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Brittle Creep of Tournemire Shale: Orientation, Temperature and Pressure Dependences

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Time and temperature dependent rock deformation has both scientific and socio-economic implications for natural hazards, the oil and gas industry and nuclear waste disposal. During the past decades, most studies on brittle creep have focused on igneous rocks and porous sedimentary rocks. To our knowledge, only few studies have been carried out on the brittle creep behavior of shale.

Here, we conducted a series of creep experiments on shale specimens coming from the French Institute for Nuclear Safety (IRSN) underground research laboratory located in Tournemire, France. Conventional tri-axial experiments were carried under two different temperatures (26˚C, 75˚C) and confining pressures (10 MPa, 80 MPa), for three orientations (σ_1 along, perpendicular and 45˚ to bedding). Following the methodology developed by Heap et al. [2008], differential stress was first increased to $\sim$ 60% of the short term peak strength (10^{-7}/s, Bonnelye et al. 2016), and then in steps of 5 to 10 MPa every 24 hours until brittle failure was achieved. In these long-term experiments (approximately 10 days), stress and strains were recorded continuously, while ultrasonic acoustic velocities were recorded every 1$\sim$15 minutes, enabling us to monitor the evolution of elastic wave speed anisotropy. Temporal evolution of anisotropy was illustrated by inverting acoustic velocities to Thomsen parameters. Finally, samples were investigated post-mortem using scanning electron microscopy.

Our results seem to contradict our traditional understanding of loading rate dependent brittle failure. Indeed, the brittle creep failure stress of our Tournemire shale samples was systematically observed $\sim$50% higher than its short-term peak strength, with larger final axial strain accumulated. At higher temperatures, the creep failure strength of our samples was slightly reduced and deformation was characterized with faster 'steady-state' creep axial strain rates at each steps, and larger final axial strain accumulated.

At each creep step, ultrasonic wave velocities first decreased, and then increased gradually. The magnitude of elastic wave velocity variations showed an important orientation and temperature dependence. Velocities measured perpendicular to bedding showed increased variation, variation that was enhanced at higher temperature and higher pressure. The case of complete elastic anisotropy reversal was even observed for sample deformed perpendicular to bedding, with a reduction amount of axial strain needed to reach anisotropy reversal at higher temperature.

Our data were indicative of competition between crack growth, sealing/healing, and possibly mineral rotation or anisotropic compaction during creep. SEM investigation confirmed evidence of time dependent pressure solution and crack sealing/healing. Our research not only has practical engineering consequence but, more importantly, can provide valuable insights into the underlying mechanisms of creep in complex media like shale. In particular, our study highlights that the short-term peak strength has little meaning in shale material, which can over-consolidate importantly by 'plastic' flow. In addition, we showed that elastic anisotropy can switch and even reverse over relatively short time periods (<10 days) and for relatively small amount of plastic deformation (<5%).