Development of slaty cleavage in a mudstone unit from the Cantabrian Mountains, northern Spain. R. J. Norris, Department of Geology, University of Otago, P.O. Box 56, Dunedin, New Zealand.

A 200 m thick mudstone unit in the Carboniferous of the Cantabrian Mountains, northern Spain, exhibits a progressive development of slaty cleavage. The increase in intensity of cleavage from top to bottom of the unit appears to be correlated with a decrease in mean grain size and an increase in proportion of matrix, leading to higher strains in the lower part. Large detrital muscovite and quartz grains have an original preferred orientation parallel to bedding.

Cleavage development occurs by the formation of spaced crenulations or strain bands, along which the detrital micas are rotated towards the cleavage. The cleavage is enhanced by pressure solution along the limbs of the crenulations, giving rise to anastomosing cleavage films within which the quartz grains become elongated. The development of the cleavage is further enhanced by growth of strongly oriented new micas within the cleavage films, which thereby increase in width. The new micas are mainly a paragonite–muscovite intergrowth and are quite distinct in composition from the large detrital micas. Pyrophyllite is also interpreted as a secondary metamorphic mineral. No clay minerals have been detected. It is suggested that metamorphism, under greenschist-facies conditions, of detrital kaolinite and illite/montmorillonite in the matrix gave rise to pyrophyllite and paragonite/muscovite, respectively. Rotation, recrystallization and enhanced growth during deformation led to the development of the mica fabric.

Bedding-parallel foliations: their nature and significance. G. Oertel, Department of Earth and Space Sciences, University of California, Los Angeles, California, 90024, U.S.A.

Like other foliations, those that are parallel to bedding are caused by the preferred orientation of grain shapes. To produce a significant effect, a large number of the rock-forming grains must have shapes far from equant. The most common grains with this property are phyllosilicates: the clays, micas and chlorites. Although bedding-parallel foliations can coincidentally be produced by tectonic deformation, their usual cause is the Earth's gravitational field, causing either a sedimentary fabric or compaction.

Detrital mica flakes with diameters of the order of a millimetre or larger tend to settle horizontally on the floor of the sea or another body of water if there are no strong currents. With bedding also horizontal, this produces a sedimentary foliation that parallels bedding. Large detrital mica grains are not rare, but they are much less common than clay-size phyllosilicate grains.

Mudstones and claystones that are tectonically undeformed also usually possess a bedding-parallel foliation. This fabric arises when the pore-water of a mud or clay is squeezed out of the sediment under the stress exerted on the grain framework by the weight of overlying, younger deposits. Fine clay or mica particles in uncompacted muds are almost always originally oriented at random. This is due either to flocculation of sedimentary particles suspended in the water column or to the passage of such particles through the digestive tracts of any of a number of planktonic or benthonic animals who mould them into faecal pellets.

The original distribution of phyllosilicate grains in the sediment is modified by the strain of compaction. The theory of homogeneous transformation explains the preferred orientation and provides a tool for the quantitative estimate of the strain, if the original orientation distribution is known or can be assumed. This is significant for the understanding of diagenetic processes and also forms the basis for factoring the compound deformation due to a tectonic strain superposed on an early compaction and causing the phenomenon of slaty cleavage.

Experimental deformation of quartz in a controlled metamorphic environment. A. Ord and B. E. Hobbs, Department of Earth Sciences, Monash University, Clayton, Victoria, Australia, 3168.

The aim of this paper is to demonstrate the dependence of the flow strength of quartz upon its chemical environment during deformation.

New experiments have been designed to test the recent development in theories which relate the flow strength of minerals to their defect chemistry. The experiments are based on traditional buffer techniques, and result in the thermodynamic activities of various chemical species being controlled during experimental deformation. This control was lacking in the early hydrolytic-weakening experiments where the source of water was dehydrating talc, and other chemical species, in particular carbon, were present, all in uncontrolled proportions.

The most recent experiments have been conducted on quartz specimens encapsulated in silver. The oxygen fugacity in this enclosed environment was controlled by the presence of chemical buffers plus water. These are, in order of decreasing oxygen fugacity (fO_2), Mn_3O_4–Mn_2O_3, Cu–Cu_2O, Ni–NiO, Mo–MoO_2 and Ta–Ta_2O_5. The middle three provide geologically relevant values for fO_2. The strength of natural single crystals of Victorian quartz deformed normal to $\{10\bar{1}0\}$, under these chemical conditions, at 1500 MPa confining pressure, 800°C, and 10^{-5} s^{-1}, after a heat treatment of 20 hours at this T and P, decreases from about 1500 MPa to 200 MPa with increasing fO_2.

Recrystallization is well developed in the specimens with low strength whereas deformation lamellae are common in the high-strength specimens. The water content of both deformed and undeformed crystals has been measured by infra-red spectroscopy.

This increased control and knowledge of chemical environment during deformation is vital to understanding the strength of rocks in geologically different terrains.

Multiple deformation of the Rischbieth megabreccial thrust complex, Willouran Ranges, South Australia. A. J. Parker, South Australian Department of Mines and Energy, P.O. Box 151, Eastwood, South Australia, 5063.

In the central Flinders Ranges and Willouran Ranges disrupted Adelaidean sediments occur in a number of tectonic structures variously described as thrust complexes, diapirs, syn-sedimentary slump breccias, and tectonic décollements. One such structure occurs at Rischbieth Well in the Willouran Ranges. Within the Rischbieth structure, intense folding and brecciation of the early Adelaidean Callanna Group has deformed it into a barely recognizable sequence of quartzites, sandy dolomites, slates and, locally, albitic monzonite–syenite–diorite plugs. The marked contrast in structural complexity between the Callanna Group and the overlying Burra Group suggests either mega-slumping within the Callanna Group, early folding preceding deposition of the Burra Group, or disharmonic folding in the cores of anticlinoria. Also, apparent thinning of Burra sediments along the margins of the Rischbieth structure can be largely attributed to stratigraphic thinning, suggesting that the Rischbieth structure was an emergent horst uplifted and deeply eroded prior to or during Burra Group deposition. Folds in the Burra Group can be traced into the core of the Rischbieth structure and overprint early formed, very tight to isoclinal folds associated with thrusts. Therefore, it is suggested that a period of folding and thrusting occurred prior to or early during deposition of the Burra Group. The early formed isoclinal folds and thrusts are analogous to steep thrust structures in the Willyama Block and suggest a W-directed thrusting leading to shallow onlap of Burra sediments from the east but deeper, more active sedimentation in front of the thrusts to the west.

Structural analysis of the Upper Ordovician turbidites near Bermagui, New South Wales. C. McA. Powell, School of Earth Sciences, Macquarie University, North Ryde, New South Wales, Australia, 2113.

Three phases of mesoscopic folding can be demonstrated by refolding relationships and overprinting of cleavages in deformed Upper Ordovician psammites and pelites near Bermagui on the south coast of New South Wales. F_1 folds are tight to isoclinal, and commonly have a differentiated axial-surface crenulation cleavage. Where not affected by F_2, F_1 is upright, or inclined steeply, facing westward. F_1 axes are generally subhorizontal and occur in domains in which orientation is constant for kilometres along axial trend. These domains, which are separated by narrow zones where the axial orientation changes, define a regionally meridional F_1 trend, even though individual F_1 domains vary in axial trend from 090 to 340°. F_1 deforms a penetrative bedding-parallel foliation defined by aligned phyllosilicates and elongate quartz grains with syntaxial overgrowths.

F_1 are open to locally tight, upright folds with a domainal axial-surface crenulation cleavage. They are nearly coaxial with F_1, commonly trending 10–15° counterclockwise from local F_1 trends. F_2 folded F_1 to recumbent and, locally, downward-facing attitudes. F_3 folds are broad to locally close, commonly kink-like, with vertical axial surfaces commonly trending SSE. F_3 fold hinges range from horizontal to vertical depending on the pre-existing attitude of the surfaces they fold. An axial-surface crenulation cleavage, S_3, occurs in two directions making an angle 55 ± 5° either side of the local F_1 trends. The conjugate F_3 folds have sinistral and dextral symmetry consistent with shortening along the F_1 axial trend.

These structures can be related to the five regional deformations recognized on the New South Wales south coast. Deformation 1 (pre-Late Silurian) formed the bedding-parallel foliation, possibly by large-scale horizontal transport or by imbricate stacking in an accretionary prism, or possibly as an early phase of cleavage formation during F_1 folding. Deformation 2 (Siluro-Devonian) formed the upright F_1 folds. Deformation 3 (Medial Devonian) produced major NE-trending dextral transcurrent faults, but no mesoscopic folds at Bermagui. Deformation 4 (Early Carboniferous) formed the F_2 folds at Bermagui in domains hundreds of metres wide. Deformation 5 (mid-Carboniferous) formed first the outcrop-scale F_3 folds, cleavages and kink folds, and later rotated all the pre-existing structures (including F_3) into the present megakink domains.

Structural map of the Bermagui region.

C. McA. Powell, P. J. Conaghan, J. Cole and D. Sims, School of Earth Sciences, Macquarie University, North Ryde, New South Wales, Australia, 2113.

Mapping at 1:25,000, with more detail in areas of critical exposure, has enabled definition of the structural and stratigraphic framework of the Bermagui region and its hinterland. Three Palaeozoic sedimentary successions are present: (1) a coastal zone of turbiditic sublitharenite and slate, (2) an inland zone of indurated quartzarenite, pelite and chert and (3) a thin succession of quartzarenite to sublitharenite, with associated red siltstones and shales and minor conglomerates and gritstones. Late Ordovician graptolites have been found in succession (2) and, although no fossils have been found in succession (1), regional stratigraphic relationships indicate that the coastal turbidites conformably overly the inland succession, and thus are of Late Ordovician or earliest Silurian age. Succession (3) contains Late Devonian fossils, and overlies the other two successions with great angular unconformity.

The coastal turbidite succession has been deformed by three phases of mesoscopic folds, and is characterized by a distinctive differentiated crenulation cleavage that becomes more closely spaced and highly differentiated inland. The contact between successions (1) and (2) is the right-lateral transcurrent Tantawangalo Fault, on which 16 km of Middle Devonian offset can be demonstrated. The Upper Devonian red-bed succession, (3), is known elsewhere to overlie paraconformably the late Middle or early Late Devonian Boyd Volcanic Complex, which is represented in the Bermagui region by silicic and mafic dykes, and the *A*-type Mumbulla Granite.

Structural and stratigraphic relationships in the region permit the following geological history to be determined.

Ma		
~90	Cretaceous	intrusion of alkaline Dromedary Complex
<290	post Carboniferous	basement to platform covers
~330	mid-Carboniferous	N–S compression producing megakinks and related structures (F_3)
~350	Early Carboniferous	second phase of regional meridional folding (F_2); upright folds refold F_1 folds
~370 to 360	Late Devonian	deposition of the red-bed Merrimbula Group
~370	Late Middle to early Late Devonian	formation of the Boyd Volcanic Complex in a continental rift; intrusion of *A*-type Mumbulla Granite
~375	Middle Devonian	wrench faulting caused by E–W compression
~390 ± 10	Early Devonian	intrusion of the *I*-type Bega Batholith
~410	Siluro-Devonian	first major meridional folding (F_1); upright folds
≤450	Late Ordovician	deposition of successions (1) and (2), possibly with imbricate stacking in an accretionary prism

Experimental deformation of quartz mylonites.

S. Ralser and B. E. Hobbs, Department of Earth Sciences, Monash University, Clayton, Victoria, Australia, 3168.

Quartz mylonites with the foliation and lineation initially at 45° to the loading direction, σ_1, have been shortened 40–50% with water in thick nickel jackets at 1500 MPa confining pressures, temperatures in the range 700–800°C and at strain-rates of 10^{-5} s^{-1} and 10^{-6} s^{-1}.

At 700°C, 10^{-6} s^{-1} strain-rate and 50% strain there is a marked change in both microstructure and crystallographic preferred orientation. Two foliations develop, the first perpendicular to σ_1, is delineated by elongate grains and is crenulated by a second foliation subparallel to the initial mylonitic foliation.

Towards the more highly strained central zone, grains become elongate and ribbonlike, with increasing misorientation of subgrains, especially in the tails of grains. Minor recrystallization and comparatively undeformed equant augen occur in this zone.

No remnant of the original asymmetric *c*-axis girdle can be seen in the strained areas. Two maxima occur in the new fabric, one generally normal to σ_1; the other, dependent on measurement location, is variable but is commonly near the σ_1 axis. The latter maximum is commonly delineated by the elongate grains. Widespread occurrence of sub-basal lamellae suggests that basal slip is important in this specimen; this is consistent with the low temperature of plastic deformation.

In contrast, at 800°C, 10^{-5} s^{-1} and 40% strain no pronounced elongation of grains occurs and deformation is concentrated in a zone subparallel to the original foliation. Conjugate with this and symmetrical about the σ_1 axis, strong kinking occurs, subgrains become misoriented and minor recrystallization occurs. The initial fabric pattern is not markedly changed.

The development of high-grade tectonothermal fabrics and mylonites associated with complex ductile deformations in metamorphic basement and cover rocks from the Harts Range, Central Australia.

L. R. Rankin and P. R. James, Department of Geology and Mineralogy, The University of Adelaide, Adelaide, South Australia, Australia, 5000.

The Proterozoic Arunta Complex within the Oonagalabi Tongue area in the Harts Range includes the Irindina supracrustal assemblage and Harts Range metaigneous complex as a cover sequence, and its basement, the Oonagalabi gneiss complex.

An early fabric formed before several phases of coaxial isoclinal folding shows variation in deformational intensity, with the formation of high-grade interlayered gneisses, amphibolites and layer-parallel mylonites in the basement. The cover sequence has undergone variable high-grade fabric development prior to at least two generations of folding.

Thrusting along the basement/cover contact has resulted in the formation of a second generation of mylonite in the basement. A megacrystic granitoid was locally intruded along this thrust, and into the overlying Irindina supracrustals and an intense *LS* protomylonitic fabric was developed within the granitoid by movements along its upper and lower surfaces.

Microfabric analysis within the basement indicates the development of a fabric varying from a granoblastic inequigranular tectonite to an anastomosing mylonite at upper amphibolite to granulite facies during early ductile deformation, with modification and attenuation of the fabric during subsequent coaxial folding. The cover sequence contains a pervasive granoblastic elongate fabric with only the granitic gneiss showing the development of an anastomosing mylonitic fabric.

The analysis of magnetic susceptibility anisotropy shows a bimodal distribution of both orientations and susceptibility ellipsoid shapes for the basement lithologies. Specimens with granoblastic fabrics show low-intensity triaxial ellipsoids and a lack of correlation to tectonic directions due to post-peak deformation randomization of crystallographic orientations. Mylonitic specimens have retained intense crystallographic preferred orientations, represented by higher-intensity triaxial ellipsoids, close correlation of magnetic and tectonic directions and oblate to plane-strain fabrics.