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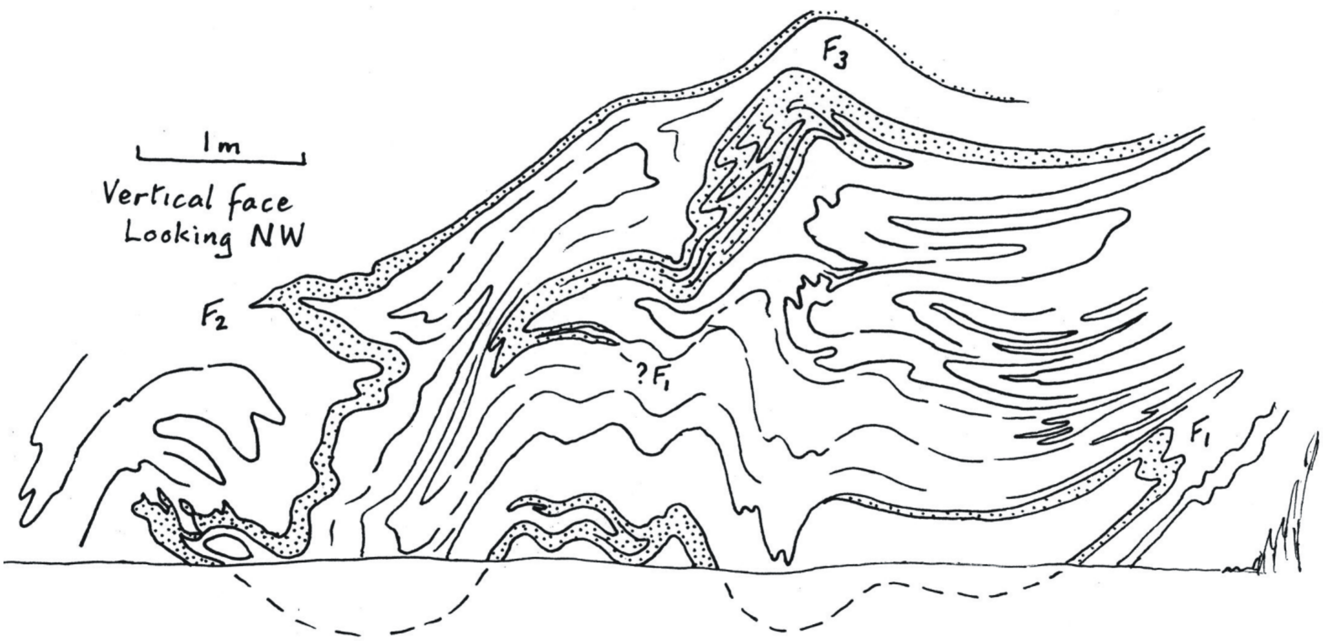

Evolution of Structures in Deforming Rocks

26-28 September 1998   Canmore, Alberta, Canada

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Shoufa Lin, Manitoba Energy and Mines, Thompson, Manitoba, Canada
Wouter Bleeker, Geological Survey of Canada, Ottawa, Ontario, Canada
Colleen Elliott, Montana Tech, Butte, Montana, U.S.A.
Cees R. van Staal, Geological Survey of Canada, Ottawa, Ontario, Canada

Kinematic and folding history of the mid- to deep-crustal levels of an arc; Swakane terrane, north Cascades, Washington

H. ALSLEBEN, R.B. MILLER
Dept. of Geology, San Jose State Univ., San Jose, CA, 95192-0102 (e-mail, helgeusa@hotmail.com)
and S.R. PATERSON
Dept. Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740

Much recent debate on the structural evolution of the Cascades crystalline core, the roots of a Cretaceous and Paleogene arc, has focused on the kinematic significance of widespread subhorizontal mineral lineations. Competing models suggest that the Cascades core represents either a broad NW-SE-striking, dextral shear zone or a SW-directed contractional system of folds and ductile thrusts associated with orogen parallel stretching.

We have examined this problem by carrying out detailed structural analysis of parts of the Swakane terrane, which records peak metamorphic conditions of 650-700EC and 10-12 kbar (Sawyko, 1994) and represents the deepest exposed level (~25 to >35 km) in the southern part of the Cascaces core. This terrane consists mostly of biotite gneiss and is intruded by numerous meter-scale pegmatitic sheets. The Swakane is the most lithologically homogeneous unit in the Cascades core, but subtle compositional layering defined by differences in quartz-mica-ratios occurs on a scale ranging from a few centimeters to several meters. Strong transposition foliation (S_T) in the gneisses generally strikes NW-SE and dips gently NE or SW. Mineral lineation is very uniformly oriented, plunging gently S to SSE (average ~8,175). A minimum of two cycles of folding is recognized in most domains. Early recumbent to gently inclined, tight mesoscopic folds deform compositional layering and a parallel transposition foliation. The pegmatite sheets also locally define recumbent folds, but more commonly are boudinaged in S_T. The shallowly plunging axes show a S to SW-trending maximum that is at a clockwise angle of 15^0 to 25^0 to the mineral lineation. These structures are refolded by regional and local outcrop-scale, open, upright folds, which plunge gently NW.

S_T is cut by widespread biotite-defined extensional crenulation cleavage. Throughout the Swakane terrane these shear bands and local asymmetric porphyroclasts and boudins consistently record “top-to-the-north” non-coaxial shear in lineation-parallel surfaces. For example, in one 2 km^2 domain, N-directed shear was recorded in ~60 out of 235 stations. Despite the small modal differences in mineralogy, the non-coaxial shear appears to be partitioned into more micaceous layers. Shearing predates the upright folds, which fold the extensional crenulation cleavage and mineral lineation, but postdates the recumbent structures. Consistent top-to-north shear indicators occur on both limbs of the latter folds, whereas evidence for earlier flexural slip is only preserved in hinge zones.

North-vergent shear is associated with movement on a detachment zone that marks the contact with the overlying Napeequa unit. Evidence for this detachment includes the markedly better development of folds in the Napeequa and the pronounced differences in intrusive rocks across the contact. The widespread N-vergent shear on nearly flat surfaces does not fit simply with either of the current models for the Cascades core. It implies that the deepest levels of this arc flowed differently than higher levels and we speculate that the N-directed shear records complex flow partitioning within an overall contractional system.

Brittle fracture patterns and reactivation in basement and cover rock sequences

L.E. BEACOM, T.B. ANDERSON
Department of Geology, School of Geosciences, Queen's University of Belfast, BT7 1NN, Northern Ireland.
and R.E. HOLDSWORTH
Reactivation Research Group, Department of Geological Sciences, University of Durham, DH1 3LE, England.

In continental basement terrains, complex overprinting histories of brittle fracturing form in brittle-ductile shear zones during the later stages of progressive exhumation. It is generally agreed that reactivation of these structures significantly influences fault zone characteristics within basement and overlying cover sequences.

This study presents a quantitative and qualitative assessment of the nature and distribution of fracture arrays in high grade basement rocks and in the overlying sediments. Examples are taken from the Late Archaean to Proterozoic Lewisian basement Complex in NW Scotland and the unconformably overlying Late Proterozoic and Early Palaeozoic sediments.

Fracture populations are classified by orientation, relative age, movement sense and direction, fault rock infill, spacing, length, width, connectivity and fractal statistics. The textural evolution and deformation mechanisms define the rheological controls on fracture development and provide a means to access the potential for reactivation of basement fault zones into the overlying sediments.

The fracture evolution pathways described for basement rocks illustrate the influence of pre-existing structures and fluid activity on fault zone development. In the deep brittle regime (>10km), rock-dominated processes produce pseudotachylyte and cataclasitic fault rocks which are controlled by pre-existing ductile foliation and lithology. Syn-tectonic fluid activity in these fault zones has led to reaction weakening and the development of phyllonitic fault rocks which overprint the products of earlier brittle deformation. This occurred in the vicinity of the main load bearing region in the crust. At shallower crustal depths, hydrofracture meshes localise around major faults and produce incohesive breccias, gouges and veining. These fractures locally reactivate basement anisotropies but largely ignore many of the pre-existing structures.

These findings suggest that significant reactivation of brittle structures only occurs in fault zones which have experienced long-term weakening. The fracture population characteristics within basement fault zones are used to classify reactivated and non-reactivated structures. Many of the large scale fracture attributes associated with the basement fault arrays are transferred into the fault zones in the overlying sediments. This allows the fracture characteristics in the sediments to be used to determine if basement structures are reactivated. The limitations of this approach can be seen at small scales, generally less than tens of metres, when bedding and lithological heterogeneities in the sediments act as the main controls influencing the fracture development.

Basement control on transverse faulting and along-strike termination of Paleozoic culminations in the Cordilleran thrust-and-fold belt, Alberta

Normand J. BEGIN
Talisman Energy Inc., 855, 2nd St. S.W., Calgary, Alberta, T2P 4J9
Deborah A. SPRATT and Don C. LAWTON
Dept. of Geology and Geophysics, University of Calgary, Calgary, Alberta, T2N 1N4

In the southern Alberta Cordilleran thrust-and-fold belt, Mississippian- and Devonian-age continental platform carbonates are exposed at surface in the cores of structural culminations, surrounded by siliciclastic rocks of the Laramide orogenic foreland basin. Examples of these are the Moose Mountain (MMC), Panther River (PRC), Marble Mountain and Limestone Mountain (LMC) culminations. Each of these exhibit distinct regional map pattern similarities, with a doubly-plunging geometry, parallel to the dominant NW-SE structural trend of the Foothills belt. The culminations are juxtaposed against open synclinoria that contain Cretaceous and Tertiary rocks (e.g. Williams Creek Syncline, WCS, near the LMC). Folded thrusts are common between the culminations and the synclinoria. The subsurface structural relationships and variation in deformation styles between the LMC and the WCS are based on a crosscutting network of 120 line-km of seismic reflection data.

The overall 3-D structural geometry of the LMC and WCS (~100 km NW of Calgary) is dominated by two major lithotectonic packages. The lower package defines the LMC and is represented by a southerly-plunging antiformally stacked duplex of up to four thrust-bounded sheets of Paleozoic carbonates. The southern plunge in the LMC is also documented by a northerly increase in the time-structure pull-up on the autochthonous Cambrian marker, up to 600 msec. The LMC has been built up beneath the upper package that consists of the east-verging thrust-and-fold belt of Mesozoic rocks. The relationship between the two packages shows that the Brazeau thrust sheet has been wedged underneath the Foothills belt. Stacking of carbonate thrust sheets in the LMC is responsible for delaminating the belt from the underlying autochthonous Paleozoic platform, tilting the imbricates toward the foreland, and cross-folding the WCS.

Along the NW trend of the Foothills, the LMC loses most of its structural relief within less than 2 km, as a result of a NE-striking transverse fault. Interpretation of two seismic strike lines, located on either side of the surface trace of the BT Thrust, suggests a complex evolution in the transverse fault, along its NE orientation. West of the BT Thrust, the hangingwall section in the Brazeau sheet is reduced southward as a result of a lateral ramp in the Brazeau Thrust, which cuts from the Cambrian to the Jurassic levels. East of the BT Thrust, the Paleozoic section in the Brazeau sheet ends abruptly to the south, against a steeply-dipping interface with a geometry similar to that of a strike-slip (tear) fault. The strike-slip fault merges downward with the Brazeau Thrust and connects with the passive roof thrust of the LMC, upon insertion structurally below the Mesozoic thickened sequence. Based on the current seismic interpretation, the surface geology and the well data, the proposed model for the structural evolution between the LMC and the WCS is as follows:
1- early thrust-and-fold belt development, thickening the Mesozoic siliciclastic succession;
2- south-plunging antiformal duplex of Paleozoic carbonate sheets, to form the LMC;
3- delamination of the deformed belt from the underlying continental platform (eastward tilt of the foreland imbricates), with cross-folding of the WCS;
4- southern termination of the Brazeau thrust sheet and the LMC as a result of a transverse fault;
5- transverse fault would evolve from a lateral ramp (dipping about 25E to the NW) in the southwest, to a strike-slip/tear fault in the northeast.

Overall, the transverse fault represents a dextral-offset link between the PRC and the LMC, across the Foothills Belt. A similar faulting mechanism may explain the along-strike termination of other Paleozoic culminations, such as at Moose Mountain. The NE trends of major transverse faults suggests that they may have been inherited from dominant Precambrian structures in the basement and reactivated during the Laramide Orogeny.

Archean tectonics: a re-investigation of one of the classic basement/cover high-strain zones in the Archean record

WOUTER BLEEKER and THE SLAVE WORKING GROUP
Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8 Canada
wbleeker@gsc.nrcan.gc.ca

The exact nature of geodynamic processes in the Archean Earth remains controversial. Did plate tectonics, analogous to that shaping the later Earth, operate in the Archean, perhaps in a context of smaller and faster moving plates or microplates driven by higher overall heatflow? Or were rigid plates not yet in existence, resulting in a fundamentally different style of interaction between lithosphere and mantle dominated by vertical rather than horizontal movements? Ultimately, the key to this important question lies in the complex geology of preserved Archean cratons. The Slave craton of the Canadian Shield holds particular promise in resolving this issue since it is well exposed and preserves an extensive rock record ranging from cryptic, >4.0 Ga metagabbros and tonalites, and a variety of younger Mesoarchean gneisses and supracrustal rocks, to voluminous 2.7-2.6 Ga supracrustal rocks and associated granitoids.

The main tectonostratigraphic framework of the Slave craton consists of a centrally situated Mesoarchean terrane, the Central Slave Basement Complex, that is surrounded by Neoarchean supracrustal domains. The detailed outline of the Mesoarchean basement terrane is becoming increasingly well-defined and is represented almost everywhere by significant high-strain zones. Hence, the important question of Archean tectonic evolution hinges to a large extent on a correct interpretation of these high-strain zones, and analogous high-strain zones in other Archean cratons.

Recent work in the Slave craton has shown that the basement/cover high-strain zones represent a single structure that can be correlated over strike-lengths of 100s of kilometers with all the characteristics of a basal décollement that accommodated thrusting of autochthonous to parautochthonous cover units over older basement. Development of the high-strain zone, constrained to about 2690 Ma or possibly slightly earlier, post-dated the apparent break-up of a Mesoarchean continental nucleus, but predated three phases of important regional folding. Unfolding of this high-strain zone suggests that it represents a regional thrust with northeast-to-southwest tectonic transport. This important regional structure clearly favours a scenario with significant horizontal tectonics and rigid plate-like behaviour. Development of the regional thrust predated calc-alkaline volcanism and the deposition of a widespread, ca. 2660-2680 Ma turbidite sequence. The turbidite sequence essentially represents an overlap sequence and, therefore, arguments that its structural style is inconsistent with an accretionary prism has no bearing on the interpretation of the older décollement.

The entire greenstone belt stratigraphy is deformed by three post-turbidite fold systems (F1, F2, F3) and major strike-slip faults. Although abundant granitoid plutons locally cause complex structural patterns, the fold systems can be mapped and correlated as regional fold belts on scales approaching the dimensions of the craton, independent of the more random distribution, size and shape of granitoid plutons. F1 deformation, which produced a northeast-trending fold belt of upright chevron folds, occurred prior to significant granitoid plutonism. In contrast, F2 refolding, interpreted as a craton-wide transpressive event, was accompanied by voluminous granitoid magmatism. However, most granitoid plutons are deformed or folded by F2 and evidently took part in the regional deformation. Granitoid emplacement appears to have been facilitated by F2 rather than being the cause of the regional deformation. Finally, late-stage strike-slip faults developed after the peak of granitoid emplacement.

In conclusion, the structural record of the Slave craton suggests a number of discrete shortening events driven by horizontal rather than vertical tectonics. The coherent structural patterns on the scale of the craton suggest that horizontal shortening was driven by plate-size entities that behaved rigidly and analogous to modern (micro) plates.

Common Elements in the Evolution of Regional Shear Zones in the Piedmont of the Southern Appalachian Mountains

Andy R. BOBYARCHICK
Department of Geography and Earth Sciences, University of North Carolina at Charlotte, Charlotte, NC 28223 USA (arbobyar@email.uncc.edu; http://anb-mac.uncc.edu)

The Piedmont province of the southern Appalachian Mountains is a wide crystalline complex composed of native Laurentian and accreted terranes. The Piedmont was assembled and deformed by multiple orogenies throughout the Paleozoic, and extended during the Mesozoic rift phase of the Atlantic Ocean. Major ductile shear zones parallel to the orogen divide the Piedmont into several tectonic zones. Some of the shear zones are coincident with sutures, but others are not. The Piedmont shear zones share some common features. They have polyphase deformation histories that include an early period of pervasive shear and later phases of discrete shear in ductile deformation zones. The youngest ductile event is late in the Alleghanian orogeny (Permian), and is an orogen-parallel dextral transpression. Cataclastic fabrics are superposed in all shear zones; some are related to Mesozoic extension but others represent a terminal contractional event in the Alleghanian orogeny. It is clear that the shear zones have acted as strain localizers throughout their histories.

The foliation in the shear zones is a mylonite foliation that is variable in intensity and appearance because of the range in rock types involved. The most distinctive rocks are "button schists", which are the products of superimposed deformations, transposition, and shear band formation. Button schist is similar to Type II S-C mylonites. The mylonite foliation (MF) is a transposition schistosity axial planar to at least one generation of isoclinal folds of an earlier layering and/or foliation. Microfolds in button schist are uniformly isoclinal or tight, and some of these folds appear to have been refolded. The MF pre-dates shear bands. The "buttons" in button schist are phacoidal relicts of layer transposition, disarticulation, and crenulation during the formation of the MF and shear bands. Most white mica buttons are the isolated closures of isoclinal folds.

Oblique shear bands and sub-horizontal stretching lineations indicate dextral strike-slip in the Piedmont shear zones. For sub-simple shear in a moderately dipping shear zone undergoing oblique compression, asymmetric structures (shear sense indicators) estimate movement sense and direction only for the rotational component of flow. Furthermore, the extensive development of shear bands in less competent layers suggests deformation partitioning that could produce structures characteristic of local strain only. For example, asymmetric boudinage of button schist occurs throughout the fault zone. Ductile faults in the schist either root into gneiss-schist layer contacts or terminate in dispersed cleavage in the gneiss. In effect, weak internal layers in the shear zones created regions of concentrated shear in which certain structures, such as shear bands, form preferentially. These kinds of relations are predicted from general shear in which the layer boundaries are oblique to maximum strain rate.

S-L tectonites in the Piedmont shear zones are the cumulative products of concentrated deformation in which the structural style progressed from pervasive to discrete, in accord with metamorphic conditions. The latest mainly ductile event indicates that the Piedmont was a dextral transpressional belt at least 600 km long and 100 km wide during the Alleghanian orogeny. Interestingly, regional mapping across some of the shear zones does not show major lateral displacement of adjacent terranes at the time.

The application of tension gashes to delineate the position of thrusts in the Cape Fold Belt, South Africa

P.E. BRÖNN, J.M. VAN BEVER DONKER, and P.J.E. SCHLOTFELDT
Earth Science Department, University of the Western Cape, Private Bag Xl7, Bellville, 7530, South Africa.

The Cape Fold Belt is an example of a multiple inversion belt. De Wit (1992) describes the history as deposition in a basin, created during collision along the southern margin of the Karroo basin towards the end of the Permian. This was followed by Permo Triassic orogenesis, causing the formation of the Cape Fold and Thrust Belt. Shortly after this compressional phase the breakup of Gondwana followed, yielding extensional conditions and the formation of Jurassic-Cretaceous limnic basins

The Kango Group of rocks belonging to the Neoproterozoic Saldania Belt in southern Africa is preserved in one of these basins. Le Roux (1977) and Le Roux & Gresse (1983) divided the Kango Group into the Goegamma and Kansa Subgroups separated by a major unconformity. The Kansa Subgroup is composed of grits, conglomerates and sandstones whereas the Goegamma Subgroup comprises alternating limestones, shales, greywackes and sandstones.

The structures described in this paper are situated in the Goegamma Subgroup.

The Kango Group has a mapped thickness of 10 400 m. These rocks are covered by sedimentary overburden of approximately 9 020 m (Tankard et al.1982), yielding a total sediment thickness of ±19 420 m. Considering a geothermal gradient of approximately 15°C/Km for an active mobile belt, projected metamorphic conditions are higher than the Greenschist Facies conditions described by Le Roux (1977) for the Kango Group.

A contact between grits and limestones in the Matjies River Formation of the Goegamma Subgroup, mapped by Le Roux (1977) as a lithological contact, is markedly associated with tension gashes. Stress regimes calculated from conjugate sets of these tension gashes indicate near horizontal compression. Considering also the stratigraphic position of both grits and limestones, this contact is interpreted as a thrusted contact. Thrusts elsewhere in the Neoproterozoic Saldania Belt are likewise associated with fault gouge, breccias and tension gashes (Gresse et al. 1992).

A plausible explanation for the discrepancy between the mapped sediment thicknesses and the described metamorphic conditions, is thought to be the result of a process of mechanical thickening through thrusting.

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Feedback relations between deformation and melting: testing implications for granite ascent and emplacement in convergent orogenic belts

Michael BROWN and Gary S. SOLAR
Laboratory for Crustal Petrology, Department of Geology, University of Maryland, College Park, MD 20742, USA (mbrown/solar@geol.umd.edu)

The common spatial relationship in convergent orogenic belts between a crustal-scale shear-zone system, high-grade metamorphic rocks, and granites suggests a feedback relation between melting and deformation that helps granite extraction and focusses granite ascent. During contractional deformation, flow of melt in crustal materials at depths below the brittle-plastic transition is coupled with plastic strain of these materials. The flow is driven by pressure gradients generated by buoyancy forces and tectonic stresses. Taking the oblique-reverse Central Maine Belt shear-zone system as an example, stromatic migmatite and concordant to weakly discordant irregular granite sheets occur in zones of enhanced deformation that we interpret to record higher strain. These features suggest percolative flow of melt to form the migmatite leucosomes and viscous flow of melt channeled in sheet-like bodies, possibly along fractures. Cyclic fluctuations of melt pressure may cause instantaneous changes in the effective permeability of the flow network if self-propagating melt-filled tensile and/or dilatant shear fractures are produced due to melt-enhanced embrittlement. Pulsed flow of individual melt batches is the result. Inhomogeneous migmatite and schlieric granite occur in intervening zones of relatively lower strain, which suggests migration of partially-molten material through these zones both en masse by granular flow and in batches by pulsed flow of melt carrying entrained residue. Ascent of melt becomes inhibited with decreasing depth as the solidus is approached. This occurs near the brittle-plastic transition during high-*T* — low-*P* metamorphism, where the balance of forces favors (sub-) horizontal fracture propagation. Emplacement of melt may be accommodated by plastic yield and/or stoping of wall rock, and inflation may be accommodated by lifting of the roof at shallower crustal levels and/or sinking of the pluton floor. The resultant plutons have (sub-) horizontal tabular geometries with floors that slope down to the ascent conduit. Granite stuck in the ascent conduit is likely to have sheeted architecture. This feedback relation requires that deformation, metamorphism, and plutonism were synchronous. If melt extraction and transport is by pulsed flow in channels, and plutons form by aggregation of multiple melt batches, we may expect similar crystallization ages among melt batches, but batch-specific chemical compositions that reflect primarily source processes may be preserved. Geochemical heterogeneity or its erasure by homogenization among successive melt batches will depend on many factors, including the interplay between rates of ascent and solidification. At the extremes, sheeted architecture may develop if an individual batch of melt crystallizes before the arrival of a subsequent batch of melt, potentially preserving heterogeneity, whereas successive arrivals of melt batches before extensive crystallization can occur is conducive to mingling and mixing, potentially leading to homogenization. In the Central Maine belt case study, precise U-Pb zircon/monazite crystallization ages of schlieric granite in migmatites, granite in sheets and in kilometric plutons are in the range *c*. 410-404 Ma, within 2 Ma at 2σ, and in one granite, the Phillips pluton, multiple samples of leucogranite and grey granite yield synchronous ages. Thus, in spatially restricted segments of orogenic belts, regionally-significant crustal melting in nature occurs within short timescales ($<10^7$a), and melt extraction and transport are fast processes ($<10^6$a). Within the hemiellipsoidal Phillips pluton, magmatic fabrics (planar biotite-rich schlieren, and modal and grain-size layering) occur locally and are oriented conformably with the northeast-striking, sub-vertical foliation in the surrounding metasedimentary rocks. The Phillips pluton may represent the ascent conduit for a large tabular pluton now lost to erosion. Granites of the Phillips pluton show heterogeneity in Nd isotope compositions (grey granite ε_{Nd} (404 Ma) of +0.1 - !1.8; leucogranite ε_{Nd} (404 Ma) of !5.3 - !8.0), which we interpret to reflect derivation from two isotopically-distinct sources, to preserve within-source heterogeneity and to imply efficient extraction and ascent. These data support the feedback model of pulsed melt flow through a crustal-scale shear-zone system.

Tectonic evolution of the hinterland of the southeastern Canadian Cordillera

Richard L. BROWN
Department of Earth Sciences, Carleton University and Ottawa-Carleton Geoscience Centre, Ottawa, Ontario, K1S 5B6, Canada

High structural levels of the Omineca Belt in the southeastern Canadian Cordillera record a Jurassic history of terrane accretion and deformation; at deeper levels the deformation becomes progressively younger and, in the deepest exposures, ductile fabrics did not develop until Paleocene time. Burial of upper crustal rocks to deeper levels progressed from west to east with the advance of the orogenic front and previously buried strata were exhumed and carried forward as a brittle carapace on the underlying ductile regime. This scenario appears to be a ductile equivalent of the "in sequence thrusting" observed to the east in the Rocky Mountain Belt where thrust sheets have been displaced large distances along discrete thrust planes that root in a basal detachment zone. In the Omineca Belt high level thrust faults do not extend down to a discrete basal thrust plane. Instead upper crustal thrusting is replaced by ductile flow at middle crustal levels. Within this middle crustal zone rocks were generally at sillimanite grade and deformation resulted in transposition of lithologies together with development of L-S fabrics and multiple fold generations. These fold generations are diachronous structures and designations of F1, F2, etc. have no time significance beyond the outcrop scale.

Since no high pressure rocks have been observed, it is assumed that the lower crust was not involved in the regional deformation. This is supported by the observation of a major strain gradient at the deepest exposed levels within the Precambrian basement of the Monashee Complex. The basal part of this middle crustal zone of ductile strain is known as the Monashee decollement.

In the Selkirk Mountains strata were deformed into a structural fan while at middle crustal depths. This occurred in the Jurassic when these distal North American rocks were well to the west of their present position and, by the late Jurassic, the fan was exhumed to upper crustal levels as deformation progressed eastward. Underlying strata were incorporated into the ductile zone in the Cretaceous and these deforming rocks carried the overlying Selkirk fan eastward with the migrating orogenic front. There is evidence of rapid exhumation of the orogen in Jurassic and Cretaceous times as well as the better documented period of rapid exhumation that was a result of tectonic denudation in the Tertiary. These observations lead to the suggestion that compression and extension may have been coeval at different levels within the orogen. It does appear from recent geochronology that Tertiary extension along the western margin of the Monashee complex was contemporaneous with compression at deeper levels and this may be linked to early motion on the higher level Okanagan Valley normal sense shear zone. This history of deformation and exhumation is readily explained in terms of critical taper theory.

Multistage Jurassic, Cretaceous and Eocene plutonic and tectonic evolution of Valhalla complex, B. C.

S. D. CARR
Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, ON, Canada K1S 5B6
P. S. SIMONY
Department of Geology and Geophysics, University of Calgary, Calgary, AB, Canada T2N 1N4
and P. M. SCHAUBS
Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, ON, Canada K1S 5B6 and School of Earth Sciences, University of Melbourne, Parkville 3052, Australia

The Valhalla complex occupies an area of 20 x 80 km in southern British Columbia, west of the Canadian Rocky Mountain thrust belt where allochthonous terranes overlap rocks of ancient North America and, with them, have undergone Mesozoic and Tertiary tectonism. The complex comprises Mesozoic and older metasedimentary rocks and orthogneisses that are disposed in gently arched sheets much injected by Cretaceous, Paleocene-Eocene leucogranite, and pegmatite. They were metamorphosed to amphibolite facies. This constitutes a lower plate separated by the Eocene Valkyr-Slocan Lake extensional fault system from an upper plate. The upper plate of predominantly chlorite-, biotite- and garnet-grade Paleozoic, Triassic and Lower Jurassic assemblages, was injected by Middle Jurassic laccoliths.

The interconnected and flat-bottomed Jurassic laccoliths acted as a barrier to rising Cretaceous, Paleocene and Eocene granitic melts. In Late Cretaceous - Paleocene time, folding, penetrative transposition foliation and shearing on the ductile Gwillim Creek shear zones related to compressional tectonics coincided with peak of metamorphism. In the Eocene, leucogranites ponded beneath the base of Jurassic laccoliths, and the trajectory of the ductile extensional detachment (the Valkyr shear zone) was controlled by the rheological contrast between an upper plate stiffened by cool tonalite sheets and a lower plate rendered hot and ductile for about 4 Ma by the injection of 4500 km^3 of leucogranite and associated pegmatitic fluids under an area of 1600 km^2 ($700 m^3 \ km^{-2} \ a^{-1}$).

Both Cretaceous compressional structures and Eocene extensional structures were localized and guided by Cretaceous and Eocene igneous rocks, respectively; whose disposition was controlled by the geometry of the pre-existing, interconnected, flat-bottomed Jurassic laccoliths. Geometry, uplift and denudation cannot be simply linked to Eocene extensional tectonic denudation.

The Selkirk fan structure, southeastern Canadian Cordillera: Tectonic wedging against an inherited basement ramp

Maurice COLPRON

Resources, Wildlife & Economic Development, Government of the Northwest Territories, Box 1320, Yellowknife, NT, X1A 2L9

A revised cross-section through the Selkirk fan structure provides the basis for a new model for the Middle Jurassic tectonic evolution of the southern Omineca belt. Palinspastic restoration of this cross-section shows that the southwest-verging structures along the west flank of the Selkirk fan structure formed as a result of tectonic wedging of distal North American strata (Clachnacudainn complex) beneath more proximal North American strata, and that the Selkirk fan structure developed outboard from a crustal ramp (Dogtooth high) inherited from Late Proterozoic – Early Paleozoic rifting along the western margin of North America.

The first episode of Mesozoic deformation in southeastern British Columbia occurred between 187-173 Ma and involved the northeastward juxtaposition of the Intermontane superterrane over the outer part of the North American continental terrace wedge. It resulted in deep burial (20-25 km) of the outer margin of North America. A crustal ramp, localized along the western edge of the Late Proterozoic – Early Paleozoic Dogtooth high, impeded the northeastward propagation of the orogenic wedge comprising the Intermontane superterrane and the imbricate, underlying northeast-verging thrust sheets of North American supracrustal rocks. Tectonic wedging, involving southwest-verging deformation, occurred within the orogenic wedge, and the resulting crustal thickening established sufficient topography and gravitational potential to drive the propagation of the deformation eastward into the Dogtooth Range and the Rocky Mountains. The southwest-verging structures along the west flank of the Selkirk fan developed between approximately 173-168 Ma concurrent with synorogenic extension and ca. 10 km of exhumation. The initial subsidence of the foreland basin during the Kimmeridgian (~154 Ma) provides the first indication of tectonic loading and lithospheric flexure of the North American plate. It is interpreted to mark the time at which the orogenic wedge over-rode the crustal ramp of the Dogtooth high and advanced onto relatively thick and rigid continental lithosphere. The tectonic model proposed for the Selkirk fan structure illustrates how the configuration of the rifted margin influenced the style of crustal thickening during subsequent compressional deformation.

Deformation Mechanisms and Kinematic Model of Evolution of the Eastern Thrust Front of the Eastern Cordillera, Colombia.

Freddy CORREDOR
Department of Geological Sciences, Campus Box 399, University of Colorado, Boulder, CO 80309

The eastern front of the Eastern Cordillera is a large east-verging poly-deformed fold and thrust belt. A detailed structural analysis and interpretation of recently acquired seismic data, surface geology and remote-sensing images along the northern portion of this belt suggests that at least three phases or episodes of deformation have occurred during the Tertiary. These different phases of deformation have given rise to varying structural geometries at different locations along the mountain front. The earliest phase of deformation, occurred during the late Eocene-early Oligocene, formed an east vergent thin skinned imbricate fan, probably controlled by a pre-existing Jurassic normal fault array, which was eroded and covered by early Oligocene deposits. A later middle Miocene phase of positive basin inversion reactivated some of the previously formed faults and created new ones, thereby forming a passive-roof duplex triangle zone, where the early Oligocene unconformity served as the roof thrust. A final late Pliocene-early Pleistocene stage of deformation occurred when the inversion affected the eastern border of the fold belt, deforming and folding the preexisting passive-roof duplex and its frontal monocline.

The identification of these variable deformation mechanisms and structural styles in the study area raises the possibility that similar structures may be more common in the eastern thrust front of the Eastern Cordillera than previously believed.

A strain gradient in a deep structural level of the Canadian Cordillera, northern Monashee Complex

J.L. CROWLEY
Department of Geology and Geophysics, University of Calgary, Calgary, AB T2N 1N4, Canada
and R.L. BROWN
Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, ON K1S 5B6, Canada

U-Pb isotopic data and field relationships indicate that an important strain gradient exists in the northern Monashee complex, one of the deepest structural exposures in the southern Canadian Cordillera. At high structural levels of the complex, immediately beneath a crustal-scale thrust-sense shear zone (Monashee décollement), a metasedimentary cover sequence and Proterozoic intrusive rocks were strongly affected by synmetamorphic compressional deformation during Cordilleran orogenesis in the early Tertiary. Cordilleran fabrics include a migmatitic foliation that conforms to the domal shape of the complex and east-west-trending lineations. The main Cordilleran structures are kilometre-scale east-verging isoclinal folds and outcrop-scale tight to isoclinal folds with axes that parallel the east-west lineation. In contrast to high structural levels that were intensely affected by Cordilleran deformation, basement rocks in deep levels were locally weakly affected to unaffected by Cordilleran deformation. The amount of Cordilleran strain in the basement is deduced from the weakly deformed to undeformed state of Precambrian granitoid dykes; these interpretations are based on (i) intrusive contacts of the dykes that are straight and discordant to fabrics in the host rock for many metres along their exposed length, and (ii) the presence of igneous fabrics and the paucity of deformation fabrics in the dykes. These relationships require that a strain gradient developed during Cordilleran orogenesis near the basement-cover unconformity. However, strain did not follow a simple gradient, as it was partitioned at various scales in the basement into high and low domains according to rock type (i.e., rheology). Paragneiss is thought to have been strongly affected because it contains a single gneissosity that is interpreted as having a Cordilleran origin. Orthogneiss typically varies on a metre scale from containing only a Proterozoic gneissosity, to containing Proterozoic and Cordilleran gneissosities, to containing only a Cordilleran gneissosity. The Cordilleran gneissosity is best developed on the limbs of tight to isoclinal folds and where the Proterozoic gneissosity had a preexisting orientation that was axial planar to these folds. Cordilleran strain had little affect on amphibolitic gneiss, in which the Proterozoic gneissosity was only significantly reoriented in the limbs of rare tight folds.

It was previously inferred that Cordilleran thrust faults or ductile shear zones exist beneath rocks exposed in the northern Monashee complex. However, the downward weakening of Cordilleran strain suggests that the base of significant Cordilleran deformation may instead lie within exposed basement rocks. Further mapping and geochronology in deep structural levels are needed to resolve this issue. The downward weakening of Cordilleran strain is an integral part of our tectonic model for the northern Monashee complex. This model holds that an inverted metamorphic sequence in the upper part of the complex and the pattern of downward younging deformation and metamorphic ages resulted from the tectonic juxtaposition of rocks that were deformed and heated at different places and times within the orogen. The juxtaposition was mainly accomplished by east-verging kilometre-scale synmetamorphic isoclinal folding and shearing along the isocline limbs.

Ductile thrusting and extension in the lower orogenic crust: western Grenville Province, Georgian Bay, Ontario

N. G. CULSHAW, R. A. JAMIESON
Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 3J5
J. W. F. KETCHUM
Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, A1B 3X5.
N. WODICKA, D. CORRIGAN
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada, K1A OE8.
and P. H. REYNOLDS
Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 3J5

The Grenville orogenic cycle, between ca. 1190 and 980 Ma, involved accretion of magmatic arcs and/or continental terranes to Laurentia. A transect across the western Central Gneiss Belt, Georgian Bay, Ontario, which mainly crosses variably parautochthonous units of the Laurentian footwall of the orogen which crosses the boundary between parautochthonous and allochthonous units at an inferred syn-orogenic depth of 20-30 km, offers some insights on the thermal and mechanical behavior of the lower crust during collisional orogeny. Although a significant conclusion from the transect is that penetrative, syn-orogenic, extensional ductile flow may profoundly mask the evidence for thrusting during convergence, a substantial history of Grenvillian convergence can be deciphered through the veil of extensional deformation. Prior to Grenvillian metamorphism, this part of Laurentia consisted largely of Mesoproterozoic (ca. 1450 Ma) granitoid orthogneisses, granulites, and subordinate mafic and supracrustal rocks. Convergence began with transport of the previously deformed and metamorphosed (ca. 1160 Ma) Parry Sound domain over the craton sometime between 1120 Ma and 1080 Ma. This stage of transport was followed by out-of-sequence thrusting and further convergence along successively deeper, foreland-propagating ductile thrust zones. An important feature of the convergent stage is that transport of thrust sheets may have been accomplished along weak, migmatitic decollements that developed after weakening of the footwall by the migmatite. A major episode of extension at ca. 1020 Ma resulted in southeast-directed transport along several midcrustal shear zones. The extensional deformation destroyed evidence for earlier thrusting along some of these shear zones and may be responsible for much of the strain (distributed ductile flow) between the shear zones and the formation of regional transverse folds with axes parallel to the stretching direction. The extensional lower crustal flow may thus have been have been the primary cause of the subhorizontal attitude of many structures and seismic reflectors in this part of the Central Gneiss Belt. The final stage of convergence involved deformation and metamorphism in the Grenville Front Tectonic Zone at ca. 1000-980 Ma. Peak metamorphism along most of the transect at 1065-1045 Ma followed initial transport of allochthonous rocks over the craton by 15-35 My. Regional cooling, which postdated peak metamorphism by >70 My, was probably delayed by the combined effects of late-stage extension and convergence.

Strain fabrics along an Archean subprovince boundary, Ontario, Canada: Evidence for a modified transpression model

D. M. CZECK and P. J. HUDLESTON
Department of Geology and Geophysics, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis, MN 55455, USA

The goal of this work has been to study the processes that led to accretion of island arcs in the Archean Superior Province especially along a boundary between two subprovinces, the metavolcanic Wabigoon and metasedimentary Quetico. We have documented that the current kinematic model of transpression needs to be modified and have proposed a revised model to be further tested.

The most widely accepted kinematic model based on field observations is transpression (Hudleston et al. 1988). Transpression involves pure shear in the vertical plane and simple shear, perpendicular to pure shear, in the horizontal plane. This model requires that the stretching lineation be either vertical or horizontal, depending on the angle of collision and the amount of deformation (Fossen & Tikoff 1993). In the field, most rock fabrics that one would expect to see with transpression are found. However, the mineral lineations are not vertical or horizontal, they plunge between 0-90E. This requires that a more complex kinematic model be proposed. While there is no unique kinematic solution to describe oblique lineations within a transpression zone, some models can be refuted by additional field evidence. Two likely models have been addressed.

The first model to create oblique lineations involves transpression with an additional thrust component (Merle 1986). Thrusting has been thought to be a dominant part of the tectonic history due to evidence of early recumbent nappe structures (Poulsen et al. 1980) which suggest similar strain partitioning to that described by Merle (1986). Although this model explains oblique lineations, it does not create a range of oblique lineations. Also, there is no evidence for asymmetrical features on the vertical plane perpendicular to the foliation plane. Therefore, this model seems unlikely.

The second model to create oblique lineations is derived from a new physical laboratory experiment. If small amounts of material are heterogeneously extruded along with transpression, a range of lineations form. This is consistent with a model of anastomosing shear zones (Poulsen 1986) which create lozenge shapes. These shear zones surround less intensely strained blocks which rotate due to the noncoaxial strain component; these rotations create similar extrusion outlets based on lozenge geometry. This model is consistent with the observation that the lineations have a wide range of plunges. In order to test this transpression/heterogeneous extrusion model, the intensity of strain and the lineations need to be correlated in the field. To be consistent with the model, the most oblique lineations should be found near the intensely strained areas whereas vertical lineations should be found in the centers of the blocks.

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Evolution of an intracratonic strike-slip fault system: the Tabbernor Fault, Saskatchewan

James R. DAVIES
Dept. of Earth and Planetary Sciences, McGill University, 3450 University Street, Montreal, Quebec, H3A 2A7, Canada
Colleen G. ELLIOTT
Dept. of Geological Engineering, Montana Tech University, Butte, Montana, 59701, USA
and Barry P. KOHN
School of Earth Sciences, La Trobe University, Bundorra, Victoria 3083, Australia

Major intracratonic faults have long been studied to explain geological and historical surficial phenomena. Despite this there is still much to learn about the processes that lead to their formation and subsequent evolution. The Tabbernor Fault Zone (TFZ), a >1500km long intracontinental strike-slip fault exposed within the Canadian Shield of northern Saskatchewan, provides an ideal vehicle for the investigation of such large-scale intracratonic features. Through a combination of detailed mapping of Proterozoic rocks in shield areas, petrographic core analysis of Phanerozoic sediments, and remote sensing imagery, a complex history containing 1.8Ga of intermittent movement has been recognized.

The earliest recognized movement along the TFZ is associated with continent-continent collision, during the climax of the Trans-Hudson Orogen, ca. 1820Ma. Fault zone development at this time was characterized by the ductile transposition of the regional gneissic foliation onto a steeply-dipping, northeast-trending flattening fabric, within north-trending sinistral shear zones. During a regional metamorphic thermal climax, at 1815Ma, the fault was intruded by a series of granitic and pegmatitic phases. Reactivation of the TFZ happened several times after its incorporation into the North American craton. Firstly, the fault appears to have reactivated as a series of brittle fault splays that have an important control on the formation of the uranium deposits in the adjacent Athabasca basin. Much later, during the Late Devonian and Early Cretaceous Periods, fault reactivation caused significant remobilization of these same deposits. At the same time, the fault controlled the deposition of sediments within the petroleum-producing Williston Basin and led to the formation of intra-basinal structures, such as the Nesson Anticline. These reactivations correlate with episodes of orogenic activity on the western continental margin. Surficial traces of the TFZ in the recent sediments indicate that it still forms a salient feature that may be reactivated in the future.

Comparison between this study and others shows that most intracratonic strike-slip faults form at the continental margin. After cratonization these structures continue to influence craton tectonics due to their deep-seated nature and inherited 'weakness'.

The Teslin subduction zone in the Northern Canadian Cordillera meets its Waterloo: Ductile thrusting and obduction as the principal process of accretion of Omineca Belt suspect terranes to ancestral North America

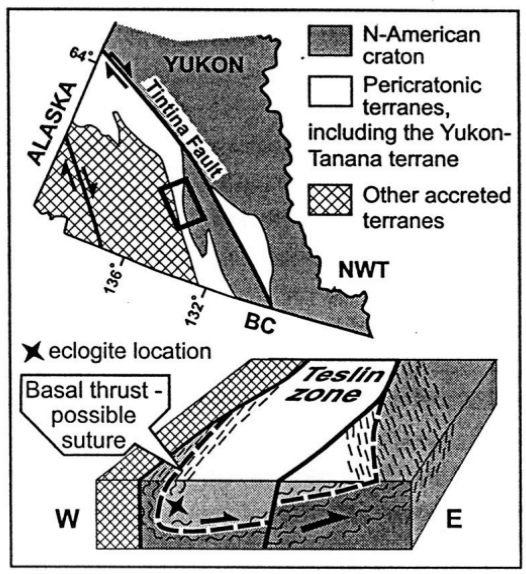
Martin DE KEIJZER* and Paul F. WILLIAMS

Department of Geology, University of New Brunswick, Fredericton, NB E3B 5A3, Canada

*(*e-mail: de_keijzer@unb.ca)*

The Yukon-Tanana terrane (YTT) is one of the largest and most enigmatic tectonic elements in the Yukon and Alaska in terms of its crustal geometry. Together with the oceanic Slide Mountain terrane and the Anvil ‘assemblage’ it forms the easternmost of the suspect terranes in the northern Canadian Cordillera which have accreted to upper Proterozoic to middle Paleozoic rocks of the North American continental margin (NA). Other workers have correlated the YTT with suspect terranes in British Columbia (e.g. the Kootenay terrane) and in the western United States (e.g. the Northern Sierra terrane) principally on the basis of similar sedimentary and plutonic rocks, and distinctive faunal assemblages.

The Teslin zone is a 15-30 km by >200 km corridor of deformed supracrustal and plutonic rocks in south-central Yukon. It is part of the Omineca Belt, includes the narrowest portion of the YTT, and is bounded to the W and to the E by N-trending post-accretionary faults. Previous workers described the Teslin zone as a discrete zone with a steep foliation unique to the zone. The steep foliation, together with the presence of rare eclogite, was considered evidence for the zone being a lithospheric suture or a crustal-scale transpression zone, and the root zone of klippen on NA to the E. We demonstrate, however, that deformation and metamorphism is the same inside and outside of the zone. The steep transposition foliation S_T (the result of F_1 and F_2 folding of primary layering) in the zone, in contrast to adjacent rocks to the E, coincides with the steep limb of a regional F_3 structure. This fold has a shallow limb in the easternmost part of the zone, and immediately E of the zone. Thus, the steep attitude of fabrics and the marked narrowness of the Teslin zone are not evidence for a steep crustal-scale shear zone, whether it be suture-related or not. Rather, the zone is a young structure and steepening of transposition fabrics post-dates widespread ductile deformation associated with juxtaposition of the Anvil assemblage, the YTT Nisutlin assemblage, and NA (see figure).



If a suture exists between the obducted Anvil and YTT Nisutlin assemblages and NA, it is a shear zone that occurs at the base of the obducted rocks, which has been folded by F_3 (see figure). However, there is no reason to interpret this obduction boundary as a suture since evidence of HP metamorphism *during* easterly thrusting is lacking: S_T development, and accommodation of shear by S_T, resulted in the breakdown of eclogite to amphibolite at the base of the hanging wall rocks. The eclogite is best interpreted as being incorporated in the YTT during thrusting (i.e. exotic relative to the rest of the sequence). A consequence of the large-scale geometry is that NA rocks pass under the eastern Teslin zone and outcrop W of the YTT (see figure). The western limit of the NA basement, which marks the ‘true root zone’ of obducted oceanic rocks in the Omineca Belt, is unconstrained in the Yukon. It is suggested that it occurs to the W of the Omineca Belt, similar to what has been proposed for southern British Columbia.

Detailed stratigraphic interpretation in a granulite-facies, multiply-deformed terrane: A case example from the Palaeoproterozoic Broken Hill Block, NSW, Australia

Tony DONAGHY, Mike HALL
Australian Geodynamics Cooperative Research Centre, VIEPS Department of Earth Sciences, Monash University, Clayton VIC 3168 Australia
and George GIBSON
Australian Geological Survey Organisation, Canberra, ACT 2601 Australia

The granulite-facies, multiply-deformed Palaeoproterozoic rocks of Broken Hill have been the subject of intense scrutiny by geologists for over 100 years, largely because they host the world's largest Pb-Zn-Ag deposit. Past models for the evolution of the local geology reflect the paradigms of the relevant era, incorporating through time various aspects of; classic European granite geology; rift tectonics and voluminous volcanic extrusion typical of the Basin and Range and East Africa Rift; alpine nappe tectonics; and the use of detailed sequence stratigraphy. Here we question earlier conclusions regarding the nature of the inferred protoliths and the structural geometry erected on the basis of the currently accepted rift volcanism and sequence stratigraphy model. We find by; (i) using a multi-disciplinary approach of detailed structural mapping, geochronology and geophysics; and (ii) utilising the previously unrecognisied geometries of high-strain, such as transposition, stretching lineations, kinematic indicators and mylonite formation; that we can make a more rigorous reconciliation of stratigraphy and structure than was previously possible.

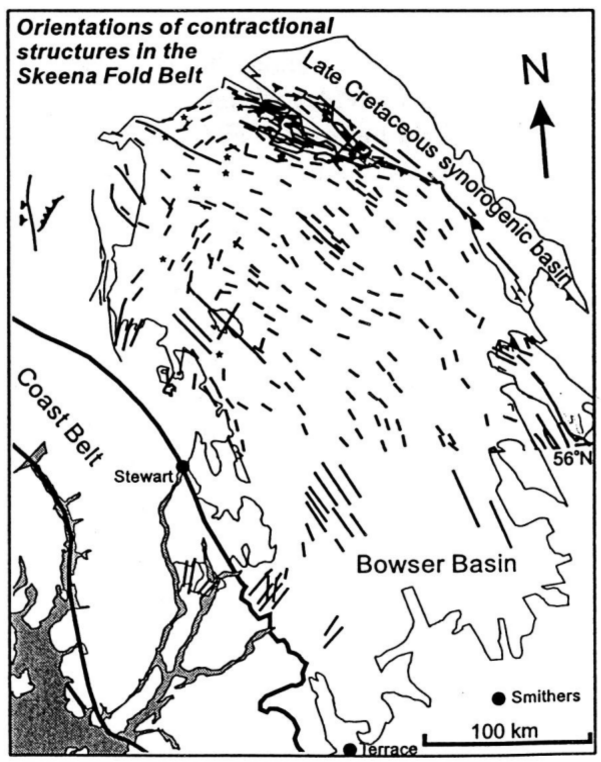
Notwithstanding the paucity of reliable sedimentary structures and younging criteria, the intense nature of strain and the degree of partial melting in the region, previous workers erected a stratigraphy using key meta-igneous, interpreted as metavolcanic, and metasedimentary marker horizons. While high strain zones were recognised, they were largely attributted to the last phase of deformation and thought to bound regions of conformable "layer-cake" stratigraphy. The possibility of internal disruptions and intrusive contacts within the stratigraphic sequence were dismissed. However, detailed mapping and SHRIMP U/Pb geochronology shows that some of the key meta-igneous marker horizons are intrusive into the surrounding lithologies and not part of the original depositional sequence. Furthermore, the identification of five regional scale deformations, including two early mylonite shear fabrics, offers an alternate explanation for the present distribution of lithologies. High-metamorphic grade, isoclinal F1 and F2 folds were rotated during successive high-strain deformation into essentially coaxial fold interference patterns and overprinted by lower-metamorphic grade, tight to isoclinal F3 and open to tight F4 folds. Coupled with the development of S2 and S3 mylonite zones, this has resulted in large scale transposition, gross attenuation and reorientation of lithologies into apparent conformity. Coupled with removal of intrusive marker horizons, this leads to a gross simplification of the local stratigraphy, with structural repetition of similar lithological associations previously separated as different stratigraphic units. This has flow-on ramifications for simplification of the local palaeoenvironmental reconstruction and for mineral exploration strategies for Broken Hill-type deposits in granulite-facies terranes, as the current model for the Broken Hill style of mineralisation is thought to be syndepositional and located within discrete lithologically similar stratigraphic units, intimately associated with metavolcanic horizons.

Evolution of sinistral to dextral transpressional structures in the Skeena Fold Belt

Carol EVENCHICK
Geological Survey of Canada, 101-605 Robson St., Vancouver, B.C., V6B 5J3

The Skeena Fold Belt is a thin skinned fold and thrust belt within the northern Intermontane Superterrane of the Canadian Cordillera. The fold belt is best expressed as widespread northwest trending folds in Middle Jurassic to Early Cretaceous clastic rocks of the Bowser Basin, but also involves underlying volcanic and clastic rocks of Stikinia, and overlying strata of the Sustut Basin. The latter is a Late Cretaceous syn-orogenic clastic basin on the northeast side of the fold belt and was partly derived from the fold belt. The fold belt accommodated at least 150 km of northeast shortening in Early to latest Cretaceous or earliest Tertiary time. It ends at the northeast in a triangle zone in the syn-orogenic Sustut Basin, and appears to root to the west in the Coast Belt.

Contractional structures vary from upright to overturned folds and thrust faults which trend northwest in most of the fold belt, but northeast in domains on its west side. The two orientations of folds interfere at domain boundaries and locally within the western domains. Interpretations of the origin of large domains in the west with fold trends orthogonal to the major structural trend has significant implications for evolution of the fold belt. One explanation for the northeast trending folds might be rotation of northwest trending folds, but mapped folds define fold interference rather than a change of orientation. Another possible explanation is the influence of pre-existing structures in the basement, but regions to the east which would have ridden over the same features have no record of them. Alternatively, the northeast trending structures may be a result of oblique sinistral convergence along the northern Cordilleran margin in a scenario where oblique convergence was not partitioned into strike slip and orthogonal components. Northwest trending structures may result from strain partitioned into orthogonal and strike slip components in either sinistral or dextral convergence. Sparse field relationships suggest that northeast trending folds predate northwest trending ones.



The Skeena Fold Belt probably evolved from a belt of southeast contraction located parallel with and close to the plate margin early in its history, to a larger belt of northeast contraction later in its history. The early history is inferred to be a result of oblique sinistral convergence, and the later history orthogonal components of sinistral and/or dextral convergence. At least some of the later structures are Late Cretaceous in age. These interpretations are consistent with plate motion studies based on the hot spot reference frame which indicate that the relative motion between the Kula and North American plates was sinistral convergent in Early Cretaceous time and dextral convergent in Late Cretaceous time. Fold relationships similar to the Skeena Fold Belt occur 600 km farther north along the margin; northeast trending folds formed between about 135 Ma and 106 Ma were overprinted by northwest trending folds.

Evolution of extensional structures in a collisional setting

M. FORSTER and G.S. LISTER
Department Earth Sciences, Monash University, Australia

The evolution of extensional structures in collisional settings may follow a well-defined pattern. Detailed studies in the central Cyclades, Greece suggest the following sequence: a) recumbent folding; b) kilometre-scale ductile shear zones that pervasively affect the rock mass; c) localised metre-scale ductile shear zones; d) multiple generations of low-angle normal faults of large areal extent (i.e. detachment faults), some associated with footwall shear zones, others associated with breccias; e) listric normal faults; f) multiple arrays of high-angle normal faults with a wide range of size and displacement.

Recumbent folds and shear zones have been considered to be spatially linked (e.g. in the Otago Schist NZ), and to be the associated with crustal shortening. An alternative possibility is that the transition from recumbent folding to the formation of shear zones marks a switch from crustal shortening to collapse, even during continued convergence. The transition from compressional to extensional tectonism may not be a simple or single process.

The metamorphic history of large-scale shear zones suggests that they can be responsible for considerable exhumation, for example on the island of Ios, where deformation commenced in the blueschist facies conditions, and ended under greenschist facies conditions. The shear zone caused a pressure drop of several kilobars.

Reactivation of existing shear zones can take place as well as the formation of new shear zones during on-going and/or different kinematic episodes. For example the central Cyclades is affected by N-S extension, and overprinted by the effects of later E-W directed extension, after the formation of the Ios dome.

The timing and characteristics of later generations of low-angle normal faults (LANFs) suggest that exhumation occurred as distinct episodes at higher structural levels and that the LANFs were responsible for late exhumation in this tectonic setting. High-angle normal faults (HANFs) represent the last period of extension, fragment earlier structures and juxtapose regions from different structural depths, with different extensional styles. They lead to domino-like rotation of fault blocks, dissection of previously formed gneiss domes, repetition of structures and juxtaposition of different metamorphic facies blocks over both a regional and local scale.

Structures preserved from on-going episodes of deformation can represent the effects of several different circumstances: a) changes in deformational style that take place with decreasing structural depth; b) variation in the rheological response; c) changing kinematics of the regional tectonics in a collisional setting. The ductile and brittle history of crustal extension does not necessarily involve a single kinematically constant deformation event. Similarly the switch from compression to extension may vary spatially and in time over a region.

Deformation-induced inverted metamorphic field gradients: an example from southeastern Canadian Cordillera

H. Daniel GIBSON, Richard L. BROWN
Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, ON, K1S 5B6, Canada
and Randall R. PARRISH
Department of Geology, University of Leicester and NERC Isotope Geosciences Centre, British Geological Survey, Keyworth, Notts., NG12 5GG, United Kingdom

Exhumed middle crustal rocks of the hinterland of the southeastern Canadian Cordillera were deformed and metamorphosed during Mesozoic and Tertiary progressive crustal thickening. High structural levels were transported northeasterly relative to lower levels through a combination of thrusting and ductile noncoaxial flow. Progressive growth of the orogen and advance of hinterland rocks toward the foreland is revealed through analysis of diachronous metamorphism and associated deformation. At the deepest exposed level, allochthonous rocks of the orogen (Selkirk allochthon) structurally overlie early Proterozoic basement and younger cover rocks (Monashee complex) that are correlated with the autochthonous North American crust underlying the eastern foreland (Rocky Mountain Belt). The crustal zone which marks the boundary between the Selkirk allochthon and Monashee complex, exhibits an inverted metamorphic field gradient. Within the footwall rocks of the complex is evidence of an inverted amphibolite-facies metamorphism with higher-grade sillimanite-K-feldspar gneiss and extensive anatexis in the immediate hanging wall. New data presented in this talk refute previous interpretations, which assert that the metamorphic inversion is a result of the downward transfer of heat from the allochthon to the underlying Monashee complex.

Monazite and zircon extracted from six samples taken at systematically deeper structural levels within the footwall were dated by U-Th-Pb isotope dilution . The U-Th-Pb geochronometry revealed a systematic younging of peak metamorphic ages (from ca. 77 to 59 Ma) with increased structural depth. The limited structural distance between the above ages (1.7 km) is not compatible with heat transfer models that ascribe the creation and preservation of an inverted metamorphic sequence to heat conduction from an overlying heat source (i.e., Selkirk allochthon). The data require that the inversion of ages and isograds was primarily accomplished mechanically. Therefore, a coupled thermomechanical model is proposed in which substantial easterly directed shear strain and attendant attenuation in the footwall led to relative lateral transfer of rocks preserving evidence of diachronous, inverted metamorphism. This model incorporates a clear role for shear strain and a probable but less important role for heat transfer from the allochthon.

Initiation and propagation of ductile shear zones in high-grade rocks: analogue experiments and comparison with natural examples

Djordje GRUJIC
Geologisches Institut, Albert-Ludwigs-Universität Freiburg, D-79104 Freiburg, Germany
and Neil S. MANCKTELOW
Geologisches Institut, ETH-Zentrum, CH-8092 Zürich, Switzerland

Analogue model experiments were conducted to investigate the influence of irregularly distributed weak sites in localising strain, as an aid to understanding shear zone development in partially molten rocks. The very weak inclusions consisted of Vaseline in a homogeneous matrix of paraffin wax, which has a power-law viscous rheology. Boundary conditions were those of pure shear at constant natural strain rate and confining stress. Two shapes of weak sites were used, namely round cylinders and elongated prisms with axes parallel to the intermediate bulk strain axis. Experiments were performed to consider both random distributions of weak inclusions and planar zones of concentrated weak material. The photographically recorded deformed grids on the upper surface of the model were digitised and the resulting data files used to determine the distribution of the finite strain, incremental strain between two stages, perturbation strain, rotation, displacement paths of material points.

Conjugate shear zones nucleate on the inclusions and link up to form an anastomosing pattern of high strain zones of concentrated shear surrounding much more weakly deformed pods of near coaxial strain. The zones initiate at angles near 45° to the bulk shortening axis Z but stretch and rotate towards the X axis with increasing bulk strain. All inclusions nucleate shear zones, so that with increasing development of the anastomosing pattern, weak material occurs only within the high strain zones. Elongate weak sites initiated shear zones dependent on their orientation with respect to the bulk strain axes, and both dextral and sinistral shear zones formed within the same model. In experiments with a high concentration of weak inclusions, irrespective of their shape and orientation, a new anastomosing planar fabric containing the weak phase resulted at higher strain. The anastomosing strain pattern developed in these analogue models, which were deformed with boundary conditions of pure shear, demonstrates that the automatic assumption of regional simple shear kinematics may not always be justified, and may lead to incorrect interpretations. The restriction of migmatite leucosomes to shear zones in natural examples could also reflect a corresponding control of melt on the sites of shear zone nucleation, rather than implying accumulation from the surrounding wall-rock. The model geometry is very similar to that observed in natural small-scale shear zones in stromatic migmatites.

Evolution of the Outer Foothills north of Grande Cache, Alberta

Nanna FRIIS
Dept. of Geology and Geophysics, University of Calgary, Calgary, Alberta, T2N 1N4
Willem LANGENBERG
Alberta Geological Survey, 9945-108 Street, Edmonton, Alberta, T5K 2G6
and Deborah SPRATT
Dept. of Geology and Geophysics, University of Calgary, Calgary, Alberta, T2N 1N4

Surface geology, new seismic and coal drilling data are integrated with regional seismic and well data to delineate the 3D geometry of the triangle zone north of Grande Cache, Alberta. Seismic sections are depth-converted and integrated with surface and well data and structurally balanced in 2D and 3D.

Upper Cretaceous and Tertiary strata at surface in the Outer Foothills are deformed by open folds, northeast-verging thrusts (such as the Muskeg and Copton Thrusts) and southwest-verging backthrusts (such as the Morley Thrust). The Morley Thrust, which forms the eastern limit of the triangle zone, ramps up-section laterally to the southeast through the Upper Cretaceous Smoky Group, from the Kaskapau shales into the Wapiabi shales. In the northwestern part of the area, near Kakwa River, minor backthrusts observed northeast of the Morley Thrust may define an incipient younger triangle zone. Structures in Lower Cretaceous strata in the subsurface are interpreted to be detachment folds similar to those exposed in the Inner Foothills. However, the steep limbs of these folds are not well imaged seismically and as a consequence folding appears to be under-represented on seismic sections. The blind, northeast-verging Findley Thrust roots in the Devonian and has several blind splays. The overlying antiformal Findley Structure shows the combined effects of detachment folding, fault-propagation folding and fault-bend folding and can be described as a modified fault-propagation fold. The Paleozoic strata in the subsurface of the Outer Foothills display additional detachment folds, some of which have limbs that are cut by northeast-verging thrust faults. These structures are better imaged in the southeastern part of the study area and can also be described as modified fault-propagation folds. A major detachment in the Jurassic shales separates these structures from the smaller scale folds and faults developed in the overlying Lower Cretaceous Luscar and Upper Cretaceous Smoky groups. This detachment appears to form the floor thrust of the incipient triangle zone interpreted in the northeastern part of the area.

Image processing of petrographic thin sections using the rotating polarizer stage

Frank FUETEN
Department of Earth Sciences, Brock University, St. Catharines, Ontario, Canada L2S 3A1

The computer controlled rotating polarizer stage replaces the polarizer and analyzer of the standard petrographic microscope for image processing applications. The stage allows a thin section to remain fixed while the polarizing filters are rotated by stepper motors. In addition to simplifying the computational requirements the stage permits the extraction of data that enhances the ease and accuracy with which grains can be identified, and area and shape calculations can be performed.

The methodology is to step the polarizers through a 180 degree rotation, capture a frame at each step and extract data. A composite data set is constructed that contains selected information obtained under crossed-polarized and under plane polarized light. The maximum/minimum intensity values correspond to the maximum/minimum interference colour of a pixel within a grain during a 180E rotation of the polarizers. Intensity variations are directly related to the orientation of the crystal lattice to the plane of the thin section as variations due to the orientation of the polarizers which are seen in single images, have been eliminated. Position values record the orientation of the polarizing filters, ie. the step number, when a pixel reaches its maximum and minimum value. The gradient value is used for the determination of grain boundaries.

- Edges calculated using an edge detector specifically designed to take advantage of the gradient values produces closed edges which are superior to edges obtained by other currently available methods.

- The automated determination of quartz c-axis orientations using the rotating polarizer stage, is a fast and accurate alternative to measuring orientation on the universal stage. As c-axis orientations are calculated for each pixel, AVAs can easily be constructed to study problems which would normally require a prohibitive amount of tedious work.

- Minerals can be identified using a variety of manual and automated methods.

The Rotating Polarizer stage is a versatile tool that can easily be adapted to a variety of specialized problems.

Initially vertical normal faults and rapid block rotations in magmatically active rifts: some observations from the Basin and Range province, USA

Phillip B. GANS
Department of Geological Sciences, UCSB, Santa Barbara, California, USA (gans@magic.ucsb.edu)
and Pip DARVALL
at large, Australia

Highly extended portions of the Basin and Range province are characterized by closely spaced normal faults and steep tilting of strata. These normal faults in some areas initiate at angles much steeper than the ~60° predicted by Coulomb shear failure. Large-magnitude extension and block rotation typically occurs rapidly (<1-3 Ma), and most of the tilting is accomplished by a single set of faults. There is often a close spatial and temporal relationship between extension and voluminous mafic to silicic magmatism, wherein volcanism begins up to several million years earlier and peaks prior to the onset of extension. Eruptive activity wanes dramatically during rapid extension, apparently suppressed by active faulting and thinning of the crust.

This structural style and tectono-magmatic evolution is spectacularly exposed in the Eldorado Mountains of southern Nevada. High precision $^{40}Ar/^{39}Ar$ ages permit the timing and rates of extension and volcanism to be assessed in unprecedented detail. Average volcanic accumulation rates increased from < 1 mm/yr at 18 Ma to a peak of 3 mm/yr between 15.8 and 15.0 Ma, abruptly dropped at 15.0 Ma, and then resumed at a much lower rate after 14.2 Ma. The volcanic sections in the Eldorado Mountains are steeply tilted (up to 90°) to the east and are cut and offset by closely spaced gently west-dipping normal faults that were initially vertical. Palinspastic reconstructions indicate a stretching factor of ~2.0, oriented N80E. There is no evidence for faulting and tilting before eruption of a 15.1 Ma ignimbrite, whereas in 15.0 to 14.1 Ma volcanic and sedimentary rocks, tilts decrease abruptly up section. Younger (14.1 to 13.0 Ma), gently tilted olivine basalt, trachyandesite, and rare silicic flows unconformably overlie the previously faulted and tilted units and provide a firm upper age bracket for most of the extension. Thus, extension began at ~15.0 Ma immediately following the peak of volcanism and that the area was stretched by > 100% between 15.0 and 14.1 Ma, during which time volcanic activity virtually ceased. Extensional faulting and volcanism continued after 14.1 Ma at a greatly reduced rate.

The fact that normal faults in the Eldorado Mountains initiated as planar, near vertical fractures implies initial tensile failure to depths of at least 5 km. Large (> 70°) rotations occurred on a single set of faults. The very rapid rates of local extension (> 1 cm/yr) imply an instability or runaway phenomena. In light of these observations, the mechanics of extensional failure and fault block rotations were evaluated using Mohr-Coulomb failure criteria. We assumed σ_1 = vertical and derived the criteria for initial failure and subsequent frictional sliding at the base of a brittle layer (i.e. its strongest part) as a function of initial layer thickness, differential stress, pore fluid pressure, tensile strength, cohesion, coeff. of friction, and amount of rotation. For nominal model values we find initial tensile failure requires relatively small differential stresses (~ 40 MPa) but elevated pore fluid pressures ($\lambda = \sim 0.8$) - a fluid pressure we attribute to the presence of an active magmatic/hydrothermal system at the base of the brittle layer. As faults rotate "domino-style" from 90° to progressively lower angles, they become progressively weaker at any given fluid pressure ratio. Surprisingly, this weakening continues even after faults rotate past the "optimum" Coulomb failure angle of 60° to fault dips of only 30°, after which they remain weak until it becomes easier to form new tensile fractures. This progressive weakening stems from the fact that the increasing proportion of normal stress acting on the fault plane is outweighed by the overall reduction in mean normal stress due to thinning of the overburden and applies only for rapid strain rates. These simple mechanical considerations may provide a general explanation for the striking differences in structural style between rapidly extending magmatically active rifts and areas of more broadly distributed slow extension.

Fabric development in the absence of metamorphism: lessons from a fault in poorly consolidated sediments

Laurel B. GOODWIN, Geoffrey C. RAWLING, and Michiel HEYNEKAMP
Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801

We have investigated structures developed in a large-displacement (~600 m throw) normal fault associated with the Rio Grande rift of New Mexico. The Sand Hill fault cuts syn-rift sediments of the Santa Fe Group, including sands, silts, clays, and gravels. The sediments vary in degree of lithification from moderately consolidated to unconsolidated; a fresh outcrop can typically be excavated by hand. Stratigraphic constraints indicate that the current fault-zone exposure was buried under less than one kilometer of sediment at the time of faulting. In this near surface environment, deformation took place in the absence of metamorphism. Our work to date shows that a surprising variety of structures developed during faulting of these poorly consolidated sediments, including both foliations and lineations. Mesoscopic observations indicate the operation of two processes that influenced fabric development. First, adjacent beds were incorporated into the fault zone through rotation and roughly fault-parallel extension, resulting in nearly fault-parallel compositional bands and laminae. Second, mixing of sediments along the boundaries between these compositional layers occurred both through disruption of bands and grain-scale mixing. These processes took place within 'mixed zones', mappable units that flank the fault core in both the footwall and hanging wall. The character of the foliation(s) and lineation within these mixed zones and the fault core varies with grain size, reflecting variations in deformation mechanisms.

Deformation of sands was accomplished by cataclasis, frictional grain-boundary sliding, and mechanical rotation of grains and grain fragments. Our work to date suggests that volcanic clasts and feldspar grains may be reduced to clay size through cataclasis, whereas quartz grains show less dramatic grain-size reduction. These processes resulted in the formation of a cataclastic foliation and lineation, in which elongate grains and grain fragments describe the fabric. The foliation is inclined with respect to the main slip surface, with the same sense of inclination that S-surfaces exhibit with respect to deeper crustal shear zone margins. The angle of inclination is small, but can nevertheless be used as a kinematic indicator. Grain lineations are parallel to slickenside striae developed in cemented portions of the fault zone, and therefore record the slip direction of the fault.

Clays exhibit well developed foliation(s) and locally developed slickenside striae. Petrographic observations suggest that these structures formed through grain boundary sliding and mechanical rotation of clays, though additional intracrystalline deformation may have taken place. We have observed clay foliations that are both parallel and inclined to the main slip surface, analogous in orientation to S- and C- surfaces. Where inclined, the angle of inclination is greater than is observed in foliated sands. In areas of mixed sand and clay beds, clays exhibit a well developed foliation that anastomoses around sand grains; elongate sand grains are not aligned. Foliation in silts is defined by compositional banding. Silts do not exhibit lineations. These structures reflect the fact that silt-sized grains are typically equant, and deformation seems to be accomplished solely by grain-boundary sliding.

These observations indicate that multiple foliations and lineations may develop by purely mechanical deformation mechanisms during faulting of poorly lithified sediments. The foliations serve as good kinematic indicators, and the lineations record slip direction. This example serves as a reminder that processes such as recrystallization and crystal plastic flow are not required to form fabrics and kinematic indicators.

Centrifuge modelling of folding during lithospheric extension: implications for the study of high grade gneiss terrains

L.B. HARRIS
Tectonics Special Research Centre, Department of Geology & Geophysics, The University of Western Australia, Nedlands 6907, Australia
and H. KOYI
Hans Ramberg Tectonic Laboratory, Institute of Earth Sciences, Uppsala University, Villavägen 16, Uppsala S - 752 36, Sweden

In studies to determine the origin and evolution of high grade gneiss terrains, it is important to be able to determine whether they signify a regional extensional or contractional tectonic setting at the time of their formation. Many granulite and amphibolite facies terrains are characterised by early foliation development and one or more generations of isoclinal recumbent folds that are commonly refolded by upright folds. Although there has been much debate about the origin of an early foliation, such fold geometries are often interpreted as indicating a regional contractional tectonic setting. Recumbent folds are often thought to form during early thrusting in a convergent orogen. Refolding by upright folds has been traditionally interpreted as being due to continued contraction across the orogen. In these models, normal shear zones accompanying folds may be attributed to orogenic collapse and/or delamination of a thickened root.

A new centrifuge analogue modelling technique and materials were developed to model the evolution of faults, ductile shear zones and folds at different structural levels during bulk extension. Models were constructed of materials whose density and viscosity scale to replicate natural systems when run in a centrifuge at between 500 and 900 times the normal gravitational force (g) over a period of several minutes.

During extension, early-formed, stepping fractures developed over a broad zone and linked to form rift basins in the upper brittle layer. The area of greatest 'lithospheric' thinning and 'asthenospheric' uplift is offset from areas of faulting in the upper 'crust', similar to theoretical simple shear rift models. Broad normal ductile shear zones developed in layers representing the ductile crust during displacement on shear zones cutting the more rigid 'mantle lithosphere' (stress-guide) layer, enhanced by footwall rotation of this layer. Uplift of 'mantle lithosphere' results in the flattening in the dip of early-formed ductile shear zones; these change in profile from concave upwards in the ductile crust to convex upwards at deeper levels. Extension, especially in thicker models, was accommodated by shear zones parallel to compositional layering away from the main zone of rifting. Normal shear zones cutting layering, nucleated in boudin necks.

Recumbent isoclinal folds with highly attenuated lower limbs developed within ductile shear zones formed by the rotation of footwall of the mantle lithosphere layer near the region of separation at high strains. Recumbent folds have been refolded by open, upright folds during continued extension and upwelling of the layer representing mantle asthenosphere. Other folds were initiated as more upright structures within necks of boudinaged competent layers; their axial surfaces were progressively rotated to shallower dips where they were dragged into normal shear zones. These experiments show that many fold geometries previously attributed to convergent tectonic settings may develop in a regional extensional environment during rifting of continental lithosphere. Extreme care must therefore be taken in basing interpretations of tectonic setting in high grade gneiss terrains on fold style and geometry.

Flow Paths and Evolution of Crystalline Thrust Sheets in the Internides of Orogens: End Members and a Newly Recognized Transitional (T) Class of Thrusts

Robert D. HATCHER, Jr.

Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410 and Environmental Sciences Division, M.S. 6400 Oak Ridge National Laboratory, Oak Ridge, TN 37831-6400, bobmap@utk.edu

Crystalline thrust sheets have previously been separated by Hatcher and Hooper into two end-member types: Type F (fold-related; purely plastic) and Type C (composite; most foreland thrusts fit here, but are much smaller). The internides of most orogens contain examples of both types, but a large group of crystalline thrust sheets present in the internides of the Alps (Pennines), Appalachians (Inner Piedmont), and Grenville (Parry Sound Region) orogens has evolved thermally to a semiductile intermediate state that fits neither class. These thrust sheets remain plastic enough to undergo penetrative deformation (mineral stretching lineations track their transport paths), yet are coherent enough to remain intact during transport. Upon continued cooling, they evolve into Type-C sheets. Flexural flow rather than passive flow (amplification) may be a critical difference in the mechanism for formation of these transitional (T)-type thrust sheets. Contrast in layer strength may provide the necessary coherence to permit the sheets to remain intact and ultimately cool to form a Type-C sheet. We have observed Type-T thrusts exploiting conveniently located and oriented weak zones (e.g., aluminous schists) thus exhibiting foreland-thrust behavior. Strain rate may also be important, with rapid rates forcing the thrust sheets into less ductile behavior modes and lending coherence to the sheets, with compression providing a small component of adiabatic heat to prevent them from evolving more rapidly into Type-C sheets. Like Type-F sheets, Type-T thrust sheets commonly form under amphibolite facies (or higher grade) conditions. One of the best examples of Type-T thrust sheets is in the 100-km wide southern Appalachian Inner Piedmont, which represents most of the Acadian metamorphic core. Regional mineral stretching lineations reveal a complex but systematic crustal flow pattern in Type-T sheets that involves initial N to NW transport in the root zone (east flank), then NW farther west, then E-W, and finally SW-directed transport in the thrust stack along the western flank.

Numerical simulation of natural fibrous vein microstructure

Chris HILGERS
Geologie-Endogene Dynamik, RWTH Aachen, D-52056 Germany, c.hilgers@ged.rwth-aachen.de
Paul D. BONS
Department of Earth Sciences, Monash University, Clayton VIC 3168, Australia, paul@earth.monash.edu.au
and Janos L. URAI
Geologie-Endogene Dynamik, RWTH Aachen, D-52056 Germany, c.hilgers@ged.rwth-aachen.de

Syntectonic fibrous veins are a unique tool for structural geologists to analyse progressive deformation in rocks, because they are assumed to track the opening of the fracture. For the basic grain-scale mechanism, Ramsay (1980) proposed the crack-seal mechanism, consisting of repeated microfracturing, each followed by sealing due to crystallization from solution.

Cox (1987) and Williams & Urai (1989) have shown, that the long axis of the fibrous crystals do not always grow parallel to the opening direction, because fibres do not connect bedding on both sides of the fracture in all cases. Therefore a simple 2-D model was presented for crystal growth in a crack-seal environment, assuming complete sealing after each cracking event and isotropic crystal growth rates (Urai, Williams and van Roermond 1991).

We used a computer programme based on the kinematic assumptions of the 2-D model, and allowing for anisotropic growth rates. First, using reasonable values of the input parameters, we successfully simulated the microstructure of an antiaxial fibrous vein in slate. Then we carried out a sensitivity analysis using different opening increments and directions, number of initial crystals and the crack morphologies

Results so far are as follows:
-The amount of initial grains does not affect the number of surviving fibres. The grain boundaries of the fibrous crystals are locked to marked ridges at the wall. Consequently the width of the fibre is determined by the spacing of the ridges along the wall. Furthermore the grain boundary will curve and become wavy if the offset of the ridge is large enough to force the grain boundary to step over the ridge.
-Whether the crystal growth is anisotropic or isotropic does not affect the fibre shape, if all grains reach the wall before the next crack event starts (complete sealing) and the crack events itself are small.
-Natural fibrous veins can be simulated with the wall and crystal size of natural veins as input parameters.

The validity of the basic assumptions of the model is discussed in the light of modern theories of crystal growth (van Suchtelen, 1995), and alternative mechanisms proposed by Bons and Jessell (1997) and Fisher and Brantley (1992).

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A Review of Recent Developments in the Evolution of Single Layer Folds and of Axial Plane Foliation

Bruce HOBBS, Hans MÜHLHAUS and Alison ORD
Australian Geodynamics Cooperative Research Centre and
CSIRO Exploration and Mining, PO Box 437, Nedlands, 6009, Australia

We review here recent theoretical and numerical results concerning the buckling of single layers and also take a brief exploratory excursion into the results pertinent to the development of "axial plane" foliations. The classical treatment of buckling of single layers embedded in another medium derived from Biot (1965) although simultaneous, identical developments were made by Ramberg (1963). These classical treatments are two dimensional, linear, small amplitude theories. The term *linear* means that only linear constitutive laws are examined (either elastic or viscous) and also that geometrical non-linearities related to large deflections or curvatures are neglected. The result of all such treatments, no matter whether the layer or the embedding materials be elastic or viscous is that one particular wavelength (the so called Biot dominant wavelength) is amplified with an exponential growth law. Thus, strictly periodic structures always result no matter what initial geometry or initial deviations from the ideal flat state exists.

Recent developments examine the influence of multiple time scales, axial constraints and extension into three dimensions. In the case of visco-elastic folds there exist three time scales: the relaxation times of the fold material and the embedding material respectively and the time scale associated with the fold evolution. If the time scale of the fold evolution is much slower than both relaxation times then the system behaves approximately like a viscous layer embedded in a viscous matrix. If, on the other hand, the fold evolution is faster than both relaxation times then elastic in viscous behaviour ensues and so on.

One of our key findings in connection with visco-elastic fold systems is the demonstration of multiple dominant wave lengths, the existence of which is related to critical ratios of the relaxation times of the fold and the embedding materials. We propose that herein lies the origin of parasitic folds.

The role of geometric and/or physical nonlinearities on the folding process has been investigated many times: Yield points or high power law exponents cause sharper fold crests; more accurate geometric modelling introduces cubic nonlinearities increasing the vigour of the instability . Both refinements lead to quantitative changes however do not introduce qualitative changes, or more or higher complexity into the model. As mentioned above one way of introducing complexity is by considering the competition of multiple time scales; another one is to consider nonlinearities related to kinematic control of the fold amplitude through prescribed axial velocities at the fold edges. It can be shown that these constraints:

- exclude periodicity of the fold amplitude distribution at all times,
- increase the fold amplitude according to a power law with a power law exponent of 1/8 and not exponentially as predicted by the linear theory, and
- decrease simultaneously the axial load, and the driving force of the instability with the square root of the time.

In three dimensions, both elastic and viscous materials develop two wavelengths, one "dominant" wavelength normal to the maximum shortening rate and another "subsidiary" wavelength normal to the intermediate shortening rate. Thus, fold patterns resembling interference structures can develop. Neither of these wavelengths coincide with the classical Biot wavelength except in special circumstances.

It is common in geological arguments to neglect elasticity under the pretext that the Deborah number, De, (relaxation time/process time) of geological processes and materials is negligibly small. The latter is true only if the deformation process is stable in the mechanical sense . Instabilities such as folds, convection cells, plastic instabilities such as shear bands usually grow and evolve at their own, separate, time scale. The Deborah number for unstable processes is given by the rate of growth of the instability times the relaxation time of the material. Neglect of instantaneous aspects of the material behaviour such as elasticity and certain types of plasticity is admissible only if De << 1 .

These characteristics of materials with coupled elastic and viscous constitutive behaviour seem to be fundamental in allowing single layers to deform into fold systems that are irregular or even chaotic with respect to the spatial distribution of wavelengths. For some such materials localisations of buckles develop; these can combine to produce irregular fold systems. In other materials the folding processes is deterministically chaotic so that the final buckled configuration is inherently sensitive to initial conditions.

We conclude this review with a numerical study concerning the development of "axial-plane" foliations. In our study the formation of the foliations is triggered by strain rate softening of the folding material. The numerical model consists of a 2D rectangular domain, subdivided into 10,000 parabolic triangular elements. The large deformation problem associated with the fold evolution is solved by domain advection; ie the volume occupied by the fold material moves, that is it is advected, through the finite element mesh. In our simplified analysis the length scale determining the spacing between the foliation planes is related to the average size of the finite elements. In reality this length scale would be provided by typical micro structural dimensions of the material such as grain size. In principle such microstructural dimensions could be considered within the framework of a continuum theory by including higher order strain gradients or additional degrees of freedom into the constitutive description of the material (Mühlhaus and Aifantis, 1991).

The foliation surfaces nucleate as shear instabilities oblique to the axial plane but rotate towards an axial plane orientation as the fold amplitude grows.

The development of crenulation cleavage and, in particular, of differentiated crenulation cleavage is considered in a separate paper in this conference by Ord et al (1998).

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A Sensitive Vorticity Gauge and Its Application to Flow in the Alpine Schist near the Alpine Fault, New Zealand

R. J. HOLCOMBE
Department of Earth Sciences, The University of Queensland, Australia
and T.A. LITTLE
School of Earth Sciences, Victoria University of Wellington, Box 600, Wellington, New Zealand

The Alpine Schist in New Zealand is an east-tilted sequence of mid-crustal rocks that has been ramped to the surface along the SE-dipping Alpine Fault. Within about 1.5 km of the present surface trace of the active Fault in the Franz Josef and Fox glaciers area, the youngest fabrics in the schist are mylonitic and broadly reflect the known kinematics of the fault (dextral with a slight reverse component, and with transpressional flow kinematics). Further away from the fault, this youngest ductile fabric is no longer pervasive and the dominant foliation is an older SE-dipping, intensely lineated fabric (D2). This high-strain fabric is locally overprinted by zones of strong asymmetric folding (F3) that result in only a modest bulk shortening but which control the orientation of the older fabric. Both biotite and garnet are developed as abundant porphyroblasts in the graphitic schist, and the growth of both is syntectonic with, or overprint, F3 folds and fabrics. The size and preservation of both species is such that individual porphyroblasts generally overgrow several graphitic laminae and each internal lamination can easily be correlated with its external parent. Thus, we have elements of a fine-scale displacement gauge in these rocks. Using these relationships, we can show that the contractional stretch across the limbs of the F3 folds is 50% since the growth of garnet, and 25% since the growth of the earliest preserved large biotite porphyroblasts. Both species show evidence of rotation associated with a slight shear and a shortening across the layers. Biotite, in particular, can be used to characterise the flow of this deformation because the rotation (relative to the external laminae) can be precisely measured using the Si/Se relationships. If we assume that the porphyroblasts exhibit a flow-coupling consistent with Ghosh and Ramberg-type flow models then the angle and sense of rotation of a biotite lath is a function of its initial orientation, the aspect ratio, the kinematic vorticity number, and the shear strain. We have compared measured orientation distributions of biotite laths with theoretical deformed distributions generated using this flow model. In particular, plots of the orientation of Si versus the orientation of the long axis of the porphyroblast, have distributions that are very sensitive to differences in kinematic vorticity number, and from which shear strain can also be estimated.

In the Alpine Schist described above, the deformation producing shortening across the F3 limbs has a low vorticity number (~0.2) and a bulk shear strain of about 0.6. The flow in these rocks has been strongly transpressional. The shear sense is consistently east-block-down (normal relative to the current steeply SE-dipping foliation orientation) and is independent of the position in the F3 folds and apparently overprints those structures, resulting in widespread oblique quartz grain-shape fabrics of uniform shear sense. We interpret this shear component to have been imprinted on the F3 fabric during late Cenozoic deformation and uplift of the schists. Remarkably, this widespread, shear deformation in the Alpine schist is dip-slip, in contrast to the strike-slip dominated kinematics of the narrow mylonite zone to the west, a relationship suggestive of marked strain partitioning of oblique motion. The kinematics of dip-slip shear in the schist is strongly transpressive (low kinematic vorticity number), similar to that of strike-slip dominated shear in the mylonite zone.

A reconstruction tool for a plane orientation from oriented thin-sections

SangGi HWANG

Department of Earth Resources and Environmental Engineering, Paichai University, DomaDong, Taejon, Korea

Pervasive planar structures are not always clear on the outcrop surface, and therefore oriented samples are often used to observe detailed nature of the planar structures. Orientation of a plane, could easily be reconstructed if more than two oriented thin-sections are used. Although simple vector calculations or careful stereonet operations can solve this problem, practical operation can be very confusing.

An automation tool for geometry calculation in oriented thin-section study utilize three oriented sample planes. Four steps are involved in the automatic reconstruction tool. Orientations of slabs, which embrace the thin-sections, are calculated by graphical process using stereonet routine. In second step, calculated slab orientations are converted to the unit normal vectors and the three intersection vectors are calculated. Intersection vectors are classified to east-west, north-south, and vertical axes of the slabed sample and their 3D geometry is constructed. In third step, each slab is rotated to horizontal plane so that user can orient the thin-section and input observations under microscope to the computer monitor graphically.

Final step involve back rotation of the three plane view and graphic input data into true geographic space. Averaging the 3D line orientations, proper plane orientation is calculated and its result is plotted to a 3D block. The 3D block can be rotated according to the three Cartesian coordinate axes.

Crustal-Thickness Fluctuation during the Grenville Orogeny - Evidence from Lithoprobe Line 55

Andrew HYNES
Dept. of Earth & Planetary Sciences, McGill University, 3450 University St., Montreal, Canada H3A 2A7
Aphrodite INDARES, Toby RIVERS
Dept. Earth Sciences, Memorial University, St-John's, Newfoundland, Canada A1B 3X5
David EATON
Dept. Earth Sciences, University of Western Ontario, London, Ontario, Canada N6A 5B7
and André GOBEIL
Minist re des richesses naturelles, 5700 4eme ave Ouest, Charlesbourg, Québec, Canada G1H 6R1

Correlation of structure observed at the surface to the seismic reflectors on Lithoprobe Line 55 provides unusually good control on the three-dimensional geometry of the Grenville province in eastern Quebec. This geometry indicates that Archean basement underlies the Proterozoic rocks exposed at the surface, along the entire length of the seismic line, and that there is a steep ramp in this basement that is immediately outboard of the broad embayment of high-pressure metamorphosed rocks comprising the Manicouagan Imbricate Zone. The high metamorphic pressures exhibited by many of the rocks in the Manicouagan Imbricate Zone (MIZ) require burial depths of more than 60 km for these rocks at about 1050 Ma. Preservation of their high-pressure assemblages, however, and the absence of evidence for metamorphism at 990 Ma, which is characteristic of the lower-pressure metamorphosed rocks that tectonically overlie them, indicates that these rocks were transported to shallow crustal levels rapidly, and early in the evolution of the orogen. The geometric, metamorphic and geochronological constraints require that there were two discrete episodes of crustal thickening during the Grenville orogeny in eastern Quebec. The first, involving imbrication of the already tectonically assembled rocks of the Labradorian orogen, culminated at ca. 1050 Ma and was responsible for the high-pressure metamorphism evident in the MIZ. The effects of much of this crustal thickening were rapidly reversed with the extrusion of the MIZ rocks to shallow crustal levels before 1020 Ma. At this stage, the Moho may have been approximately flat through much of the region, at a depth of ca. 50 km. The crust was, however, again thickened, with the Moho subsiding to depths of more than 60 km and perhaps as much as 70 km, in an event culminating at 990 Ma. The upward extrusion of the MIZ between 1050 and 1020 Ma, and the shallowing of the Moho that accompanied it, indicate that this process involved much more than internal readjustment of the growing orogenic wedge. The causes of the extrusion are not well established, but are possibly related to detachment and subsidence of the upper mantle from the zone of crustal thickening, which is suggested by the unusually high geothermal gradients evident from metamorphic assemblages in the region.

Slip partitioning in transpressional regimes and the resultant high-strain zone deformation

Dazhi JIANG, Paul F. WILLIAMS
Department of Geology, University of New Brunswick, Fredericton, NB. Canada E3B 5A3
and Shoufa LIN
Manitoba Energy and Mines, 59 Elizabeth Drive, Thompson, MB Canada R8N 1X4

In most transpressional plate boundaries, the relative plate convergence velocity vector, $\mathbf{v}$, is partitioned into an inter-plate component, $\mathbf{v}_a$, taken up by the subduction slip and an intra-plate component, $\mathbf{v}_b$, taken up by deformation within the overriding plate. Generally, the obliquity of the relative plate velocity (γ, the angle between $\mathbf{v}$ and the trench normal) is partitioned (Fitch 1972; McCaffrey 1992). The degree of obliquity partitioning can be measured by the parameter κ (= $1-\psi/\gamma$) defined by Liu et al. (1995), where ψ is the subduction slip obliquity, the angle between the azimuth of the subduction slip vector and relative plate velocity vector $\mathbf{v}$. There is abundant evidence that the convergence component of the relative velocity ($v\cos\gamma$) is generally also partitioned. We define a parameter R= $v_a\cos\psi/(v\cos\gamma)$ to measure the degree of such convergence component partitioning. For a general transpressional boundary, 0#κ#1 and 0#R#1. We show that this will generally cause a trench-parallel high-strain zone in the overriding plate to follow a triclinic deformation path on the bulk scale. Monoclinic deformation paths are special cases.

We have modeled the deformation of a general high-strain zone taking also into consideration volume change. Five independent parameters are required to characterize the rate of deformation of the flow; four are sufficient to characterize the flow kinematics. The model is generally triclinic, and orthorhombic and monoclinic deformations are subgroups. By varying the values of the characterizing parameters, the various types of high-strain zones can be represented. The kinematics of flow within such zones and the accumulated finite deformation geometry are investigated. Our general model increases the possibilities for structural interpretation. Many ancient high-strain zones such as the Roper Lake shear zone in Nova Scotia and the Southern Knee Lake shear zone in Manitoba are likely triclinic shear zones resulting from oblique transpression. Alpine fault in New Zealand may be a presently active high-strain zone with triclinic deformation path. Fold geometry and the occurrence or lack of sheath folds in some shear zones where folds have been significantly rotated may also be related to triclinic deformation path.

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Syntectonic Quartz Veining in Granitic Mylonite

Zhenting JIANG and Klaus WEBER
Institut fuer Geologie und Dynamik der Lithosphaere, University of Goettingen, Goldschmidt Str. 3, 37077 Goettingen, Germany

Pure quartz layers (Stuenitz & Fitz Gerald, 1993) or pure quartz bands (Fliervoet, et al., 1997; Hippett, 1998) belong to significant microfabric elements in mylonites derived from granitic rocks. Conventionally, these foliation-concordant quartz domains are considered to be formed by strong elongation of former large quartz grains or pre-existing quartz aggregates. However, such interpretation is not always supported by the microstructural features. In this paper, we present concrete evidences to support that pure quartz domains can also be formed due to syntectonic quartz veining.

The studied samples were collected from a metre-scale shear zone developed within a granitoids in the Elbe Zone, Saxony, Germany. In the outcrop, the shear zone boundary is defined by a sharp contact between well-foliated shear zone mylonites and weaker deformed massive granitoids in the wall. The mylonite is characterized by well-developed domainal microfabric defined by an alternation of pure quartz domains and polymineralic domains of quartz, muscovite and feldspar. In the XZ section (cut parallel to the stretching lineation), pure quartz domains appear as foliation-concordant, polycrystalline ribbons with widths ranging from several µm to 0.5 mm and extend across the entire thin section, indicating that there exists no constant length/width ratio for these quartz ribbons. Quartz within the ribbons show strong undulatory extinction, but they are not dynamically recrystallized. Under crossed microscopy, quartz in all of the ribbons exhibit very low interference color from dark gray to permanent extinction. In the thin section cut perpendicular to the lineation (YZ-plane), pure quartz domains can be better described as foliation-parallel veinlets, in which fibrous quartz crystals show a growing-direction almost perpendicular to vein boundaries, suggesting that the quartz veins precipitated in foliation-parallel tensile fractures with a opening tensor parallel to the Z axis of the sample reference system. The quartz veins show a obvious convergence along the foliation, which is in contrast to the parallelisms of quartz domainal boundaries observed in the XZ section, indicating that the propagation of tensile fractures must be much faster along the X axis than it does along the Y axis. By inserting a gypsum plate under crossed microscopy, it is interesting to note that all quartz veins under the observing field are dominated by a certain interference color and they will change their color synchronously between green-blue and yellow when rotating the thin section, indicating that not only quartz within a vein but in all of the veins possess a similar crystallographic orientation. U-stage measurement has confirmed that c-axes of fibrous quartz tend to be concentrated around the Y axis, suggesting that the c-axes tend to be oriented almost perpendicular to their growing direction of fibrous quartz.

A two-stage model has been proposed for the generation of foliation-concordant quartz veins. Opening of foliation-parallel tensile fractures should be related to the development of high anisotropy of host rocks and high fluid pressure. Fibrous quartz crystals were growing under the influence of a local stress configuration which is different to the regional tectonic stress condition.

Magmatic vs. Amagmatic Extension: Examples from the Colorado River Extensional Corridor, southern Basin and Range

Barbara E. JOHN
Dept. of Geology and Geophysics, University of Wyoming, Laramie, WY 82071
Erin A. CAMPBELL-STONE
Chevron U.S.A., P.O. Box 69100, Lafayette, LA 70596)
and David A. FOSTER
Dept. of Geology, University of Florida, Gainesville, FL 32611

The Colorado River extensional corridor (CREC) accommodated up to 100% asymmetric extension (~50 km) between ~23 and 12 Ma. New structural, geophysical, and geochronologic data document the episodic character of both magmatic and amagmatic/tectonic accommodation to extension, and along-strike variations in the dominant mode of extreme crustal stretching. The adjacent Chemehuevi and southern Sacramento mountains core complexes demonstrate the relative roles these two mechanisms play in crustal extension at equivalent structural depths.

Extreme extension involving the upper and middle crust in the Chemehuevi Mountains core complex was accomplished along a stacked, anastomosing sequence of brittle, NE-dipping low-angle normal or detachment faults discordantly cutting deformed Proterozoic and Mesozoic crystalline basement. The large displacement (>18 km) Chemehuevi-Sacramento detachment fault (CSDF) separates footwall and hanging wall rocks from different crustal depths. Hanging wall rocks above the CSDF were distended by innumerable high-angle normal faults that rotated to more gentle dips through time, and together accommodated up to ~100>% extension regionally. In contrast, footwall rocks originally of mid-crustal affinity were only gently rotated and accommodated minor extension (<2%) by normal and strike-slip faulting, local ductile shearing, and very limited dike emplacement. These relationships imply that extension of the upper and middle crust was dominantly tectonic or amagmatic, and nonuniform.

In contrast, crustal stretching in the adjacent southern Sacramento Mountains was both magmatic and tectonic. There, footwall rocks to the CSDF comprise syntectonic magmas emplaced into variably mylonitized country rocks as three intrusive pulses between ~19 and 16 Ma. These diorites to granites together form the Sacram suite, which accommodated 5-18 km magmatic extension (10-20% total extension) in the CREC at this latitude. Each of the three pulses was emplaced as steeply dipping, dike-like bodies of variable strike (~125°, ~110°, and ~105°, respectively, oldest to youngest), implying rotation of the extension direction through time. The three intrusive pulses bear brittle and/or semi-brittle fabrics, and show no crystal-plastic deformation.

Th regionally developed CSDF separates the footwall from hanging wall in both core complexes, and was apparently active during three separate episodes of tectonic extension. Detailed U-Pb-zircon, Ar/Ar, and fission track chronology suggest that earliest extension occurred between 23-19 Ma, prior to emplacement of the Sacram suite. Faulting resumed after emplacement of the Sacram suite but before doming of the footwall in each core complex at ~16 Ma. A secondary breakaway fault was initiated after doming of the footwall (~15-14 Ma), and was active only on the dip-sip side (NE) of the core complexes.

Together these data indicate that stretching in this part of the CREC was initiated with tectonic slip along a detachment fault system, with localized, pulsed, magmatic accommodation of extension beginning at ~20-19 Ma. The three discrete magmatic episodes documented in the southernmost Sacramento Mountains record magmatic extension and rotation of an inferred least principal stress direction over the following ~3 Ma. Amagmatic or tectonic extension to completely denude and erode the core complexes, and deposit footwall rocks in the hanging wall, dominated the final 3-4 Ma of stretching.

Ductile extensional deformation along the west flank of the Monashee complex, southern Canadian Cordillera.

Dennis H. JOHNSTON
Petro-Canada Oil and Gas, P.O. Box 2844, Calgary, Alberta, Canada T2P 3E3
Paul F. WILLIAMS and Paul MCNEIL
University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3

Two basement-cored antiformal culminations of high-grade metamorphic rock, Thor–Odin and Frenchman Cap, comprise the Monashee complex in the hinterland of the southern Canadian Cordillera. Rocks in the studied area along the west flank of the Thor–Odin dome are thoroughly transposed (into S_2). The extent of the transposition, and a well-developed northeasterly-trending L_2 lineation, indicate intense strain during F_1/F_2 throughout the culmination (4-5 kilometre thickness exposed). Penetrative northeastward ductile flow parallel to the transposition foliation continued, resulting in northeasterly-verging F_3 folds and related fabrics. West of Thor–Odin dome, in the Selkirk allochthon, F_3 folds verge west-southwest. Along the west flank of the Thor–Odin dome, in the Greenbush shear zone (GSZ), the L_2 lineation was rotated to a west-southwest trend, folds were truncated and abundant mesoscopic WSW-dipping top-to-WSW shear bands formed as a result of D_5 extension and reactivated slip on S_2. The shear bands are interpreted as having formed after significant ductile slip had occurred and the prominent WSW-trending L_5 lineation in the GSZ had developed. L_5 pull-aparts are filled with muscovite, biotite and rare chlorite, indicating the pull-aparts likely formed at the same time as the retrograde shear bands. Shear bands in the GSZ are typically in the order of 2-5m in scale. Similar microscopic-scale shear bands are common west of the GSZ in the Joss Mountain area. Meso- and microscopic top-to-W shear bands, that also are interpreted as having formed during extensional deformation, have been reported along the west and northwest flanks of the Frenchman Cap dome. On the east side of the dome in the vicinity of Revelstoke S_2 was also reactivated. First in the ductile field with the development of sheath folds plunging southeasterly and then in the brittle field. The reactivated S_2 surface locally truncates F_3 folds and shear bands indicate that the movement is down to the south east.

The regional lineation along the west flank of the Monashee complex and through the remainder of the Shuswap complex trends westerly. The lineation becomes more pronounced towards the top-to-W Okanagan Valley normal fault system which forms the western boundary of the Shuswap complex. The regional lineation in the Shuswap complex may have formed, at least in part, during ductile extensional deformation, not during earlier contractional deformation alone as interpreted by previous workers. Geochronological data from this study and others dictate that this ductile extensional deformation younged downward through the Shuswap complex structural pile from the Late Cretaceous to Early Eocene. The possibility that within the Cordilleran orogenic wedge protracted ductile extensional deformation in the hinterland was coeval with thrusting in the foreland warrants further investigation.

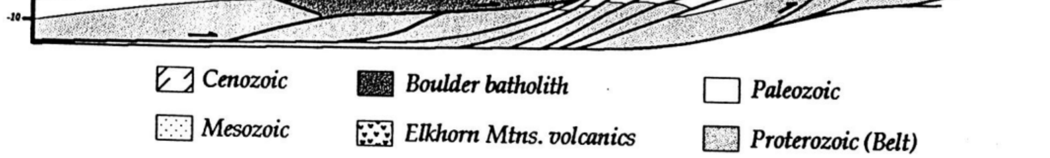
Shallow level synkinematic batholith emplacement within fold-and-thrust belts

Thomas J. KALAKAY
Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071-3006
David R. LAGESON
Department of Earth Sciences, Montana State University, Bozeman, MT 59717
and Barbara E. JOHN
Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071-3006

The synkinematic emplacement of large-volume, shallow level silicic plutons into orogenic belts undergoing regional shortening has escaped clear understanding despite decades of field-based research. The basic problem centers on the need to make room for magma in an environment where shortening, rather than extension, is occurring on regional scales. This problem is nowhere more evident than in the U.S. Northern Rocky Mountains where the Late Cretaceous, continental margin magmatic arc invaded the Sevier fold-and-thrust belt, Laramide basement uplift province, and western interior foreland basin.

In western Montana, the Boulder and Pioneer batholiths were intruded from 80-70 Ma within the Sevier fold-and-thrust belt, synchronous with regional contractile deformation at the same latitudes. Collectively, these batholiths and their satellitic stocks have an aerial extent in excess of 10,000 km^2. The volcanic carapace of the Boulder batholith, the Elkhorn Mountains volcanic field, is estimated to have been >5 km thick and to have covered over 25,000 km^2, comprising one the largest ash-flow fields on Earth. These enormous magma volumes affected both the geometry and rheology of the fold-and-thrust wedge at regional scales, the effect being variable through time as a function of cooling rate and strain rate. The Boulder and Pioneer batholiths expose tabular bodies that were intruded at slightly different crustal levels. The epizonal nature of the Boulder batholith is underscored by the fact that it intrudes its own superjacent volcanic field, whereas the Pioneer batholith represents a slightly deeper slice through the thrust belt as evidenced by pervasive contact metamorphism and plastic deformation of wall-rocks. In both cases the foreland-facing intrusive contact is generally concordant with country rocks and subparallel to major thrust traces.

Balanced regional cross-sections, deep seismic reflection data, data from deep boreholes, and tectonic reconstructions suggest that the Boulder and Pioneer batholiths were emplaced as composite tabular bodies at the top of frontal thrust ramps between the hinterland and foreland portions of the Sevier orogen. We propose a model of magma emplacement in the thrust belt that takes this geometry and structural position into account. Frontal thrust ramps involve three elements that may facilitate pluton emplacement: 1) extension along the ramp interface produced by incremental plane-strain simple-shear faulting, creating a feeder zone for magma migration; 2) a dilatant space or "releasing step", at the top of the ramp, serving as a nucleation point for pluton growth; and 3) antithetic back-thrusts that assist in pluton ascent. The model predicts that pluton ages should "young" towards the ramp, as indeed they do in the Pioneer batholith; radiometric data from the Boulder batholith are too sparse to make a similar determination. Previous models that attempt to explain the emplacement of batholiths in western Montana invoke transtensional "pull-apart" zones along reactivated faults, gravitational detachment from the roof of the Idaho batholith to the west, or compound sill-like intrusions of magmatic sheets. However, these models do not that take into account the ramp-top structural setting of the two largest volume batholiths.



Gneiss Canyon shear zone: P-T-t-D paths and character of Proterozoic midcrustal suturing in the western Grand Canyon, Arizona

K. E. KARLSTROM
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, 87131.
Michael L. WILLIAMS
Department of Geology and Geography, University of Massachusetts, Amherst, MA, 01003.
and Samuel A. BOWRING
Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, 02139.

The Gneiss Canyon shear zone, exposed in the Lower Granite Gorge of the Grand Canyon, may be part of a cryptic middle crustal "suture zone" between island arcs or different parts of the same arc. It juxtaposes crustal blocks with different P-T-t-D histories, and perhaps different isotopic signatures, over a 10-km-wide subvertical, west-side-up, reverse-sense, high strain zone. The main fabric in the zone records an intimate interaction of deformation, metamorphism, and melt transfer during shortening; this overprints and obscures a possible earlier accretionary history. This type of wide distributed high strain zone may be a typical expression of sutures at 10-20 km crustal levels because of unique rheological and thermal structure of the middle crust.

Volcanogenic protoliths, the character of pre- and syn- assembly plutons, ca. 1.7 Ga timing of progressive contractional deformation, and structural geometries are similar in rocks across the shear zone. But, rocks within and west of the Gneiss Canyon shear zone are similar to the Mojave province, with Pb 207\204 ratios indicating significant 2.0-2.5 Ga crustal material reworked into the 1.7-1.8 Ga rocks. Rocks east of the shear zone have Pb 207/204 ratios more similar to juvenile arc rocks of central Arizona. A second difference is seen in P-T paths: the western side (hanging wall) is characterized with a looping P-T path with a clockwise portion to peak conditions of 650 EC and 5 kbar, followed by decompression from 5-3 kbar and stabilization of crust at 3 kbar. The eastern side (footwall) has a counterclockwise P-T path involving prograde heating to 550 EC and 3 kbar then isobaric cooling.

Peak portions of both paths were synchronous with 1700-1685 Ma deformation. On the eastern side, the deformation path involved initiation of S2 and appreciable D2 shortening before growth of prograde garnet and andalusite in pelites and orthoamphibole in mafic rocks. Intensification of S2 during peak metamorphism is recorded by syn-S2 sillimanite and cordierite and inclusion-free rims on garnets. U-Pb sphene dates of 1698 +7 date the peak metamorphism. On the western side, the deformation path involved progressive flow of gneissic rocks near peak conditions and formation of S1 and S2 fabrics, neither of which correlate in orientation or kinematic significance with S1 and S2 east of the zone. Western fabrics were synchronous with plutonism and formed between 1700 and 1685 Ma as shown by U-Pb monanzite dates on syn- and late- tectonic granites. Sill-like plutons and injection networks at 4-5 kbar were apparently important in creating the low-P high-T metamorphism, and in changing lower middle crustal rheology to that of partitioned subhorizontal flow on the west side. Presence of migmatites in the Gneiss Canyon zone also suggests that the shear zone acted as a conduit for melt transfer, such that present crystallized plutons represent a last quench of a dynamic system that may have operated for 10s of m.y. during arc collision.

Mechanical Behaviour of a Bimineral Shear Zone Across Brittle-Plastic Transition

Eiko KAWAMOTO
Earthquake Research Institute, University of Tokyo, JSPS Research Fellow

Shearing behaviour of polycrystalline halite-calcite mixed layers (0.7 mm thick) have been studied experimentally to understand the effect of mineral composition on the overall strength profile of the lithosphere, using a high temperature biaxial testing machine. Experiments were performed at temperatures to 700EC, increasing linearly with increasing normal stress with the experimental geotherm of 22EC/MPa, under the slip rate of 0.3 μm/s, and with shear strains to 30.

Experimental results are summarized in Fig. 1. 100 % halite shear zones provide a complete experimental strength profile of the lithosphere, which can be divided into brittle, intermediate and fully-plastic regimes. Stick-slip (unstable fault motion) was recognized down approximately to the strength peak, slightly below the middle of the intermediate regime. For 100 % calcite shear zones, on the other hand, the shear stress increases almost linearly with increasing normal stress for temperatures up to 700EC, and stick-slip occurred in all tests. For mixed halite-calcite shear zones (halite/calcite = 20/80 in volume %), the strength profile is close to that for 100 % halite shear zones, and stick-slip disappears around the point where the stick-slip of pure halite shear zones vanishes. Figure 1 indicates that when a fault zone consists of a mixture of minerals, the strength and behavior of the fault is determined primarily by the weaker mineral. Experimental results in Fig. 1 disproved fault models of Strehlau (1986) and Scholz (1988).

In order to evaluate the content of weaker mineral controlling the bulk strength of mixture, experiments were performed on bimineralic shear zones with various portions of halite at 600EC. Ultimate and residual frictional strengths can be described, respectively, by the framework model of Tharp (1983) and by the two-block model of Jordan (1988). The weaker member influences the bulk strength when its content is as small as 5 % in volume at large strains. This result brings out the significance of phyllosilicates in natural fault zones in determining their frictional properties.

Preliminary shearing experiments on mixed chlorite-calcite layers have been performed to study an influence of phyllosilicates on mechanical properties of fault, at room temperature, about 25 MPa normal stress, at a displacement rate of 3 μm/s and under wet conditions. The shear strength of the specimens considerably decreases even when chlorite content is as small as 5-10 % at large displacements near the residual frictional strength.

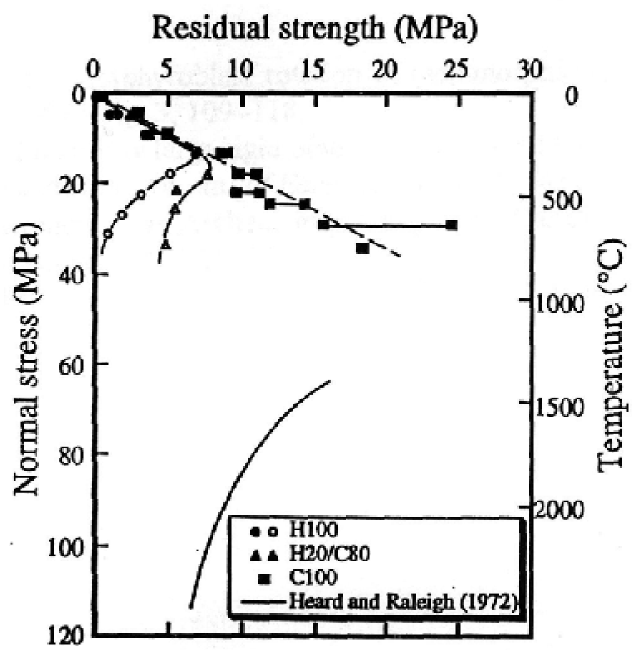


Figure 1. Strength profile on halite, calcite and halite-calcite mixed shear zones for residual strength. In case of stick-slip, the maximum and minimum shear stresses are given by closed symbols tied with a horizontal line, and stable slip is shown by open symbols. Flow law in calcite by Heard and Raleigh (1972) extrapolated to this test conditions is also drawn.

Microstructural and geochemical evidence for a Salinian tectonic event in the Gaspé Peninsula

Donna KIRKWOOD
Département de géologie et de génie géologique, Université Laval, Sainte-Foy, Québec, G1K 7P4
and Martine M. SAVARD
Delta-lab, GSC-Québec, Centre géoscientifique de Québec, 2535 Laurier, CP 7500, Ste-Foy, Québec, G1V 4C7

Recent work in northeastern Gaspé has helped identify brittle structures related to an upper Silurian/lower Devonian Salinian event. The Salinian orogeny has been recognized as a major tectonic event in the northeastern Appalachians. Up until recently, evidence for this event in the northeastern Gaspé belt rocks has been provided by detailed sedimentological analysis. The Salinian unconformity, recognized throughout the peninsula, is presently related to regional synsedimentary normal faulting during Late Silurian-Early Devonian. New field and laboratory work documents the development of brittle faults and fractures during this Salinian event within the Upper Ordovician-Lower Silurian White Head Fm in northeastern Gaspé.

The chronological relationships between the different microstructures was determined by combining microstructural and microgeochemical studies. Petrography and isotope geochemistry were used to verify if the microfractures were enhanced by potential Salinian karsting. Samples from outcrops stratigraphically 200 to 1000 meters below the Salinian unconformity helped identify five sets of structures within the White Head Fm. They include bedding-parallel stylolites (T1); irregular dissolution planes and microfractures (T2), V-shaped veins (T3); subhorizontal veins and subvertical stylolites (T4); and subvertical veins (T5). $\delta^{13}C$ and $\delta^{18}O_{VPDB}$ of primary pore cement and vein calcites indicate that the general diagenetic trend for the White Head Fm evolves from marine conditions ($\delta^{13}C$=0.5; $\delta^{18}O$=-4.5‰), to progressively deeper burial conditions ($\delta^{13}C$=0.2; $\delta^{18}O$=-9.7‰). However at two sites, following a period of burial, the formation was subjected to shallower conditions during T3 ($\delta^{13}C$=-1.0; $\delta^{18}O$=-3.5‰). Cross-cutting relationships indicate that structures formed during T2-T3 events are post-lithification (T1) and pre-Acadian, because T4 and T5 are structurally compatible with the well-documented transpressional regime of the Gaspé Middle Devonian. T2 and T3 structures are brittle structures that imply shallow level P-T conditions, an interpretation which supports the isotopic indication. Results from fluid-inclusion microthermometry also suggest that rocks of the White Head Fm were buried, fractured, uplifted and then buried again. Thus, we conclude that T2 and T3 were brittle structures formed during a tectonic event of regional importance related to the Salinian disturbance.

Rotating porphyroblasts during folding: real or unreal?

Jürgen KRAUS and Paul F. WILLIAMS
University of New Brunswick, Department of Geology P.O. Box 4400, Fredericton, N.B., Canada E3B 5A3

It has been claimed that rigid porphyroblasts, that grow before or during folding and concurrent cleavage development, do not rotate with respect to a geographical reference frame (GRF), even if the straining is non-coaxial (Bell 1985, Bell and Johnson 1990). The explanation offered is based on strain partitioning. It is argued that the initial orientations of early fabrics included as internal foliations (S_i) in the porphyroblasts have been preserved after polyphase deformation, and even after successive orogenies. According to the strain partitioning model, the porphyroblasts are fixed in domains of coaxial straining (microlithons) and are isolated from the non-coaxial straining associated with the enveloping septa (S_e). This hypothesis, and its discussions both pro and contra, suffer from insufficient attention to reference frames.

We attempt to demonstrate (a) the need for rigorous treatment of reference frames in geological interpretations; (b) that grains in coaxial domains generally rotate with respect to the GRF; and (c) that the non-rotation hypothesis is in conflict with heterogeneous deformation (cleavage refraction). Finally, we question the validity of the evidence in studies by Ramsay (1962) and Fyson (1980), cited in support of non-rotation with respect to the GRF during folding.

In detail, we show that rotations with respect to different reference frames are not kinematically equal, because any two reference frames are incongruent. Consequently, the strain partitioning model *does not* preclude porphyroblast rotation with respect to the GRF, unless S_e is fixed with respect to the GRF throughout folding. The latter condition demands rare folding mechanisms (slip-fold model, or a special case of the flexural-flow fold model).

Fyson reported orientations of S_i that are constant, after folding, over a large area; this scenario is a product of selective data acquisition. Ramsay's model requires a special folding mechanism, which does not appear to be generally applicable in natural rocks.

In summary, our investigation shows that non-rotation of porphyroblasts with respect to a GRF during folding, while possible, is not universal. The development of microstructures (e.g. curved S_i) is only related to the local deformation path, the characterisation of which does not rely on the GRF.

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Microstructural, petrological and geochronological studies on the Thor-Odin dome, Monashee Complex, southern Canadian Cordillera

Yvette D. KUIPER

Department of Geology, University of New Brunswick, Fredericton, N.B., E3B 5A3
and Department of Earth Sciences, Carleton University, Ottawa, Ontario, K1S 5B6

Sharon D. CARR

Department of Earth Sciences, Carleton University, Ottawa, Ontario, K1S 5B6

and Paul F. WILLIAMS

Department of Geology, University of New Brunswick, Fredericton, N.B., E3B 5A3

The basement-cored Monashee Complex of the southern Omineca Belt comprises two structural culminations; Frenchman Cap in the north and Thor-Odin in the south. The Selkirk Allochthon, which structurally overlies the Monashee Complex has been interpreted as having been emplaced onto the Monashee Complex by NE-directed transport on the Monashee Décollement (Brown et al., 1986, 1992). The location and the character of the décollement are based on lithologic, metamorphic, structural, geochronologic and regional arguments from a number of segments studied on the flanks of both Frenchman Cap and Thor-Odin domes (Journeay, 1986; Brown et al., 1986, 1992, and references therein; McNicoll and Brown, 1995, and references therein). However, recent work by Williams, Spark, and Johnston on the western flank of Thor-Odin has failed to reveal the décollement. Instead, a zone of uniform transposition extending throughout the exposed depth of the complex is observed. Transposition was followed by younger folds, E-W boudinage and regional extension (Johnston et al., 1996; Johnston, 1997; Spark, 1997).

U-Pb data indicate a younging of structures and thermal peak of metamorphism with decreasing structural level in the Selkirk Allochthon and Monashee Complex (Parrish, 1995, and references therein; Crowley, 1997; Gibson, 1997; Carr, 1992). Data from western Thor-Odin generally show the same pattern (Johnson, 1994; Johnston, 1997; Johnston et al., 1998). Metamorphic monazite ages are 94-90 Ma in the Selkirk Allochthon west of the Joss Pass brittle fault and are ~57-55 Ma in the Monashee Complex east of the Joss Pass fault (Johnston, 1997). Enigmatic U-Pb metamorphic ages from Three Valley Gap (73.4±1.7 Ma zircon, Parkinson 1992; 89.5±0.5 Ma zircon, Wasteneys, unpublished data, 1998; ca. 72, 59.5 and 49 Ma monazite, Kuiper and Carr, unpublished data, 1998) do not fit this pattern. This is being adressed by new fieldwork and laboratory studies.

The apparent structurally downward younging of thermal peak of metamorphism in the Selkirk Allochthon and Monashee Complex may have resulted from either 1) downward heat conduction from an overthrusted hot crustal slab with or without hot intrusions, 2) the juxtaposition of rocks with different metamorphic grades and ages by thrusting, normal faulting, or folding, or 3) a combination. On the western flank of Thor-Odin, more data are required to establish the variation of metamorphic grade and age with structural depth, to test whether there is a gradient or whether there are two age domains present.

Detailed metamorphic and U-Pb geochronology studies will be conducted on the northwest and west flanks of Thor-Odin in order to characterize the protolith age of rocks as well as the conditions and timing of deformation, high-temperature metamorphism and cooling history at all structural levels and on both sides of identified structures. This may: 1) allow Selkirk Allochthon and Monashee Complex rocks to be distinguished, 2) establish the presence or absence of the Monashee Décollement as a syn- or post-F_1 structure, 3) deduce the thermal history throughout the structural profile, 4) place some constraints on the magnitude of displacement of structural discontinuities, 5) test ideas as to whether or not Frenchman Cap and Thor-Odin are at the same structural level, and 6) test existing tectonic models for the area (cf. Johnston et al., 1998; Parrish 1995, etc.). Research is being carried out under the supervision of P.F. Williams and S.D. Carr. This project will elucidate the structural relationships between the Monashee Complex and the Selkirk Allochthon, between the Frenchman Cap and Thor-Odin culminations, and distinguish between compressional and extensional fault systems.

Components of syn- and post-deformational coalification in the Mountain Park area, west central Alberta

C. Willem LANGENBERG
Alberta Geological Survey, Alberta Energy and Utilities Board, 9945-108 Street, Edmonton, Alberta, T5K 2G6
and Wolfgang KALKREUTH
Instituto de Geociências, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, Rio Grande do Sul, Brazil

Cardinal River Coals Ltd. obtained permission to develop a coal mine in the Mountain Park area, south of Hinton, which will be known as the Cheviot Mine. The coal will be exported for use in the steel industry. The Lower Cretaceous Jewel seam, which is generally about 10 meters thick, is the major economic coal seam of the Cheviot Mine Project area. The strata of the area are folded and cut by several thrust faults. Total amount of shortening is estimated to be 50 percent. Vitrinite reflectance of the Jewel seam (and other coal horizons) was measured from samples collected at outcrops and drill holes from close to hundred, evenly distributed, locations. The mean maximum vitrinite reflectance of the Jewel seam ranges from 0.94 to 1.28 percent, with the highest values in the lowest thrust sheet. In addition, there is a slight east to west increase in reflectance in each thrust sheet.

In order to examine relationships between coalification and deformation, vitrinite reflectance anisotropies were determined from oriented coal blocks. Several blocks have biaxial anisotropies, indicating a relation to tectonic stress fields. These biaxial coals display maximum reflectance axes parallel to nearby fold axes, which suggests a relationship between vitrinite anisotropy and local deformation. The biaxial vitrinite reflectance ellipsoids result from superposition of tectonic strains on a primary, sedimentary burial related, uniaxial anisotropy. These relationships indicate that coalification resulted largely from pre-deformational sedimentary burial, with components of syn-and post-deformational coalification during the later stages. It also appears that thrusting in the area took place after folding.

Do outcrop-scale structures reflect regional kinematics: examples from the Chiwaukum schist, Cascades core, Washington

H. LEBIT, C. LUNEBURG, S.R. PATERSON
Department of Earth Sciences, University of Southern California, Los Angeles, CA, 90089;
e-mail: hlebit@earth.usc.edu
and R.B. MILLER
Department of Geology, San Jose State University, San Jose, CA 95192-0102

Mineral lineations in ductilely deformed rocks are commonly used for evaluating regional kinematics. However, interpretations of regional displacements from strain-related structures are based on kinematic models which require isotropic rheological properties and thus homogeneous material behavior. These models are not suited to address the role of mechanical instabilities such as folding, although folds are common structures at all scales in orogenic belts. Therefore it is important to determine if local strain features reflect kinematics of regional displacements, or local mechanical instabilities. This question is exemplified by the controversy over the tectonic interpretation of mid-crustal rocks exposed in the Cascades crystalline core in Washington and SW British Columbia. Subhorizontal, NW-SE trending mineral lineations, thought to be parallel to fold hinges, have been used in support of strike-slip dominated transpression. Opposing models suggested SW-directed thrusting in which the mineral lineation is orthogonal to thrust displacement. Our detailed structural analysis demonstrates that the geometrical relationship of mineral lineations and folds is much more complicated than previously assumed. Although mineral lineations are often subparallel to upright, gently plunging axes close to the fold hinges, they tend to form at larger angles in the limbs. At least two other, partly isoclinal fold sets predate these folds indicating that the finite strain pattern developed in an already strongly anisotropic material. Fold superposition is almost coaxial and forms a complex type III interference pattern. Local kinematic indicators and the schistosity patterns in fold profile sections match the typical morphology of mechanically active folds, although this section is at high angles to the mineral lineation.

We suggest that the mineral lineations reflect the cumulative strain resulting from the superposition of folds onto pre-existing isoclinal folds. Corresponding finite strain geometries are successfully simulated by numerical models of two successive deformations, with mechanical buckle folds superposed onto the limbs of initial almost isoclinal similar folds. Hinge line parallel finite (total) stretching axes are obtained under pefect coaxial fold superposition when one or both periods of folding are associated with bulk flattening strains. When the folds are superimposed under an oblique axial arrangement stretching lineations still remain parallel to the fold hinges but make acute angles with the fold axes on the limbs. These results and the fact that mineral lineations form geometries that are not continuously parallel to the fold hinges, indicates that the lineation is in these examples is related to local fold development and not regional displacements.

Evolution of Folds in a Transpressive Deformation Regime Inferred from Texture and Grain Shape Analyses

Bernd LEISS, Siegfried SIEGESMUND and Klaus WEBER
Institut für Geologie und Dynamik der Lithosphäre (IGDL), University of Göttingen, Goldschmidtstr. 3, 37077 Göttingen, Germany, e-mail: bleiss1@gwdg.de

In the Witberg-Mountains in Namibia, the dolomitic carbonate platform of the Southern Margin Zone of the Damara Orogen exhibits two fold generations with fold axes perpendicular to each other. One of the fold generations show isoclinal recumbent folds with amplitudes in the km-scale. The other fold generation shows open to tight and gently inclined folds with amplitudes in the 100 m scale and occurs preferentially in areas where the general thickness of the carbonate body (2000 m) decreases significantly. The stretching lineation is parallel to the fold axes of the 100 m-scale folds. No clear features have been found indicating an age-related ranking of the fold generations.

For the understanding of the fold evolution, the fold mechanisms and the age-related ranking of the fold generations, this study focuses on a geometrical correlation of fabric elements like foliations, fold axes, stretching lineations, grain shape fabrics and crystallographic preferred orientations (textures). Such correlations were carried out for the normal dipping fold limb, for the overturned fold limb and for the fold hinge for one of the 100 m-scale folds. The results show that the dolomite grains are elongated subparallel to the stretching lineation and form an oblique grain shape preferred orientation in respect to the axial-planar foliation. The elongation of the grains is strong in the normal limb, moderate in the hinge and very weak to absent in the overturned limb. Quantitative x-ray and neutron texture analyses reveal different texture types for the different positions within the fold. In the normal dipping limb, the texture shows an inclined c-axis maximum in respect to the foliation. This indicates a simple shear deformation regime with a shear sense as inferred from the grain shape preferred orientation. The texture in the overturned limb shows a c-axis girdle around the fold axis. The formation of the girdle can be explained by the superposition of the simple shear
deformation regime by the rotation of the overturned limb in relation to the instantenous stretching axis during the fold process. In the fold hinge a transitional texture type is found. Numerical texture modeling confirms the inferred texture forming mechanisms. Looking at a whole 100 m-fold train, a progressivly increasing angular deviation between the fabric elements from the open to the tight folds can be observed.

Considering the appearance of the 100 m-scale fold trains in areas where we have to assume deformation heterogenities, this case study allows for the following conclusions:
- the 100 m-scale folds developed in zones within local transpressive deformation regimes,
- the regional fold development can be explained by a single deformation event instead of two or several events as it was claimed in former studies,
- a careful interpretation of the dolomite textures can reveal complex information about the deformation path and
- dolomite textures might be a quantitative tool for the investigation of deformation paths.

S-C foliated cataclasites in granitic rocks

Aiming LIN
Department of Earth and Planetary Sciences, Faculty of Science, Kobe University, Kobe 657-8501, Japan.
E-mail: lin@kobe-u.ac.jp

Cataclastic rocks such as cataclasite, fault breccia-microbreccia, and fault gouge commonly are considered as the largely random-fabric rock products of friction-dominated faulting within the seismogenic regime (e.g. Sibson,1977). Foliated fabrics like those in mylonitic rocks, however, have been recently recognized in cataclastic rocks such as fault gouge and cataclasites formed by brittle shear (e.g., Chester et al., 1985; Lin, 1997). Foliations found in cataclastic rocks commonly are characterized by fine-grained matrix, preferred orientation of clay, porphyroclasts, and compositional lamination. In S-C mylonitic rocks, elongated mica (biotite or muscovite) showing “fish” and kink bands in shape are generally considered as products of ductile-dominated shearing and often used as a criteria for the shear sense (e.g. Lister and Snoke, 1984).

This paper describes the S-C fabrics of foliated cataclasites along the Rokko-Awaji fault zone, Japan and discusses their formation mechanisms and implications for the tectonic history.

S-C foliated cataclasites found in granitic rocks along the Rokko-Awaji fault zone, Japan, where the 1995 M7.2 Southern Hyogo Prefecture earthquake occurred, are examined at mesoscopic and microscopic scale. This fault zone are mainly composed of cataclastic rocks including S-C foliated cataclasite, cataclasite, fault breccia-microbreccia, and fault gouge. The S-C foliated cataclasites involve S-surfaces defined by preferred orientation of mica (mainly biotite) clasts and grain aggregations of quartz and feldspar porphyroclasts, and C-surfaces defined by shear bands (or displacement discontinuities) and some mica “fish trails” like that of S-C mylonites. All quartz and feldspar clasts show a brittlely-deformation character in textures. The biotite clasts, however, have some fabric characters of ductile deformation like those observed in S-C mylonites, such as cleavage-step, mica “fish”, elongated grain shapes, kink bands and some recrysterllizations, and are generally asymmetric in shape which indicate a dextral shear sense. These fabric variations between the biotite, quartz and feldspar suggest that there are marked differences in their relative deformational behavior, that the former mainly ductilely deformed, and the latter two mainly by brittle processes. It is shown that the S-C fabrics in foliated cataclasite can be produced by cataclasis-dominated mechanism.

The foliated cataclasites were overlain by the Miocene-Pleistocene Kobe-Osaka Groups which were fractured but not foliated. The coexsitence of ductile-dominantly deformed biotite and cataclastically-fractured quartz and feldspar suggests that the foliated granitic cataclasite in the Rokko-Awaji fault zone formed before the Miocene-Pleistocene Kobe-Osaka Groups at temperature between 150-250EC, corresponding to depths of 5-8 km, assuming a continental geothermal gradient of 30EC/km, and have been uplifted and exposed. The structures and geological evidence show that the Rokko-Awaji fault zone has moved as a right-lateral strike-slip fault with some reverse component since it formed.

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Natural triclinic transpressional shear zones: from the present to the Archean

Shoufa LIN
Manitoba Energy and Mines, 59 Elizabeth Drive, Thompson, MB, Canada R8N 1X4
Dazhi JIANG and Paul F. WILLIAMS
Department of Geology, University of New Brunswick, Fredericton, NB, Canada E3B 5A3

In most previous transpression models, the boundary-parallel component of velocity is assumed to be horizontal, and the movement picture and the predicted geometry of resultant structures are of monoclinic symmetry, in which the stretching lineations are either horizontal or down-dip. We have suggested that the boundary-parallel velocity component is generally oblique, and the movement picture and resultant structures are generally of triclinic symmetry. The stretching lineations in triclinic transpressional zones can vary continuously from subhorizontal to down-dip. In this presentation, we describe three natural examples of triclinic transpression zones, ranging in age from the Archean to the present. We conclude that triclinic transpression zones are common in nature.

The Alpine Fault in New Zealand is an active transpressional fault (Norris and Cooper, 1997). The current plate movement vector is 15-20E oblique to the average strike of the fault. The movement along the fault is oblique to its dip line (Norris and Cooper, 1997 and references therein), and the movement picture is thus most likely triclinic. Available structural data from the fault (Sibson et al., 1979; Norris and Cooper, 1997) shows that the stretching lineations do not plot along the vorticity-normal section (VNS, the section parallel to the shear direction and perpendicular to the shear zone boundary) and the structures are thus of triclinic symmetry.

In the Palaeozoic Roper Lake shear zone in the Canadian Appalachians, the orientation of a stretching lineation is oriented approximately down-dip near the shear zone boundary and becomes gradually shallower towards the centre. The structures in the central portion of the shear zone exhibit approximately monoclinic symmetry where the poles to both the S- and C-surfaces, the stretching lineation on the S-surfaces and the striations on the C-surfaces all plot in a great circle girdle. However, the lineations from the marginal portion do not plot in the same girdle, and the bulk symmetry of the shear zone is triclinic. Comparison of the observed geometry with results of theoretical modelling shows that the shear zone can be interpreted as a triclinic transpressional zone.

The Archean Southern Knee Lake shear zone in the Superior Province curves from NNW-trending in the east to W-trending in the west. Movement along both segments of the shear zone is dextral transpressional. The geometry, kinematics and the observed structures indicate that the W-trending segment has a larger portion of zone-boundary-normal velocity component (more pure shear) than does the NNW-trending segment. The structural geometry in the W-trending segment is very similar to that in the Roper Lake shear zone described above. The lineations vary from subhorizontal in the centre and get progressively steeper to down-dip towards the margins of the zone. The finite strain here is oblate ($K<1$) and both the foliation and lineations are mostly well developed. In contrast, in the area where the shear zone curves, the lineations are always steep, the finite strain is prolate ($K>1$) and only lineations are generally well developed. Theoretical modelling shows that this geometry can be produced in shear zones with both boundary-normal and strike-parallel compression (constrictional deformation), which is expected here at the curve of the shear zone.

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The collapse and the destruction of mountain belts

G.S. LISTER and T.J. RAWLING
Australian Geodynamics Cooperative Research Centre, Department of Earth Sciences, Monash University, 3168 Melbourne, Australia

We review the factors that lead to the collapse and destruction of mountain belts. The issue is whether mountain belts "collapse" under the influence of their own gravitational potential energy, or whether they are "torn apart" as the result of in-plane stresses generated by variation in the conditions at the plate boundaries. We make the observation that the most extended regions on Earth form adjacent to retreating slabs, in the over-riding plate, and this is where coherent high pressure metamorphic terranes are exhumed. We suggest that continental collision (initially) forces the closure of marginal basins in the over-riding plate, and this can be the cause of a major epoch of "constructional" orogenesis along the entire length of a convergent zone. Coherent high pressure metamorphic terranes form in the crustal roots of the resultant mountain belt. Where continent meets continent, and convergence continues, collapse of the orogen involves "surges" (as in glaciers). But these episodes of extensional tectonism take place during continued convergence, and they are not the result of "extrusion". Where the newly formed mountain chain faces actively subducting oceanic lithosphere it will be "torn apart" as the result of extensional tectonism induced by seawards retreat of the flexure of the subducting slab (i.e., as the result of "roll back"). Coherent high pressure metamorphic terranes are exhumed as a result. However, more than one switch from compressional orogenesis to extensional tectonism can take place, and exhumed coherent high pressure metamorphic terranes are often once again subject to crustal shortening in the complex oscillating tectonic environment that characterizes the over-riding plate. We conclude that: (1) whereas the effect of overall gravitational potential energy cannot be discounted in terms of its mitigating influence on the collapse of a mountain belt; (2) mountain belts are in general "torn apart" as the result of "roll-back".

What is a metamorphic core complex and how does it form?

Gordon LISTER
Australian Crustal Research Centre, Monash University, Melbourne 3168, Australia

Metamorphic core complexes have now been described from several parts of the globe, formed in several different orogenic belts, with a large range of specific characteristics. It is thus now difficult to define a "typical" metamorphic core complex, except if we consider core complexes by region. To this purpose this paper will describe the basic characteristics of metamorphic core complexes from several different tectonic environments: (a) the Colorado River extensional corridor; (b) the Solomon Sea, PNG; (c) the Cyclades, Aegean Sea, Greece. These regions have in common the rise of gneiss domes above the surface, and it is clear therefore that the term metamorphic core complex should be reserved for the surficial exposure of these extensional phenomena.

Metamorphic core complexes are active tectonic features that should be recognized in the evolving geomorphology of a region. There has been a tendency in recent work to be overgenerous with the use of the term "metamorphic core complex" and some recent works have described entities that are in fact not really metamorphic core complexes at all! A metamorphic core complex is not the appropriate term to describe any feature that involves the outcrop of metamorphic rocks surrounded by less metamorphosed or less deformed rock packages.

The rise of gneiss domes as an intrinsic part of the evolution of a metamorphic core complex raises some interesting questions, particularly in respect to the role of plutonism.. There is no doubt that the progressive bowing of areally extensive low-angle normal faults (LANFs) is part of the process. There is also no question that these detachment faults do form at shallow-dipping orientations. It is possible to dismiss arguments to the contrary that have been made on theoretical geodynamic grounds and/or on the basis of observational seismology. LANFs are what is to be expected if semi-ductile crust with layered inhomogeneity is extended. The role of ductile shear zones in the exhumation process has been underestimated however, and there is interesting science to be explored in the link between episodes of metamorphism and the subsequent initiation and rapid operation of vcrustal-scale ductile shear zones.

Malpica-Lamego Deformation Zone: a major crustal-scale shear zone in the Iberian Variscan Belt (Galicia, N Portugal)

S. LLANA-FUNEZ and A. MARCOS

Departamento de Geolog'a, Universidad de Oviedo, Spain

In the stages following continental collision, compressive deformation is commonly accommodated in orogens by development of crustal strike-slip faults which often result in escape tectonics parallel to orogens (Tapponier et al., 1986; Coward, 1994). It is not surprising that old structures, that have been steeped by continuos shortening, are preferred as weak zones to accommodate these strike-slip tectonics. In the present work we review the Malpica-Lamego Deformation Zone (MLDZ) within the Variscan Belt of Iberia, where some of these features are seen (Iglesias and Choukroune, 1980; Ferreira et al. 1987).

The MLDZ is the western boundary of the Malpica-Tui Unit (MTU), which belongs to the basal units of the allochthonous nappe complexes of the Variscan Belt of Iberia (Martínez Catalán et al. 1996). The MLDZ has a complex kinematic history in the orogen. Two main movements are differentiated: the first one is considered to have a main vertical slip and is interpreted in relation to an out-of-sequence reverse faulting event; the second one has a main strike-slip movement.

The out-of-sequence reverse faulting event is inferred from: (i) the shape control of the MLDZ on the MTU (see figure); (ii) the horizontal differences in metamorphic record, raising HT rocks in the west (granites and migmatites) next to the HP relicts of the MTU (situtated higher in the first generation thrust pile); and (iii) the tardi- post-tectonic intrusion of granodioritic-rock bodies (I-type) along the fault zone. The ascent of these rocks, deep-seated in the Variscan Belt of Iberia (Gallastegui, 1993; Capdevila et al. 1973), would be favoured and channelled by the presence of crustal-scale shear zones as has been pointed out in this and other orogenic belts (Pitcher, 1982; Hutton and Reavy, 1992).

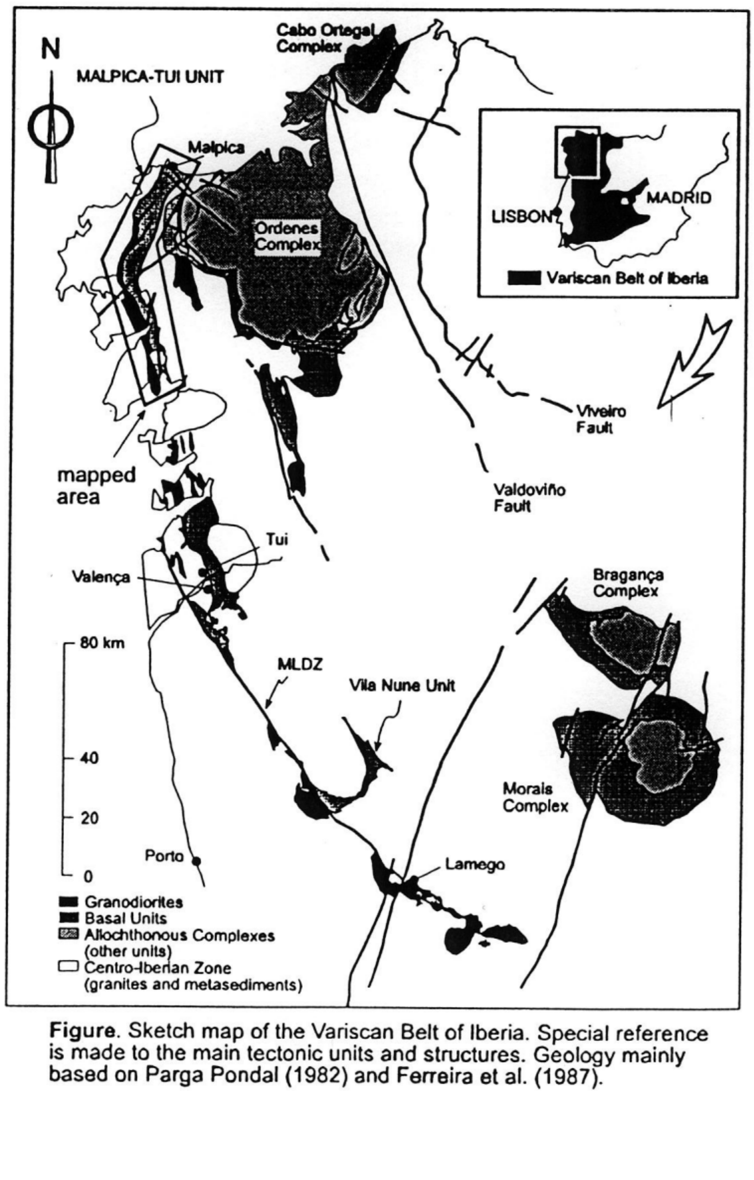

Figure. Sketch map of the Variscan Belt of Iberia. Special reference is made to the main tectonic units and structures. Geology mainly based on Parga Pondal (1982) and Ferreira et al. (1987).

Subsequently to the out-of-sequence reverse faulting, an extensive strike-slip reworking on greenschists facies is observed obliterating most structures formed during the previous event. A main shear zone (~2 km wide) is recognized affecting the late reverse fault as well as the granodiorites (Gallastegui, 1993). A dextral shear sense is inferred from S-C' fabrics in micaschists and from S-C fabrics in syn-tectonic S-type granites (Iglesias & Choukroune, 1980). To the east, an anostomosing dextral shear zone system 4-8 km wide) deforms the rocks of the MTU.

Minor discontinuous left-lateral displacements are seen reworking the eastern boundary of the MTU and are interpreted in relation to the latest movements within the MLDZ. The steep foliation within the shear zones shows an horizontal stretching lineation, which affects a previous subhorizontal lineation.

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Remobilization structures in massive sulfide deposits: the fluid connection

Brian MARSHALL
Department of Appled Geology, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia
Adrienne C. L. LAROCQUE
Department of Geological Sciences, The University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada
and Frank M. VOKES
Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Remobilization involves translocation (during deformation/metamorphism) of pre-existing, massive, semi-massive or disseminated mineralization by solid-state, liquid-state, or mixed-state transfer. The principal deformation mechanisms contributing to the transfer processes comprise cataclasis and granular flow, dislocation flow, and dry- and wet-state diffusion, the latter commonly accompanied by advective transfer. Structures in remobilized sulfide ores reflect and may preserve evidence of these mechanisms.

Cataclasis, dislocation flow and dry-state diffusion have been variously invoked to explain: 'healing' of fractures in high-competence sulfides by low-competence species; pressure-fringe development; 'breccia' or durchbewegt ore; ore-shoots formed by hinge-zone thickening or elongation processes; piercement cusps and veins; and discordant, shearzone-hosted bodies of enriched mineralization. These examples of supposed solid-state transfer mainly reflect interpretation of relationships (rather than proof) and the desire to pigeonhole structural processes. In even the simplest case ('healing'), fluid facilitation of fracturing and inflow is possible; in most other cases, wet-state diffusion and localized advective transfer probably contribute significantly. Support is provided by: (1) presence of gangue phases; (2) peak-metamorphic fluid inclusions in sulfides and gangue; (3) replacement textures and porphyroblasts; (4) compositional changes (e.g. separation and concentration of precious metals); and (5) comparison with fluid-transfer structures (e.g. solution cleavage, pressure fringes, boudinage partitions) in non-sulfide rocks.

Significant internal and external remobilization of massive sulfides mainly involves mixed- or liquid-state transfer. This implies aqueous (non-metamorphic?) infiltration, despite the relatively low permeability of homogeneous massive sulfide. Metamorphic devolatilization is not a serious option, because intercalated or admixed silicate phases release relatively little water, and sulfide species have low solubility in typical metamorphic fluids. Evidence of infiltration includes the above 5 items plus: (1) alteration assemblages; (2) compositions of fluid-inclusion assemblages; (3) isotopic studies; and (4) documented examples of remobilization, including the 'emplacement-site' consequences of dilational vein-systems and replacement effects over a range of scales. Liquid-state participation in mixed-state transfer ranges from subordinate to solid-state processes, to totally dominating, before passing into true liquid-state transfer. The spectrum of fluid-related processes is introduced.

The fluid connection means that the rates and distances involved in external remobilization can be substantial. External remobilization seems to be extremely common to a meter, very common to ten meters, moderately common to a few tens of meters, uncommon to a few hundred meters, extremely uncommon to a thousand metres, and unproved beyond that. Despite this, a high degree of external remobilization is highly improbable, and comprehensive external remobilization is even more improbable.

Reaction-enhanced formation of ductile shear zones: application of scanning X-ray analytical microscope for the petrographic characterization of rock sections

K. MICHIBAYASHI*, M. MURAKAMI
*Institute of Geosciences, Shizuoka University, Shizuoka 422, Japan (*present address: Laboratoire de Tectonophysique, Universit Montpellier II, Montpellier 34095, France)*
S. TOGAMI and M. TAKANO
Department of Earth and Planetary Sciences, Nagoya University, Nagoya 464-01, Japan

Reaction-enhanced formation of a ductile shear zone

A ductile shear zone within a metasomatic biotite band in the Ryoke granite, Teshima, SW Japan has been studied using the scanning X-ray analytical microscope (SXAM). The SXAM revealed quantitative distributions of major elements such as Si, K, Fe, Al and Ca within the shear zone. These element maps were processed by computer to transform them into images showing distributions of minerals such as quartz, biotite, plagioclase and K-feldspar, which are the major constituent minerals within the biotite band as well as the protolith granite. Both element and mineral profiles across the shear zone, from the center to the margin, have been interpreted to result from mineral reactions induced by the introduction of iron-bearing hydrous fluid phases in the granite. Comparison of the mineral profiles with the simple shear strain profile shows that the shear zone is intensely developed within the zone where quartz and biotite dominate, whereas the deformation is weak where the mineral assemblage of the protolith granite has been preserved. As the metasomatic zone is commonly wider than the shear zone, this suggests that the mineral reactions have resulted in reaction softening or reaction enhanced ductility. Consequently, the stresses imposed on the granite caused the shear strain to localize along these zones to produce the observed shear zones.

Flow partitioning revealed by geometric analysis of planer fabrics

A simple geometric analysis of spectacular shear band cleavages within this shear zone has revealed an evolution of such planer fabrics in conjunction with a possible flow partitioning in the shear zone. Two types of shear band cleavages are distinguished: intra-layer and inter-layer shear band cleavages. The intra-layer shear band cleavages occurred within the biotite-feldspar compositional layers as a result of stretching of the layers during deformation. They took place from low strain and became intenser as increasing strains. Angles between the intra-layer shear band cleavages and the shear plane decrease as S-foliations are inclined from 60E to 10E to the shear plane. We employed a strain-partitioning model to explain the orientation of the intra-layer shear band cleavages. The model shows that the intra-layer shear band cleavages have been rotated as a result of 10 to 20% of the bulk extensional strain that is parallel to the S-foliation. It implies that the strength of the layer became significantly stronger due to the amount of feldspar composition in the layer than that of the quartz-dominated layer. The model also reveals that the most of strain tend to occur in the quartz-dominated layers during shearing. The inter-layer shear band cleavages occurred subsequently where this type of strain partitioning could not be accommodated with the increasing bulk shear strain in the shear zone.

Rheology of the mid- to deep crustal section of an arc, north Cascades, Washington

R.B. MILLER
Department of Geology, San Jose State University, San Jose, CA 95192-0102, rmiller@geosun1.sjsu.edu
S.R. PATERSON
Department of Earth Sciences, University of Southern California, Los Angeles, CA, 90089-0740
H. ALSLEBEN
Department of Geology, San Jose State University, San Jose, CA 95192-0102
H. LEBIT and C. LUNEBURG
Department of Earth Sciences, University of Southern California, Los Angeles, CA, 90089-0740

The Cascades core contains a composite crustal section of a Cretaceous magmatic arc with paleodepths ranging from ~5 to 40 km. The shallowest rocks (~ 5-12 km) in the Cascades crustal section are in the Late Jurassic Ingalls Complex, which is characterised by Jurassic serpentinite melange, but with Cretaceous, ductile deformation in the lower, amphibolite-facies part of the complex. This ophiolite overlies the Chiwaukum Schist along a major Cretaceous thrust that shows distributed ductile deformation, discrete slip, and is folded. The Chiwaukum Schist and structurally lower Napeequa complex form the bulk of the crustal section (10- to $\geq$ 30 km). The Chiwaukum consists of interlayered pelitic and psammitic schists, lesser amphibolite and ultramafite, and rare marble, whereas the Napeequa is dominated by amphibolite and quartzite, with considerable marble, metaperidotite, and schist. These units are intruded by tonalitic bodies including large plutons and abundant meter- to kilometer-scale concordant sheets, particularly in the lower half of the Chiwaukum and Napeequa units.

The Chiwaukum Schist and Napeequa unit both record two or more transposition cycles marked by nearly coaxial, generally mesoscopic, tight recumbent to gently inclined folds of compositional layering and foliation(s), which are refolded by upright, meso- to macro-scale structures. Structures change little with depth, but become more complex and intense near larger intrusions. Intrusive bodies display a wide range of structures ranging from magmatic to subsolidus fabrics and folds.

The Swakane terrane, separated from the Napeequa unit by a ductile detachment, is the structurally lowest and lithologically most homogeneous unit in the crustal section. It is almost entirely biotite gneiss. The Swakane is characterized by intense, gently dipping foliation. Preserved folds are much less common than in the higher units, but the same sequence of recumbent followed by upright folds is present. Folding and shear bands recording top-to-the-N shear are concentrated in domains where micaceous compositional layering is most pronounced. Thin concordant pegmatitic sheets are generally less deformed than the biotite gneiss, typically are boudinaged, and locally define recumbent folds.

These observations indicate that ductile deformation throughout the Cascades core was strongly influenced at various scales by competence contrasts between rock types. This is best shown by the active role of layering during folding and boudinage and the focusing of shear in weaker layers at all crustal levels. Deformation is more evenly distributed in the deepest part of the section, as predicted by many models of crustal rheology, but even here subtle compositional layering localized deformation. Finally, plutonic rocks throughout the section played an important role during deformation with their behavior temporally changing from incompetent to competent and in both cases focusing deformation.

Evolution of stress fields in a tension sinistral fault duplex
(The Pridorozhnoe tin deposit, Russian Far East)

A.N. MITROKHIN, B.K. SOROKIN, V.P. UTKIN
Far East Geological Institute, Far East Branch, Russian Academy of Sciences, Vladivostok, 690022, Russia

The Pridorozhnoe hydrothermal deposit is in the eastern part of the Komsomolsky tin region being within the Khabarovsk Territory of the Russian Far East. Together with other deposits of the Komsomolsky region it is an occurrence of the tourmaline type of the cassiterite-silicate formation (according to E.A. Radkevich, 1956). There occur mineral associations (stages) with the succession, as followed: quartz-tourmaline (Qtz-Tur), quartz-arsenopyrite-cassiterite (Qtz-Apy-Cst), early (Qtz-Py-Pyr-Ccp) and late (Qtz-Ccp-Sp-Gn) quartz-sulfide, and quartz-carbonate-sulfosalt (Otz-Clc-Sf). Structurally, the deposit is the linear stockwork of quartz-tourmaline metasomatites controlled together with the late veinlet mineralization by the tension duplex of the NNE 000-010^o trending Tzentralny and Pridorozhny sinistral faults. Development of the duplex is established to be accompanied by successive superposing of minor stress fields with the compression vectors σ_1^2 (NW 300-310^o), σ_1^3(W 265-275^o), and σ_1^4 (ENE 60-70^o) with the major (regional) stress field with the compression vector σ_1^1 (NNW 340-350^o). This process went by pronounced one-way sinistral faulting. The latter resulted in the sharp predominance of sinistral (S) faults to dextral (D) and tension (T) ones to be fixed by sturctural-statistical analysis. The analysis gives the four structural parageneses to form under the revealed stress fields: S_1 (NNE 000-010^o) + D_1 (NW 310-350^o) + T_1 (NW 340-350^o) under σ_1^1; S_2 (NW 340-345^o) + D_2(WNW 275-280^o) + T_2 (NW 310-315^o) under σ_1^2; S_3 (NW 310-315^o) + D_3 (ENE 065-070^o) + T_3 (NW 275-280^o) under σ_1^3; and S_4 (WNW 285-290^o) + D_4 (NE 040-045^o) + T_4 (ENE 065-070^o) under σ_1^4. Observations in situ show the S-systems as generations with forming of the following age succession: $S_1 6 S_2 6 S_3 6 S_4$. This succession stands for the process of stress field superposing process by means of the spatial-temporary complicating step-by-step of structural geometry of the tin-bearing duplex. In fact, being complicated structural assemblages, the Tzentralny and Pridorozhny master sinistral faults, see the paragenesis $S_1 + D_1 + T_1$ under σ_1^1 within their shear segments and the paragenesis $S_2 + D_2 + T_2$ under σ_1^2 within tension ones during all mineral stages: from Qtz-Tur to Otz-Clc-Sf. Nevertheless, there is superposing of the paragenesis $S_2 + D_2 + T_2$ under σ_1^2 within the shear segments during the last Otz-Clc-Sf stage. Between the master faults dynamo-kinematical zonality is on more clearly. To quote, the Qtz-Tur stage sees here the paragenesis $S_1 + D_1 + T_1$ under σ_1^1 within the underlap section and the paragenesis $S_2 + D_2 + T_2$ under σ_1^2 within the overlap one. As a result, stress fields' superposing within the overlap section surpassed in the one paragenesis. In other words, the underlap section has succession of parageneses $S_{1\text{-}3} + D_{1\text{-}3} + T_{1\text{-}3}$ whereas the overlap one has $S_{2\text{-}4} + D_{2\text{-}4} + T_{2\text{-}4}$ during, accordingly, Qtz-Tur, Qtz-Apy-Cst, both Qtz-Py-Pyr-Ccp and Qtz-Ccp-Sp-Gn, and Otz-Clc-Sf stages. At that, the next paragenesis developed, adapting to itself fault network of each previous one. The described tendencies correspond to the transtensional strike-slip fault overlap model of P. Segall and D.D. Pollard (1980) that allows to look on the lateral growth of the master faults as "heart" of stress field superposing. At that, the observed age subordination of the $S_{1\text{-}4}$-systems and $\sigma_1^{1\text{-}4}$-vectors with the constant angle interval between them at closely 30^o shows the "life" of the process to be quite compared with the widely known scheme of J.D. Moody and M.J. Hill (1956) for genetic (hierarchical) subordination of strike-slip faults that confirms thus its correctness for description of stress field evolution in the tension duplex with the essentially strike-slip fault style of dislocations such as the described object is.

Tectonic evolution of the late Paleozoic Antigonish basin, Nova Scotia: basin formation and inversion along the Avalon-Meguma terrane boundary during the amalgamation of Pangea

J. Brendan MURPHY
Department of Geology, St. Francis Xavier University, Antigonish, Nova Scotia, B2G 2W5.

The St. Marys Basin, central mainland Nova Scotia, lies along the southern flank of the composite Magdalen Basin and along the Avalon-Meguma terrane boundary, which is defined by the E-W Minas Fault Zone. The basin fill consists of Late Devonian-Early Carboniferous continental clastic rocks deposited in fluvial and lacustrine environments that were predominantly derived from the Meguma terrane to the south. These rocks were deformed by two phases (D1 and D2) that occurred between the late Visean and Westphalian B.

D1 deformation produced en echelon northeast-southwest trending periclinal folds and related predominantly NW-directed thrusts. The intensity of D1 increases from southeast to northwest across the basin. In the southeast, the rocks are gently tilted. In the central part of the basin, folds are open and upright, whereas in the northwest, Horton Group rocks are deformed by tight to isoclinal folds and thrusts. To the north, these structures are rotated clockwise into parallelism with the E-W Chedabucto Fault, of the Minas Fault Zone. D2 deformation occurs adjacent to NNW-trending lineaments.

Basin formation and evolution was strongly influenced by dextral motion of Gondwana relative to Laurentia associated in which the Minas Fault Zone acted as a lateral ramp during the formation of Pangea. Facies variations suggests a strong tectonic influence on sedimentation during basin formation where subsidence along the southern basin margin occurred along northerly dipping listric normal faults. Kinematic indicators from shear zones along the basin margin indicate basin formation was accompanied by dextral shear. The NE orientation of D1 folds and their clockwise rotation is related to progressive dextral motion along the Chedabucto Fault, the current northern boundary of the basin.

The role of sandbox modelling in structural interpretation and validation

D.A. NIEUWLAND
Shell Research, Volmerlaan 8,2288GD Rijswijk The Netherlands;
and Free University, Faculty of Earth Sciences, De Boelelaan 1085, 1081HV, Amsterdam

For a good understanding of complex tectonic structures, it is necessary to study the geometry, kinematics and the mechanics of such structures. Sandbox models have proven to be a powerful supplement to field work and numerical modelling. The strength of scaled sandbox models lies in the fact that geometry and kinematics can be studied in 3D under carefully controlled circumstances. In nature it is very difficult if not impossible to separate the effects caused by the many parameters that influence the deformation process. In the laboratory it is possible to vary only one parameter, thus enabling an assessment of its effects and the relative importance of that parameter for the deformation process. 3D computer tomograph scans, acquired at different stages of deformation, make it possible to study the development of complex structural geometries in space and in time. Sandbox model analysis has moved from simply using cross sections, to 3D CT scans and video-laser scans, interpreted, measured and visualised using advanced computer tools, developed for 3D seismic interpretation and visualisation. The use of sandbox models has evolved from geometrical examples of relatively simple structures, to complex modelling of specific complex structures and from sand-only to multi-layer models incorporating viscous and non-viscous ductile interlayers. In-situ stress measurements in sandbox models are a significant step foreward in the understanding the mechanics of tectonic faulting. Thanks to these new developments the 3D geometry of faults and fault systems, the interaction between faults and the mechanics of tectonic faulting, can now be studied in detail. The results are of great practical use for professional seismic interpreters and structural geologists as well as for educational purposes.

Kinematics of the Crowsnest Deflection In the Eastern Cordillera of Canada, with global application to curvilinear, compressional orogens

D.K. NORRIS
444 Okaview Road, Kelowna, B.C. V1W 4L4, Canada

In the vicinity of the Crowsnest Pass the strike of the Rocky Mountains deviates significantly from the regional 325E Bow Valley – Montana trend. This deviation, known as the Crowsnest Deflection, comprises two structural salients and an intervening reentrant or embayment. Southward from Bow Valley, the curvilinear shape of the orogen in plan, traces out first the Highwood Salient as the structural grain deviates in arcuate fashion from a south-southeast trend to a near north-south trend in the neighbourhood of the Crowsnest Pass to form the Crowsnest Reentrant. There it swings rather abruptly to the east-southeast around the north flank of the Clark Range Salient and returns to the south-southeast (Bow Valley-Montana) tend in the vicinity of the International Boundary with the United States.

The distribution of the mean azimuths for slickenlines on bedding on the north flank of the Highwood Salient in the Canmore area appears to be normal with a preferred direction of 055E, that is perpendicular to the Bow Valley-Montana trend. The fact that the main direction of transport is characteristically more easterly in the Crowsnest Pass area (averaging 077E), moreover, suggests that the overall movement picture for the compressional collapse of the Rocky Mountains may not have been entirely unidirectional. Rather, there appear to have been two preferred directions of slip (051E and 077E) within the deflection and one (055E) away from it, all interwoven with time so that none is the relatively younger.

These kinematic fabric data, in conjunction with the alignment of remanent magnetic dipoles in Precambrian (Helikian) rocks, support the hypothesis that when the eastern Cordillera underwent differential contraction during the Laramide Orogeny, any changes in net shortening along strike must have been not only gradual but also progressive. There was no significant differential rotation of the Rocky Mountains about vertical axes and, correspondingly no folding about these axes that would require either synkinematic longitudinal contraction and buckling of the orogen or stretching of the supracrustal wedge in and around the Crowsnest Deflection. The curviplanar form of the shelf-miogeocline would appear to have been preordained by the initial and fundamental shape of the Archaean(?) crystalline basement surface upon which the supracrustal wedge was deposited. Should the initial geometry and the layered anisotropy of the supracrustal wedge have controlled the orientation and shape of the failure surfaces within it, then they must have been the underlying control for the orientation and curviplanar shape of both family of contraction (thrust) faults comprising the eastern Cordillera and of the eastwardly migrating, Laramide exogeocline. The proposed origin and tectonic significance of the Crowsnest Deflection is very similar to that of the great arcs comprising the north-eastward salient of the Mackenzie Mountains west of Norman Wells in the northern Cordillera of Canada, and of the northwestward salient of the central Appalachians.

Differentiated Crenulation Cleavage: A Coupled Deformation - Fluid Flow - Chemical Transport Problem

Alison ORD, Bruce HOBBS, Yanhua ZHANG and Hans MUHLHAUS
Australian Geodynamics Cooperative Research Centre and
CSIRO Exploration and Mining, PO Box 437, Nedlands, 6009, Australia

We examine here the progressive development of differentiated crenulation during the evolution of a fold system. The study involves a numerical simulation of new foliation development in an initially foliated material sandwiched between layers of stronger material. This material is comprised of quartz and mica. The following fully coupled processes operate during the operation of this model:

- The materials have non-associated elastic-plastic constitutive behaviour involving deformation induced dilatancy; the materials yield according to a yield criterion involving the effective stress but the plastic strain increment is governed by the dilatancy.
- Dilatancy induces changes in the fluid pore pressure (and hence in the effective stress) and in the permeability.
- Changes in the Darcy fluid velocity are produced by the resulting changes in the gradient of fluid pore pressure and by changes in the permeability.
- The pore fluid is initially saturated with quartz for a given initially imposed temperature and pore fluid pressure; deformation is isothermal so that quartz solubility is influenced only by local changes in pore fluid pressure resulting from deformation.
- The solubility of quartz is incorporated in the model as a function of temperature and pore fluid pressure; the kinetics of dissolution and precipitation are also included with the ability of dissolution and precipitation to also influence permeability and pore volume; quartz is advected with the moving fluid.

As shortening begins, small buckling instabilities develop in the weaker, foliated, sandwiched, layer. The axial planes of these buckles are parallel locally to a principal plane of strain. The regions of highest shear strain, ie., the limbs of the crenulations, suffer the highest changes in pore volume and in permeability. These two processes ensure that all fluid flow is focussed through the developing limb areas. Even though the solubility of quartz is low in these low pore pressure regions, the high flow rates plus the kinetics of dissolution and precipitation of quartz, ensure that these limb areas are progressively depleted in quartz relative to local hinge regions.

In fact there is a strong positive feedback process in operation here and the differentiated limbs of the microfolds develop as planar "fingers" of dissolution in much the same manner as described by Aharonov et al. (1997, Figure 3a). The dissolution fingers develop because the initial permeability differences focus fluid flow and hence the dissolution of quartz. Thus high-permeability regions dissolve more rapidly than neighbouring regions, increasing their permeability yet again, in a positive feedback process.

As the fold system grows in the bulk layered specimen these processes amplify until finally a well developed layered structure evolves approximately parallel to the axial plane of the large folds. This new layered structure progressively rotates away from a principal plane of strain (defined in a region where the deformation may be considered homogeneous) as the fold system amplifies.

The incorporation of pressure and temperature in the solubility law for quartz enables a study to be made on the influence of pressure and temperature upon the development of differentiated crenulation cleavage.

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Fringe-Folds

C.W. PASSCHIER
Institut für Geowissenschaften, Universität Mainz, 55099 Mainz, Germany

In many strongly deformed rocks, isolated trains of mm to m-scale folds (synform-antiform pairs) in a layering or foliation trend along the fringe of migmatitic, intrusive or fibrous veins or even along burrows or mudcracks (Fig. 1). Such fringe folds are particularly common in gneissic layering and schistosity adjacent to intrusive veins in medium to high-grade rocks (Hudleston, 1989), but also occur in slates (Passchier & Urai, 1988).

Some fringe-folds around migmatite patches may have developed by partial melting in the core of a pre-existing fold structure, but all other types can be shown to develop by relative rotation of an originally planar foliation and a cross-cutting younger structure (vein, burrow). In such rotation-type fringe-folds, the foliation near the cross-cutting structure is thought to rotate little or (rarely) not at all with respect to the latter in response to flow partitioning, thus initiating folding. The process is thought to be similar to the relative rotation of foliation and layering during the development of some types of cleavage refraction in deformed sediments. However, much higher relative rotations, up to 120°, are observed in fringe-folds. Analogue modelling indicates that fringe-folds do not normally develop if material close to a vein has the same rheology as that further away. Apparently, vein intrusion must alter the composition of the wall rock for rotation-type fringe-folds to develop along them.

In many high-grade gneiss terrains, fringe-folds are the only asymmetric structures that could potentially be used as a shear sense indicator. Unfortunately, numerical modelling of fringe-fold development shows that this is only possible in special cases where at least some additional information on the initial orientation of veins or foliation is available: most reliable are extensional veins in monoclinic flow where the original angle between veins and foliation was small, and the flow vorticity number was smaller than 1. In some fringe-folds, a strip of material directly adjacent to the vein is though to preserve the original angle between vein and older fabrics; such structures could be used as quantitative kinematic indicators.

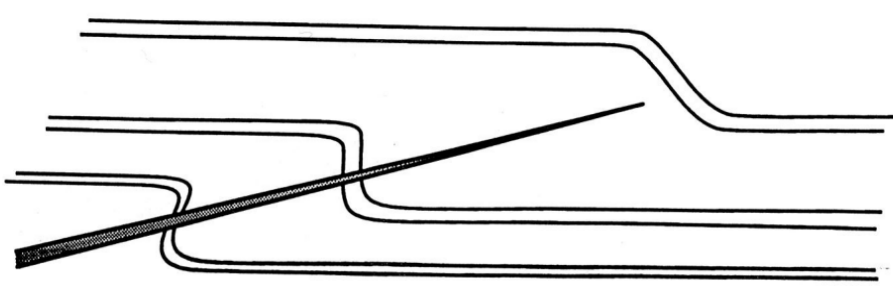

Fig. 1. Schematic drawing of typical fringe-folds along a vein.

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A Review of Magma Emplacement Processes: Stressing the Weakly Coupled Processes of Tectonism and Emplacement

Scott R. PATERSON
Department of Earth Sciences, University of Southern California, Los Angeles Ca 90089-0740
email: paterson@usc.edu

A variety of magma emplacement studies continue to reach very different conclusions about emplacement mechanisms. In part this reflects the complex lateral and vertical variations in host rock material transfer processes (MTP's) that occur during emplacement. However disagreements remain about the importance of vertical versus lateral MTP's and about the role of regional deformation during emplacement. Our studies of intrusive systems at a variety of crustal levels continue to indicate that vertical, and largely downwards, transport of host rock dominates during emplacement and that stoping is an important MTP, at least during final emplacement.

Spatial, geometric, temporal, and mechanical relationships between pluton populations and regional structures must be evaluated before a genetic relationship between tectonism and magmatism is established. For example, our initial statistical studies of fault and pluton populations indicate that plutons preferentially occur at 1/4 to 1/2 (depending on the orogen evaluated) the average fault spacing, and not preferentially along faults as is often suggested. Statistical studies also show that pluton long axes have a wide range of orientations but with a tendency for plutons with the largest length/wide ratios to have their long axes subparallel to nearest faults. Finally comparison of rates of magma emplacement to rates of host rock displacement during regional tectonism continue to show that magma transport is a fast to very fast process relative to rates of regional host rock displacement. I therefore suggest that at best only a weak coupling exists between magma emplacement and regional deformation and that this coupling is probably driven by stress and not displacement of host rock.

Rheological controls on meso-scale structures and kinematics near a mid-crustal detachment: an example from the Napeequa complex, Cascades core, Washington

S.R. PATERSON
Department of Earth Sciences, University of Southern California Los Angeles, CA 90089-0740; email paterson@usc.edu
and R.B. MILLER
Department of Geology, San Jose State University, San Jose, CA 95192-0102

In the Chelan block of the Cascades core, Washington, a Cretaceous, gently folded, midcrustal detachment separates the structurally lower Swakane biotite gneiss from the structurally higher Napeequa complex. The latter unit varies from garnet-bearing amphibolite (meta-basalt) at lower structural levels to thinly layered metacherts, schists, marble, and hornblende-biotite schists at higher levels. These host rocks are intruded at 20-24 km depth by numerous, meter- to kilometer-scale 68-73 Ma tonalite to granodiorite subparallel sheets as well as the largely tonalitic and moderately discordant 73 Ma Entiat pluton. Partial melting occurs in schists in narrow aureoles near some sheets and in the garnet amphibolites near the detachment. Immediately below the detachment, minerals in the Swakane biotite gneiss coarsen and garnet ± kyanite increase in abundance. Structures in the Swakane are described in a separate abstract (Alsleben et al., this volume).

In the Napeequa complex all units display a NW striking, moderately NE-dipping foliation that is magmatic in some of the sheets, subsolidus in others, and defined by amphibolite facies minerals in non-intrusive units. Most units also display a NE-trending mineral lineation (average=42 plunge towards 17) although in detail the intensity and orientation of this lineation varies dramatically between units. Folds of foliation vary from open to isoclinal, have hinge lines defining a great circle (318/46) subparallel to the average foliation with a maxima at 26/344, that is at 30^{o} counterclockwise from the lineation maxima. Folds in the Napeequa are best developed in narrow zones in thinly layered metasediments and hornblende schists adjacent to more competent layers and occur in what we interpret to be discrete ductile shear zones. Kinematic indicators are variable, occurring in both lineation parallel and lineation perpendicular sections, locally varying between fold limbs, but showing an overall pattern of top-to-the-NNE motion. We interpret these data to indicate that although all units in the Napeequa Complex were weak enough to deform at these crustal levels, the relative strengths of units controlled local deformation including mechanically active folding, localized shear in weak units, and complex 3D flow within layers. Meso- and micro-scale structures reflect this local deformation which formed in a macro-scale regime of top-to-NNE shear at depths of 20-24 km. Thus even at these crustal levels deformation is quite heterogeneous, in sharp contrast to models assuming a weak, homogeneously deforming middle and lower crust.

Variable mechanical controls on meso-scale kinematics in the mid-crust, Cascades core, Washington

S.R. PATERSON
Department of Earth Sciences, University of Southern California, Los Angeles, CA, 90089-0740
e-mail paterson@earth.usc.edu
R.B. MILLER
Department of Geology, San Jose State University, San Jose, CA 95192-0102
H. LEBIT
Department of Earth Sciences, University of Southern California, Los Angeles, CA, 90089-0740
H. ALSLEBEN
Department of Geology, San Jose State University, San Jose, CA 95192-0102
and C. LUNEBURG
Department of Earth Sciences, University of Southern California, Los Angeles, CA, 90089-0740

The degree to which outcrop-scale structures provide information about regional displacements and inferred boundary forces is often controversial. In this context we find kinematic models difficult to reconcile with natural examples of structures in orogens for the following reasons: (1) they ignore the mechanical effects of deforming heterogeneous rocks; (2) they assume that information about regional displacement is obtainable from outcrop-scale structure; (3) they place unrealistic boundary constraints on displacement; and (4) they assume a simple strain history in originally isotropic rocks. We present three natural examples from mid-crustal levels (~ 5 to 40 km) of a Cretaceous arc exposed in the Cascades core, Washington where we believe local, mechanically controlled deformation influence preserved structures to varying degrees.

The structurally highest unit, the Chiwaukum Schist is dominated by pelitic and psammitic layers. Here fold interference during mechanically active folding during NE-SW shortening, sometimes involving intrusions, strongly control most outcrop-scale structure including meso- and micro-scale mineral lineations and kinematic indicators. Results of finite element modeling are used to show that the complex strain and structural patterns in this unit can commonly be produced by mechanically active superposed folding. The structurally lower Napeequa complex is a strongly layered unit dominated by amphibolites, metasedimentary layers, and intrusive sheets all subparallel and moderately dipping. Although these units are all deformed during top-to-NNE shear, meso-scale structures and kinematics are strongly controlled by slip between units with different strengths analogous to fold and thrust belts at shallower crustal levels. The structurally lowest and most homogeneous unit is the Swakane biotite gneiss. This unit is also the most homogeneously deformed in the Cascades core typically preserving flat-lying compositional layering, subparallel foliation, and structures formed during pervasive top-to-north shear. But complex kinematics preserved near old fold hinges and the intensity of the noncoaxial shear are controlled by local compositional variations.

Thus with increasing rock homogeneity, and orientation of rock anisotropy parallel to regional directions of non-coaxial shear, meso and micro-scale structures increasingly reflect these regional displacements. However, in all cases pre-existing anisotropy and relative strengths of adjacent layers play an important role in the development of local structure in contrast to kinematic models and rheologic models assuming a weak, homogeneously deforming middle and lower crust.

Structural analysis of a transverse fault zone in the Front Ranges of the Canadian Rockies near Banff: Implications for models of the evolution of thrust and fold belts

Raymond A. PRICE
Department of Geological Sciences, Queen's University, Kingston, ON K7L 3N6

The Rocky Mountain foreland thrust and fold belt is an accretionary wedge comprising stratified supracrustal rocks that were scraped off the under-riding North American craton and accreted to the over-riding Intermontane terrane. Conventional wisdom holds that in foreland thrust and fold belts the major thrust faults develop sequentially from the hinterland to the foreland, and from the top to the bottom of the evolving accretionary wedge. Critical-taper theory requires that, in general, lateral growth of an accretionary wedge must be accompanied by horizontal compression and vertical thickening of the interior of the wedge; and therefore, that "out-of-sequence" thrust and fold structures must continue to develop in the interior of the wedge as it grows in width. Structural relationships in the Front Ranges near Banff show that the Canadian Rockies did indeed evolve in this way.

A transverse monoclinal flexure in the Rundle thrust, at Cascade Mountain, near Banff Alberta, marks the locus of an oblique lateral ramp along the hanging wall of the Rundle thrust fault. Across this ramp, the Rundle thrust fault cuts abruptly northward through the stratigraphic succession in its hanging wall, from one décollement zone in the Middle Cambrian into another near the base of the Upper Devonian Palliser Formation. The overlying Sulphur Mountain thrust sheet is folded by the monocline, and therefore must have formed prior to some of the displacement on the Rundle thrust; however, a transverse ramp along the footwall of the Sulphur Mountain thrust shows that the transverse monocline, and therefore, some of the displacement along the Rundle thrust occurred before displacement on the Sulphur Mountain thrust had ended. A transverse extension fault occurs within the Sulphur Mountain thrust sheet where its is folded over the underlying monocline in the Rundle thrust sheet. This extension fault extends into the overlying Bourgeau thrust sheet; but the stratigraphic separation across it decreases abruptly upward where it crosses the Bourgeau thrust; and this shows that some of the extension within the Sulphur Mountain thrust sheet occurred before displacement on the Bourgeau thrust had ended. The transverse fault is offset by the overlying Sawback thrust fault, which is a splay from the Bourgeau thrust. This shows that some of the displacement on the Sawback thrust occurred after the development of the transverse extension fault, and therefore, after much of the displacement had occurred on the Rundle thrust fault.

This transect across the Rocky Mountain Front Ranges at Banff shows that, as predicted by critical taper theory, even though the major thrust faults originated sequentially from hinterland to foreland, and from top to bottom of the accretionary wedge, displacement on one did not end when displacement on another began. The major thrusts were active simultaneously, and the accretionary wedge continued to be horizontally shortened and vertically thickened as it grew in width.

Fault reactivation at Ute dome, northwest New Mexico, USA: structural evolution interpreted from a 3-d seismic study

Steven RALSER
Dept. Earth and Environmental Science, New Mexico Tech, Socorro, NM, 87801
and Bruce HART
New Mexico Bureau of Mines and Mineral Resources, New Mexico Tech, Socorro, NM, 87801

Ute Dome is an asymmetric dome located at the southeastern margin of the of the Four Corners Platform in northwest New Mexico, and lies immediately to the northwest of the Hogback Monocline. The monocline is deflected around Ute Dome, and has previously been interpreted as flexure over a blind high angle reverse fault.

We have interpreted a 3-D seismic survey to determine the structural evolution of the area. Three fault populations are recognized: 1) a series of WNW-trending faults, best observed by offset of the Middle Jurassic Entrada Formation and Cretaceous Dakota Sandstone. These faults do not extend SE across the Hogback Monocline. Only one WNW trending fault is observed cutting Paleozoic age rocks. The WNW trending faults have 60-90m throw at the surface but only 30-60m throw at the Dakota Sandstone level. None of these faults can be connected to the WNW-trending fault observed in the Paleozoic section. 2) NE-trending faults bound the NW side of Ute Dome and also occur in the Paleozoic section (but west of the Hogback Monocline). 3) NW-verging thrust faults localized between the Entrada Formation and Dakota Sandstone.

We are evaluating two scenarios to determine the origin of the observed faults: 1) Previous work has shown that both NW- and NE-trending structures occur in the Proterozoic basement underlying the Colorado Plateau. Both the NE- and the NW-trending faults observed in the Paleozoic section of the seismic data probably represent reactivated basement structures, with the NW-trending fault being the younger of the two. In this scenario the faults observed in the upper part of the section may represent faulting to accommodate drag over the deeper reactivated faults. The thrust faults between the Entrada Formation and Dakota Sandstone represent accommodation faults associated with formation of the Hogback Monocline. 2) A strike-slip origin has been proposed for some monoclines in the Colorado Plateau. Stratigraphic constraints restrict any strike-slip motion along the Hogback Monocline to less than a few kilometers. In a dextral strike-slip regime (consistent with the kinematic history of other Laramide structures in the southwest U.S.A.) Ute Dome is located in releasing bend. Here, the NW-trending faults would be associated with extension related to strike-slip movement, and the thrust faults may be associated with a related flower structure.

The structural geometry revealed by the 3-D seismic data have allowed us to better understand the tectonic evolution of the Ute Dome area.

Low viscosity shear zones within broader ductile transpression zones

Pierre-Yves F. ROBIN and Alexander R. CRUDEN

Department of Geology & Erindale College, University of Toronto, Mississauga, ON L5L 1C6,Canada

We investigate a model of ductile transpression in which a thin, low-viscosity layer is sandwiched in the middle of a higher viscosity zone. In nature, the high viscosity transpression zone could be a crustal-scale transpression domain, while the low viscosity zone might be a narrow, vertical, softened shear zone within that domain. In the field, the narrow central shear zone would thus appear as 'the shear zone', while the broader transpressive zone would simply appear as less deformed 'wall rock'. Because the thickness of 'the shear zone' is small compared to its other two dimensions, it is constrained to match the in-plane strain of the 'wall rock'. The strain response of such models is examined analytically and with analogue experiments. The significant parameters are convergence angle, α, and viscosity ratio, R_η.

Analytical modelling deals with small strains within zones of infinite extent and idealised geometry. Analogue models are used to confirm the analytical models as well as to study the consequences of finite strains, heterogeneities, and end-effects. As expected, the horizontal shear strain is concentrated in the low viscosity shear zone, but that zone is also stretched vertically, to match the vertical extension of the wall rock. Varying convergence angle and viscosity ratio leads to a number of interesting situations. For examples: 'lineation' (i.e. the direction of maximum principal strain) in the narrow shear zone can be horizontal, while those in the adjacent wall rock are vertical; or the strain in the walls can be dominantly vertical stretches ($k > 1$), whereas flattening strain ($k = 0$) occurs in the shear zone. Such 'dual viscosity transpression' thus appears to be a viable explanation for shear zones reported to exhibit flattening strains rather than plane simple shear strain.

Multiple shape fabrics in a quartz mylonite: evidence for a thickening shear zone

James J. RYAN and Paul F. WILLIAMS
Department of Geology, University of New Brunswick, Box 4400, Fredericton, New Brunswick, E3B 5A3

A specimen of naturally deformed quartz mylonite has three distinct foliations: (a) the shear foliation (C-surface) defined by compositional layering, local grain shape and yield surfaces (thin zones of ultra-fine grain size); (b) an oblique shape fabric (S_a) defined by large (1–4 mm) ghost grains with oblate shapes ($0 < k < 1$), inclined 20–40E to the C-surface; and (c) a secondary shape fabric (S_b) in fine-grained (20–50 μm) dynamically recrystallized quartz with oblate shapes ($k - 0$), oriented 60–70E to the C-surface. Subgrains and dynamically recrystallized grains defining S_b tend to obscure, but not obliterate the larger, ghost grains that define S_a. To our knowledge, this association of fabrics has not been previously reported.

A number of hypothetical models may explain the development of the microstructure, three of which include: (I) An overprinting relationship where S_a and the C-surface formed during one deformation, and was overprinted by S_b associated with a later deformation. (II) A thinning zone (e.g., transpression) with flow partitioning where the quartz ribbons formed S_a parallel to the S-surface, controlled by the bulk instantaneous stretching axes (ISA), and rotated towards the C-surface. Partitioning of flow between individual quartz ribbons promoted a local flow, with local ISA controlling the obliquity S_b to S_a and the bulk C-surface. The microstructure in this model represents, in essence, a C/S within a C/S fabric. (III) A thickening zone (e.g., transtension) without partitioning, in which S_a initiated at a high angle (>70°) to the C-surface and rotated towards the extensional eigenvector during progressive deformation (forming quartz ribbons). Small, new grains formed S_b at a high angle to the C-surface, and thus at a lower angle to S_a. If the thickening zone has no horizontal change in length, the fabrics represent a *transtensional* microstructure, whereas, if the zone has no vertical change in length, the fabrics represent a *thickening zone* microstructure. A spectrum is possible between the two end members.

Model I is not viable, because overprinting is inconsistent with field observations. Model II is problematic for a number of reasons. Conceptually, a partitioning of strain between the quartz ribbons, as they rotate towards the C-surface, can induce an antithetic flow between the ribbons relative to the bulk flow. In this case, a secondary shape fabric should develop at a lower rather than higher angle to the bulk C-surface; a contradiction to the observation. Model II also implies that the local flow was highly non-steady, due to the 'spinning' of the local eigenvector towards the bulk eigenvector parallel to the C-surface. This is a further contradiction to the apparent steady state fabric in the specimen. Model III is favored, because the large angle between S_b and the C-surface indicates that the maximum ISA is greater than 45° to the C-surface. It explains the orientation of the three fabrics simply, such that: (a) the C-surface is parallel to the shear zone boundary; (b) S_a records some finite strain of larger grains (and is thus finite strain sensitive); and (c) S_b is more sensitive to the instantaneous strain, and probably defines a steady state fabric.

Of particular interest is the observation that the C-surface in this mylonite does not seem to represent the extensional eigenvector of the flow; a result that has been theoretically predicted but never documented for naturally deformed rocks.

Plastic Deformation of Ultrahigh Pressure Eclogites from the Dabie-Sulu Region, China

Kazuko SARUWATARI, Shaocheng JI and Zichao WANG
Department of geology, University of Montreal, C.P. 6128, Succursale 'Centre-Ville', Montreal, Quebec, Canada H3C 3J7

Rheological properties of eclogites are critical for understanding deformation, structures and geodynamics of subducting slabs. Most observations of deformation microstructures so far have been carried out on eclogites from the lowermost part of continental crust (<70 km depth). Recent discovery of coesite and diamond bearing eclogites, which were a part of oceanic slab subducted to depths larger than 120 km and then tectonically uplifted to the Earth's surface, provides us an excellent opportunity to investigate rheological and deformation characteristics of subducting slabs. Moreover, studies on seismic velocities and anisotropy related to compositional layering and mineral preferred orientation can shed significant light on the origin of seismic reflections in the upper mantle. For the above purposes, we studied deformation of eclogites from the Dabie and Su-Lu ultrahigh pressure (UHP) metamorphic terranes in the central China. These eclogites occur as pods, layers and blocks ranging from tens of centimeters to hundreds of meters in size within ultramafic blocks, metapelites (garnet-quartz-jadeite gneisses), kyanite quartzites and marbles. The eclogites developed pronounced foliation, stretching lineation and strain-induced compositional (garnet-rich and omphacite-rich) layering, indicating a strong ductile deformation. Garnet contents vary from 70 to 95 % in garnet-rich layers. Both equigranular and porphyroclastic textures have been observed. Equigranular garnet grains show ellipsoidal shapes with average axial ratios (X/Y/Z) of 1.32/1/0.67, suggesting a quasi-plane-strain (K=1) in Flinn diagram. These garnet grains have higher Fe and lower Ca contents at the core than at the margin. In the porphyroclastic eclogites, garnet porphyroclasts are surrounded by equidimensional fine-grained neoblasts. The compositions of fine grains are same as the rims of the porphyroclasts. Boundaries between porphyroclasts and neoblasts are commonly serrate, indicating the presence of dynamic recrystallization during ductile deformation. Eclogites containing porphyroclastic garnets have the higher density (>3.8 g/cm3) than those containing equigranular garnets (<3.6 g/cm3). In both types of eclogites, omphacite and rutile grains are strongly elongated. Omphacites develop strong shape-preferred and lattice-preferred orientations. Our preliminary geothermobarometrical studies suggest that peak metamorphism of these eclogites occurred at 730-900EC and >28 kbar, consistent with previous studies in the same region. The study allowed us to draw the following conclusions: (1) The eclogites can be plastically deformed under the UHP metamorphic conditions and are not rheologically rigid as thought previously. Plastic flow of eclogites will preclude effective shear heating, rendering the cool thermal structures within the subducting slab. This makes it possible to preserve the relict subducted oceanic crust within the upper mantle for long geological time. (2) Strong seismic anisotropy of eclogites results from strong LPO of omphacite and particularly from compositional layering with varying relative contents of garnet and omphacite. (3) The mantle reflectors are most likely originated from garnet-rich and omphacite-rich layering within eclogites and the boundaries between eclogite and peridotite layers.

Heterogeneous deformation in a syn-tectonically intruded fan-like structure, Peninsular Ranges batholith, Baja, Mexico

Keegan L. SCHMIDT and S.R. PATERSON
Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740.
kschmidt@usc.edu

Continental arcs are extremely dynamic environments in which both intense magmatism and deformation are concentrated in relatively narrow regions along plate boundaries. It is commonly assumed that the final structures we examine in these deforming zones were produced in approximately homogeneously deforming materials and, therefore, can be directly related to plate motions. Arc environments provide a unique opportunity to test this assumption because: 1) relative and absolute age controls are generally readily available from cross-cutting relationships; and 2) materials in these deforming arcs clearly displayed a wide spectrum of rheological states at the time of deformation because plutonic rocks ranged from magmatic to solid state rheologies at the time of deformation.

An example is the early-mid Cretaceous arc exposed in the southern Sierra San Pedro Martir. A ~20 km wide zone of shallow- to mid-crustal L-S tectonites comprise a fan-like structure, pre- to syn-tectonically intruded by plutons of the Peninsular Ranges batholith. The fan-shaped pattern results from shallowly inward dipping mylonitic foliation on the sides of the structure and steeply-dipping plutonic sheets and magmatic foliations in the center of the structure; fabrics between the center and sides of the fan-like structure show a smooth transition within plutonic rocks from mylonitic towards the sides to magmatic towards the center. Mineral lineations display a similar transition from mylonitic, moderately-plunging, and inward trending on the sides to magmatic, moderately-plunging, and N-trending in the center. Kinematic indicators developed in sections parallel to lineations (none observed in other orientations) show reverse shear sense on the sides of the structure (n=13 and 6 from west and east sides respectively) and ~50%/50% sinestral/dextral (n=38) in the center.

Overall this zone shows a relatively simple pattern of structures that indicates largely contractional deformation and might readily be interpreted as having formed in a transpressive plate margin setting. However, more detailed observations suggest that deformation was quite heterogeneous and that both the relative strengths of materials and presence of older anisotropy influenced deformation on a variety of scales. For example, plutonic suites within the fan-like structure are of several different ages, indicating that structures across the fan also formed at several different times. The smooth transitions in orientation of these diachronous fabrics indicates that a composite fabric was formed in some locations. Folding occurs at mm to km scales across the fan-like structure, and folded fabrics range from solid state to magmatic. Some of these folds refold older fabrics; others form parallel to older lineation and were clearly influenced by the orientation of this older anisotropy.

The fan-like structure records several pulses of dominantly contractional deformation spanning tens of M.y. Similar deformation occurred across a broad region and along the length of the Peninsular Ranges batholith and is compatible with plate motion control on deformation. The intrusions of plutons at various times complicated deformation. Sheeted plutons oriented parallel to the arc provided relatively weak zones that probably focused deformation that is now recorded as magmatic fabrics in the center of the fan-like structure. Once these bodies cooled, they became relatively strong and focused deformation in the sides of the fan-structure to form mylonitic fabrics and regions of intense folding between plutons.

3D asymmetry of inclusion wings in ductilely deformed rocks

Frank SCHRADER

Geology Department, Uiversity of Toronto, 22 Russell St., Toronto M5S3B1, Canada

Textures of ductile deformation are often analysed with the concept of the ellipsoid of finite strain, which has three mutually orthogonal principal axes X, Y, and Z. 2D sections parallel to its principal planes, especially the XZ-plane, seem to be sufficient to understand the texture.

The transposition of the material particles during deformation may have similarly simple pathline arrays with or thogonal principal axes of material contraction (particle path divergence - AD), material stretching (particle path convergence - AC), and the intermediate axis (AI), like in the case of pure shear (Fig. 1a). Furthermore, contraction and stretching axes may make smaller angles (oblique shear, Fig. 1b) down to 0° (simple shear, Fig. 1c); finally the particles may rotate about the intermediate axis (Fig. 1d), and rolled-up vortices may be formed.

However, also the intermediate axis may make non-orthogonal angles with the contraction and/or the stretching axis, which may be related to shearing and vortex effects beyond the geometric possibilities of simple shear: divergence shear (Schrader 1988: J. Struct. Geol. 10: 41-52) with non-orthogonal intersection of contraction and intermediate axes (Fig. 1e) may be related to spiral stretching (Fig. 1f), and convergence shear with non-orthogonal intersection of stretching and intermediate axes (Fig. 1g) may be related to spiral contraction (Fig. 1h).

Representations of particle path arrays are distinctive in some conglomerates (e.g. in moderately deformed foreland basins) on pebble surfaces in the form of slip lineation arrays, which were produced by relative displacements of neighbor pebbles. Representations of particle path arrays are also found at the surfaces of garnet nodules from highly strained metamorphic rocks (for convenient analysis nodules must be larger than 2 cm in diameter and must be ex tractable from the matrix). Especially at such nodules, non-orthogonal intersections of the contraction and/or stretching axis with the intermediate axis and spiral stretching (with twisted wings of matrix material adherent to the nodules) are distinctive in places (e.g. at the Grenville Front close to Sudbury/Ontario).

Contemporary concepts of rock deformation related to finite strain usually deal with pure shear and simple shear in the XZ-plane or particle rotation about an axis normal to it. In such cases, rock inclusions may have pairs of straight wings or wings curved only in this plane, and 2D sections parallel to this plane may be sufficient to determine the sense of simple shear by classifying asymmetric wing profiles as σ- and δ-types (Passchier and Simpson 1986: J. Struct. Geol. 8: 831-843).

A pair of spiral wings, however, may show arbitrary and opposite asymmetries in parallel sections of different levels through an individual inclusion. So σ- and δ-analysis with 2D sections can be done only after having determined that the inclusion wings are not curved like spirals.

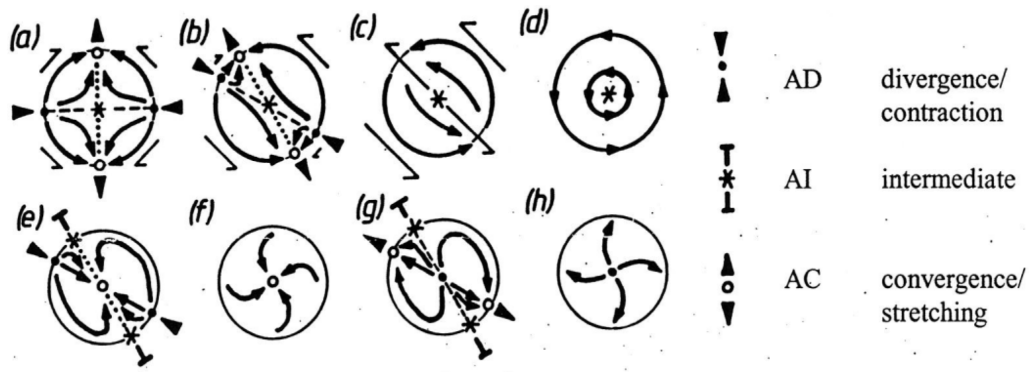

Fig. 1 Stereoplots of deformational particle path arrays. Pathline trajectories are plotted on the surface of the pro jection sphere (tangential representation): (a) pure shear, (b) oblique shear, (c) simple shear, (d) particle rotation, (e) divergence shear, (f) spiral stretching, (g) convergence shear, (h) spiral contraction.

Strain analysis of boudinaged porphyroclasts in mylonites along the Median Tectonic Line, southwest Japan: Implication for the lineation-normal stretch of ductile shear zone

Koji SHIMADA* and Hideo TAKAGI

Institute of Earth Science, School of Education, Waseda University, Tokyo, 169-8050, Japan

*(*e-mail : 698g5040@mn.waseda.ac.jp)*

Three dimensional deformation of the Ryoke southern marginal shear zone (RSMSZ) along the Median Tectonic Line (MTL) will be discussed on the basis of the strain analysis of boudinaged feldspar porphyroclasts. The RSMSZ is mainly composed of the granitic mylonites originated from the Late Cretaceous foliated granitoids. It is one of the major shear zones in Japan, and it extends more than 300 km long discontinuously.

The MTL in the study area (eastern Kii Peninsula) strikes nearly W-E, and dips northward steeply. The mylonitic foliation (Sm) in the RSMSZ strikes W-E to WNW-ESE and dips north steeply. The attitude of mylonitic lineation (Lm) and their asymmetric microstructures show the sinistral sense of shear. The width of continuous ductile shear zone (RSMSZ) ranges about 1 km. Grain size of recrystallized quartz reduces from north to south (MTL).

The orthogonal reference system is defined as the *Z* axis: perpendicular to the Sm, *Y* axis: lying within the Sm and being perpendicular to the Lm (*X*). The stretch of boudinaged feldspar were measured on *XZ*, *XY*, and *YZ* thin sections prepared from one cubic chip. Stretch is defined by $S = Lf / \Sigma Li$ (Bailey et al., 1994), where Lf is the total length of the boudinaged-feldspar system and ΣLi is the summation of feldspar fragment lengths.

From our preliminary data, the protomylonite sampled from about 300 m north of the MTL has the maximum stretches as $X/Z = 1.5$, $Y/Z = 1.5$. The mylonite sampled from about 200 m north has the maximum stretches as X/Z=1.6, Y/Z =1.4. They show the stretch along *Y*-direction as well as *X*-direction, and the three dimensional strain on the sample scale deviates into flattening strain from the plane strain. Thus, the RSMSZ possibly behaved as a ductile 'stretching shear zone' with lineation-normal stretch on the shear zone scale, under the relatively low temperature condition.

We will also report the relationships between the strain and other microstructures such as subgrain size and grain size of recrystallized quartz, LPO of quartz, DPO and morphology of all minerals, and discuss the meaning of *Y*-stretching in the ductile shear zone.

Structural evolution during high-temperature dextral transpressive orogenesis: reading the evidence recorded in porphyroblasts

Gary S. SOLAR and Michael BROWN
Laboratory for Crustal Petrology, Department of Geology, University of Maryland, College Park, MD 20472, USA, (solar/mbrown@geol.umd.edu)

High-*T* deformation increases the potential for tectonic fabrics to be partially to completely modified because static crystallization continues without deformation, and internal strain effects in crystals are annealed. Thus, despite the presence of preferred orientations of these crystals to form foliations and lineations, internal strain is not recorded within the annealed matrix grains, and included foliation in porphyroblasts may provide the only record of the progressive evolution of matrix fabrics. We illustrate the use of microstructures to constrain evolution of regional tectonics with examples from the Central Maine belt (CMB), northeastern USA. In the CMB of west-central Maine, during Devonian (Acadian) high-*T* dextral transpressive orogenesis, strain was accommodated heterogeneously, partitioned into zones of enhanced deformation and localized into pelite-rich units. These rheologically weaker strata accommodated relatively more displacement and higher strain (higher strain zones; HSZs) during the contraction of the orogen. The stronger strata composed of psammite-rich units formed intervening zones of lower strain rocks (LSZs). Both zones include a penetrative moderately NE-plunging mineral elongation lineation that is parallel across the region. Together these structures define the CMB shear zone system. Perturbations in the ductile flow within the shear zone system caused folding and thrusting, but the different rheological behavior between stratigraphic units resulted in enhanced fold tightening, overturning and limb shear strain in HSZs that was not recorded in LSZs. Oblique dextral-reverse kinematics is determined from asymmetric boudinage and strain shadows around porphyroblasts to show SE-side-up and to the S sense of displacement. In HSZ rocks, the tectonic fabric is defined by a penetrative continuous mica and quartz-ribbon foliation, and bladed muscovite and biotite mineral elongation lineations (S $ L tectonites; apparent flattening to plane strain). In contrast, LSZ rock fabrics are defined by a penetrative bladed muscovite mineral elongation lineation, and a foliation that is weakly developed to absent (L > S tectonites; apparent constrictional strain). In both types of zone, deformation and mineral growth were coeval because the same minerals define the fabrics at the same grade. In HSZ rocks, parallel cm-scale alternating P- and Q-domains suggest mesoscopic differentiation. Textural zones within porphyroblasts record episodic interkinematic porphyroblast growth. Asymmetric and symmetric quartz-dominated strain shadow tails around porphyroblasts are elongate parallel to the mineral elongation lineation to record matrix shear strain during and/or after porphyroblast growth in the λ_1-λ_2 plane (foliation), in the λ_1 direction (lineation). In thin sections cut parallel to mineral elongation lineation, S_i in garnet and staurolite is typically oblique, although some S_i are parallel to S_e. Apparent dips of S_i have pitches relative to S_e either in an up- or down-plunge direction of the lineation, with a constant pitch direction in any one thin section. S_i is always discontinuous with S_e, and only rarely are S_i gently crenulated to suggest interkinematic-to-syntectonic porphyroblast growth. The angle of obliquity is continuous in most samples in the range 10-50°. In LSZ rocks, porphyroblasts only rarely have an included foliation which forms opens crenulations in the lineation-perpendicular view. These S_i - S_e relations are interpreted to record fold tightening and/or layer parallel shear strain inside HSZs. In examples from HSZ rocks, the angle of obliquity between S_i and S_e decreases during general shear by either new growth over reoriented axial-planar foliation, or by porphyroblast rotation about λ_2 in the reorienting λ_1-λ_2 plane. In either case, porphyroblast growth was interkinematic to envelope straight S_i. The range in obliquity between S_i and S_e suggests that porphyroblast growth began once folds of stratigraphy were established, and continued late into the deformation history. The sense of obliquity is constant in single thin sections, but switches in the sense of displacement occur from location to location across strike. This suggests porphyroblast growth on opposite fold limbs. Examples of S_i parallel to S_e suggest final porphyroblast growth at the end of deformation.

Structural style and its implications for structural evolution and economic development of thrusted lower Cretaceous, Ricinus, Alberta

Greg SOULE
Amoco Canada Petroleum Company, P.O. Box 200 Stn. M, Calgary, Alberta T2P 2H8 Canada
(Now at Rigel Oil & Gas, 1900 Bow Valley Square 3, 255 Fifth Avenue S.W. Calgary, Alberta T2P 3G6)

The Ricinus area covers approximately 5 Townships (460 sq. km) over the eastern edge of the Southern Alberta Foothills of the Rocky Mountains. The Cretaceous section was deformed, predominantly by thrusting, by the Laramide orogeny. The basal detachment in this area of Mesozoic deformation is in the Mannville coals, with other major detachments in the Upper Blackstone, Lower and Upper Wapiabi, and Middle Brazeau Formations. Drilling of the Viking Formation gas pools provides a good dipmeter database to constrain the deformation style of the structural unit between the basal detachment in the Mannville coals and the Upper Blackstone detachment.

The Mannville/Viking structural unit (interbedded sandstone and shale sequence) can be described as a transported fault-propagation fold which is consistently present at the leading edge thrust cutoff of the interval. The geometry of the fold is a steep to overturned NE facing forelimb with a 30E-50E SW dipping backlimb. The geometry is very well constrained by ten wells, with dipmeter data, which penetrated the forelimb and were sidetracked to intersect the backlimb. Utilizing a plot of the axial angle of the fold vs. ramp cutoff angle indicates the fold geometry is a fault propagation fold (Suppe, 1985).

Good dipmeter data indicate the leading edge tight fold at the Mannville/Viking level is cylindrical, and that the fold axis is parallel to the strike of the thust cutoff. Well penetrations and seismic data suggest the backlimb is a simple southwest-dipping panel carried in the hanging wall of the thrust faults while northeast dipping strata are only associated with leading edge folds also supporting the idea these were formed as fault propagation folds. The leading edge fold is mapped in the along strike direction in the order of 6 km on individual thrusts and 20 km on linked thrust fault systems. The parallel fold/fault strike relationship was successfully used to locate step-out wells in Viking gas pools up to 3 miles away from the existing well control, with a significant positive economic impact by saving the $500 000 cost of a sidetrack.

The transported fault propagation fold model is important because it indicates the structural style will consistently have a tight leading edge fold with a fractured hinge zone. As fractures are key to the high gas deliverability of Ricinus Viking Fm. wells, the fold model is significant because it predicts the fractured hinge will be a very narrow zone as the volume of rock which passes through the active hinge is small (Suppe, 1985). Furthermore, plotting the fold geometry parameters on geometric analysis plots predicts forelimb thinning (Jamison, 1987). This prediction is supported by the presence of bedding-parallel stylolite surfaces which, although commonly observed in core, are enhanced in the steep to vertical forelimb producing localized late stage quartz cements. The conclusion from these two aspects of the structural style, fracturing and forelimb thinning, is the ideal well location for the Viking gas wells is in the backlimb close to the zone of maximum curvature and this in turn impacts drilling strategy.

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Along-strike variation within the triangle zone and external Foothills, southwestern Alberta: The influence of mechanical stratigraphy on structural style

Glen S. STOCKMAL
Geological Survey of Canada (Calgary), 3303-33rd Street NW, Calgary, AB, T2L 2A7
Daniel LEBEL
Geological Survey of Canada (Québec), 2535, boul. Laurier, P.O. Box 7500, Sainte-Foy, Québec G1V 4C7
and Margaret E. MCMECHAN
Geological Survey of Canada (Calgary), 3303-33rd Street NW, Calgary, AB, T2L 2A7

The eastern margin of the Foothills belt, southwestern Alberta, is characterized by a thin-skinned, NNW-striking, structural triangle zone (tectonic wedge) and steep, imbricated, dominantly foreland-vergent thrusts. New, detailed 1:50,000 scale mapping, undertaken for the Geological Survey of Canada's Southeastern Cordillera NATMAP project (Foothills map-sheets between 49°00' N and 50°45' N), demonstrates that structures between Oldman River (49°45' N) and Turner Valley (50°40' N) vary significantly. These variations occur in concert with lateral changes in foreland stratigraphy and the composition of units structurally inserted into the triangle zone; we interpret these variations to reflect the influence of mechanical stratigraphy.

Between Oldman River and Chaffen Creek (50°05' N), deformation is characterized by a series of dominantly hinterland-vergent structures in the hanging wall (east of) the triangle zone upper detachment (the Big Coulee Fault zone), including thrusts and large, kilometre-scale folds and folded thrusts. The upper detachment (a broad regional backthrust shear zone) lies within the mechanically weak Bearpaw Formation marine shale interval, which locally is greatly thickened structurally.

At Chaffen Creek, a smooth and continuous eastward step of the trace of the upper detachment coincides with exposure of a southward-plunging antiformal stack in its footwall. The prominent, orogen-vergent structures in the hanging wall of the upper detachment, characteristic of the southern area, apparently die out at this latitude. Instead, the triangle zone resembles a simple passive roof duplex, with the upper detachment remaining within the structurally thickened Bearpaw interval. The antiformal stack reflects the presence at depth of a mechanically competent beam of Mississippian carbonates carried on the blind, foreland-vergent Outwest Thrust. A hanging wall lateral ramp cuts out the carbonates to the south, coincident with the southward plunge of the duplex stack and the eastward swing in the trace of the upper detachment. Early Cretaceous Blairmore Group rocks are exposed along the crest of the antiformal stack to the north, only one kilometre from the trace of the upper detachment.

Between Chaffen Creek and Stimson Creek (50°23'), the triangle zone continues to resemble a simple passive roof duplex, but the Outwest Thrust splays to the surface and the hinterland-vergent upper detachment in the Bearpaw Formation is apparently offset by younger foreland-vergent thrust(s). A younger hinterland-vergent roof thrust has developed to the east in younger foreland strata at Stimson Creek.

Between Pekisko Creek (50°26') and Sheep River (50°40'), the Bearpaw stratigraphic level remains the locus of an internally complex, hinterland-vergent upper detachment zone. However, the Bearpaw thins substantially from south to north, becoming an increasingly poor detachment horizon; this results in the distribution of shear strain over a broad zone, involving marginal marine sediments in adjacent units. On Pekisko Creek, primarily hinterland-vergent folds and faults are developed in the overlying St. Mary River Formation, forming a mappable zone 2 km wide, and on Highwood River (50°32') a similar broad zone also involves strata of the underlying Belly River Group. This broad, mappable zone of intense strain may represent a transition to the "intercutaneous wedge"-style triangle zone documented farther north.

Fibrous vein microstructures: an overview of recent developments

Janos L. URAI, and Chris HILGERS
Endogene Dynamik, RWTH Aachen, Lochnerstrasse 4-20 D-52056 Aachen, Germany,
J.Urai@ged.rwth-aachen.de

Syntectonic fibrous veins and strain shadows provide one of the few tools available for structural geologists to analyse progressive deformation at low metamorphic grades. This is well illustrated by their use in many recent studies, even without the validation of the technique by checking if fibres connect bedding on both sides of the fracture. This check is necessary however, as clear examples of non-tracking fibres are documented, e.g. in Williams & Urai (1989). The classic crack-seal model of Ramsay (1980) is only one of the several mechanisms which can produce fibrous crystal microstructures. Another well documented mechanism is growth from pore openings (Means 1995). All studies to date (Mügge 1928) agree that two necessary (but not sufficient) conditions for the growth of calcite or quartz fibres are: (i) progressive deformation and (ii) some kind of contact between vein and wall rock.

Clearly the formation fibrous morphologies can occur by a range of different processes, each with its own significance and characteristic microstructure. They can be formed in a crack with laterally moving fluid or by diffusion along a stationary fluid. Although models of crystallization from a supersaturated solution in cracks have given useful constraints on the rates of precipitation and have illustrated the order of magnitude of the critical parameters involved, further understanding of the evolution of fibrous microstructures requires experimental work. The critical process to be investigated is how grain boundaries propagate during crystal growth of a polycrystal, under a wide range of conditions. We present the first results of the development of an apparatus which allows study of crystal growth in transmitted light, in a progressively opening crack. The design allows for flow of supersaturated fluid along the crack, as well as growth in a stationary fluid.

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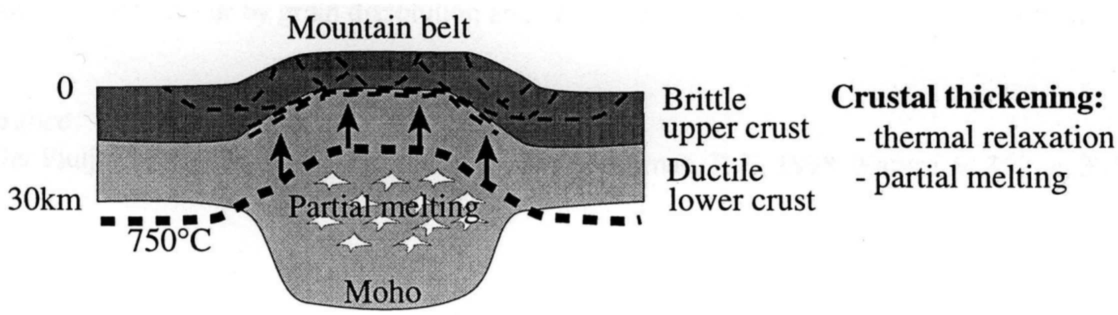
Role of partial melting during late-orogenic collapse: from migmatite to granite in the Shuswap metamorphic core complex, Canadian Cordillera

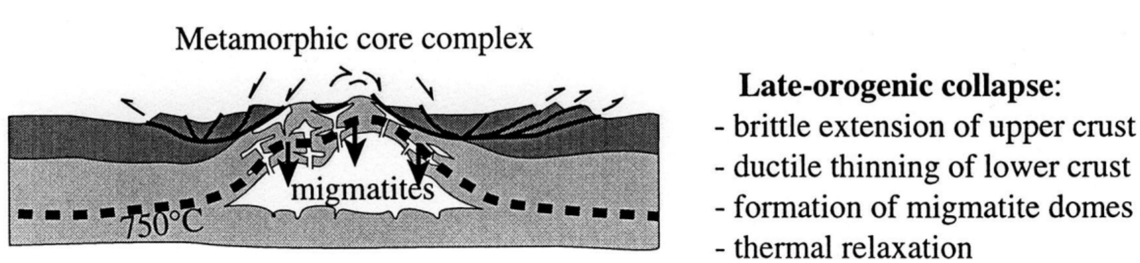
Olivier VANDERHAEGHE* and Christian TEYSSIER
Geology & Geophysics, University of Minnesota, 310 Pillsbury Dr. SE, MN 55455 USA
**Current address: Oceanography, Dalhousie University, Halifax, Nova Scotia, B3H 4J1, Canada*

At the latitude of the Thor-Odin dome, the Shuswap Metamorphic Core Complex (MCC) displays a ~15 km structural section composed of an upper unit that preserved Mesozoic metamorphic assemblages, structures and cooling ages, separated from the exhumed metamorphic core by a low-angle detachment zone. Below the detachment, the core of the complex consists of an amphibolite-facies middle unit overlying a migmatitic lower unit exposed in the Thor-Odin dome. Combined structural study and U-Pb geochronology using the SHRIMP analytical facility indicate that pervasive shallowly-dipping foliation and east-west lineation developed in the presence of melt during Paleocene time.

The elliptical shape of the Thor-Odin dome is delineated by the metatexite-diatexite transition across which the rocks lose their solid framework and behave like a viscous magma. Leucogranite probably dominantly generated by partial melting in the migmatitic Thor-Odin dome, migrated upward through a network of dikes and sills that permeated the middle unit, and ponded to form laccoliths spatially related to the detachment zone.
SHRIMP analysis of complexly zoned zircons from the migmatitic leucosomes and leucogranite samples reveals that the migmatitic rocks of the lower unit crystallized at ~ 56 Ma and the syntectonic granite in the detachment zone crystallized at ~ 60 Ma. The similarity in age between inherited cores in the migmatite and leucogranite samples suggests a genetic link consistent with the structural analysis.

We propose that exhumation of the core of the Canadian Cordillera during the formation of the Shuswap MCC occurred from 60 to 56 Ma at a time when the crust was significantly partially molten. Following the crystallization of migmatites, the terrane cooled rapidly, as indicated by muscovite, biotite, and K-feldspar $^{40}Ar/^{39}Ar$ ages clustering at ~50-45 Ma. The structural and temporal relationships from the Shuswap MCC suggest a genetic link between mechanical weakening of the crust by partial melting, late-orogenic collapse and exhumation of high-grade rocks in the hinterland of a thermally mature orogenic belt.





Static Recrystallization and Preferred Orientation of Phyllosilicates; Michigamme Formation, northern Michigan

Ben A. VAN DER PLUIJM, Nei-Che HO, and Donald R. PEACOR
Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109, USA.

The Michigamme Formation of the Marquette District in Michigan's Upper Peninsula preserves a sequence of cleaved rocks of increasing metamorphic grade. Metamorphism occurred after cleavage formation, so the area provides the special opportunity to study preferred orientation of phyllosilicates under conditions of static recrystallization.

Nine samples were collected from the greenschist facies zone, with varying distance from the bounding chlorite/biotite and biotite/garnet isograds. The main mineral constituents are muscovite, biotite, chlorite and quartz. Phyllosilicate fabric orientation and intensity for each sample were measured using high-resolution X ray pole figure goniometry and characterized by electron microscopy.

Results from X-ray texture goniometry show (1) that the preferred orientation of phyllosilicates is always parallel to the cleavage direction, and (2) that the degree of the preferred orientation of phyllosilicates improves as a function of increasing metamorphic grade (from <4 to >9 m.r.d.). Scanning electron microscopy on these samples shows (3) that the length/width ratio increases with increasing grade, and (4) that grain shapes are better defined with increasing grade.

Our previous work on slates from lower grade environments showed that mechanical processes dominate at low metamorphic grade, whereas chemical processes are favored at higher grades (e.g., van der Pluijm et al. 1998). Indeed, these medium-grade samples indicate that improvement of preferred orientation is achieved solely by dissolution neocrystallization. Evidence for mechanical processes, such as kinking or bending of grains, is absent. Groundmass material and non cleavage parallel phyllosilicate grains were preferentially dissolved, likely facilitated by internal strain energy from mineral defects, whereas cleavage parallel phyllosilicates grew preferentially along their (001) planes. These results show that significant fabric improvement can occur by grain dissolution and crystallization in the absence of deformation.

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Structural evolution of an Appalachian subduction complex and the role of fluid in localization of strain

Cees R. VAN STAAL, Neil ROGERS, Bruce TAYLOR and Ken CURRIE
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A OE8

The Brunswick Complex in northern New Brunswick is one of the best preserved subduction complexes in the Appalachian/Caledonian Orogen. The complex formed by NW-directed subduction of marginal basin oceanic crust beneath Laurentia. Small semi-continental, volcanic fragments and parts of the Gander margin were underplated to the accretionary wedge during the Ashgill and the Early Silurian (445-425 Ma), and reached conditions of c. 8 - 6 Kb, 330-370EC. The Brunswick Complex, which covers an area of at least 7000 km^2, is anomalous in that it contains a very large quantity of silicic igneous rocks (c. 3000 km^3) that were subjected to the HP-LT metamorphic conditions. Sodic amphiboles and pyroxenes are abundant in the basalts and occur locally also in the felsic rocks.

The structural evolution of the underplated rocks is extremely complex and comprises 4 different kinematic events that took place sequentially between 445 and 370 Ma. Discussed here are the earliest structures (D1) that formed during the HP-LT metamorphism. D1 comprises at least two, but locally probably three generations of ductile structures, which are represented by narrow shear zones, characterised by large strain gradients and large-scale, steeply inclined isoclinal folds that consistently have a sinistral asymmetry. The F1 folds folded the earliest shear zones and rotated them into steeper attitudes. Careful regional mapping combined with geochronological studies and aided by detailed geophysical surveys has shown that the two generations of shear zones are accompanied by major structural cut-offs in their footwalls. The earliest shear zones consistently put old rocks over younger rocks and kinematic indicators are consistent with a reverse sense of motion.The second generation shear zones cut the earlier shear zones and locally put young rocks over old. We have interpreted these shear zones as out-of sequence thrusts, although a low-angle, extensional origin for some of these faults cannot be overruled at this stage. All D1 structures were refolded into upright tight, generally dextral F2 folds during D2.

Oxygen and hydrogen isotope data for the blueschists ($\delta^{18}O$ = 7.7 to 8.8‰; δD = -62 to -51‰) and the low strain greenschists ($\delta^{18}O$ = 8.4 to 10.9‰; δD = -79 to -52‰) suggest that D1 was accompanied by channeling of large amount of H_2O-rich fluids into the shear zones. Channeling predisposed the affected rocks to pervasive metamorphism, development of strong fabrics, metasomatic weakening (albitization and sericitization) and localization of the subsequent strain increments.

Aluminosilicate relationships in the Chiwaukum Schist, northern Cascade Range, Washington, USA

R.H. VERNON
School of Earth Sciences, Macquarie University, Sydney, NSW 2109, Australia
S.R. PATERSON
Department of Earth Sciences, University of Southern California, 3651 University Avenue, Los Angeles, CA 90089-0740, USA
and R.B. MILLER
Department of Geology, San Jose State University, San Jose, CA 95192-0102, USA

In contact metamorphic rocks around the Mount Stuart Batholith in the northern Cascade Range, Washington, USA, andalusite porphyroblasts in the Chiwaukum Schist are variably replaced, commonly coaxially, by sillimanite. Some has grown adjacent to cracks in the andalusite, suggesting that fluid may have assisted sillimanite nucleation. Outside the contact metamorphic aureole, andalusite has been partly replaced by commonly idioblastic staurolite-quartz symplectites, possibly in response to the reaction: andalusite + biotite = staurolite + quartz + muscovite, which is sensitive to both P and T changes. In places, the unreplaced andalusite has been replaced by kyanite, evidently in response to entering the kyanite field with increasing/decreasing P, increasing/ decreasing T, or any combination of these changes. The kyanite appears to have grown later than the staurolite-quartz symplectite, because (1) some andalusite replaced by symplectite has not been replaced by kyanite and (2) where andalusite has been replaced by kyanite, the symplectite crystals have the same shapes and relationships as where kyanite is absent. This sequence implies that the staurolite-forming reaction proceeded at a lower P than that of the kyanite-forming reaction, which is consistent with previous inferences of a regional P increase based on P-T determinations. Staurolite and kyanite also occur independently of andalusite. The staurolite has overgrown folded opaque (graphitic?) inclusion trails. The microstructural relationships are consistent with initial contact metamorphism, followed by a P increase (possibly accompanied by a T change) to form staurolite + quartz, followed by kyanite; both staurolite and kyanite continued to grow in the matrix at the elevated P.

Evidence of late fibrous sillimanite replacing kyanite is uncommon, and implies increase/decrease in T, increase/decrease in P, or any combination of these changes. Fibrous sillimanite also rarely replaced staurolite. Some of the coarse-grained muscovite surrounding kyanite may have been formed in a "Carmichael-type" reaction of kyanite to sillimanite. Retrograde metamorphism is indicated by the replacement of andalusite and kyanite by muscovite, presumably reflecting a decrease in T, though the ratio of K^+ to H^+ in fluid may also have been important.

Continental break-up seen from a mantle perspective: a case study in an alpine lherzolite massif

R.L.M. VISSERS
Vening Meinesz Research School of Geodynamics Utrecht, Netherlands

The Erro-Tobbio peridotite in the Voltri ophiolite of northwest Italy is a fragment of subcontinental mantle that, prior to its emplacement during Alpine convergence and collision, was first uplifted during Jurassic rifting and oceanization. The periotite is dominated by spinel-lherzolites, with some dunites, spinel pyroxenites and plagioclase-bearing lherzolites. The peridotite shows a complicated history of shear deformation. A kilometer-scale domain of virtually undeformed granular peridotites is transected by five generations of shear zone structures. These include porphyroclastic spinel-bearing tectonites, developed in a several km wide shear zone, overprinted by several hundreds of metres wide plagioclase-, hornblende- and chlorite-peridotite mylonites, eventually cut by serpentinite mylonites. All of these shear zone structures are transected by nMOR gabbroic and basaltic dykes which, in turn, are transected by serpentinite mylonites and brittle thrusts related to the Alpine collision.

There is a systematic correlation between the deformation microstructures and the compositions of the mineral phases, reflecting ambient pressure and temperature conditions during syntectonic recrystallization in the different shear zones. The PT history of the peridotite and the crosscutting nMORB dykes both indicate that the shear zones formed during extensional tectonics. The PT history suggests essentially subsolidus exhumation, from deep levels in the subcontinental mantle towards the developing ocean floor. More specifically, the PT trajectory is consistent with the thermal history expected for the footwall of a lithosphere-scale, dipping extensional shear zone, and differs from that of clearly oceanic peridotites commonly showing an adiabatic uplift history at much higher temperatures related to convective upwelling. The shear zone structures in the peridotites are therefore interpreted as fragments of an extensional detachment system. This interpretation is consistent with the overall asymmetric architecture of the coeval passive margins bordering the Piemonte-Ligurian ocean. It is suggested that the uplift of the peridotites occurred by tectonic denudation in a slightly to strongly asymmetric oceanic rift.

The tectonite shear zone and crosscutting mylonites indicate that the deformation in the pertinent upper mantle became increasingly localized in a network of fine-grained and hydrated mylonite zones. Such localization of the deformation must have had a drastic mechanical effect, in view of existing experimental evidence indicating that progressively finer-grained, hydrated mylonites will tend to change their dominant deformation mechanisms from grainsize-insensitive dislocation creep to diffusion-assisted, grainsize-sensitive mechanisms. In addition, reaction softening may have weakened the shear zone rocks. The development of very- to ultra-fine grained upper mantle shear zones may thus have lead to progressive weakening of the lithospheric column, facilitating break-up and opening of the Piemonte-Ligurian oceanic basin.

Microstructural evidence for a coupled link between foliation development and porphyroblast nucleation and growth

Alison J. WARWICK, Mark W. ANDERSON
Department of Geological Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK
and Andrew J. BARKER
Department of Geology, University of Southampton, Southampton Oceanography Centre, Southampton, SO14 3ZH, UK

Geometrical relationships between internal (Si) and external (Se) foliations preserved in multiply foliated garnet mica schists from the Caledonides of north Norway provide evidence for mechanical controls upon porphyroblast nucleation and growth intimately linked with foliation development. Inclusion trails preserved within garnet porphyroblasts from three profiles through a single amphibolite facies nappe record a protracted period of growth during predominantly SE-ESE directed simple shear. Observed consistencies in angle of absolute rotation between limbs of inclusion trails within individual samples suggest porphyroblast nucleation may initiate in response to microcracking during early crenulation development, with subsequent rapid crenulation overgrowth preserving the instantaneous deformation history.

Angular relationships between Si and Se (here referred to as alpha) are frequently observed to be consistent at thin section scale, suggesting a degree of decoupling between matrix and porphyroblast occurred during development of Se and later cross-cutting shearbands. This decoupling may be related to strain partitioning during initial microfolding of the early foliation. Furthermore, a high degree of variability within alpha distributions observed from several samples may be a reflection of the following: 1) minor late-post Caledonian extensional or contractional deformation, suggesting a degree of differential rigid body rotation with respect to geographical co-ordinates, 2) original variability in Si or 3) protracted phases porphyroblast nucleation and growth at thin section scale. A coupled model for foliation development and porphyroblast nucleation and growth throughout the nappe is presented, based on comparison of observed geometries within and between separate profiles.

Ultra-fine-grained granulites from the Minas Fault Zone, Nova Scotia - aseismic or seismic deformation in the lower crust?

Joseph Clancy WHITE
Department of Geology, The University of New Brunswick, Fredericton, NB, E3B 5A3
and Wes GIBBONS
Department of Earth Sciences, University of Wales, Cardiff, CF1 3YE, UK.

The Minas Fault Zone forms the boundary between Avalon and Meguma terranes in Nova Scotia. At Clarke Head, granulite blocks entrained in a carbonate/evaporite megabreccia have witnessed a protracted deformation history associated with the Minas fault zone. Late Devonian deformation (zircons-369 Ma) under deep-crustal conditions is overprinted by amphibole veins (^{40}Ar/^{39}Ar-336 Ma) at a higher crustal level, with ultimate incorporation into the megabreccia at ca. 310-305 Ma. The granulite blocks preserve mineralogy and textures indicative of deformation at about 850EC and 800 MPa. The chemo-mechanical features of these rocks have been examined by analytical TEM. Of particular note are ultra-fine-grained (<1 µm) granulite assemblages that develop during intense localized deformation. The rapid transition from mylonite to ultramylonite is intimately associated with transient micro-melt related cataclasis. The localization of melt veinlets within zones of mechanical yield can mask the ductile6brittle6 ductile sequence that leads to the ultramylonites. Synchronous with this process is grain size reduction by "normal" dynamic recrystallization that can further exacerbate the difficulties in identifying the micromechanical sequence. The importance of this study resides in characterizing the range of processes active in the lower crust through examination of material preserved throughout exhumation.

Folding and axial plane cleavage development

Paul F. WILLIAMS and Dazhi JIANG
Centre for Deformation Studies, University of New Brunswick, Fredericton, N.B. Canada E3B 5A3

Two folding experiments, intended to be identical, were carried out on layered salt - salt mica schist specimens. The resulting folds and fabrics are very different and the difference is believed to be due to slight variation in the initial geometry of the specimens. The specimens were shortened 84 and 85% under the same experimental conditions. Experiment A produced isoclinal folds of the salt layers with boudinaged limbs and no axial plane foliation. Experiment B produced tight folds with no boudinage and an axial plane foliation defined by mica. Great care was taken to make the experiments identical, but it is impossible to control the shape of layers such that they are perfectly planar. Variation in the amount of curvature from specimen to specimen is inevitable and since the curvature develops during initial application of confining pressure its magnitude is unknown except for experiments terminated immediately after application of confining pressure. From such control specimens we know that the curvature of the salt layers can be as great as 5E. Slight variation in this magnitude is believed to be responsible for the different behaviour of the two specimens during deformation.

All potential deformation paths responsible for folding can be described in terms of some combination of four end member paths. They are: pure shear flattening orthogonal with the folded surface, flexural flow, tangential longitudinal straining (TLS) and slip folding. Our experiments demonstrate that the pure shear component can be large and persistent in the early stages of folding as well as the late stages, i.e. the early stages of folding can be primarily due to passive amplification of pre-existing curvature. We suggest that the pure shear component is dominant until the evolving geometry results in a buckling instability. At that stage TLS and flexural flow components become dominant and remain so until the folds become so tight that pure shear flattening becomes increasingly important again. An important corollery of the early pure shear component is that it not only explains the development of axial plane foliation (commonly an early feature of natural folding) but also explains the bimodal orientation pattern characteristic of most such foliations. In addition, observations of rotated garnets, in natural folds of varied tightness, strongly support our three stage model.

Microstructures and Chemical Maps of Garnet in the Annapurna Area, central Nepal Himalaya

Haruka YAMAGUCHI and Mitsuhiro TORIUMI
University of Tokyo

Himalayan metamophic complex occurs along the Main Central Thrust (MCT), the intracontinental thrust of the Indian Plate. As a result of much attention to this collision zone, many structural studies revealed large-scale ductile deformation and the normal faults of South Tibetan Detachment System (STDS), whereas petrological works suggested clockwise retrograde T-P paths and thermal profiles showing inverted metamophism within the footwall and lower part of the hangingwall. Ductile extrusion and exhumation models has been proposed but early stage synmetamorphic deformation kept unclear.

Here we carried out petrological and microstructural studies of garnet, because it preserves the metamorphic and deformational conditions. Analysed garnet grains were derived from pelitic schists and gneisses which commonly contain quartz, plagioclase, biotite and rare kyanite and epidote, but not from calcsilicate or basic rocks to avoid the influence of bulk composition.

Four types of microstructure were classified; a) euhedral, b) spiral, c) flower, d) irregular, where b) is synkinematic type including snowball, c) has the rim looks like flower, and e) displays round or irregular outline.

Garnet is also divided into three types by means of its chemical maps; A) normal zoning, B) normal-to-reverse zoning, and C) reverse zoning. A) is defined by increase Mg, whereas C) is characterized by Mn-increase and Mg-decrease, and B) shows the Mg- and Fe- increase and Mn-decrease from the core to the mantle, and Mg-decrease and Mn-increase from the mantle to the rim. The core assigned by high Ca-content and outlined by low narrow Ca zone can be observed in the B) and C) grains. In spite of discrete Ca-zoning in these garnet grains, chemical maps of Mn show a gradual change, suggesting modification of chemical compositions of garnet by diffusion.

The spatial occurances of microstructures and chemical zoning types are shown in the figure below. It concludes that, spiral and flower types of normally zoned garnet grains occur in the footwall, where hangingwall contains all types of garnet bearing normal-to-reverse or reverse zoning. Since spiral types suggest rotational growth (i.e. snowball garnet), the following three stages of metamorphism can be recognized: 1) ductile deformation with prograde metamorphism in the hangingwall, 2) ductile deformation with decompression heating (extrusion), 3) ductile deformation with cooling in the hangingwall and heating in the footwall (hot iron stage).

		<< microstructure >>				<< zonal structure >>		
		type a	type b	type c	type d	type A	type B	Type C
hangingwall								
	(upper)	O	O		O		O	O
	(lower)	O	O	O	O		O	
--- MCT ---								
	(upper)		O	O		O		
	(lower)		O			O		
footwall								