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SPECIAL

The elastic thickness of the British Isles

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Free-air gravity and topography data from the British Isles have been analysed in the frequency domain to determine the mechanisms of topographic support. First, we calculate how the admittance between measured free-air gravity and topography varies as a function of wavelength. A simple model, which consists of a crust with two layers of different densities overlying a higher density mantle, was then used to calculate admittance functions. The misfit between observed and calculated admittance was minimized by varying elastic thickness and the proportion of the total load due to internal loading. At short wavelengths λ < 200 km), the fit between observed and calculated admittance is consistent with an elastic thickness of 5 ± 2 km and a small proportion of internal loading (*c.* 0.2). The general behaviour of the observed admittance suggests that topography is primarily supported by elastic stresses in the crust. A small departure between observed and calculated admittance at the longest wavelengths (400< λ <1000 km) is consistent with modest dynamic support which is probably convective in origin.

Keywords: British Isles, models, gravity anomalies, topography, elastic thickness.

The relationship between free-air gravity anomalies and topography within the frequency domain helps to constrain mechanisms for supporting lithospheric loads. Previous studies have shown that elastic stresses within the lithosphere support short-wavelength gravity and topographic anomalies (e.g. Watts 2001). Longer wavelength gravity anomalies are probably dynamically supported and are the surficial expression of mantle convection. The long-term ($>10^6$ years) elastic properties of the lithosphere and the transitional wavelength which separates flexural and convective support are described by T_e, the elastic thickness. Over the last 30 years, there has been considerable interest in calculating the spatial and temporal variation of T_e on Earth and on other planets. In oceanic lithosphere, T_e increases with thermal age of the plate although the relationship has considerable scatter (Watts 2001). In continental lithosphere, there is less evidence for a systematic relationship between T_e and the lithosphere's thermal properties although Maggi *et al.* (2000) have suggested that T_e scales with thickness of the seismogenic layer.

The distinction between flexural and dynamic support, the ratio of internal to total loading, and the value of T_e are best determined by using spectral methods. Here we show how a spectral approach can be applied to free-air gravity and topographic data from a region which encompasses the British Isles (Fig. 1). The free-air gravity data were compiled and gridded by the BGS (1997) using a combined format of Bouguer anomalies over land and free-air anomalies over sea. For our purposes, we have converted the Bouguer anomaly into a free-air anomaly by removing the Bouguer correction which we calculated using the infinite slab approximation and a density of 2.67 $\mathrm{Mg\,m^{-3}}$. In selected areas, the BGS (1997) used a variable Bouguer correction based upon local rock density. The effects of a variable correction on our results were analysed by recalculating the onshore free-air gravity anomaly with densities of 2.6 and 2.75 $\mathrm{Mg\,m^{-3}}$. Topography was taken from the ETOPO5/GTOPO30 compilation of Smith & Sandwell (1997). We then interpolated the gravity and topography data onto a 5 km grid using a minimum curvature algorithm and an oblique Mercator projection which minimized distortion.

Admittance modelling. $Z_f(k)$ is the admittance between free-air gravity and topography where k is the magnitude of the wavenumber. It is calculated using

$$\overline{g} = Z_f(k)\overline{t} + \overline{n}$$

where $\overline{g}$, $\overline{t}$ and $\overline{n}$ are the Fourier transforms of free-air gravity, topography and noise, respectively. These datasets were transformed using an FFT algorithm. A multitaper method with three windows in the x and y directions helped to reduce spectral leakage between different wavenumber bands (Thomson 1982). As we shall see, this approach produces reliable estimates of T_e for regions of this size. A detailed discussion of methodology and error analysis is given by McKenzie & Fairhead (1997).

The observed admittance for a box which encompasses the British Isles is plotted as a function of k in Figure 2a. At the shortest wavelengths (<100 km), Z_f has a value of *c.* 100 $\mathrm{mgal\,km^{-1}}$. Between 100 and 300 km, Z_f decreases linearly to 40–50 $\mathrm{mgal\,km^{-1}}$. At the longest wavelengths (>300 km), Z_f has a more or less constant value of about 40 $\mathrm{mgal\ km^{-1}}$. The coherence between free-air gravity and topography, γ_f^2, is plotted in Figure 2b. If $\gamma_f^2 = 1$, we can infer that any internal loading is coherent with topography. If $\gamma_f^2 = 0$, then any internal loads are not associated with topography. The proportion of the free-air gravity field which results from internal loading with no surface expression is $1 - \overline{\gamma_f^2}$ if there is no coherent internal loading, where $\overline{\gamma_f^2}$ is the average coherence in the waveband of interest. Over the British Isles, the value of $\overline{\gamma_f^2}$ within the 80–200 km waveband is about 0.5 which is suitable for our purpose (McKenzie 2003). At longer wavelengths, $\overline{\gamma_f^2}$ significantly decreases, which can be explained in several different ways. First, this decrease could imply that incoherent internal loading becomes more important. Alternatively, this decrease could be an indirect indication of long wavelength dynamic support: when two processes with different Z_f functions operate together, representation by a single Z_f function will generate incoherence. We also found that coherence varied with box size and location. A larger box which includes greater amounts of the offshore region has smaller average coherence than a smaller box centred on, say, Scotland. The reason for this difference is the presence of significant topography onshore which is strongly coherent with the free-air gravity signal. Offshore, there is generally less coherence.

This observed admittance pattern can be compared with theoretical admittance which is calculated from the behaviour of a thin elastic plate. In our model, we are concerned with loads which affect the crustal column, which we have divided into two layers (Fig. 3). The upper crust, t_u, has the same density as

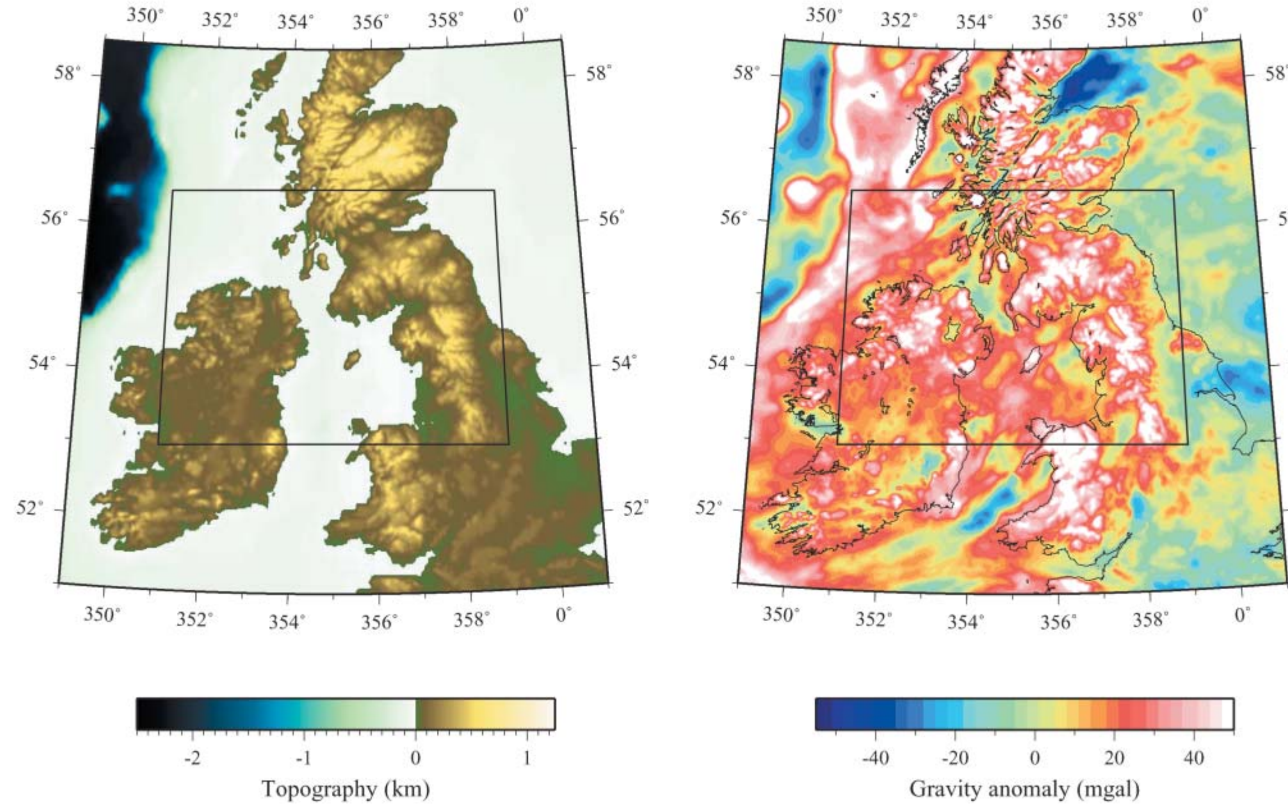

Fig. 1. (**a**) Topography of British Isles taken from ETOPO5/GETOPO30 dataset (ETOPOS Database 1988; Smith & Sandwell 1997). (**b**) Combined onshore/offshore free-air gravity map (BGS 1997). In both cases, data were interpolated onto a grid in an oblique Mercator Projection with axis at $-90°$ longitude and mesh size of 30 km. Admittance calculations were carried out for this map region but we also analysed data from the smaller outlined box.

topography. The lower crust, $t_c - t_u$, has a density which is intermediate to that of the upper crust and underlying mantle. This layered configuration is stress-free when all interfaces are horizontal. The elastic thickness, T_e, does not necessarily equate with any one layer or combination of layers although Maggi *et al.* (2000) have suggested that T_e is a function of the thickness of the seismogenic layer in actively deforming regions. Surface loads of upper crustal density are included by adding material to the top surface. Internal loads are included by adding material of lower crustal density to the interface between the upper and lower crust or by adding material of mantle density to the Moho interface. Here we only consider the possibility of surface and intra-crustal loading and F_2 is defined as the proportion of the total load due to internal loading. When $F_2 = 0$, there is no internal loading and when $F_2 = 1$, all of the loading is internal. A full description of this simple model and of all relevant equations are given by McKenzie (2003).

The admittance modelling uses topography, which is a known load, and that part of the free-air gravity signal which is coherent with topography to estimate T_e, the elastic thickness. In other words, the observed admittance is fitted using the theoretical admittance which itself depends upon the value of T_e. Any incoherent gravity signal effects the goodness of fit but not the value of T_e.

We have optimized the fit between theoretical and observed admittance by varying T_e and F_2. Figure 3a shows that the observed admittance can be accurately fitted at all but the longest wavelengths if $T_e = 4.8$ km and $F_2 = 0.13$. The variation of the misfit function, $H(T_e,F_2)$, demonstrates the existence of a global minimum whose shape governs the degree of trade-off between T_e and F_2. Our results suggest that internal loading could represent up to about 30% of the total loading but that the value of T_e is not significantly different from 5 ± 2 km.

Discussion. Our analysis of free-air gravity and topography shows that the elastic thickness of a region which encompasses the British Isles is $T_e = 5 \pm 2$ km. This result was determined by minimizing the misfit between observed and predicted admittance for the large box which includes the whole British Isles. Data from the smaller box was also analysed and although coherence varies significantly, the calculated value of T_e changes little and is therefore robust. These results were obtained using a Bouguer correction of $2.67\ \mathrm{Mg\,m^{-3}}$. We have also recalculated the onshore free-air gravity anomaly and the observed admittance using alternative Bouguer corrections of 2.6 and $2.75\ \mathrm{Mg\,m^{-3}}$. The smaller correction yields $T_e = 5.2$ km and $F_2 = 0.16$ while the larger correction yields $T_e = 4.6$ km and $F_2 = 0.11$. Thus surficial density variations used to calculate parts of the published Bouguer gravity data are likely to have little effect upon our results.

There is considerable disagreement about the variation of T_e on the continents. More recently, this protracted debate has focused on the reliability of different techniques for retrieving T_e (e.g., McKenzie & Fairhead 1997; Simons *et al.* 2000; Banks *et al.* 2001). The predominant view is that T_e can vary from as little as 5 km to greater than 100 km (Burov & Diament 1995). An

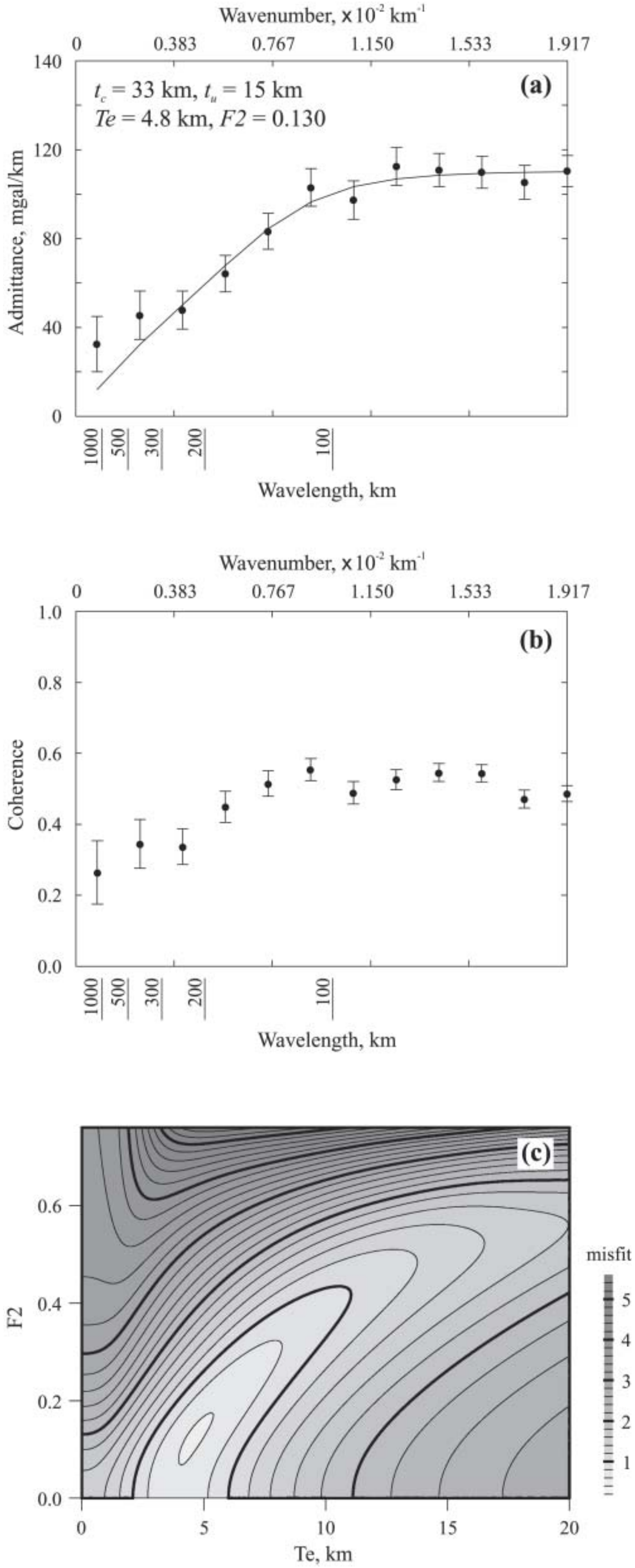

Fig. 2. Admittance and coherence calculations for map region of Figure 1. (**a**) Vertical error bars are observed values of $Z_f(k)$ calculated from topography and free-air gravity; the solid curve is the best-fitting theoretical $Z_f(k)$ determined by varying T_e and F_2. (**b**) Observed coherence between free-air gravity anomaly and topography. (**c**) Contour plot of misfit function, $H(T_e, F_2)$. Note positive trade-off between T_e and F_2.

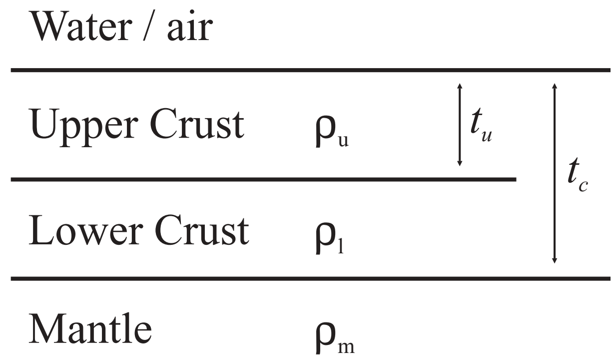

Fig. 3. Sketch of model used to calculate response to surface and internal loads. $t_c = 33$ km; $t_u = 15$ km; $\rho_u = 2.67$ Mg m^{-3}; $\rho_l = 2.9$ Mg m^{-3}; $\rho_m = 3.33$ Mg m^{-3}. Figure constructed using Generic Mapping Tools of Wessel & Smith (1998).

alternative view is that T_e is generally lower and more uniform (i.e. 10–40 km: McKenzie 2003). Either way, we conclude that the elastic thickness of a region which includes the British Isles is at the lower end of the range. According to McKenzie's (2003) compilation, our value is lower that that obtained for typical shields and for regions of active extension.

It is not clear why our value of T_e is so low. Our result can be compared with other estimates of T_e for the British Isles. Barton & Wood (1984) used admittance analysis to calculate T_e for the North Sea Basin. Their work suggested that $T_e \leqslant 5$ km. This value is supported by Bellingham & White's (2000) two-dimensional strain rate modelling of basin subsidence data which suggests that $T_e \leqslant 3$ km. Onshore, Barton (1992) used a simple approach to estimate T_e from Bouguer anomalies and topographic loads. She suggested that T_e is *c.* 5 km. More recently, Watts *et al.* (2000) calculated T_e from topographic profiles of a plateau surface in south-central England. Using a simple model of flexural unloading, they showed that an average of seven profiles were best fitted when T_e was about 10 km. According to Watts *et al.*(2000), their value of T_e is smaller than expected. Here we argue that T_e is even smaller. This discrepancy between profile and spectral analysis could be due to a range of causes but the most likely are a small amount of internal loading or regional dynamic support. The profile modelling of Watts *et al.* assumes that a point load is applied at one end of the profile. Their value of T_e could be an overestimate if the load is partly distributed beneath the profile. This distributed load could be permanent (e.g. a thin wedge of magmatic underplating) or transient (e.g. regional dynamic support).

Our analysis shows that there is little evidence for internal loading in the crust which is coherent with topography. White & Lovell (1997), amongst others, have suggested that during the Palaeogene significant magmatic underplating occurred beneath what is now the Irish Sea. This underplated body is thought to have dimensions of 10^2 km and if $T_e = 5$ km, it can hardly be supported by elastic stresses within the crust. Instead, this body must be in a state of almost complete Airy isostatic equilibrium. We are surprised that admittance analysis does not yield clearer evidence for regional magmatic underplating. The only suggestion is the small drop in coherence at a wavelength of about 200 km. Thus our analysis does not rule out the existence of underplating, but neither does it provide much corroborative support.

Finally, the small discrepancy (about 30 mgal km^{-1}) between observed and predicted admittance at high wavelengths suggests that the longest wavelength topography is dynamically supported (see, e.g., D'Agostino & McKenzie 1999). At these wavelengths, admittance values of 30–50 $\mathrm{mgal\,km^{-1}}$ are consistent with convective models. Density anomalies with a viscous mantle together with buoyancy forces induce convective motions that transmit stresses to the base of the overlying lithosphere. The value of T_e places a limit on the smallest resolvable surface effect of mantle convection. Since the elastic thickness of the British Isles is small, this damping effect only occurs when $\lambda < 300$ km.

Conclusions. We have used gravity and topography datasets from a region encompassing the British Isles to calculate admittance as a function of wavelength. A simple elastic model was then used to calculate theoretical admittance for different elastic thicknesses. Inverse modelling shows that the elastic thickness of the crust is 5 ± 2 km. Several checks were carried out which demonstrate that this estimate of elastic thickness is robust. When our results are taken in conjunction with other published estimates, we can reasonably conclude that the lithosphere underlying the northwest continental shelf of Europe is weak.

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