Geophysical Research Abstracts
Vol. 14, EGU2012-5994-1, 2012
EGU General Assembly 2012

From KTB amphibolite to Bentheim sandstone: the diminishing effect of the intermediate principal stress on faulting and fault angle

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The introduction of the “true triaxial” testing machine by Mogi (JGR, 1971) and later by Haimson and Chang (JGR, 2000; IJRMMS, 2000) was instrumental in discovering the hitherto largely unrecognized effect of the intermediate principal stress (σ_2) on rock brittle failure (or faulting) and fault angle (angle between fault-normal and direction of the major principal stress σ_1). It was observed that generally for a given σ_3, the threshold of strain localization and the level of σ_1 at which rock fails ($\sigma_{1,peak}$) rise monotonically with σ_2 beyond the base magnitudes under axisymmetric compression (AC) when $\sigma_2 = \sigma_3$. An inflection point is reached at some $\sigma_2$that defines its maximum $\sigma_{1,peak}$. Further rise in σ_2 leads to a gradually lower $\sigma_{1,peak}$. However, even when σ_2 approaches σ_1, strength is still somewhat higher than under AC. Similarly, fault angle for a given $\sigma_3$increases with the rise in σ_2, at least until the maximum $\sigma_{1,peak}$ is reached. These important roles of σ_2 in fault formation and angle are totally neglected by the commonly accepted Mohr-Coulomb theory, which assumes that faulting is a function of only the two extreme principal stresses, and considers fault angle a unique material property.

Our first true triaxial experiments, conducted on two crystalline rocks (under 1% porosity), Westerly granite (Haimson and Chang, IJRMMS, 2000) and KTB amphibolite (Chang and Haimson, JGR, 2000), exhibited a remarkable σ_2 effect. At low σ_3 (for example: 30 MPa), raising σ_2 increased $\sigma_{1,peak}$ in the amphibolite by up to 59% (at σ_2 = 200 MPa) over its AC magnitude. Similarly, peak $\sigma_{1,peak}$ in the granite at σ_3 = 20 MPa increased by a maximum of 49% (at σ_2 = 200 MPa) over its $\sigma_2 = \sigma_3$ level. As $\sigma_3$was raised, the increase in strength dropped steadily, but even at σ_3 = 100 MPa maximum $\sigma_{1,peak}$ in both rocks increased by 18% to 39% over the base level. The increase in fault angle with the rise in σ_2 reached a maximum of 20° for all levels of σ_3 in the KTB rock. In the granite, fault angle steepened by 10° to 15° as σ_2 rose above σ_3.

A milder effect of σ_2 on strength and fault angle was observed in a low porosity (ϕ = 7%) siltstone, extracted from the TCDP, Taiwan test hole (Oku, et al, GRL, 2007). At low σ_3 (25 MPa), the maximum $\sigma_{1,peak}$ was 28% larger than the AC level, when σ_2 reached 200 MPa. At higher σ_3 (100 MPa), the maximum $\sigma_{1,peak}$, reached at σ_2 = 300 MPa, was only 12.5% higher than the strength at $\sigma_2 = \sigma_3$. Fault angle increase with σ_2 for the same σ_3 was limited to less than 10°, irrespective of σ_3 level.

Currently, we are studying the true triaxial mechanical behavior of two quartz-rich sandstones. In the Coconino sandstone (ϕ = 17%), an even smaller σ_2 effect was observed. $\sigma_{1,peak}$ as a function of σ_2 at σ_3 = 20 MPa reached a maximum of just 10.5% higher than under AC. At σ_3 = 150 MPa, $\sigma_{1,peak}$ maximum increase was also about 10%. Fault angle rise with σ_2 for the same σ_3, was less than 10° at any σ_3 level. By far the smallest σ_2 effect on rock strength and fault angle was found in the high porosity (ϕ = 25%) Bentheim sandstone. In this rock at low σ_3 = 30 MPa, $\sigma_{1,peak}$ reached a maximum of just 4% over its AC magnitude. At higher σ_3, such as at σ_3 = 150 MPa, it showed a maximum increase of 8% as σ_2 rose. Average fault angle decreased from about 80° at σ_3 = 0 MPa, to 48° at σ_3 = 80 MPa, to near 0° at σ_3 = 150 MPa (compaction band). For any given σ_3, however, fault angle rise with σ_2 was limited to less than 10°.

In conclusion, our research shows that the intermediate principal stress affects the resistance to faulting and fault angle in both crystalline and clastic rocks. However, the effect in clastic rocks is less pronounced, and appears to decrease with the rise in porosity.