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RESEARCH NOTE

Note on estimates of the glacial–isostatic decay spectrum for Fennoscandia

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SUMMARY

For more than 30 years, Sauramo's (1958) shoreline diagram of the Fennoscandian uplift has been used in geophysical studies for estimates of the glacial–isostatic decay spectrum in order to infer from it the viscosity stratification in the Earth's mantle below Fennoscandia. The intent of the present note is to point out that more recent geological studies suggest that Sauramo's shoreline diagram is an incorrect representation of the Fennoscandian uplift. Geophysical interpretations based on the diagram may therefore require revision.

Key words: Fennoscandia, glacial rebound, isostasy, mantle viscosity, sea level.

1 INTRODUCTION

More than 30 years ago, McConnell (1963, 1968) (henceforth called MC) estimated the relaxation-time spectrum of glacial–isostatic uplift in Fennoscandia using a shoreline diagram published by Sauramo (1958). MC also interpreted the spectrum in terms of the viscosity stratification below Fennoscandia; similar interpretations of MC's spectrum were later proposed by Parsons (1972) and Cathles (1975). Recently, Mitrovica & Peltier (1993) (henceforth called MP) re-estimated the Fennoscandian relaxation-time spectrum using Sauramo's shoreline diagram. As pioneered by Parsons (1972), they used inverse theory for assessing the resolving power of the spectrum. This allowed them to infer improved bounds on the viscosity stratification below Fennoscandia.

The significance of any inference of viscosity is obviously related to the quality of the data used. The purpose of the present note is to point out that Sauramo's (1958) shoreline diagram seems to be of inadequate quality and contingent upon several questionable assumptions. In fact, more recent shoreline diagrams proposed by Donner (1980), Eronen (1983) and others are in fundamental disagreement with Sauramo's diagram. The viscosity stratifications inferred from it may therefore require revision.

2 DIFFERENCES BETWEEN SAURAMO'S AND RECENT SHORELINE DIAGRAMS

Sauramo's (1958) construction of ancient shorelines in Finland and adjacent regions (Fig. 1) implies two basic hypotheses: (1) a mode of uplift in individual jerks and/or the existence of a large number of alternating transgressions and regressions of the Baltic Sea; (2) the existence of lines of weakness in the Earth's crust resulting in its decomposition into a mosaic of decoupled rigid blocks. Whereas the first hypothesis allows Sauramo to construct from isolated pieces of observational evidence a *multitude* of shorelines, the second hypothesis leads him to introduce a number of *kinks* into several of these shorelines.

The validity of Sauramo's two hypotheses in the light of the observational evidence has been questioned by several Finnish geologists. Apart from this, the hypotheses express his belief in a spatially and temporally *discontinuous* nature of the uplift, a concept which is at variance with geophysical interpretations of this uplift in terms of *continuous* earth models. In the following paragraphs, the arguments against Sauramo's shoreline construction are briefly reviewed and examples of more reliable shoreline diagrams are given.

Sauramo's first hypothesis

Sauramo's (1958) diagram distinguishes about 15 individual shorelines. The field evidence employed for their delineation depends on the area studied but may be classified as *geomorphological* (e.g. beach ridges, bluffs, deltas) or *stratigraphical* (e.g. microfossils, pollen remnants, varved clays). A common problem with both types of evidence is that they consist of observations from isolated locations and are associated with unknown uncertainties. Any attempt to delineate continuous shorelines on the basis of such fragmentary evidence is therefore conjectural.

This fundamental problem with Sauramo's construction has been addressed by several Finnish geologists (e.g Hyvärinen &

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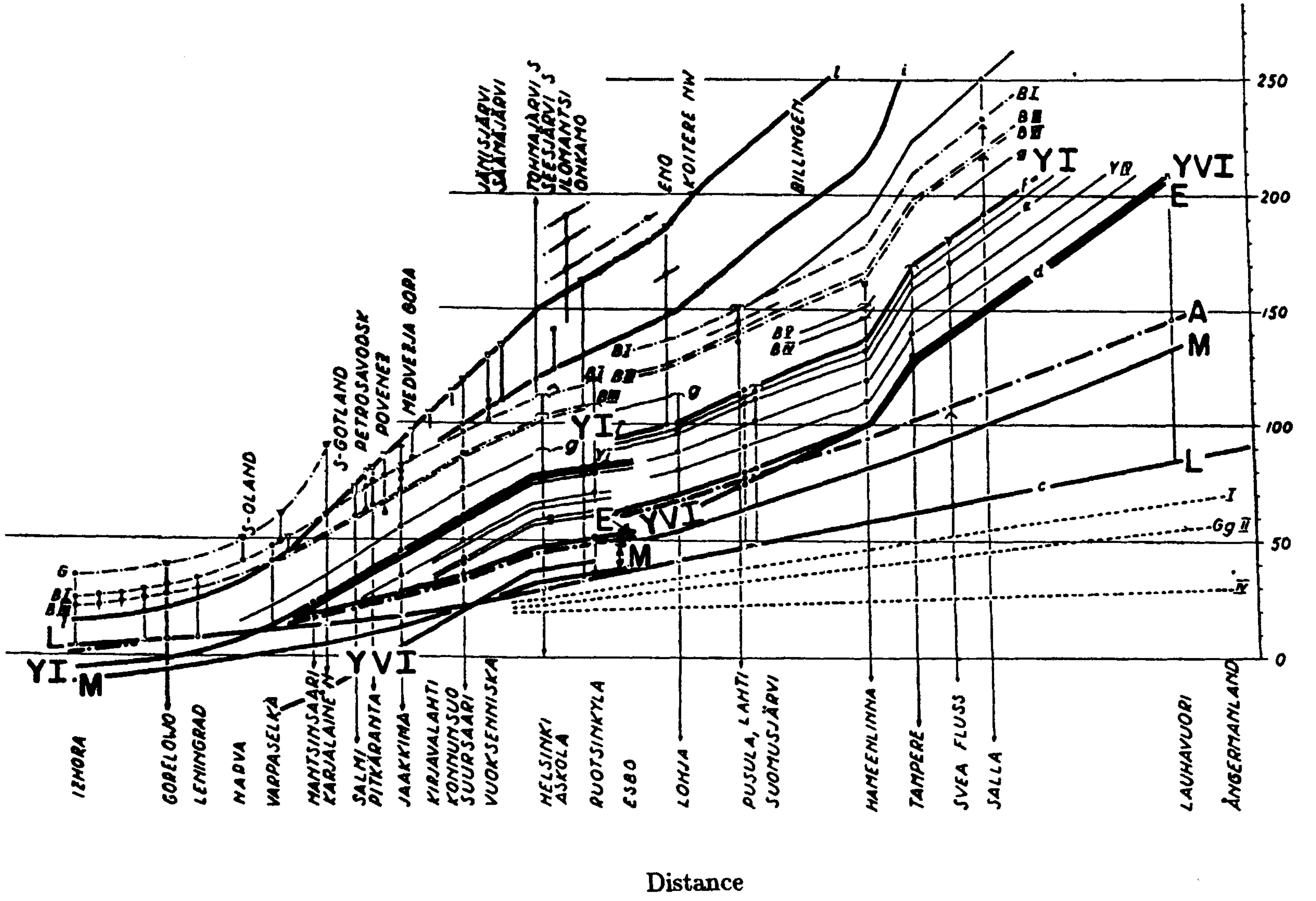

Figure 1. Shoreline diagram as proposed by Sauramo (1958). The direction of shorelines is approximately SE–NW and perpendicular to the Fennoscandian ice margin. Shorelines denoted by YI (Yoldia I), YVI (Yoldia VI), E (Echineis), A (Ancylus), M (Mastogloia) and L (Litorina) have been selected by MC and MP for estimates of the free-decay spectrum.

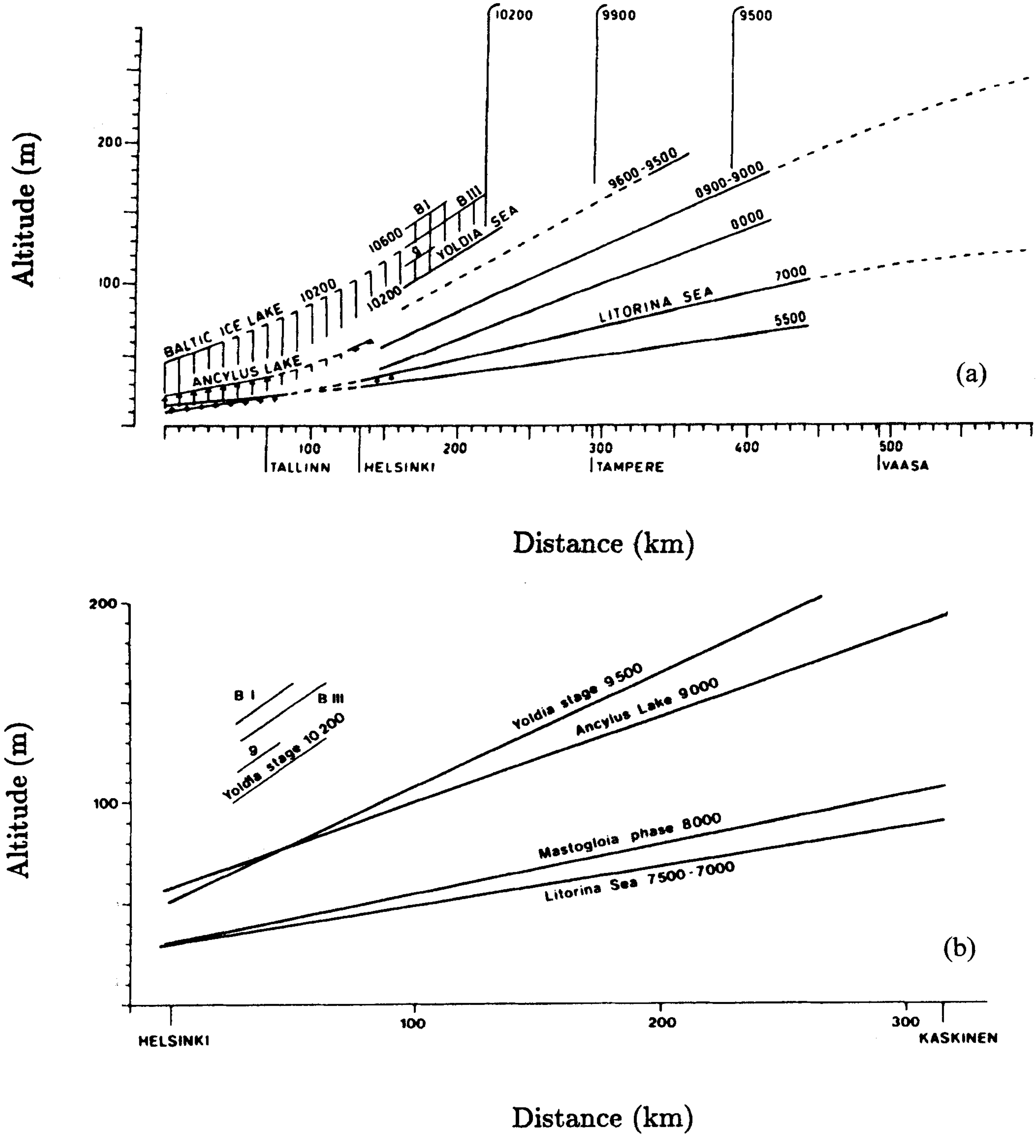

Figure 2. Shoreline diagrams as proposed by (a) Donner (1980) and (b) Eronen (1983). The direction of shorelines is approximately SE–NW and perpendicular to the Fennoscandian ice margin. *Numbers* adjacent to lines indicate ages in years. In (a), *dashed lines* show interpolated portions of shorelines, *short vertical lines* indicate altitudes of Baltic Ice Lake and Ancylus Lake above past sea level and *long vertical lines* give positions of terminal moraines.

Eronen 1979; Donner 1980, 1987). As they point out, strict adherence to the observational data only admits the delineation of a small number of shorelines in Finland and the surrounding regions (Fig. 2). These shorelines have been associated with the major transgressions of the ancient Baltic Sea.

Sauramo's second hypothesis

Kinks in Fennoscandian shoreline reconstructions first appeared in a diagram shown in Sauramo (1939); the fully developed form of this diagram can be found in Sauramo (1958). In his explanation of sudden changes of shoreline tilt, Sauramo referred to Goldthwait (1908, 1910), who had introduced the concept of *hinge lines* in his construction of ancient shorelines in the Great Lakes region of North America.

Goldthwait, who was influenced by Chamberlin as the major proponent of rigid-earth models in the United States at that time, defined hinge lines as lines of weakness separating rectilinear portions of individual shorelines conforming with essentially rigid portions of the Earth's crust. This concept was immediately challenged by Robinson (1908), who pointed out that most of the observational evidence available to Goldthwait could be explained equally well with continuously curved shorelines. The sole hinge line in the Great Lakes region accepted by Robinson has only recently disappeared as a result of improved observational evidence (Larsen 1987).

Whereas the delineation of the ancient Great Lakes shorelines is largely based on geomorphologic evidence, Sauramo mainly relied on stratigraphic evidence in his reconstructions of the ancient Finnish shorelines. As he conceded himself (Sauramo 1955), he was the only proponent among Finnish geologists of sudden changes of tilt in the shorelines. In agreement with this, early (Hyypää 1963, 1966) and modern (Fig. 2) reconstructions by other investigators result in shorelines without these complications. Donner (1987) has discussed Sauramo's kinks in the light of recent research and concludes that they are due to erroneous correlations of different stratigraphic horizons.

3 GEOPHYSICAL SIGNIFICANCE OF DIFFERENCES

The most obvious difference between Sauramo's (Fig. 1) and recent (Fig. 2) diagrams is the markedly *reduced number* of shorelines in the latter. However, more important to geophysical interpretations of land uplift is the *smoothness* of the shorelines in recent diagrams. Another feature of geophysical significance is the *ages* of the shorelines, both in absolute terms and relative to the completion of deglaciation in Fennoscandia.

The effects of kinks on estimates of the relaxation-time spectrum for Fennoscandia were pointed out by Walcott (1980); the same problem was also briefly addressed by Peltier (1982), Wu & Peltier (1982) and Wolf (1985). Clearly, sudden changes of shoreline tilt must control the short-wavelength end of the spectrum, which, in turn, is used to infer the thickness of the lithosphere and the viscosity of the asthenosphere below Fennoscandia. The parameter values arrived at for the lithosphere and asthenosphere by MC, MP and the other investigators may therefore require revision.

One of the assumptions in previous geophysical interpretations of the Fennoscandian relaxation-time spectrum is that the departures from *free* decay of the Fennoscandian surface depression are small compared with the uncertainties of the observations. Whereas this assumption is probably satisfied for the *postglacial* period (when deloading due to the removal of water from the northern Baltic Sea constitutes the main departure), enhanced deviations can be expected for the *glacial* period. MC discussed the ages of the Fennoscandian shorelines and noted that, whereas the oldest (Yoldia I) of the six shorelines he selected from Sauramo's diagram (Fig. 1) may be a glacial feature formed while Fennoscandia was still partially covered with ice, the remaining five (Yoldia VI, Echineis, Ancylus, Mastogloia and Litorina) are probably of postglacial origin. Parsons (1972) also addressed this problem and pointed out that Fennoscandia may have been deglaciated after the Ancylus shoreline was formed. MP essentially followed MC and considered respectively the five youngest or all six shorelines in their estimates of the relaxation-time spectrum.

When using Sauramo's age estimates, it should be noted that he largely relied on *stratigraphic* techniques. Modern *radiocarbon* methods have resulted in a revision of Sauramo's ages; in addition, the times of the Fennoscandian deglaciation have been revised. Of significance to geophysical interpretations based on the relaxation-time spectra estimated by MC or MP may be the possibility that even the Ancylus shoreline (radiocarbon age: 8900–9000 a) formed before the deglaciation of Fennoscandia was completed (Donner 1980; Eronen 1983). Thus, only the Mastogloia (radiocarbon age: 8000 a) and Litorina (radiocarbon age: 7000–7500 a) shorelines are clearly postglacial. If older shorelines are included, enhanced departures from free decay must therefore result.

4 CONCLUSIONS

The differences between Sauramo's (Fig. 1) and recent (Fig. 2) shoreline diagrams are of significance to estimates of the free-decay spectrum for the Fennoscandian uplift in two important ways.

(1) Modern diagrams show smooth shorelines without kinks. This modifies the short-wavelength end of the spectrum, which, in turn, may modify the inferences of the thickness of the lithosphere and the viscosity of the asthenosphere.

(2) Radiocarbon-dating techniques have revised the ages of shorelines and the timing of deglaciation, and only the two most recent (Mastogloia and Litorina) of the six shorelines considered in previous spectral analyses are clearly of postglacial age. Analyses that include the older shorelines thus result in enhanced departures from free decay. Since previous geophysical interpretations were based on the assumption of small departures from free decay, they may require revision.

As is evident from their publications, MC and MP recognized the possibility of errors associated with Sauramo's shorelines. Whereas MC simply mentioned the uncertainty, MP took an additional step and furnished Sauramo's shorelines with suitable measures of this uncertainty. The procedure they adopted is based on the hypothesis of *random* errors. However, the supposed existence of kinks where the shoreline is actually smooth and the assumed postglacial age of all but the oldest shoreline introduce unaccounted *systematic* errors into their spectral analyses. At present, we are testing the validity of the viscosity stratifications inferred from MC's and MP's spectra using a revised spectrum based on the currently accepted shoreline diagrams (Wieczerkowski, Mitrovica & Wolf, in preparation).

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