i$, $i = 1...n$, the formula connecting two points 1 and 2 is:

$$\frac{1}{2}\langle(\dot{\mathbf{x}}_1 + \dot{\mathbf{x}}_2) \cdot \mathbf{e}_{12}\rangle \approx -\frac{D}{2}\frac{\dot{h}_2 - \dot{h}_1}{d_{12}},$$

where $\mathbf{e}_{12}$ is the unit vector in the plane pointing from 1 to 2, d_{12} the inter-point distance, and $\langle\cdot\rangle$ signifies the scalar or dot product of two vectors.

We can now traverse the whole list of n points, forming $\frac{1}{2}n\,(n-1)$ pairs i, j, and for those pairs for which D from the above expression is sufficiently well determined, compute D for the midpoint $\left(\frac{1}{2}(x_i + x_j), \frac{1}{2}(y_i + y_j)\right)$ of each pair.

Fig. 3 gives a graphical representation of the computation process.

The figure shows two points with their plane coordinates (`x1,y1`) and (`x2,y2`), and the midpoint of the line connecting them with coordinates (`xm,ym`), which forms our location tag for the lithospheric thickness estimate. In both points horizontal velocity vectors (`no1,ea1`) and (`no2,ea2`) are shown. At the midpoint, the velocity vector components are computed as the arithmetic mean. Next, the unit vector (`xy_dot`) with its length is computed. Also, the projection of the velocity unit vector to the line connecting two points (denoted `ip`) and the angle (`a`) are computed.

Considering relationship (1), the horizontal stresses are many times smaller than the vertical ones which drive GIA in formerly glaciated areas. In our modelling, stresses are not even considered; the computations are based solely on velocity values obtained from GPS. As the BIFROST project has shown, these values are dominated by the GIA signal. One could argue that one should also take into account the horizontal stresses imparted on the lithosphere by the mantle; however, this argument reverts to one about the definition of the lithosphere, indeed a tricky problem: in order to transmit stresses, material has to be high viscosity, i.e., rigid. Suffice to say that the lithosphere's lower edge remains a rather fuzzy concept.

4. Case study

The principal uplift of North America (the Laurentide uplift) and the Fennoscandian uplift have many points of similarity : in both regions the shield merges in one direction with a continental platform and in the other with heavily glacierized mountains; both have a broadly elliptical shape with an ellipticity of about 0.8 (Walcott, 1973). But as described earlier, the difference of North American and Fennoscandian uplift areas is in horizontal velocity – in North America there is no radial pattern visible in uplift area as it is in Fennoscandia.

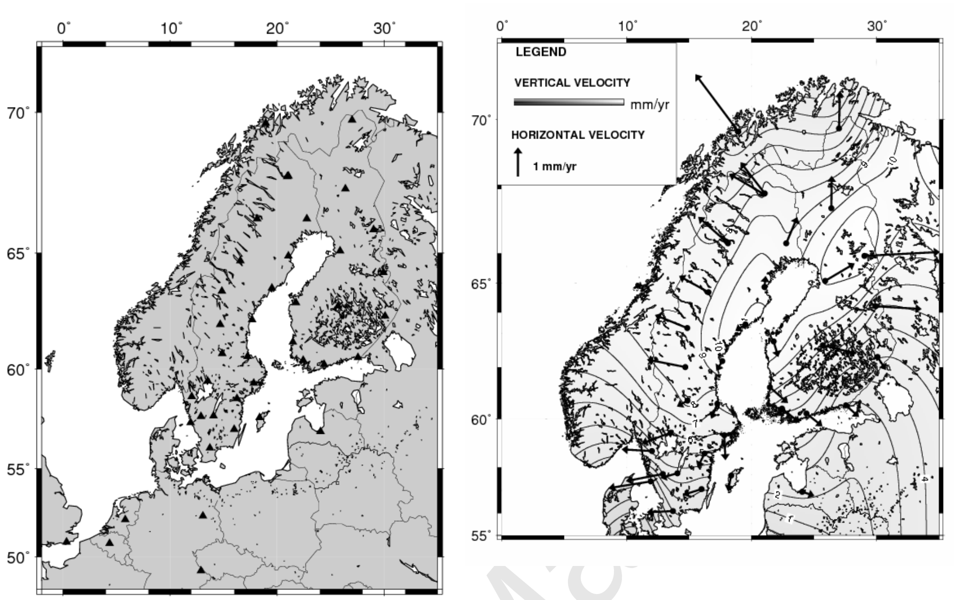


Figure 4: **(Left)** Data points used in the lithospheric thickness computation. **(Right)** Post-glacial rebound

4.1. Fennoscandian area

The BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and tectonics) project was started in 1993. It combines networks of continuously operating GPS stations in Finland and Sweden to measure ongoing crustal deformation in the Fennoscandian area. Its primary goal the three-dimensional measurement of Earth crustal motions, in order to constrain models of the GIA (Glacial Isostatic Adjustment) process in Fennoscandia (Lidberg et al., 2006). The computations are tied to an ETRF reference frame. Fig. 4 (left) shows the Fennoscandian land uplift pattern and Fig. 4 (right) the data points used.

Altogether 42 points from Fennoscandia (i.e., the BIFROST project) were included to the computations.

4.2. North American area

A discussion with Geoffrey Blewitt (pers. comm.) revealed that in the North American land uplift area there are no clearly systematic horizontal motion patterns of the kind found in Fennoscandia. This might point to important differences between the two areas. It could be that the North American lithosphere is more fragmented and subject to intra-plate motions of a tectonic nature than in Fennoscandia. Also, monumentation could be poor in places. Furthermore, the number of GPS sites within the actual uplift area was small compared to Fennoscandia.

For North-America we received data in the form of a SINEX file (Henton et al., 2007). The following values were provided:

1. `B`, `L` and `h` values of the GNSS permanent stations;
2. Cartesian co-ordinates for the stations;
3. Velocity (`VEL X, VEL Y, VEL Z`) values for the stations.

For this dataset the SNARF reference system is used. The vertical datum is consistent with the ITRF2000 in that the center of mass of the whole Earth system is taken to be the origin while the horizontal datum differs by a rotation rate that brings the rotation of the stable part of North America to rest (Craymer, 2006).

5. Computations

Firstly, velocity plots were produced to validate the data and initial data reduction steps. Fig. 4 (right) shows the results for Fennoscandia. The velocities are obtained from the BIFROST project.

For the Fennoscandian uplift area, one sees that the magnitude of the horizontal velocity is maximum in a ring around the uplift centre and goes to zero at the uplift centre (i.e., the vertical velocity maximum). This situation gives us the possibility to estimate lithosphere thickness according to the formulae presented above.

The same figures were produced for North America. Velocities were extracted from the SINEX file of the SNARF solution (Henton et al., 2007). Firstly the horizontal and vertical components were computed. Then, the plate motion according to the NNR-NUVEL-1A model was removed. For these calculations, the Plate Motion Calculator from UNAVCO was used (UNAVCO, 2008).

After the plate motion reduction process, the velocity picture was obtained (see as well Sella et al. (2007)). Unfortunately, there is no clear radial pattern of horizontal velocity at the region of uplift centre (i.e. Hudson Bay region), as well in all other places in North America one sees randomly pointing horizontal velocity vectors. These kinds of scattered horizontal velocity may be due to a fragmented lithospheric structure as pointed out earlier. This means that there are no patterns visible for determining lithospheric thickness by the above described formulas.

After the velocity component estimation, the plane co-ordinates for all points, as well as the inter-point direction unit vectors per point pair, were computed. In the computation process, we eliminated all negative lithosphere thickness values and the maximum inter-point distance was set to 200 km. Finally, the lithospheric thickness computation was carried out.

6. Results

Lithospheric thickness values obtained for Fennoscandia are presented in Fig. 5. For North America, we do not present results, for the reasons given above.

For the Fennoscandian area we see that lithospheric thickness has a range varying from 56 km to 250 km, having its maximum of about 266 km near the uplift maximum (11 mm/a) and the average thickness being about 115 km. Altogether 23 computation points were used in this computation (in Fig. 5, these computation points, i.e., point pair midpoints, are plotted).

7. Conclusions

We used horizontal and vertical crustal motion data from Fennoscandia to invert for lithospheric thickness, finding that it ranges from 56 to 266 km. These values agree reasonably well with those from geological studies (for Fennoscandia 140 to 350 km).

The method presented is well suited for Fennoscandia, where most of the values computed from point velocities fall within the expected lithospheric thickness range. From the velocity picture for Fennoscandia (see Fig. 4 (right)), we see that the lithospheric thickness maximum is close to the vertical velocity maximum. Also, the horizontal velocity shows a radial structure around the vertical maximum.

For North America the lithospheric thickness computation was not carried out because there was no suitable horizontal motion pattern visible, so our technique could not be used. We may conclude that according to the velocity field picture, the lithosphere seems to have a fragmented structure. Other

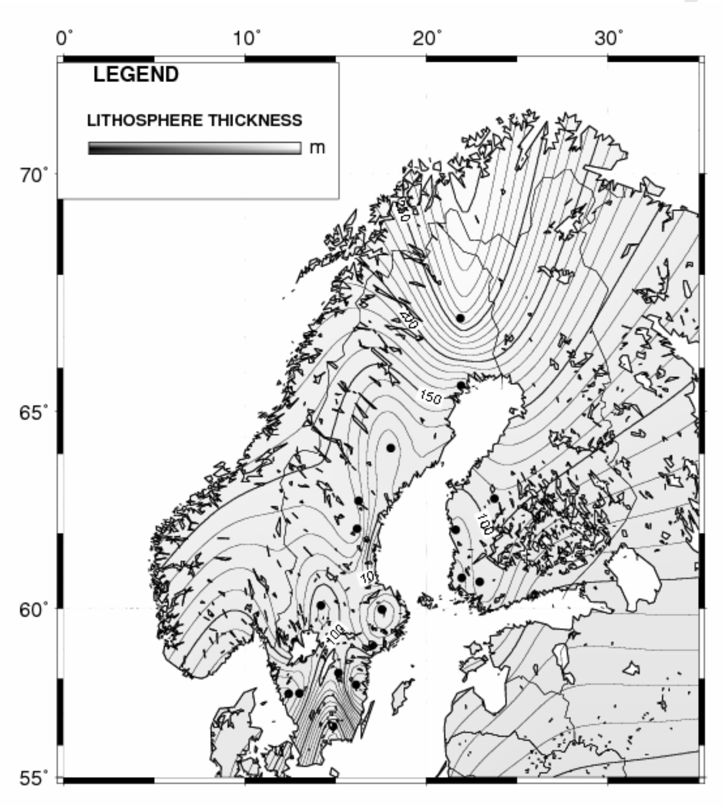


Figure 5: Lithospheric thickness estimated using horizontal-vertical rates method. Computation points are indicated

sources, however (Sella et al., 2007) indicate that a careful processing of the data, including careful removal of rigid plate motion, might help to recover some useful pattern.

In spite of our exclusion of the North American dataset at this point, we wish to emphasise the importance of such a study and we plan to return to the matter in future work.

Acknowledgements

We wish to acknowledge funding by the Academy of Finland, Grant No. 123113: "Regional Crustal Deformation and Lithosphere Thickness Observed with Geodetic Techniques (RCD-LITO)", as well as the International Lithosphere Programme (ILP) for travel support to the Copenhagen DynaQlim meeting. Two anonymous reviewers for the Journal of Geodynamics are gratefully acknowledged.

References

Altamimi, Z., Angermann, D., Argus, D., Blewitt, G., Boucher, C., Chao, B., Drevers, H., Earnes, R., Feissel, M., Ferland, R., Herring, T., Holt, B., Johannson, J., Larson, K., Ma, C., Manning, J., Meertens, C., Nothnagel, A., Pavlis, E., Petit, G., Ray, J., Ries, J., Scherneck, H.-G., Sillard, P., Watkins, M., 2008. The International Terrestrial Reference Frame. URL http://comp.uark.edu/~mattioli/geol_4733/ITRF2000.EOS.FINAL.pdf

Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B., Boucher, C., 2007. ITRF2005: A New release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. J. Geophys. Res.Doi: 10.1029/2007JB004949.

Anon., July 2008. Post-glacial rebound. Wikipedia. URL http://en.wikipedia.org/wiki/Post-glacial_rebound

Anon., 2009. Plate Tectonics. Accessed Nov. 11, 2009. URL http://www.dnr.sc.gov/geology/images/Tectonics-pg.pdf

Artemieva, I. M., 2002. Section 16.6.1.3: Continental crust. UNESCO Encyclopedia of Life Support Systems, Oxford, UK. URL http://www.eolss.net/

Artemieva, I. M., Mooney, W. D., 2002. On the relations between cratonic lithosphere thickness, plate motions and basal drag. ELSEVIER, Tectonophysics 358, 211–231.

Craymer, M. R., May 31 2006. The Stable North American Reference Frame. In: GSD S&T Presentation. URL ftp://geod.nrcan.gc.ca/pub/GSD/craymer/pubs/snarf_gsd2006.pdf

Ekman, M., 2009. The Changing Level of the Baltic Sea during 300 Years: A Clue to Understanding the Earth. Summer Institute for Historical Geophysics, Åland Islands.

Henton, J., Craymer, M., Lapelle, E., Piraszewski, M., 2007. Contributions of the North American Reference Frame Working Group to the next realization of the Stable North American Reference Frame (SNARF)

(poster). In: Eos Transactions, AGU, 88(52), Fall Meeting Supplement, Abstract G21B-0498.
URL ftp://geod.nrcan.gc.ca/pub/GSD/craymer/pubs/snarf_agu2007fall_poster.pdf

Jaupart, C., Mareschal, J., Kaminski, E., 2002. Deep thermal structure and thickness of the continental lithosphere. AGU.

Jaupart, C., Mareschal, J. C., Guillou-Frottier, L., Davaille, A., 1998. Heat flow and thickness of the lithosphere in the Canadian shield. Journal of Geophysical Research 103 (B7), 15269–15286.

Kollo, K., Vermeer, M., 2008. Heights, Height Systems, Height Models and their Error Propagation. Final Report. Tech. rep., Helsinki University of Technology, Department of Surveying, Geodesy.

Lidberg, M., 2007. Geodetic Reference Frames in Presence of Crustal Deformations. Ph.D. thesis, Departement of Radio and Space Science, Chalmers University of Technology, Gothenburg, Sweden.

Lidberg, M., Johansson, J. M., Scherneck, H.-G., Bergstrand, S., Milne, G. A., 2006. BIFROST: A new improved velocity field for Fennoscandia - Implications for models of Glacial Isostatic Adjustment. In: Proceedings of the NKG General Assembly, May 29 - June 2, Copenhagen, Denmark.

Mäkinen, J., 2000. Geodynamic Studies using Gravimetry and Levelling. Ph.D. thesis, University of Helsinki, Faculty of the Science, Helsinki.
URL ethesis.helsinki.fi/julkaisut/mat/geofy/vk/makinen/geodynam.pdf

Peltier, W. R., 1990. Glacial Isostatic Adjustment and Relative Sea-Level Change. In: Geophysics Study Committee; Commission on Physical Sciences, Mathematics, and Resources; National Research Council (Ed.), Studies in Geophysics: Sea-Level Change. National Academy Press, Washington D. C.

Sella, G. F., Stein, S., Dixon, T. H., Craymer, M., James, T. S., Mazzotti, S., Dokka, R. K., 2007. Observation of glacial isostatic adjustment in "stable" North America with GPS. Geophys. Res. Lett. 34 (L02306), doi: 10.1029/2006GL027081.

Torge, W., 2001. Geodesy. Walter de Gruyter, Berlin, New York.

UNAVCO, September 2008. Plate Motion Calculator.
URL `http://sps.unavco.org/crustal_motion/dxdt/model/`

Van der Lee, S., 2002. High-resolution estimates of lithospheric thickness from Missouri to Massachusets, USA. Earth and Planetary Science Letters 203, 15–23.

Walcott, R. I., 1973. Structure of the earth from Glacio-Isostatic Rebound. In: NASA Astrophysics Data System (Ed.), Earth Physics Branch. No. 426. Annual reviews Inc, pp. 15–37.

Wu, P., Ni, Z., Kaufmann, G., 1998. Postglacial Rebound with Lateral Heterogeneities : from 2D to 3D modeling. In: Wu, P. (Ed.), Dynamics of the Ice Age Earth: A Modern Perspective. Trans Tech Publ. Switzerland, pp. 557–582.