LETTERS

The long-term strength of Europe and its implications for plate-forming processes

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Field-based geological studies show that continental deformation preferentially occurs in young tectonic provinces rather than in old cratons¹. This partitioning of deformation suggests that the cratons are stronger than surrounding younger Phanerozoic provinces. However, although Archaean and Phanerozoic lithosphere differ in their thickness²⁻⁴ and composition^{4,5}, their relative strength is a matter of much debate. One proxy of strength is the effective elastic thickness of the lithosphere, T_e . Unfortunately, spatial variations in T_e are not well understood, as different methods yield different results. The differences are most apparent in cratons, where the 'Bouguer coherence' method yields large T_e values $(>60 \text{ km})^{6-9}$ whereas the 'free-air admittance' method yields low values $(<25 \text{ km})^{10}$. Here we present estimates of the variability of T_e in Europe using both methods. We show that when they are consistently formulated¹¹, both methods yield comparable T_e values that correlate with geology, and that the strength of old lithosphere (\geq 1.5 Gyr old) is much larger (mean T_e > 60 km) than that of younger lithosphere (mean T_e < 30 km). We propose that this strength difference reflects changes in lithospheric plate structure (thickness, geothermal gradient and composition) that result from mantle temperature and volatile content decrease through Earth's history.

The current debate concerning the strength of continental lithosphere is focused on the values of T_e estimated using both forward and inverse (spectral) methods based on the Bouguer coherence and free-air admittance. For example, forward models in the Slave craton (Canadian shield) reveal a T_e of about 12 km (ref. 12), which is much smaller than the \sim 100 km obtained using Bouguer coherence in the same area⁶. This strength difference arises because, in cratons, forward models and Bouguer coherence yield estimates of the strength at different times $¹²$. Forward models are generally based</sup> on the reconstruction of the original (surface and subsurface) loads and their associated flexures and reveal the strength at the time of a specific loading event (for example, orogeny or rifting), while Bouguer coherence is based on present-day topography and gravity anomaly data and yields the current strength of thick, cooled, cratonic lithosphere¹². Because the free-air admittance is also based on present-day topography and gravity anomaly data, it should yield a T_e similar to that obtained using the Bouguer coherence. However, in some regions, it yields $T_e < 25$ km (ref. 10), while the Bouguer coherence yields values in excess of 60 km (refs 6–9).

Recently, it has been shown that this discrepancy occurs because the free-air admittance and Bouguer coherence methods have not been consistently formulated¹¹. The calculation of both functions involves the estimation of the spectra of finite and non-periodic data. Therefore, the wavelength dependence of the admittance and coherence varies with the size of the data window analysed. In the admittance method, analytical solutions of the predicted spectra (which correspond to infinite data windows) have been compared to

observed spectra of the data within a finite window¹¹. When the underlying T_e is large ($>$ 30–40 km), this can lead to an underestimation of T_e by a factor of 2 (ref. 11). However, when the observed and predicted admittance functions are calculated in the same data windows, as is usually the case in the coherence method, then the results from the two techniques are equivalent 11 .

We present here estimates of the T_e structure of Europe using both Bouguer coherence and free-air admittance. The resulting T_e structures are similar, and correlate well with the tectonic provinces in Europe inferred from geological and other geophysical data¹³ (Fig. 1). High- T_e regions correlate with Precambrian Baltica and Avalonia. Low- $T_{\rm e}$ regions, in contrast, correlate with the younger provinces accreted during the Caledonian, Variscan and Alpine orogenies. These results are in agreement with local studies of T_e in Europe^{14–17}. Figure 1 also shows that the largest changes in T_e occur at the sutures that separate different provinces. Deep seismic data indicate that these sutures coincide with major tectonic boundaries in the crust and shallow lithospheric mantle (for example, Iapetus suture¹⁸, Thor suture¹⁹). Our results show that, in addition, these sutures correlate with major changes in lithospheric strength.

The recovered T_e is generally consistent with other physical properties of the lithosphere. High- T_e regions generally correlate with areas of large thermal thickness (as derived from heat flow data³) and fast seismic S-wave velocities²⁰ and vice versa (Fig. 1c, d). This indicates that $T_{\rm e}$ is high in regions where the lithosphere is thick and cold. In addition, a close correlation exists between T_e and seismicity: high- and low- T_e regions show sparse and abundant seismicity, respectively (Fig. 1d). This suggests that in high- T_e areas, the strength of the lithosphere is large enough to reduce the background level of $seismicity²¹.$

The dependence of T_e on age is shown in Fig. 2. The figure shows a plot of the mean T_e obtained from Bouguer coherence for each of the main tectonic provinces versus their age (Table 1). Unlike T_e values in oceanic lithosphere, spectrally derived continental T_e estimates do not necessarily reflect the strength at the time of loading. This is because spectral estimates reflect the present-day response to loads, which resulted from specific geological events (for example, orogeny and rifting) as well as from subsequent sedimentation and erosion. The relatively young Caledonian, Variscan and Alpine provinces still have significant topography such that their spectrally derived T_e also mainly reflects the strength of the basement at the time of these orogenies (that is, it is the T_e at the time of loading which is recovered). However, cratons have subdued topography, and so their spectrally derived T_e mainly reflects the response to postorogenic erosion and sedimentation, both of which may continue up to the present day. Because forward models reflect the T_e at the time of loading¹², they generally coincide with estimates of spectrally derived T_e in young tectonic provinces (see, for example, ref. 17) but differ in cratonic areas¹².

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Figure 2 shows that Archaean and Early/Middle Proterozoic tectonic provinces (\geq 1.5 Gyr old) are much stronger than younger ones. This strength increase with tectonic province age cannot be explained by conductive cooling of a lithospheric plate with a given thermal thickness as in oceanic lithosphere. For example, both the Sveconorwegian (\sim 1 Gyr old) and Karelian (\sim 3 Gyr old) tectonic provinces have had sufficient time $(>1$ Gyr) to conductively cool and thermally equilibrate, yet T_e in the former is at least half that of the latter (Fig. 2). Therefore, there must be fundamental differences in the mechanical structure between old and young continental lithosphere in Europe.

We suggest that these structural differences may reflect changes in continental plate forming processes related to the decrease in temperature and volatile content in the sublithospheric mantle during Earth's history. In the Archaean, higher mantle temperatures and/or volatile content probably favoured a larger degree of melting to greater depths than today and, hence, the formation of a thick lithosphere, with a highly depleted, buoyant root^{4,22}. At that time, the

Figure 1 | T_e structure of Europe obtained using two different methods, and comparison with other geophysical data. a, b, T_e obtained from Bouguer coherence (a) and free-air admittance (b). c, d, Other geophysical data: c, thermal thickness³ (defined as depth to the 1,300 °C isotherm); and d , S-wave velocity anomaly, $\delta v_S/v_S$, at 100 km depth²⁰ given in per cent with respect to an isotropic version of PREM (decribed in ref. 20). Note that even if T_e values do not exactly coincide in **a** and **b**, the general pattern of T_e variation is equivalent. Free-air admittance has a poorer T_e recovery ability than the Bouguer coherence (Methods); we consider the results obtained with the latter more reliable. The T_e structure in **a** and **b** is based on CRUST 2.0³⁰, Poisson ratio = 0.25, and Young's modulus = 100 GPa. Because the maximum T_e that can be recovered with confidence is 60 km, larger T_e estimates exceed this value by an undetermined amount (Methods). Hence

the relative strength between the Precambrian Baltica and Avalonia (Av) can not be resolved. White lines define the sutures: I, Iapetus; T, Thor; R, Rheic; and S, Sorgenfrei-Tornquist and Teisseyre-Tornquist zones, between the Precambrian provinces and younger ones. Italic labels show the approximate location of the tectonic provinces: Ko, Kola; Ka, Karelia; Svf, Svecofennian; EEC, East European Platform; Svn, Svecononorwegian; Ca, Caledonian; Va, Variscan; and Al, Alpine. Dashed white line (A) shows the Alpine deformation front. Grey lines in indicate the main boundary faults of the North Sea rift, which borders the high- T_e area in Avalonia. Grey dots in d are earthquake locations (US Geological Survey Earthquake Data Base, M_b > 4.0). Black dots in **a** show locations of Bouguer coherence analysis shown in Supplementary Information.

Figure 2 | Mean T_e determined from Bouguer coherence within each of the major tectonic provinces of Europe versus their age. Filled circles show data points; age is taken from Table 1. The age of the tectonic province corresponds to the age of those portions of the province that have not been deformed by later orogenic events at their edges. For example, the East European Platform consists mainly of Archaean and Early Proterozoic basement that are largely undeformed, so we assign this age instead of that of the later orogenies that have modified its edges. For tectonic provinces comprising only orogenic belts such as the Alps, we assign the age of the orogeny (see Table 1). To distinguish between tectonic province and orogenic age, we have coloured them in light and dark grey respectively. Error bars indicate the standard deviation in T_e and the age span of the tectonic provinces. Dashed error bars and question marks indicate uncertainty in the age of the tectonic province (see Table 1). As mentioned in Fig. 1, the maximum T_e estimate that we can recover is 60 km (Methods). Hence, variations in strength between tectonic provinces with $T_e > 60$ km cannot be interpreted.

response of the lithosphere to loading would have reflected a combination of weakening due to the high geothermal gradients and any strengthening due to compositional effects (related to melt extraction²²). These two competing factors might have resulted in an Archaean lithosphere, which despite its thickness, had a low strength and hence low T_e . However, with time, conductive cooling of the lithosphere to a stable state, as well as the Earth's secular cooling itself, would have increased its strength. This probably explains the high present-day T_e values that have been determined (both in this Letter and elsewhere) using spectral methods in old tectonic provinces (for example, North America⁶⁻⁸, Australia⁹, South America²³ and Africa 24).

The decrease in temperature and volatile content in the sublithospheric mantle through time²² has resulted in Late Proterozoic and Phanerozoic lithosphere that is associated with smaller degrees of melting at shallower depths^{5,22}. Hence, this lithosphere is thinner⁵, has a higher geothermal gradient⁵, and is less depleted in basaltic constituents than Archaean lithosphere⁵. This makes Late Proterozoic and Phanerozoic lithosphere intrinsically weaker than older lithosphere, even after conductive cooling. This weakness is reflected, we believe, in the low T_e values obtained here in young tectonic provinces using spectral methods (Fig. 2).

It is interesting to note that the youngest ages for lithosphere

Table 1 | Age of European tectonic provinces

Tectonic province	Age range (Gyr)
Kola*	$3.5 - 2.5$
Karelia*	$3.5 - 2.5$
Svecofennian ⁺	$2.2 - 1.5$
East European Platform‡	$3.5 - 1.6$
Avalonia§	$1.3 - 1.8$
Sveconorwegian	$1.05 - 0.9$
Caledonian	0.488-0.416
Variscan	$0.359 - 0.27$
Alpine	$0.12 - 0$

*The Kola and Karelian tectonic provinces comprise Archaean basement with a U–Pb age in the range 2.5–3.5 Gyr (ref. 13) and were amalgamated 2 Gyr ago. Hence, we assign them an age span of 3.5–2.5 Gyr. In Fig. 2 we extend the age error bar to 2 Gyr, as the extent to which the amalgamation 2 Gyr ago modified the Kola and Karelia lithospheres is uncertain. †The Svecofennian tectonic province contains material younger than 2.2 Gyr and was accreted and underwent collision 2.0–1.8 Gyr ago. It was later locally reworked by melting 1.8-1.5 Gyr ago¹³. We assign an age range of 2.2-1.5 Gyr to this tectonic province ‡The East European Platform consists mainly of basement of Archaean and Early Proterozoic age and locally middle Proterozoic age³¹. We assign an age range of 3.5–1.6 Gyr. In Fig. 2 we extend the age error bar to 0.9 Gyr, with a question mark to indicate that the extent to which the local middle Proterozoic basement is represented in the T_e of this province is uncertain. §The Avalonia basement is structurally very heterogeneous and rarely exposed. Therefore, we have based our age range on Sm–Nd model ages, which vary from 1.3 to 1.8 Gyr (ref. 32). Note that in Fig. 2 we have extended the age error bar up to 443 Myr ago (when Avalonia docked against Baltica¹³), with a question mark to indicate the uncertainty about the extent to which later tectonic events affecting Avalonia's edges modified its lithospheric core.

with seismic and thermal thicknesses greater than 200 km are around 1.6–1.7 Gyr (refs 2, 3), a similar age to that at which T_e , in this study, appears to change markedly, except, perhaps, for Avalonia (Fig. 2). However, given that Avalonia is structurally very heterogeneous, its highest T_e values may reflect the areas where the basement ages are oldest (see Table 1).

Although it is not yet known exactly when cratons acquired their strength and stability^{12,25}, it is likely that, at least, they were strong throughout the Phanerozoic. If so, continental deformation would preferentially occur at the edges of stable cratonic provinces. Figure 1 shows some weakening of Baltica, for example, where it is juxtaposed to the Caledonian, Variscan and Alpine orogenic belts. We follow Dixon et al.²⁶ and speculate that water introduced during subduction may have further weakened the Phanerozoic tectonic provinces. The net result is a tectonic province that because of its weakness acts as a focus, such that sites of orogeny become repeatedly involved in both compressional and extensional deformation, as is predicted in the Wilson cycle.

Finally, our results indicate that the T_e of old tectonic provinces $(\geq 1.5 \text{ Gyr})$ is significantly larger ($> 60 \text{ km}$) than their mean crustal thickness $({\sim}40 \text{ km})^{27}$. This suggests that the lithospheric mantle is strong, consistent with dynamical models that indicate that the stability of cratons is due not only to the chemical buoyancy of their root but also, importantly, to root strength^{28,29}. It appears that only when the cratonic lithosphere is subjected to processes such as enrichment by hot upwelling mantle will the old cratons be weakened enough to deform⁵.

METHODS

Calculations and data. The Bouguer coherence and free-air admittance are statistical methods that determine the relationship between the Bouguer and free-air gravity anomaly and the topography as a function of wavelength⁷. Both methods consist in finding a 'best fit' T_e by minimizing the root-meansquare difference between observed and predicted coherence and admittance functions⁷.

We base our analysis on a continent-wide 8×8 km grid of gravity anomaly (Bouguer onshore and free-air offshore) and topography data. These were compiled by GETECH (UK) as part of their West-East Europe Gravity Project (WEEGP). The gravity anomalies have been corrected for terrain, and we estimate that the data are accurate to better than 1–2 mGal. The calculation of the Bouguer anomaly offshore and the free-air anomaly onshore is described elsewhere¹¹.

The calculation of the Bouguer coherence and free-air admittance follows refs 7 and 11. The only differences from the methods followed in ref. 11 is that we: (1) deconvolve the loads in the same data window as the observed functions, (2) assume that subsurface loads occur at the boundary of the upper and middle crust, and (3) combine the T_e results obtained using windows of different sizes.

The load deconvolution consists of extracting the contribution to the

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reduction of T, due to the inclusion in the analysis of low T, areas that flank the **jecter and Mhitman[57] Mo** recover the spatial variation in T_e (Supplementary Fig. 3 illustrates how T_e varies particular, for $T_e \le 20$ km, $20 \le T_e \le 40$ km, $40 \le T_e \le 60$ km, and 0 undated methods of $\frac{1}{20}$ white A B & Burov E Lithospheric strength and its relationship to the elast 600×600 km, 800×800 km and $1{,}000 \times 1{,}000$ km, respectively. Limitations. On the basis of tests with synthetic topography and gravity long thet exp st&ring and a
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In that of the Bouguer coherence owing to the relatively low power of the free : 2. LOACING A put Lille high- $T_{\rm e}$ areas. We therefore only place a lower limit on the largest $T_{\rm e}$ obtaine ${\rm H}$ (60 km), and attach little significance to local spatial variations of T_e within the Baltica and Avalonia tectonic provinces.

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The most op Yious regional them and the manufacturer of the belt Separati for comments and discussions about the Letter. This work was
belt Separating the Amazonia and Sao Francisco cratons. Amazonia craton Reprints and permissions information is available at de la Plata craton. For these regions greater than oned be below these regions there are strong lateral variations in Previous authors studying the isostatic compensation of the Amazon basif₅₈], also concluded that anomalously and TILOSTy OO LOO HALE COMPRENT, AND BINOW∑man, QIOW∑ NIOCaill, supported by NERC. The figures presented here were constructed using GMT33. npg.nature.com/reprintsandpermissions. The authors declare no competing