What Have We Learned from Studies of the 1999 M_s7.6 Chi-Chi, Taiwan, Earthquake for Resolving Three Paradoxes in Earthquake Physics?

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Abstract: There have been three paradoxes in earthquake physics(Sornette,1999; Wang, 2019): (1)the strain paradox (localized strain versus non-localized strain); (2)the stress paradox (high stress versus low stress); and (3)the heat flux paradox (high heat flux versus low heat flux).From the past studies of the September 20, 1999 M_s7.6 Chi-Chi earthquake, we can resolve the three paradoxes.The strain paradox concerns localization (Pearson et al., 1995) or non-localization (Walcott et al., 1978; Shen et al., 1996; Snay et al., 1996) of strain along the earthquake fault. Based on the Reid's elastic rebound model (see Turcotteand Schubert, 2002), the width, 2w, in which the shear strain develops progressively across the fault prior to the earthquake, is 2w=mD/Ds where m, D, and Ds are, respectively, the rigidity of fault-zone material, final slip, and static stress drop. For the 1999 Chi-Chi earthquake, the estimated values of related model parameters are: D=3.1–6.0 m (Wang, 2006a), Ds=4.2–10.0 MPa (Wang, 2006a), and m=19 GPa (Wang et al., 2009), thus leading to 2w=5.9–27.1km, with an average of 18 km. This is consistent with the surface deformations through field surveys made by Yu et al. (2001). Results suggest strain localization.The stress paradox is that the fault strength is high or low fault strengthfor an earthquake occurs.From the Mohr-Coulomb relation, the lithostatic stress, which is s_L=rgH (g=9.8 m/s^2) at a depth of H, is ~300 MPa and the shear stress is ~200 MPa at a depth of H=10 km, thus resulting in m_f≈0.7. Hickman (1991) obtained s_o=35 MPa for normal faults, 150 MPa for thrust faults, and 60 MPa for strike-slip faults.His results give a high fault strength. On the other hand, Bird (1989) and Bird and Kong (1994) gained m_f=0.17–0.25 for faults inCalifornia. Hence, they proposed a low fault strength.From near-field seismograms, Wang (2006b)obtainedthe initial stress on the fault, s_o, is 52% and 70% less than average crustal stress,s_L, respectively, on the southern and northern segments. This implies that the Chelungpu fault was weaker during faulting, and the southern segment was weaker than the northern one. The heat flux paradoxconcerns the total heat generated during faulting, which is E_f=s_fDA (s_f=dynamic friction; D=slip; and A=the area of ruptured plane).The strength of the heat source Q=DTh is Q=s_dD/ C_vr.Hence, we have DT=Q/2(pat)$^{1/2}$ (a=the heat diffusion coefficient, in m^2/sec). Bullard (1954) proposed thata fault should have large m_f to allow for large earthquakes, so thatit can store a large amount of elastic energy and overpass large barriers. This would yield a high heat flux near the fault. However, if m_f is large, large earthquakes should generate a large quantity of heat by rubbing the two surfaces. This heat would be not easily dissipated in a relatively insulating earth. Underrepetition of earthquakes, the heat should accumulate and either result in localized melting (whichshould inhibit the occurrence of further earthquakes because slow continuous sliding should thenoccur) or develop a high heat flux at the surface. Hickman (1991) first pointed out the heat flux problem. However, observations made by some authors (e.g., Henyey and Wasserburg, 1971; Lachenbruch and Sass, 1980) over the entire state of Californiahave shown the absence of anomalous heat flow across the major faults. From the borehole data, Wang (2006b, 2011) inferred generation of energy and heat and thermal history of the earthquake during faulting. Results suggest that the heating time span was short, temperature decreased very fats, and heat flux during the earthquake was low.

Key words: the 1999 Chi-Chi earthquake, strain, stress, heat flux

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