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New Insights Into the Lithospheric Structure of Southern Norway

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Topography can result from a balance, called isostasy, between the overlying weight of the crust and the buoyancy of the mantle beneath it. The principle of isostasy was put forward almost two centuries ago as a method of explaining variations in mountain heights, and it does a good job of explaining most of the first-order variations in the Earth's topography.

For example, when the crust is in local isostatic balance, elevation increases can be compensated for by an increase in crustal thickness, which in mountainous areas is in the form of a crustal root. Called Airy isostasy, compensation through crustal roots involves a correlation between surface topography and crustal thickness. However, topography may not be solely compensated for by crustal thickness, as other mechanisms such as flexural rigidity, low mantle densities, and dynamic topography can also be in effect.

For southern Norway, simple Airy-type isostatic models for the crust do not fully explain the observed topography. The Mantle Investigations of Norwegian Uplift Structure–Refraction Experiment (Magnus-Rex), a new seismic refraction experiment, is part of a multidisciplinary project studying the lithosphere in southern Norway. The project, TopoScandiaDeep, is a component of the larger European Science Foundation's Topo-Europe program, which studies the four-dimensional evolution of topography in Europe. Magnus-Rex set out to shed light on the relationship between topography and

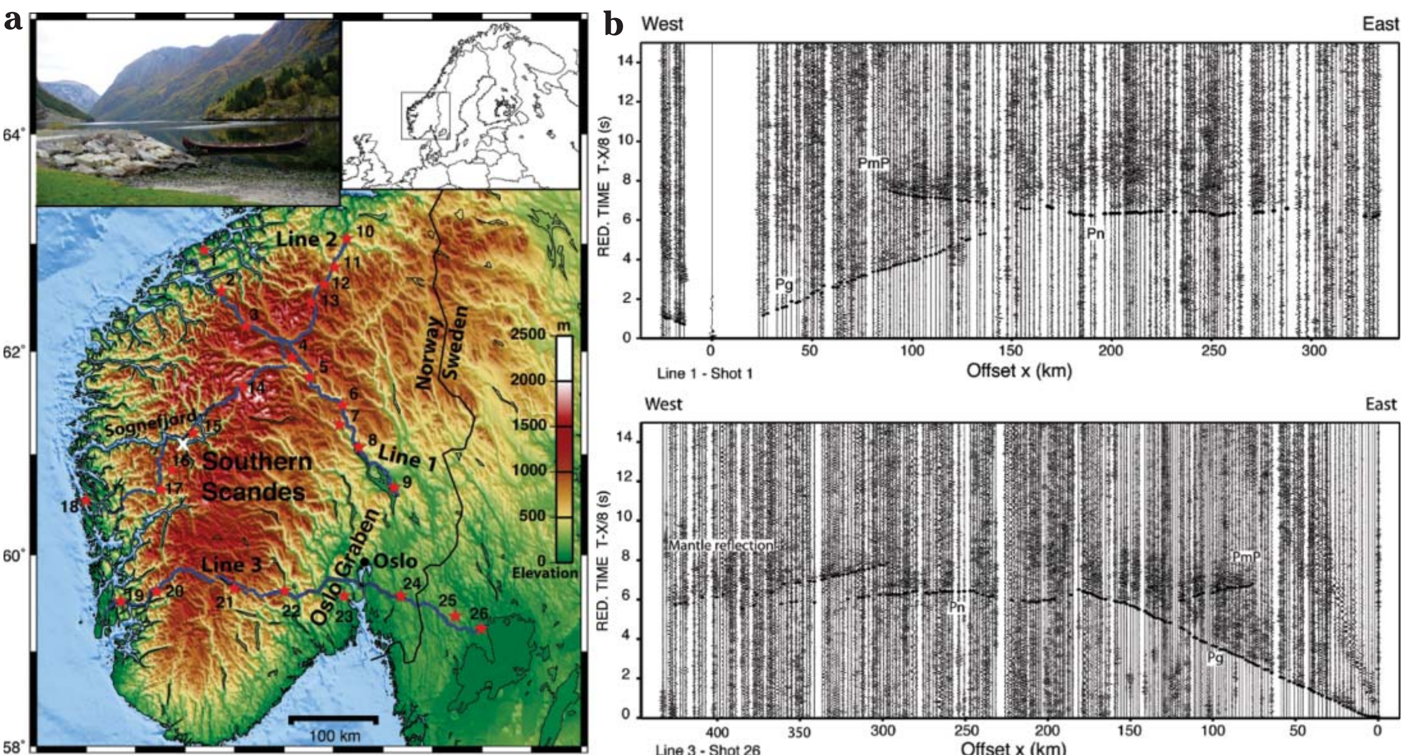

*Fig. 1. (a) The Mantle Investigations of Norwegian Uplift Structure–Refraction Experiment (Magnus-Rex). The inset of Scandinavia shows the field area outlined in a rectangle. Red stars are shot locations, and seismograph stations lie approximately every two kilometers on the blue lines connecting the stars. The white X on the map is the location of Nærøyfjord (see photo inset). This fjord, a United Nations Educational, Scientific, and Cultural Organization World Heritage Site, is a branch of the roughly 200-kilometer-long Sognefjord, which reaches inland into the southern Scandes Mountains. Mountains more than 2000 meters in elevation rise above the fjord to the northwest, and the fjord reaches depths of more than 1300 meters below sea level with shear sides of more than 1000 meter relief. (b) Examples of seismic data from Magnus-Rex. Data are plotted at reduced travel time where reduced time (*T*) = *absolute time (*t*) – offset/8. The arrivals marked as* Pg *are turning waves that travel through the crust at velocities of 6–6.4 kilometers per second. Arrivals marked* PmP *are seismic waves that have reflected off the Moho interface.* Pn *arrivals are from waves that refract at the Moho interface and travel through the mantle at velocities of about 8.0 kilometers per second. The times at which these different arrivals occur, their velocities, and at which offsets they arrive give information on the thickness and structure of the crust. The strong mantle reflection is of interest because it is interpreted to have come from below the Moho, i.e., from within the upper mantle.*

the depth of the Mohorovičić discontinuity (the Moho, the boundary between the crust and the mantle) in southern Norway and to assess the role of crustal thickness in compensating for topography.

The Magnus-Rex Experiment

To remotely image the structures beneath southern Norway, three seismic lines, each roughly 400 kilometers long, were deployed in October 2007 (see Figures 1a and 1b). A total of 26 shots, with charge sizes ranging from 100 to 400 kilograms, were fired along the lines. Vertical-component seismographs were deployed every 2 kilometers along each line to record the explosions.

Three different structural domains were covered by the refraction seismic lines: the southern Scandes Mountains, the Oslo Graben, and the Fennoscandian Shield crust in western Sweden. Finer-scale structure in the Oslo Graben was targeted by reducing the instrument spacing in a 120-kilometer-long section across the graben on line 3 to 750 meters, thus increasing the resolution of the data for this area.

The Southern Scandes Mountains

Previous crustal structure studies of the southern Scandes led to models that predict both the presence and the absence of a crustal root. A 43-kilometer-thick crust and a root beneath the highest mountains have been inferred from passive seismology studies [*Svenningsen et al.,* 2007]. In contrast, results from early refraction profiling indicate that the crust is only about 38 kilometers thick [*Sellevoll and Warrick,* 1971]. Low mantle densities were subsequently invoked as a means for isostatic support of topography [*Olesen et al.,* 2002].

In an effort to help resolve the existence of the southern Scandes crustal root, new depths of the Moho were determined from the Magnus-Rex data. Analysis reveals that the Moho is up to 40 kilometers deep in an area beneath the central southern Scandes. To the east and west of this area, the crust thins, probably due to the presence of the Oslo Graben and the passive continental margin. According to simple Airy isostasy models where high topography is compensated for with thicker crust, average elevations of the southern Scandes should be roughly 500 meters less than observed. Another mechanism, such as low densities in the upper mantle [*Olesen et al.,* 2002], lower densities in the crust, or flexural strength of the lithosphere [*Ebbing and Olesen,* 2005], is needed to explain the elevated mountains.

Such an explanation for how the Earth compensates for mountain elevations is not without precedent—recent studies of several mountain ranges provide examples of deviations from the simple crustal root model. For example, in the Sierra Nevada an inverse correlation between topography and crustal thickness is observed: The thickest crust is associated with the lower-elevation northern Sierra [*Louie et al.,* 2004] and the thinnest crust is associated with the southern High Sierra [*Zandt et al.,* 2004]. This reverse correlation is thought to be due to the loss of the dense eclogite root from beneath the southern Sierra [*Zandt et al.,* 2004].

The Oslo Graben and the Fennoscandian Shield

For the Oslo Graben, a new crustal thickness of 34 ± 2 kilometers is inferred. Here there is no correlation between surface topography and Moho depth. High seismic velocities are observed in the middle and lower crust, which imply higher densities at depth than in crust just to the east and west. This change in density distribution with depth affects the balance between elevation and Moho depth, and crustal thickness measurements are higher than surface elevations imply.

Similarly, the crust thickens into southwestern Sweden without an increase in surface elevation. Here, in the Fennoscandian Shield, a thicker lower crust [*Ebbing and Olesen,* 2005] and a thicker mantle lithosphere [*Artemieva and Thybo,* 2008] affect isostatic balance.

Future Work

The estimated excess topography of about 500 meters for the southern Scandes highlights the inadequacies in modeling topography with simple local Airy isostatic models, especially in areas that exhibit lateral changes in lithospheric structure, crustal density structures, and tectonic domains. Inferred mechanisms for providing this excess topography are diverse and include rebound induced by incisional erosion, uplift caused by the Iceland plume, rift shoulder uplift around the North Atlantic Ocean, stress release at the ocean-to-continent transition, buoyancy differences in the Earth between the ocean and continent, magmatic intrusions that influence buoyancy, and density anomalies in the crust and mantle. Currently there is no generally accepted mechanism.

Constraining the crustal structure is an important step to learning more; however, further information on the structure of the upper mantle beneath southern Norway is required to help establish where the support for topography might lie. Understanding the origin of excess topography is key to constraining models of isostatic response to glacial erosion, tectonic uplift, and evolution for the region.

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