Earthquake-induced transformation of the lower crust

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The structural and metamorphic evolution of the lower crust has direct effects on the lithospheric response to plate tectonic processes involved in orogeny, including subsidence of sedimentary basins, stability of deep mountain roots and extension of high-topography regions. Recent research shows that before orogeny most of the lower crust is dry, impermeable and mechanically strong1. During an orogenic event, the evolution of the lower crust is controlled by infiltration of fluids along localized shear or fracture zones. In the Bergen Arcs of Western Norway, shear zones initiate as faults generated by lower-crustal earthquakes. Seismic slip in the dry lower crust requires stresses at a level that can only be sustained over short timescales or local weakening mechanisms. However, normal earthquake activity in the seismogenic zone produces stress pulses that drive aftershocks in the lower crust2. Here we show that the volume of lower crust affected by such aftershocks is substantial and that fluid-driven associated metamorphic and structural transformations of the lower crust follow these earthquakes. This provides a ‘top-down’ effect on crustal geodynamics and connects processes operating at very different timescales.

The structural and metamorphic evolutions of the lower crust are key elements in the dynamics of the lithosphere. Frequent observations of fluid-induced metamorphism associated with ductile deformation along shear zones on scales ranging from millimetres to kilometres inspired early models of the lithosphere such as the ’jelly-sandwich’ model3. In this model, the lower crust is assumed to be wet and mechanically weak, and plate tectonic stress is transmitted through the brittle upper crust and a strong upper mantle. This model was challenged4 with the argument that a strong lower crust is essential for the survival of thick mountain roots and high mountains. The lower crust is dominated by granulite facies rocks of mafic to intermediate composition5 and such rocks will be nominally dry at normal steady-state geothermal gradients for a wide range of crustal heat flow and heat production conditions4. Hence, the rheology of the lower crust before an orogeny will in most cases be controlled by the properties of dry mineral assemblages dominated by plagioclase, pyroxene, garnet and olivine, with plagioclase being the most abundant phase. This is consistent with the estimated viscosity of the lower crust (≥1024 Pa s) required to generate the crustal support needed for intraplate seismicity such as the Bhuj earthquake6 in western India in 2001 of moment magnitude $M_w = 7.6$. Recent modelling7 furthermore suggests that the Indian lower crust remains strong beneath the entire southern half of the Tibetan plateau.

Observations of structural and metamorphic transformation of initially dry lower crust during orogenic events indicate an early stage involving seismic failures8–10. Metamorphism and shear zone development then follow in the wake of lower-crustal earthquakes. These observations raise an enigma that has so far been unresolved, because frictional failure of dry rocks at the confining pressures of the lower crust (≥1 GPa) requires differential stress levels exceeding 2 GPa. Although dry plagioclase-dominated rocks deforming by dislocation creep can in theory develop extremely high differential stress at lower-crustal temperatures and high strain rates, the stress level that can be sustained over orogenic timescales for reasonable strain rates in coherent crustal volumes will be far below what is required for brittle faulting (<1 GPa; see Methods). Deep crustal earthquakes occurring under constant loading in intact rocks thus seem to require a local weakening mechanism.

During subduction of the Indian plate under south Tibet, earthquakes occur at 60–100 km depth (Fig. 1), but are confined to regions very close to the Mohorovičić discontinuity (Moho) at temperatures7 below 600 °C. Interestingly, the pressure and temperature conditions in the region where these earthquakes nucleate overlap the conditions at which serpentine breaks down to produce hydrous fluids in mantle rocks. Fluid production near the Moho can both reduce effective pressures and weaken the crust and mantle by mineral transformation processes and thus it is a plausible explanation for the observed seismic activity.

In the absence of such local weakening mechanisms, seismicity in the lower crust may be driven by transient ‘stress pulses’8–10. Here we propose that earthquakes in the brittle upper crust provide a natural mechanism for sustained generation of stress pulses and associated seismic failures in the lower crust. During the occurrence of large earthquakes the strain rates around and below the rupture area increase by many orders of magnitude. A representative strain accumulation of 15 mm per year across a width comparable to a geodetic locking depth of 15 km corresponds to an interseismic strain rate of $3 \times 10^{-11}$ s$^{-1}$. In contrast, seismic slip velocities of $1–10$ m s$^{-1}$ across a rupture localization length of 1–10 mm lead to seismic strain rates of $10^{-3}$–$10^{-2}$ s$^{-1}$. Such large co-seismic jumps can explain a transient increase in seismic rupture within the lower crust.

Observational evidence for very high, short-lived stresses in the lower crust come from the occurrence of fossil earthquakes. A recent study of the Woodroffe Thrust located within the Musgrave Block in central Australia11 documents the formation of large volumes of pseudotachylytes in completely dry lower-crustal granulites. Stress levels exceeding 0.5 GPa have also been inferred from lower-crustal earthquakes, leading to pseudotachylyte formation in gabbros and ultramafic rocks in the Alpine subduction complex of Corsica, France14.

Simulated deformation on faults using various versions of rate- and state-dependent friction models show that large earthquake slip penetrates into the nominally stable deeper regions of the crust15,16. Simulations of aftershocks in a viscoelastic damage model consisting of a brittle upper crust over a lower crust with power-law viscosity constrained by laboratory experiments indicate that the hypocentres of early aftershocks are deeper than the regular seismogenic zone2. Depending on model parameters and thermal gradients, the maximum depth of the early aftershocks can approach twice that of the usual seismicity. Details of these results depend on the constitutive laws and parameters used, but lower-crustal aftershocks are generic outcomes of the high strain rates generated by large earthquakes at the bottom of the seismogenic zone.

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Below we use basic scaling relations to demonstrate that observed worldwide earthquake activity in the regular seismogenic zone of subduction zones and seismically active continental regions is expected to produce considerable fracture area and rupture zone volume in the lower crust. This, in turn, generates transient pathways for fluids from the wet upper crust above, or the slab below, to the dry lower crust (Fig. 1). Fluids have a key role in the long-term evolution of the lower crust. As an example, we describe earthquake-triggered eclogite-facies metamorphism and shear zone development of lower-crustal granulites from the Bergen Arcs in Western Norway (Fig. 2a). The observations highlight the close association between earthquakes, fluid migration and transformation processes in the lower crust.

The Bergen Arcs represent a series of thrust sheets where granulite facies remnants of Proterozoic lower crust recrystallized to an anhydrous mineralogy 930 million years ago. During the Caledonian continent–continent collision between Laurentia and Baltica between 420 and 440 million years ago, fluid-induced metamorphic transformations formed eclogites and amphibolites in shear zones, breccias and along fractures. The estimated eclogitization conditions are about 670–690 °C and 2.1–2.2 GPa. Pseudotachylytes, fine-grained or glassy fault rocks believed to reflect earthquake-related frictional melting are abundant on faults where granulites facies rocks experienced Caledonian retrograde metamorphism (Fig. 2a). Such faults show single rupture displacements reaching 1.7 m (Fig. 2b), corresponding to an earthquake exceeding magnitude 7. Single pseudotachylyte veins range in thickness from millimetres to a few centimetres (Fig. 2c), and also occur as a thin ‘matrix’ between rotated blocks of brecciated granulite that sometimes cover areas exceeding 100 m². Microstructures developing in the fault wall rocks display intense fragmentation with no, or very minor, shear strain, followed by healing processes through grain growth and formation of eclogite facies minerals, including hydrous phases such as amphibole, mica and clinzoisite. Infiltration of hydrous fluids is thus directly associated with seismic slip.

A substantial rheological weakening associated with formation of the fine-grained and hydrous eclogite often leads to development of ductile shear zones in areas initially deformed by brittle failure. Relict pseudotachylytes can occasionally be observed ‘floating’ in the shear...
zones, providing unambiguous evidence for ductile deformation pre-dated by brittle failure of granulite facies rocks (Fig. 3). In the following, we explore the feasibility that lower-crustal earthquakes, such as those described, are aftershocks triggered by stress pulses generated by mainshocks in the normal seismogenic regime of a plate boundary. Basic seismological scaling relations provide an order-of-magnitude estimate of the lower-crustal rock volume affected by aftershocks. We show that this is substantial, with conservative parameter values and ignoring probable contributions from penetration of large mainshocks into the lower crust as well as ductile/thermal instabilities.

Lower-crustal earthquakes are not expected to occur repeatedly in the same location because rock melting and subsequent solidification is a strengthening process. This is consistent with observations of distributed ‘fields’ of pseudotachylytes (Fig. 2a), each associated with a single event. The total volume of rock damage $V_{td}$ produced by crustal earthquakes in the magnitude range $M_1 < M < M_2$ is then given by

$$V_{td} = \int_{M_1}^{M_2} A(M) t_{rd}(M) n(M) dM$$  \hspace{1cm} (1)

Here $A(M)$ is the rupture area of an earthquake with magnitude $M$, $t_{rd}(M)$ is the damage zone thickness around the rupture area and $n(M)$ is the event density given by the Gutenberg–Richter relationship

$$\log_{10} n(M) = a - bM$$  \hspace{1cm} (2)

where $a$ and $b$ are empirical constants. The scaling relations for $A(M)$ and $t_{rd}(M)$ are found using basic theoretical relations from fracture mechanics and empirical relation between the magnitude and potency of earthquakes (see Methods). An explicit relationship for the total volume of damage produced by earthquakes in the considered magnitude range can be expressed as:

$$V_{td}(M_1 < M < M_2) = \beta[e^{\alpha M_2} - e^{\alpha M_1}]$$  \hspace{1cm} (3)

where $\alpha$ and $\beta$ are positive parameters that account for the combined scaling relations of $A$, $t_{rd}$ and $n$ with $M$. By using observationally constrained parameters, the volume of rock damaged by crustal earthquakes is estimated to be $V_{td} = 1.2 \times 10^{-5}$ km$^3$ per year per square kilometre of the Earth’s surface in the seismically active region (see Methods). For the lower-magnitude limit, we use $M_1 = 0$ with slip distance of the order of the grain size of granulites. For an upper limit relevant to the lower crust, we take $M_2 = 8.3$ since the largest subduction zones events can have $M \geq 9.5$, and the largest aftershock magnitude is typically about 1.2 units below that of the mainshock.

The parameters of the Gutenberg–Richter relationship are taken from recent analysis of global earthquakes with depths of less than 70 km. Analysis of earthquake clusters indicates that about 75% of all events with $M > 0$ are aftershocks. We therefore use 75% of the observed intensity of events to estimate the average annual production of damaged rock volume by aftershocks with $0 < M < 8.3$. On the basis of previously conducted simulations, we assume conservatively that 1% of the aftershock population is in the lower crust. The estimated annual production of rupture zone volume in the lower crust is then $1.2 \times 10^{-7}$ km$^3$ yr$^{-1}$ per square kilometre of the Earth’s surface.
As a concrete example, Western Norway was an active subduction zone during the Caledonian orogeny for more than two million years. From the estimates above, the total seismically damaged volume in the lower crust of Western Norway is estimated to be 0.24 km$^3$ per square kilometre of the Earth's surface. For a 20-km-thick lower crust, this implies a rupture zone volume exceeding 1.2% of the total lower-crustal volume. The Bergen Arcs example demonstrates that in the presence of fluids, lower-crustal earthquakes initiate metamorphism of rock volumes typically 1–2 orders of magnitude larger than that of the rupture zone (that is, a 0.1–1-m-thick eclogite forming around the 1-cm-thick rupture zone). Hence, the overall process can alter a large fraction of the lower crust. The sensitivity of the results to input parameters is discussed in the Methods and shows that the 1.2% estimate of lower-crust volume damaged by earthquakes is based on conservative values of input parameters and is likely to be higher.

Our results indicate that aftershocks triggered by major earthquakes in the regular seismogenic zone have the potential to initiate pervasive transformation of the lower crust on a timescale of a million years. Direct recording of a transient deepening of early aftershocks requires a dense observational network around large mainshock ruptures. Although this situation is not often met, such lower-crust aftershocks are sometimes observed. Recent examples of deep aftershocks include the 2001 $M_w=7.6$ Bhuj intraplate earthquake in India where aftershocks occurred down to Moho depths$^{28}$, and the 2015 $M_w=7.8$ Gorkha earthquake in Nepal where the hypocentre occurred near the Main Himalayan Thrust at a depth$^{28}$ of 10–15 km and aftershocks penetrated the Indian crust to a depth exceeding 30 km (Fig.1a).

Earthquakes in dry lower crust driven by stress pulses generated in the seismogenic zone have a number of important consequences, many of which are illustrated by the Bergen Arcs example. The most important is arguably the increased impart in permeability, which may connect the dry lower crust to an external fluid reservoir. In the Bergen Arcs, pseudotachylite formation is always associated with an influx of hydrofruid$^{29}$. Fluid-driven metamorphic reactions are fast owing to microseismicity, and large earthquakes in models of long-term fault slip. J. Geophys. Res. 122, 6491–6523 (2017).

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Online content
Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0045-y.

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**METHODS**

Controls on lower-crustal stress levels. We used the flow law creep parameters for synthetic plagioclase aggregates for variable water contents from ref. 34. Extended Data Fig. 1 shows the relations between temperature, strain rate and differential stress for water-poor plagioclase aggregates based on these experimental data. At 660–680 °C, the estimated temperature during seismic faulting in the Bergen Arcs, the maximum differential stress developing for a strain rate of $10^{-14}$ s$^{-1}$ would be about 0.3 GPa, and clearly insufficient to cause brittle failure. Such strain rates would probably only apply within zones where strain was localized. In a coherent crustal volume, the internal strain rate would be far less. Strain rates are estimated at around $10^{-16}$ s$^{-1}$ for the subducting Indian plate beneath eastern Tibet. Even if local strain rates increase should be able to push stress levels beyond what would be expected in coherent crustal slabs, or if the crustal temperature was lower than for the Bergen case so that the effective viscosity was higher, stresses much higher than 1 GPa would be unrealistic owing to the onset of Peierls creep35, or even cataclastic flow36.

**Volume of damage produced by earthquakes.** The step-by-step derivation of equation (3) and the calculation of the volume of rock damaged by earthquakes in the crust, $V_d$, are detailed here. The total volume of rock damaged produced by crustal earthquakes in the magnitude range $M_1 < M < M_2$ is given by equation (1). Each term in the integral of equation (1) is described below.

The density of events $n(M)$ in equation (1) is provided by the Gutenberg–Richter relationship, equation (2), where $a$ and $b$ are empirical constants. Assumming that each earthquake is approximately a circular rupture with radius $r$ and surface area $A = 2\pi r^2$ that sustains a uniform strain drop $\gamma$, the seismic potency $P_s$ (moment divided by rigidity) is given by $P_s = 16(7/\pi)\Delta \varepsilon r^3$.

The seismic potency and magnitude of earthquakes spanning a relatively small range ($\leq 4$) of magnitudes are related empirically by a relation of the type $P_s = dM + e$.

The fraction of lower-crustal volume affected by earthquake ruptures (1.2%) is determined in the text. The result is sensitive to the input parameters, but it is based on realistic values of earthquake intensities in active subduction zones (4.5 annual aftershocks with $M > 0$ per square kilometre), assumed lower and upper limits of aftershock magnitudes (0 and 8.3), average strain drop ($\Delta \varepsilon = 5 \times 10^{-7}$), ratio of damage zone thickness to rupture radius $\alpha = 0.002$, and the fraction of aftershocks with hypocentres in the lower crust (1%). Reducing the lower magnitude limit will increase the rupture surface area but not change the estimated damage zone volume much; decreasing the upper magnitude limit from 8.3 to 7.5 will decrease the estimated volume of damaged rock by 32%. Changing the assumed average strain drop $\Delta \varepsilon = 5 \times 10^{-7}$ to average strain drops of $5 \times 10^{-4}$ and $5 \times 10^{-6}$ will modify the estimated damage volume by factors of 0.21 and 4.64, respectively. Changing $\alpha$ or the deformation timescale by a given factor (for example, 2) will modify the damage volume by the same factor. Thus, reasonable variations of these parameters will have only minor effects on the estimated lower-crust volume affected by earthquake ruptures.

**Data availability.** All of the data used are contained within the paper.

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Extended Data Fig. 1 | Rheology of dry anorthite. Shear stress versus temperature diagram contoured with respect to strain rate.