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Macroscopic Strength Profiles Determined from Hydrothermal Deformation Experiments on Granular Quartz Sand

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Numerous processes influence how porous materials deform within the Earth. These mechanisms not only depend on the intrinsic properties of the granular aggregates (e.g. composition, porosity, grain size, sorting), but also on the tectonic and diagenetic history of the buried rocks. As such, temperature is a fundamental parameter that influences the mechanical properties of rocks. While the thermal sensitivities of dilatant fracture and frictional strength of sheared surfaces are known to be subtle, few studies have explored the temperature dependence for granular compaction - particularly when reactive fluids are present. We investigated hydrothermal deformation of St. Peter quartz sand (250-350 μm) through hydrostatic and triaxial compression experiments performed at temperatures between 25-200 ^{o}C. Throughout each test we monitored pressures (P_f held constant at 12.5 MPa, $P_c < 300$ MPa), pore fluid volume, temperature, and acoustic emissions. Two sequential modes of stressing were imposed: 1. hydrostatic loading achieved by increasing confining pressure at a constant rate; and 2. triaxial (or non-hydrostatic) deformation for which axial load is applied after a target hydrostatic pressure has been established.

With increasing hydrostatic load, quartz sand compacts by a combination of elastic and inelastic mechanisms. Hydrostatic loading at low effective pressures (P_e), produces relatively large volumetric strains and these strains gradually decrease to a quasi-linear trend at intermediate P_e (e.g. the hydrostat curve in Figure 1a). At greater effective pressures we observe a second transition to rapid compaction that correlates with a maximum in acoustic emission (AE) rates. Microstructural analyses coupled with our AE data indicate grain fracturing and crushing is more pervasive at greater pressures, consistent with previous observations of a critical effective pressure (P*) for cataclastic flow. Our hydrostatic deformation results show a reduction of P* as temperature increases (P*~107 MPa at 25^{o}C, ~95 MPa at 150^{o}C).

For triaxial loading (Figure 1a), samples show quasi-elastic deformation followed by yielding. Prior to yielding, porosity evolution for triaxial deformation follows the trend of the hydrostatic curve. After yielding, samples dilate when deformed at low effective pressures and compact at when deformed at greater pressures. Qualitatively similar results were obtained for all temperatures studied.

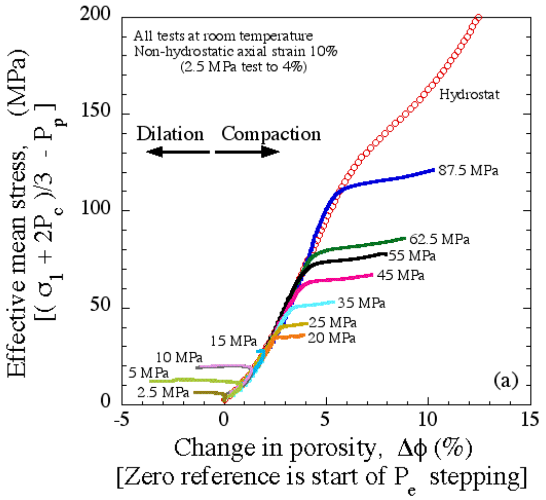
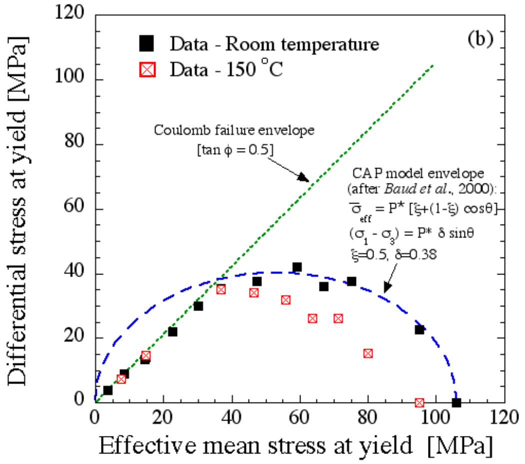


Figure 1: (a) Compaction data from room-temperature experiments shown against effective mean stress. The hydrostatic compaction curve is shown for reference. Triaxial data are shown as a function of effective pressure for each experiment (denoted by the numbers by each curve). Similar results were obtained from experiments at 150 ^{o}C.



(b) Yield data presented in terms of differential stress and effective mean stress. Triaxial deformation at low effective pressures defines a quasi-linear yielding trend consistent with brittle Mohr-Coulomb failure. Deformation at higher effective pressures defines an elliptical failure curve that departs from the lower pressure linear trend.

Our experiments define an elliptical yield envelope that is consistent with Critical State studies and CAP models of soil mechanics (Figure 1b). However, the character of the yield curve varies with temperature. We observe little or no variation in macroscopic yield strength with temperature for samples that exhibit dilatant behavior. Yet, samples deformed in the compactive part of the yield envelope were weaker when deformed at elevated temperature.

Laboratory deformation experiments can be related to burial depth in sedimentary basins by considering the mean stress in various tectonic settings, as follows:

Isotropic basin: $$\bar{\sigma}_{eff} = {}^{1}\!/_{3}\left(\sigma_V + 2\sigma_H\right) - P_p \;=\; \sigma_V - P_p \;= P_c - P_p \qquad \text{(3a)}$$

Extensional basin: $$\bar{\sigma}_{eff} = {}^{1}\!/_{3}\left(\sigma_V + 2\sigma_H\right) - P_p \;=\; {}^{1}\!/_{3}\left(\sigma_1 + 2P_c\right) - P_p \qquad \text{(3b)}$$

Contractional basin: $$\bar{\sigma}_{eff} = {}^{1}\!/_{3}\left(\sigma_H + 2\sigma_V\right) - P_p \;=\; {}^{1}\!/_{3}\left(\sigma_1 + 2P_c\right) - P_p \qquad \text{(3c)}$$

Here, $\bar{\sigma}_{eff}$ is effective mean stress, σ_V and σ_H are the overburden and horizontal stresses in the basin, P_p is interstitial fluid pressure, σ_1 is axial stress applied to our samples, and P_c is confining pressure used in our experiments. We define the difference (σ_V-P_p) as the effective vertical stress which we use to compare our results to deformation in natural sedimentary basins (Figure 2).

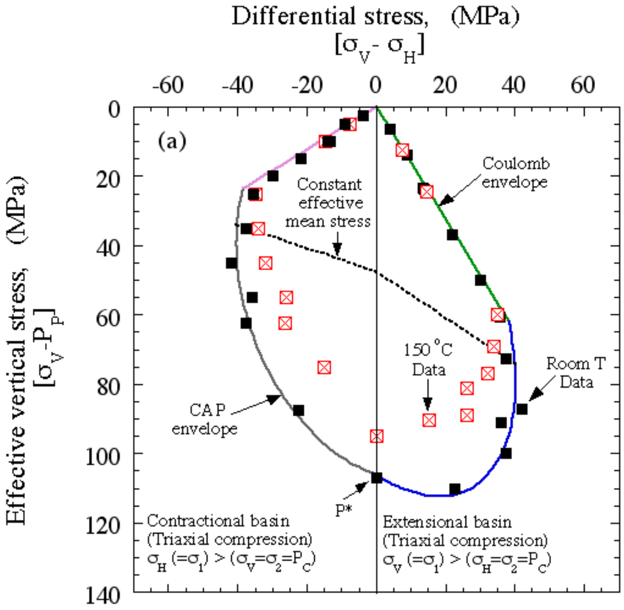


Figure 2: Macroscopic yield strength envelope for St Peter quartz sand cast in terms of vertical stress within sedimentary basins. We predict a skewing of the failure envelope towards shallower depths in contractional basins. Increased temperatures serve to shallow the non-linear (higher stress) portions of the failure curve. Within the failure envelope, porosity evolution may be predicted from a knowledge of mean stress.

Our data predict very different macroscopic strength characteristics for sands buried in extensional basins relative to contractional basins. Furthermore, our results show that elevated temperature significantly affects the load-bearing capacity of granular sands at depth within these basins. Microstructural observations from our experiments are in qualitative agreement with fracture density data obtained from laboratory creep-compaction experiments and observations from natural sandstones of the northern Gulf of Mexico basin that show greater damage with deeper burial. We use our results to investigate the contribution of mechanical deformation to fluid pressure evolution, with particular application to sedimentary systems that display zones of fluid overpressure. For a closed system, we find that mechanical compaction of sand with burial can raise pore pressures by as much as 50% above the fluid pressure hydrostat.