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Contradictions of slate formation resolved?

Slate is formed from clay-rich mud in response to tectonic stress. It has been studied for more than 150 years and was among the first geological features to be analysed on the microscopic scale[1]. Early observations[2] recognized the importance of micaceous minerals to the splitting of slate into thin sheets, whereas current hypotheses for slate formation emphasize either mechanical processes (grain rotation and grain kinking) or chemical processes (grain dissolution and new growth). Despite a vast body of work, no single scenario incorporates these seemingly contradictory mechanisms[3,4]. Here we offer a unifying model that views the mechanisms as a function of the combined thermal and strain energy of the system.

This model for slate cleavage has arisen from recent electron microscopy and X-ray work on slates from different, well constrained environments. The model focuses on the respective roles of phyllosilicates of depositional origin (detrital grains) and those formed during diagenesis and metamorphism (authigenic grains). Optical and scanning electron microscopy can be used to resolve detrital grains, which are about 10 micrometres in size, whereas transmission electron microscopy is needed for authigenic grains, which are about 10 nanometres. To measure the crystallographic orientation of all phyllosilicates in proportion to the volume of a particular population in a specific orientation, X-ray texture goniometry is used.

The Rhayader district of the Welsh basin in the United Kingdom preserves a sequence of progressively cleaved mudstones that range in metamorphic grade from diagenetic zone (zeolite facies) to epizone (lower greenschist facies) over a distance of about 10 kilometres[5]. In the lower-grade portion of the area, the detrital mica and chlorite progress from bedding-parallel to cleavage-parallel orientations[6]. Electron microscopy shows variably oriented authigenic mica (Fig. 1a). In higher-grade samples, detrital phyllosilicates remain parallel to bedding, whereas fine-grained, relatively strain-free, metamorphic phyllosilicates are parallel to cleavage (Fig. 1b). Transitional bedding-cleavage orientations are rarely observed.

In contrast, mudstones at Lehigh Gap, Pennsylvania, in the United States, show gradual cleavage development over a distance of about 100 metres in response to a local strain gradient under constant (anchizonal) metamorphic grade[7]. X-ray texture goniometry and electron microscopy show that mechanical rotation of detrital grains dominates cleavage formation in the low-strain region, whereas dissolution of primarily authigenic phyllosilicates and neocrystallization produced cleavage in the high-strain region[8,9].

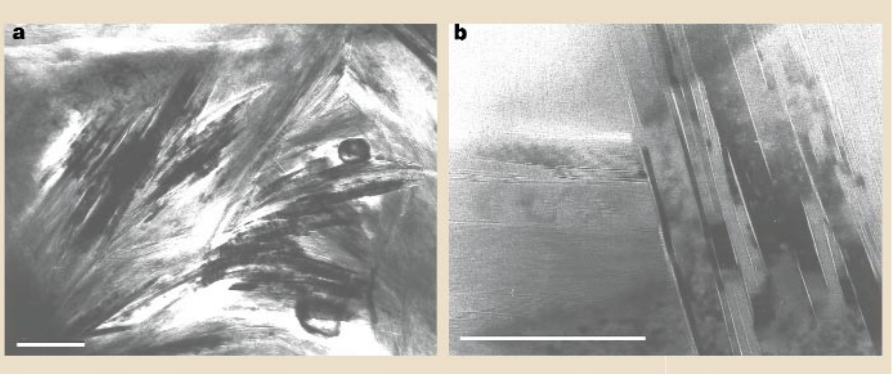

Figure 1 Transmission electron micrographs from Welsh basin rocks. **a,** Irregularly oriented and bent authigenic mica from low-anchizonal slates. **b,** Recrystallized, cleavage-parallel metamorphic mica from epizonal slates. Bedding in both images is horizontal, whereas cleavage is nearly vertical. Scale bar, 100 nm.

Grain deformation and rotation of detrital phyllosilicates dominate cleavage formation in the lowest-strain and lowest-grade rocks, from Lehigh Gap and Rhayader, respectively. But the higher-strain and higher-grade rocks of these areas show that dissolution and neocrystallization of fine-grained, authigenic phyllosilicates are primarily associated with cleavage formation. Evidence for mechanical deformation is either obliterated by subsequent neocrystallization in the high-strain samples of Lehigh Gap, or was developed only sporadically in the high-grade samples from Rhayader.

Despite distinctly contrasting environmental conditions, the two rock sequences show the same progression of deformation processes. In both the Rhayader samples that developed under a metamorphic/thermal gradient and the Lehigh Gap samples that developed under a strain gradient, we find a progressive change from dominantly mechanical processes in detrital grains to chemical processes in authigenic grains.

This indicates that the roles of thermal and strain energy are indistinguishable during cleavage formation. Also, assuming that the total energy defines the dominant deformation mechanism, the preference of mechanical processes in ‘low-grade’ and ‘low-strain’ regions indicates that mechanical work requires less energy than chemical work.

The mechanism that predominates in slate cleavage-forming is thus a function of the combined effects of thermal and strain energy in rocks. The contribution of either source to the total energy of the system is complementary and interchangeable. Mechanical processes (grain kinking and rotation) are favoured in relatively low-energy environments, whereas chemical processes (grain dissolution and neocrystallization) are favoured in relatively high-energy environments.

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