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Improved concept of lithospheric strength and earthquake activity at shallow depths based upon the fan-head dynamic shear rupture mechanism

Boris G. Tarasov *, Mark F. Randolph [1]

The University of Western Australia, Centre for Offshore Foundation Systems, 35 Stirling Highway, Crawley, WA 6009 Australia

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A B S T R A C T

The typical depth–frequency distribution of earthquake hypocentres (DFDE) demonstrates that, below an upper cutoff, the earthquake frequency increases with depth up to a maximum value and then decreases and ceases at a lower cutoff. Such regular behaviour of earthquakes implies the existence of some fundamental mechanisms responsible for the distribution. Conventional models of lithospheric strength based upon the assumption that the frictional strength along pre-existing faults represents a lower limit on the rock shear strength do not provide any intrinsic logic for the observed DFDE. The paper shows that these models ignore the specific properties of intact hard rocks which can exhibit extremely low *transient strength* (significantly lower than the frictional strength) during failure under the high confining stresses corresponding to seismogenic depths. The low transient strength is provided by a recently identified fan-head shear rupture mechanism which can be initiated in intact rocks in the proximity of pre-existing faults. The low transient shear strength of intact rock determines the correspondingly low transient strength of the lithosphere, which favours generation of new earthquake faults in the intact rock mass adjoining pre-existing faults in preference to frictional stick-slip instability along these faults. The efficiency of the fan-mechanism within the seismogenic layer is variable, with maximum efficiency at the middle range between the upper and lower cutoffs, thus providing minimum transient strength of the lithosphere and maximum earthquake frequency at that depth. We believe that this intrinsic property of hard rocks is responsible for the observed DFDE. Importantly, the formation of new faults in intact rock generated by the fan-mechanism can be accompanied by very small stress-drops (similar to, or lower than, stress-drops for frictional stick-slip instability) combined with abnormally high energy release. The paper proposes an improved concept of lithospheric strength and earthquake activity at seismogenic depths.

1. Introduction

New knowledge derived from experimental study of the fracture and friction of rock, geological observations of faults, and relevant seismological observations improves our understanding of earthquake mechanics. Well-established concepts of earthquakes, which considers earthquake mechanism as frictional stick-slip instability on pre-existing faults, can explain many earthquake features observed in nature. However, some aspects of earthquakes are still in question, in particular that associated with typical depth–frequency distribution of earthquake hypocentres (DFDE) which demonstrates that when starting from the upper cutoff the earthquake frequency increases with depth up to a maximum value and then decreases and ceases at the lower cutoff. Such regular behaviour of earthquakes implies the existence of some fundamental mechanisms responsible for the distribution. Conventional models of lithospheric strength do not provide any intrinsic logic for the observed DFDE. The paper introduces new knowledge about hard rock properties under high confining stresses which changes fundamentally the conventional understanding of hard rock strength within the seismogenic layer and, consequently, the lithospheric strength. An approved concept for lithospheric strength and earthquake mechanism based upon the new knowledge proposes an alternative explanation for different earthquake features: e.g. upper and lower cutoffs, the typical shape of depth distribution of earthquake hypocentres, potentially low magnitudes of stress drop, and observed spatial patterns of earthquake occurrence. To facilitate understanding of the main differences between the conventional and new concepts we describe briefly in this extended introduction the most important basic principles involved in both concepts. Detailed discussion of the new concept is presented in the main body of the paper.

* Corresponding author: Tel.: +61 8 6488 7368; fax: +61 8 6488 1044.
E-mail addresses: boris.tarasov@uwa.edu.au (B.G. Tarasov), mark.randolph@uwa.edu.au (M.F. Randolph).
[1] Tel.: +61 8 6488 3075; fax: +61 8 6488 1044.

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1.1. Post-peak properties of hard rocks at high confining stresses

1.1.1. Conventional understanding

Fig. 1a shows five stages of shear rupture propagation through an intact hard rock specimen subjected to axial compression σ_1 at confining pressure σ_3. Studies by Reches and Lockner (1994) showed that hard rocks under high confinement exhibit a special shear rupture mechanism which differs principally from the well-known failure mechanism where the fault surface forms by coalescence of pre-existing (generated at loading), randomly distributed arrays of microcracks. According to Reches and Lockner (1994) the fault front, nucleated at one site near the peak stress, moves through the rock as a distinct entity (fracture head) in the direction of propagation. The advancing fracture itself induces organized damage which is restricted to its own plane. In Fig. 1a the fracture head is shown in red. Shear resistance in front of the head corresponds to cohesion; behind the head it corresponds to friction; shear resistance of the head has an intermediate level (above the frictional strength).

Fig. 1b shows a conventional stress–displacement curve for brittle Class II rocks obtained at controllable post-peak failure on stiff and servocontrolled testing machines. Points on the curve indicate identical stages of shear rupture propagation shown in Fig. 1a. Point 1 at peak stress τ_u corresponds to the intermediate stage of the fracture head formation (the head formation starts at the pre-peak stage). At point 2 the head has completed. The formation of fracture head and its further propagation through the specimen are totally controllable. This means that at any post-peak stage (e.g. 2, 3 and 4) the rupture process can be stopped by a slight unloading of the specimen (for example, from point 2 to point 2′ in Fig. 1b). When the fracture head has crossed the specimen (stage 5) the shear resistance along the fault is totally frictional (residual strength τ_f) representing the lower limit on rock shear strength. The post-peak curve in Fig. 1b demonstrates that to cause shear rupture propagation at any stage of failure by the conventional mechanism the applied shear stress must be above the frictional strength. The yellow area on the graph represents elastic energy released from the specimen at failure up to point 5.

Fig. 1c shows conventional profiles for fracture τ_u and frictional τ_f strength. The frictional strength of faults is less than the stress necessary to form them and once formed they constitute planes of weakness that may be reactivated in stress fields in the stick-slip manner. This understanding of rock properties represents the basis for the conventional understanding of lithospheric strength and earthquake mechanism.

1.1.2. New understanding

Special studies of hard rocks characterised by uniaxial compressive strength (UCS) above 250 MPa have shown that the rock behaviour discussed in Fig. 1b takes place only at relatively low levels of confining pressure σ_3. At high confining pressures corresponding to the seismogenic depths (above a critical level $\sigma_3 > \sigma_{3cr}$ different for different rocks) post-peak control of shear rupture propagation becomes impossible even on ultra-stiff and servocontrolled testing machines and unstable dynamic fracture growth occurs with extreme violence. The term 'instability' used in the paper means 'unstable (dynamic) fracture growth'. The extreme violence prevents recording of the true post-peak characteristics (will be discussed in the paper) and the direct study of shear rupture mechanism operating at these conditions. The initial structure of shear ruptures after the violent failure is completely destroyed representing pulverized gouge. Post-peak properties of rocks with UCS > 250 MPa at high confining pressure $\sigma_3 > \sigma_{3cr}$ are still experimentally unexplored.

Comprehensive analysis of different side effects accompanying the process of spontaneous failure in such hard rocks at $\sigma_3 > \sigma_{3cr}$ (Tarasov, 2014a) resulted in the identification of a unique shear rupture

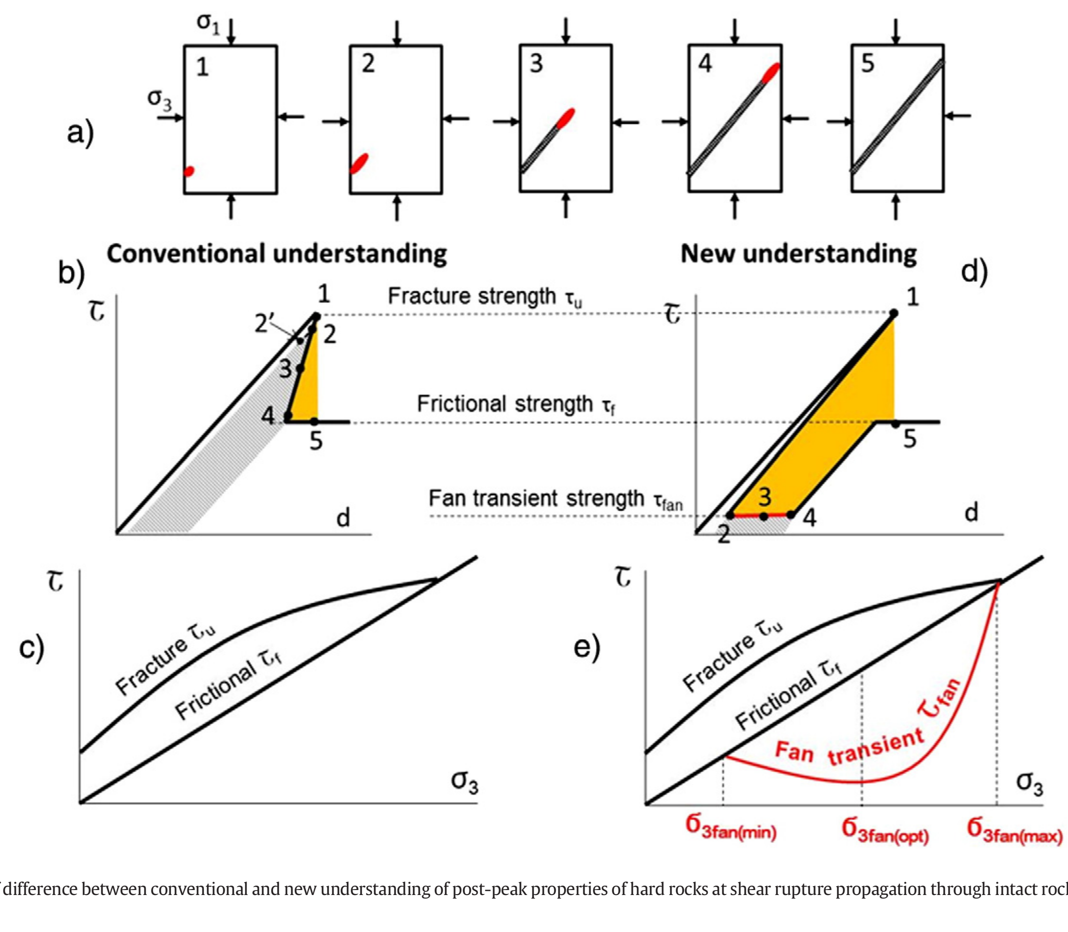

Fig. 1. Illustration of difference between conventional and new understanding of post-peak properties of hard rocks at shear rupture propagation through intact rock under high confining stresses.