Evolution of self-similar hierarchical geometry of fault zones: Implications for seismic nucleation and earthquake size

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1. Experiments

The evolution of fault geometry was investigated by cyclic loading-unloading-photographing-loading experiments for calcareous siltstone nodule under 100 MPa confining pressure. After several cyclic runs, the samples were broken down at about 300 MPa peak stress associated with stress drop smaller than 40 MPa.

2. Evolution of hierarchical self-similar fault geometry

1) Conjugate microfaults, appearing just like brushing trails, were densely developed with the fracture angle at 80 degrees.

2) A part of the microfaults grew selectively to form en echelon patterns when they grew up to about 1 mm length. The fracture angle of them is about 70 degrees.

3) The tips of fault segments that constitute en echelon faults curve away from the maximum compressional stress axis to interconnect with adjacent microfaults, forming constriction type jogs.

4) Once the number of segments reached 3 to 5, they behaved as a longer segment and it interconnect with other longer segments, forming larger segment+jog structures.

5) Through such nesting of segment+jog structures, a hierarchical self-similar fault geometry evolved. The small segment+jog structures of low hierarchical ranks were inherited as internal structures of the shear zone of the higher hierarchical rank.

3. Interrelation among geometrical elements of fault zones

Among the total length of a fault zone L0, segment length LS, jog length LJ and jog width WJ, four relations below are found.

LS=0.343*L0^0.999 ------(1)

LJ=0.0935*L0^1.00 ------(2)

WJ=0.0456*L0^0.691 ----(3)

Eq. (1) and (2) represent self-similar and are rewritten as LS=Csl*L0 and LJ=Cjl*L0, while eq. (3) is a power function, representing the smoother fault plane, the more fault evolves.

4. Derivation of Mo=C*Lc^3

Let i as the hierarchical rank, and a larger i denotes low rank. Based on the hierarchical self-similar geometry, (a) LS(i)=Csl^i)*L0, (b) LJ(i)=Cjl*[Csl^(i-1)]*L0, and (c) NS(i)=Csl^-1 are derived, where NS(i) represents the total number of i-th rank segments. Using eqs.(a) and (b), the equation below is obtained.

LS(i-1)=(1/Cjl)*LJ(i) -----(4)

Assuming LS(i-1) and LJ(i) as the length of a seismic fault Lseis and the length of the seismic nucleus Lnucle, and using the relationships among the fault length, fault plane area, and magnitude, and the definition of seismic moment Mo, the well-known empirical relation:

Mo=(10^8.84)*Lnucle^3 ------(5)

is obtained. This result suggests that earthquakes nucleate at jogs of a hierarchical rank, and terminate at the jogs one rank higher.

5. Derivation of Gutenberg-Richter's law

Assume that a fault zone with L0xrL0 is hierarchically nested by self-similar segment+jog structures, and that the NS(i+1) segments will activate k*nS(i+1)^2 times in total until anyone of the i-th rank jogs is ruptured, and thereafter every NS(i-1) segments with LS(i-1) activate individually.

Denoting the activated fault length as L and its number as N, they are written as L=LS(i) and n=k*NS(i)^2. Using eqs. (a) and (c), they are rewritten as L=(Csl^i)*L0 and N=k*Csl^-2i. From these equations, we have an equation below.

logN=log(k*L0^2)-2logL ----(6)

Using logL(m)=0.5M+1.12, eq.(6) is expressed as:

logN=[log(k*L0^2)-2.24]-M ----(7)

being consistent with Gutenberg-Richter's law.

Our results suggest that seismic rupturing mimicks the hierarchically nested fault zone structure.