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Semi-brittle transient creep in Carrara marble: Hardening and Twinning-induced Plasticity

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Abundant observations of field- and micro-structures in marble rocks in both natural and laboratory settings indicate that these rocks have deformed by various combinations of mechanical twinning, dislocation motion, and dilatant fracturing. To better constrain the systematics of this semi-brittle flow, we performed a set of about 80 experiments at eight different temperatures (20°C<T<800°C). At each T, deformation conditions included different confining pressures ($50 < P_C < 300$ MPa) and strain rates ($10^{-6} < ε' < 10^{-4}\ s^{-1}$). Under almost all these conditions, both the strength (σ) and the hardening coefficient ($Θ=∂σ/∂ε$) are affected by changes in P_C and ε', but the functional relationships of $σ(P_C, ε')$ and $Θ(P_C, ε')$ are unique. For example, at 20°C, σ is a non-linear function of both P_C and ε', while Θ depends on P_C alone. In contrast, at 600°C, the dependence of σ on P_C is very weak, and Θ depends on ε' alone.

At T<650°C (less than half the absolute melting point of calcite), and P_C greater than 50 MPa, the hardening coefficients are substantial (1% or more of the shear modulus), similar to steels and hexagonal metals that deform in a regime called twinning induced plasticity (TWIP). During TWIP, deformation proceeds with "easy" mechanical twinning, combined with dislocation glide on several slip systems whose glide planes are at high angles to the twin plane. In the calcite rocks, depending on conditions, the hardening resulting from twinning may be reduced by dilation and failure owing to brittle processes (at low pressures and temperatures), or by recovery and recrystallization (at higher temperatures or slower strain rates). Thus, both microstructural observations and mechanical deformation data are consistent with the interpretation that the hardening coefficient and strength are determined by the relative partitioning of inelastic strain amongst mechanical twinning, dislocation mechanisms, and dilatant fracturing. One important aspect is the nature of the mechanism that accommodates of discontinuous inelastic strain at the termination of twins at grain boundaries.