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Regional pore-fluid pressures in the active western Taiwan thrust belt: A test of the classic Hubbert–Rubey fault-weakening hypothesis

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ABSTRACT

We document regional pore-fluid pressures in the active Taiwan thrust belt using 55 deep boreholes to test the classic Hubbert–Rubey hypothesis that high static fluid pressures (depth normalized as $\lambda = P_f/\rho_r gz$) account for the extreme weakness of thrust faults, since effective friction $\mu_f^* = \mu_f(1-\lambda)$. Taiwan fluid pressures are dominated by disequilibrium compaction, showing fully compacted sediments with hydrostatic fluid pressures at shallow depths until the fluid-retention depth $z_{FRD} \approx 3$ km, below which sediments are increasingly undercompacted and overpressured. The Hubbert–Rubey fault weakening coefficient is a simple function of depth $(1-\lambda) \approx 0.6 z_{FRD}/z$. We map present-day and pre-erosion fluid pressures and weakening $(1-\lambda)$ regionally and show that active thrusts are too shallow relative to z_{FRD} for the classic Hubbert–Rubey mechanism to be important, which requires $z \geq \sim 4 z_{FRD} \approx 12$ km to have the required order-of-magnitude Hubbert–Rubey fault weakening of $(1-\lambda) \leq \sim 0.15$. The best-characterized thrust is the Chelungpu fault that slipped in the 1999 ($M_w = 7.6$) Chi-Chi earthquake, which has a low effective friction $\mu_f^* \approx 0.08$–0.12, yet lies near the base of the hydrostatic zone at depths of 1–5 km with a modest Hubbert–Rubey weakening of $(1-\lambda) \approx 0.4$–0.6. Overpressured Miocene and Oligocene detachments at 5–7 km depth have $(1-\lambda) \approx 0.3$. Therefore, other mechanisms of fault weakening are required, such as the dynamical mechanisms documented for the Chi-Chi earthquake.

1. Introduction

The Hubbert and Rubey (1959) fluid pressure fault-weakening mechanism has long been accepted as the most plausible solution to the classic problem that long, thin thrust sheets require very weak basal detachments, typically with an effective friction coefficient $\mu_b^* = \tau_b/\sigma_n$ about an order of magnitude weaker than lab static friction measurements of $\mu_b \approx 0.6$–0.85 (Byerlee, 1978) (for list of parameters see Table 1). The Hubbert–Rubey hypothesis in its classic form argues that ambient high pore-fluid pressure (P_f) reduces the critical shear stress (τ_b) required for frictional sliding on the base of the sheet, because frictional strength is controlled by effective normal stress, which in the case of a horizontal detachment is $(\rho_r gz - P_f)$

$$\tau_b = \mu_b^*(\rho_r gz) = \mu_b\left(\rho_r gz - P_f\right) \tag{1a}$$

where ρ_r is the mean rock density. This role of pore-fluid pressure is normally expressed in depth-normalized form, using the Hubbert–Rubey fractional weakening coefficient $(1-\lambda)$

$$\mu_b^* = \mu_b\left[\frac{\rho_r gz - P_f}{\rho_r gz}\right] = \mu_b(1-\lambda) \tag{1b}$$

where $\lambda = P_f/\rho_r gz$ is the pore-fluid pressure normalized with respect to overburden pressure. The Hubbert–Rubey weakening coefficient $(1-\lambda)$ typically ranges between ~0.6 for hydrostatic fluid pressures and ~0 for lithostatic pressures, for which the effective friction μ_b^* would be near zero.

There have been some *in situ* tests and measurements to address the Hubbert and Rubey effect on faulting. The physics of fluid-pressure induced fault weakening is now well established from soil and rock mechanics and successful field-scale experiments, in which earthquakes have been triggered by increases in pore-fluid pressure that result from pumping or waste injection (e.g. Healy et al., 1968; Raleigh et al., 1972, 1976; Ohtake, 1974; Ahmad and Smith, 1988; Zoback and Harjes, 1997; Evans, 2005; Evans et al., 2005a,b). A key element of the original argument of Hubbert and

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Table 1
Parameters used in the paper.

τ_b	Shear traction
σ_τ	Basal shear traction
ρ_r	Mean density of the sedimentary rocks[a]
ρ'_r	Effective rock density
ρ_m	Drilling mud density
ρ_w	Density of pore water[b]
μ_b	Basal coefficient of friction
μ_b^*	Basal effective coefficient of friction
λ	Hubbert–Rubey pore-fluid pressure ratio[c]
λ_b	Basal Hubbert–Rubey pore-fluid pressure ratio[c]
g	Acceleration of gravity[d]
P_f	Fluid pressure
S_{op}	Slope of the overpressure gradient in a given fluid-pressure plot
Z	Thickness of the thrust sheet or depth
Z_e	Equilibrium compaction depth at which the shale porosity on the normal compaction trend equals the shale porosity at depth Z
Z_{FRD}	Fluid-retention depth
α	Surface slope of a wedge
β	Basal detachment slope of a wedge
σ_1	Maximum compressive normal stress
σ_3	Minimum compressive normal stress
F	Fault strength
W	Wedge strength

[a] 2.3 g/cm^3, Magara (1978), Mouchet and Mitchell (1989).
[b] 1.0 g/cm^3.
[c] Hubbert and Rubey (1959).
[d] 9.8 m/s^2.

Rubey (1959) was the observation that fluid pressures approaching lithostatic values had been observed in some fold-and-thrust belts; they showed fluid-pressure data from wells in the Zagros thrust belt in Iran and Iraq, and from the western Pakistan foldbelt. Since 1959 there has been a great expansion of knowledge of *in situ* overpressures (e.g. Fertl, 1976; Magara, 1978; Behrmann et al., 1988; Hunt, 1990; Bigelow, 1994; Osborne and Swarbrick, 1997; Japsen, 1998, 1999; Law and Spencer, 1998; Swarbrick and Osborne, 1998; Michael and Bachu, 2001; Lee and Deming, 2002; Swarbrick et al., 2002; Luo et al., 2003; Bilotti and Shaw, 2005). However, there still has been a general lack of documentation of *in situ* fluid pressure and stresses in relation to active detachments in fold-and-thrust belts or accretionary wedges, which is necessary for more direct testing of the classic Hubbert–Rubey hypothesis.

Here we present such a test in the presently active western Taiwan fold-and-thrust belt, based on 55 regionally distributed petroleum-exploration wells with *in situ* fluid-pressure measurements (Fig. 1). These exploration wells were drilled to depths of 3–5.5 km and display regionally and vertically consistent patterns of overpressuring, which we document. These pressures can be extrapolated to depths beyond 5 km with sufficient accuracy for testing the Hubbert–Rubey hypothesis, based on well-defined overpressure gradients observed at shallower depth and on a new technique outlined in this paper which uses observations of the fluid-retention depth z_{FRD} in sonic logs.

We evaluate the role of pore-fluid pressures in thrust mechanics in western Taiwan by bringing these observations of fluid pressure together with extensive data on the petroleum structural geology of the fold-and-thrust belt (e.g. Stach, 1957; Hsiao, 1968; Chang, 1971; Chen, 1978; Suppe and Namson, 1979; Suppe, 1980a,b, 1984, 1986; Suppe and Chang, 1983; Namson, 1981, 1983, 1984; Yang et al., 1991, 1994, 1996, 1997, 2006; Hung and Wiltschko, 1993; Wang et al., 2000; Hickman et al., 2002; Lee et al., 2002; Huang et al., 2004; Yue et al., 2005, 2011). We especially focus on the well-documented Chelungpu thrust fault (Yue et al., 2005, 2011), which ruptured to the surface in the 1999 ($M_w = 7.6$) Chi-Chi earthquake and is currently the best-studied thrust-belt earthquake in the world. Furthermore, the effective friction μ_b^* of the Chelungpu thrust ramp and detachment are independently constrained to be $\mu_b^* = 0.07–0.11$, both locally by post Chi-Chi scientific borehole studies of the principal-slip zone on the thrust ramp at ~1 km depth (Sone and Shimamoto, 2009; Kuo et al., 2011), and regionally by critical-taper wedge analysis, which gives both regional wedge strength and effective friction on the detachment at ~5–6 km depth (Suppe, 2007). Knowing μ_b^*, P_f, and $\rho_r gz$, we determine the intrinsic friction μ_b required for the large-scale fault motion using equation (1b), which we compare with lab measurements of friction μ_b that have been obtained for Chelungpu fault gouge (Mizoguchi et al., 2008; Tanikawa and Shimamoto, 2009), as a direct test of the Hubbert–Rubey hypothesis.

2. Geological setting

The very young and ongoing compressional tectonics of Taiwan provides a well-instrumented natural laboratory for the study of many active processes, including faulting. Thrust faulting in western Taiwan consumes about one third of the ~9 cm/yr Philippine Sea-Eurasia plate convergence rate (e.g. Le Béon et al., 2014). This shortening is taken up in a complex stratigraphy overlying Mesozoic basement, involving three stratigraphic packages. (1) A Paleocene to early Oligocene failed rift system that largely predates the main opening of the South China Sea created a series of half grabens, including the Hsuehshan trough, which is outcropping just interior to the foothills thrust belt, as well as offshore rift basins to the west and north (Teng et al., 1991; Teng and Lin, 2004). (2) Those half graben systems were buried by thick Oligocene to Miocene syn-rift to post-rift passive margin strata (Yu et al., 2013). (3) An arc–continent collision between the Philippine Sea plate and the Eurasian continental margin began ~4–5 Ma, producing a propagating sub-aerial mountain belt which initiated a foreland basin sequence, including Chinshui Shale, Cholan Formation, Toukoshan Formation and Holocene strata in western Taiwan and the offshore Taiwan Strait (Suppe, 1981; Ho, 1988; Teng, 1990; Teng and Lin, 2004). The currently active western Taiwan fold-and-thrust belt deforms the entire Oligocene to Holocene syn-rift to post-rift to foreland basin sedimentary package, which in many areas exceeds 6 km in thickness (Lin et al., 2003). This composite set of overlapping basins rapidly thins towards the Taiwan Strait where reduced development of overpressures is observed. This tectonostratigraphic history provides an opportunity to study not only the transition from rifting to collision in one place, but also the corresponding fluid pressure evolution, including the disequilibrium compaction history in the early rift-related sedimentary package, later altered by collision-related uplift and erosion effects. We begin by presenting the fluid pressure data from western Taiwan.

3. Pore-fluid pressure data in western Taiwan

Pore-fluid pressures from 55 wells in western Taiwan (Figs. 1–5) are based on largely unpublished data of the Chinese Petroleum Corporation (CPC), including: (1) *in situ* borehole formation tests (including fluid pressures reported by Chan (1964), Kuan (1967, 1968, 1971), Chang (1972), Suppe and Wittke (1977)), (2) densities of drilling mud (mud weights), and (3) continuous sonic logs, using standard petroleum methods outlined in Section 3.1 (Hottmann and Johnson, 1965; Fertl, 1976; Magara, 1978; Chapman, 1983; Dutta, 1987). Formation tests, which include both initial and final flow and shut-in measurements, provide direct pore-fluid pressure data in permeable strata. Pore-fluid pressures calculated from densities of drilling mud $\rho_m gZ$ provide an upper bound to fluid pressures based on standard drilling procedures,