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Long-range static directional stress transfer in a cracked, nonlinear elastic crust

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Abstract

Seeing the Earth crust as criss-crossed by faults filled with fluid at close to lithostatic pressures, we develop a model in which its elastic modulii are different in net tension versus compression. In constrast with standard nonlinear effects, this "threshold nonlinearity" is non-perturbative and occurs for infinitesimal perturbations around the lithostatic pressure taken as the reference. For a given earthquake source, such nonlinear elasticity is shown to (i) rotate, widen or narrow the different lobes of stress transfer, (ii) to modify the $1/r^2$ 2D-decay of elastic stress Green functions into the generalized power law $1/r^\gamma$, where γ depends on the azimuth and on the amplitude of the modulii asymmetry. Using reasonable estimates, this implies an enhancement of the range of interaction between earthquakes by a factor up to 5–10, that is, stress perturbation of 0.1 bar or more are found up to distances of several tens of the rupture length. This may explain certain long-range earthquake triggering and hydrological anomalies in wells and suggest to revisit the standard stress transfer calculations which use linear elasticity. We also show that the standard double-couple of forces representing an earthquake source leads to an opening of the corresponding fault plane, which suggests a mechanism for the non-zero isotropic component of the seismic moment tensor observed for some events.

1. Introduction

There are many evidences that faults and earthquakes interact, as suggested by calculations of stress redistribution [1], elastodynamic propagation of ruptures using laboratory-based friction law [2–4], simplified models of multiple faults [5,6], as well as general constraints of kinematic and geometric compatibility of the deformations [7]. Maybe the simplest mechanism for earthquake interaction involves stress re-distribution, both static [8,1] and dynamical [9] associated with a given earthquake modeled as a set of dislocations or cracks. In this simple mechanical view, earthquakes cast stress shadows in lobes of stress unloading [10,8] and increase the probability of rup-

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ture in zones of stress increase [11], according to the laws of linear elasticity. These elastic stress transfer models are useful for their conceptual simplicity and are increasingly used. Notwithstanding their extended use, the calculations of stress transfer have large uncertainties stemming from (i) the usually poorly known geometry of the rupture surfaces, (ii) the unconstrained homogeneity and amplitude of the stress drop and/or of the slip distribution on the fault plane, (iii) the use of simplified models of the crust (3D semi-infinite, or thin elastic plate, or plate coupled to a semi-infinite visco-elastic asthenosphere, etc.), and (iv) the unknown direction and amplitude of the absolute stress field that pre-existed before the event, including its possible spatial inhomogeneity. Such elastic stress transfer models seem unable to account for a growing phenomenology of long-range earthquake interactions. For instance, many large earthquakes have been preceded by an increase in the number of intermediate sized events over very broad areas [12,13]. The relation between these intermediate sized events and the subsequent main event has only recently been recognized on a large scale because the precursory events occur over such a large area that they do not fit prior definitions of foreshocks [14]. In particular, the 11 earthquakes in California with magnitudes greater than 6.8 in the last century are associated with an increase of precursory intermediate magnitude earthquakes measured in a running time window of five years [15]. What is strange about the result is that the precursory pattern occured with distances of the order of 300–500 km from the future epicenter, i.e. at distances up to 10 times larger that the size of the future earthquake rupture. Furthermore, the increased intermediate magnitude activity switched off rapidly after a big earthquake in about half of the cases. This implies that stress changes due to an earthquake of rupture dimension as small as 35 km can influence the stress distribution to distances more than 10 times its size. These observations of earthquake–earthquake interactions over long times and large spatial separations have been strengthened by several other works on different catalogs using a variety of techniques [13,16]. These results defy usual mechanical models of linear elasticity and one proposed explanation is that seismic cycles represent the approach to and retreat from a critical state of a fault network [16,17]. Within the critical earthquake concept, the anomalous long-range interactions between earthquakes reflect the increasing stress–stress correlation length upon the approach of the critical earthquake. Another explanation involves dynamical stress triggering [18] (see however [19]). Additional seismic, geophysical, and hydrogeological observations [20] cannot be accounted for by using models derived from the elastic stress transfer mechanism. In particular, standard poro-elastic models underestimate grossly the observed amplitudes of hydrogeological anomalous rises and drops in wells at large distances from earthquakes.

2. Mechanical model of the Earth's crust

Here, we investigate the hypothesis, and its implications for the above observations, that the crust is a nonlinear elastic medium characterized by an asymmetric response to compressive versus extensive perturbations around the lithostatic stress. We call this a "threshold nonlinearity." This nonlinearity stems from a mechanically justified argumentation based on the fact that the Earth's crust at seismogenic depth is criss-crossed by joints, cracks or faults at many different scales filled with drained fluid in contact with delocalized reservoirs at pressures close to the lithostatic pressure. It has been argued that rock permeability and thus microcracking adjusts itself, so that fluid pressure is always close to rock pressure irrespective of the extend of hydration/dehydration [21,23]. One possible mechanism for this involves a time-dependent process that relates fluid pressure, flow pathways and fluid volumes [24].

2.1. Presence and role of fluids

Indeed, a lot of data collectively support the existence of significant fluid circulation to crustal depths of at least 10–15 km. Much attention has been devoted to the role of overpressurized fluid [25–30]. It is more and more recognized that fluids play an essential role in virtually all crustal processes. Ref.[31] reviews the historical development of the conciousness among researchers of the ubiquitous presence and importance of fluids within the crust. Numerous examples exist that demonstrate water as an active agent of the mechanical, chemical [32] and thermal processes that control many geologic processes that operate within the crust [21,22]. The bulk of available information on the behavior of fluids comes from observations of exposed rocks that