Earth and Planetary Science Letters, 85 (1987) 248–252
Elsevier Science Publishers B.V., Amsterdam - Printed in The Netherlands

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Are impact-generated lower-crustal faults observable?

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Received November 6, 1986; revised version received June 30, 1987

Theoretical calculations coupled with present-day knowledge of the dynamic tensile behaviour of rock indicate that the propagating shock wave, and accompanying rarefaction wave, from a large meteoritic impact event may fracture the crust down to the Moho. Diapiric action by trapped upper mantle fluids could lead to annealing of these sub-vertical faults by material of high carbon content. Are these faults observable on the surface using geophysical methods? One possible means proposed is to try to monitor current flowing down them by an appropriate natural-source electromagnetic experiment. An example is discussed for which such current flow may be occurring.

1. Introduction

Many geophysicists are currently of the opinion that the continental lower crust generally behaves as a ductile solid which is mechanically decoupled from the brittle upper crust [1–6], and that possibly the upper mantle directly below the Moho is also brittle [4,6], although this is more difficult to confirm. Evidence for this two-layer rheology of the continental crust is fourfold: (1) earthquakes occur where the lithosphere is brittle, and there are no earthquakes located in the lower crust in intra-plate regions [4,6–8]; (2) a typical seismic reflection profile on the continent displays a "transparent" upper crust underlain by a zone of short, sub-horizontal reflectors between 6 and 10 s (two-way time), which is interpreted as evidence for ductile deformation of the latter [3]; (3) reflection profiling has shown that many faults within the upper crust do not penetrate into the lower crust [3]; and (4) brittle materials such as rock tend to become ductile when subjected to compression from all sides [9], and the transition from brittle to ductile behaviour occurs at confining pressures corresponding to depths of 20 km and over [9] (for regions with a typical continental geotherm).

However, when considering whether a material reacts either in a brittle or in a ductile manner, the time rate-of-change of the applied stress must be taken into account [9]. The gradual build-up of strain from tectonic and other processes is such that the stress can be released by creep mechanisms in the lower crust, but it must be released by failure, giving rise to geological faulting, within the upper crust, as evidenced by (1) and (3) above. In contrast, under the instantaneous loading of a hypervelocity meteoritic impact, the lower crust will react in an anelastic fashion to the propagating impulsive shock wave, and if the meteorite is sufficiently large, then sub-vertical faulting of the lithosphere is postulated to occur to great depth—possibly through the lower crust to the mantle.

2. Impact structures

Excavation depths alone of the very large impact events are of the order of kilometers, with an empirical relationship of *excavation depth* $= 0.06 \times$ *(final crater diameter)*$^{1.1}$ apparently valid for crystalline targets [10]. At these depths, the rocks are shocked to approximately 25 GPa [10] and are compressed and displaced downwards such that they define the base of the *transient cavity* [10,11], which is at a depth of approximately twice the above defined excavation depth [10]. Beyond this depth, tensile fractures will occur down to a depth at which the lithostatic pressure exceeds the strength of the rarefaction wave which would pro-

Geological Survey of Canada Publication 14386.

duce tensile failure at zero confining pressure [12]. Given that the dynamic tensile strength of crustal rocks is typically 0.04 GPa [13], Grieve [12], using a currently accepted shock-wave attenuation model [14], determined that impact-induced fracturing could occur beneath the Siljan structure in Sweden (estimated pre-erosional crater diameter of 52 km [15]) to depths of the order of 35–40 km. Such a model of deep faulting and fracturing has been proposed for the Sudbury astrobleme [16,17], which, with a diameter of the order of 140 km [11], should have excavated crater and transient crater depths of approximately 14 km and 28 km respectively.

One possible present-day signature of such whole-crustal effects of an impact event could be variation in the Moho beneath the site. Unfortunately, such evidence is extremely difficult to obtain due to the inhomogeneity of the impact crater itself absorbing and scattering the vertically incident seismic energy, and thus not permitting adequate resolution of structure at depth below by traditional vertical seismic reflection profiling techniques. A sophistocated seismic reflection survey conducted over one impact structure, the 22 km diameter [18] Nördlinger Ries in the Federal Republic of Germany [19], is tentatively interpreted as indicating a weakly anticlinal structure to the Moho directly beneath the astrobleme. If this is confirmed, then one obvious interpretation is that an impact which generated a final crater of diameter 22 km [18], with known brecciation down to 6 km [19] was able to cause an upwelling in the Moho at a depth of 26–29 km [19].

3. The rôle of mantle fluids

If fluids exist in the uppermost mantle and are trapped by the overlying impermeable ductile lower crust, then they will rise up in a diapiric fashion in the fractures created by the impact. Mantle-derived fluids and gases are thought to have a high carbon content [20–22], either in the form of CO [22], CO_2 or methane, as proposed by Gold [20,23] and others [24] (although this is a hotly contested issue [25]). Consideration of stress within the crust has led Gough [26] to conclude that fluid-filled vertical cracks can remain open at all depths at which the response to stress is elastic and in the absence of tectonic horizontal compression. The ductile nature of the lower crust will ensure that deviatoric horizontal compressive stress is not sustained, but is released by creep processes [7]. Injection by mantle fluids of density greater than 1/3 of that of the lower crustal rocks, with Poisson ratio of 0.25 (valid for eastern Canada [27]), will ensure that the vertical fissures remain open, due to the hydrostatic pressure being in excess of the minimum horizontal pressure given by the vertical load, for a time of the order of the creep processes in the lower crust. These fluids of mantle origin will then be in an environment of far lower P-T conditions than they were in the mantle, and, over fairly short geological time, they will either react with the neighbouring country rock, or their minerals will precipitate out. Alternatively, it has been suggested that high temperatures may cause a joint decomposition of carbonate and amphibole with the subsequent evolution of a CO_2-rich fluid [28]. Thus, country rock in the lower crust in direct contact with the hotter mantle material may itself produce a carbon-rich fluid. Whichever of these two mechanisms occur, these carbon-rich fissures will have a far higher electrical conductivity than the surrounding unfractured lower crust.

Another potential source of fluids is the lower crust itself, and interconnected fluid-filled pores at these depths is the current panacea within the electromagnetic induction community to explain the moderate resistivity observed [29]. Fluids might accumulate within the fractures, but over geological time the ductile response of the lower crust is thought to collapse these pore spaces to a vanishingly small volume [28,30–32], which also makes untenable the interconnectivity hypothesis stated above. Thus these fractures filled with fluid of lower crustal origin will eventually become unrecognisable from the host country rock.

Typical values for lower crustal conductivities are of the order of 0.01–0.003 S/m or lower (Types I and II of Jones [33]), whereas for the uppermost part of the continental mantle a conductivity of 0.025–0.010 S/m appears reasonable [34–36]. Thus, the conducting channels offered to current flow by the annealed fractures would be a short-circuit path for near-surface currents that want to find more favourable paths to the lower lithosphere or the electrical analogue of the astenosphere [34].

4. Electromagnetic detection of annealed fractures in the lower crust

At an ocean-continent boundary currents induced in the oceans at periods shorter than about 1 hour must either build up time-varying charges on conductivity-boundaries, or find preferential paths, such that in the continents they are flowing in the deep lithosphere. The former of these is clearly an *inductive* problem, whereas the latter describes *conductive* current flow. For example, for a 20-minute period electromagnetic wave, over the ocean 80% of the electromagnetic energy flows in the sea water, whereas on the continents such energy flows within a depth of 175 km (for a continental lithosphere of 0.01 S/m). The conductive channels are too small to be observable by an inductive survey—the natural electromagnetic fields cannot induce a sufficient amount of anomalous current in such narrow, small-scale structures to be resolvable at the surface. Hence, a fortuitous positioning of these fractures is required such that a significant amount of current flow through them by Ohm's Law. It is beyond the scope of this initial speculative paper, and indeed it is beyond the scope of current numerical modelling capability, to undertake a substantial three-dimensional modelling study to address more quantitatively the question of the efficiency of such a short-circuit path to current flow. Numerical modelling of this form will hopefully be possible as fast and efficient algorithms become available for solving for electromagnetic fields associated with highly complex three-dimensional structures. However, we can examine previous studies for evidence of effects of current perturbation.

Such a situation, of currents in the Atlantic ocean flowing up the St. Lawrence then leaking vertically into the lithosphere, to conducting layers at depth, at the location of the Charlevoix impact structure is the preferred interpretation of their geomagnetic induction vectors at 1220 s by Bailey et al. [37]. In the literature, the estimated rim diameter of the Charlevoix crater ranges from 34 km [38] to 58 km [39], which is larger than that of the Nördlinger Ries and of the same size as the Siljan ring. A shock analysis of rocks in the crater infers that the depth of the transient crater, as defined by the 25 GPa isobar, was of the order of 6–8 km [40]—the Moho at this location is presently at a depth of $\approx$ 40 km [41].

5. Conclusions

In this letter, we have developed the thesis that impact-induced fractures penetrating the lower crust become conducting paths for current by the subsequent annealing of upper mantle fluids that filled them. These conducting paths are probably not resolvable in data from an inductive survey, and thus if these conducting fractures exist beneath most intraplate craters they cannot be observed by electromagnetic methods. To be able to define qualitatively their existence, three combining circumstances need to be met:

(1) the impact event needs to be large enough that fracturing of the lower crust to below the Moho occurs, which appears to require the final crater to have a diameter of at least 24 km (Nördlinger Ries), which is true of 25 probable impact craters [42];

(2) the lower crust must be in an environment such that these vertical fractures can be held open by injected fluids for reasonably short geological times to permit the annealing to occur; and

(3) the crater needs to be fortuitously located such that a significant amount of electrical current will flow through the annealed fractures.

The most obvious locations for requirement (3) are on land at passive ocean-continent margins—obviously at consuming margins either these craters will have been subducted into the mantle, or the lower crust will have been dramatically altered. Another potential site is at the edge of deep sedimentary basins—such as the Nördlinger Ries. Given that the probability of all three criteria being satisfied is extremely low, perhaps Charlevoix is the only impact structure at which electromagnetic studies can identify the presence of faults in the lower crust. However, certain sites do appear favourable on the recent world compilation of 116 impact structures [42], such as Kara and Ust-Kara on the Arctic Ocean. Accordingly, systematic induction studies should be undertaken over all potential structures that might meet the three criteria specified.

In conclusion therefore, one answer to the question posed by the title of this paper is a qualified "yes" by using a specifically-designed electromagnetic survey.

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