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Deep crustal and local rheological controls on the siting and reactivation of fault and shear zones, northeastern Newfoundland

R. S. D'LEMOS[1], D. I. SCHOFIELD[1], R. E. HOLDSWORTH[2] & T. R. KING[1]
[1]*Geology & Cartography Division, Oxford Brookes University, Oxford OX3 0BP, UK*
[2]*Department of Geological Sciences, Durham University, Durham DH1 3LE, UK*

Abstract: The siting of a *c.* 25 km wide, transpressive, high-strain zone at the eastern margin of the Gander Zone of NE Newfoundland corresponds to the trace of a fundamental contact between two Gondwanan basement blocks displaced sinistrally relative to one another during Silurian orogenesis. Changes in plate motion during the Devonian led to kinematic reversal and reactivation of the shear zone and, at high structural levels, the development of a major brittle-ductile fault system. At a local scale within the Silurian ductile high-strain zone, the focus of deformation and shifts in siting of shear were closely related to magma presence. We consider that granite magmas exploited shear zones within the crust to aid ascent, and in doing so enhanced local deformation. Cessation of magma supply and/or cooling of magmas within conduits caused deformation to relocate elsewhere. NE Newfoundland hence provides an example of how fault/shear zone siting and reactivation may be controlled by regional-scale pre-existing basement configuration and more localised processes affecting rheology, notably plutonism.

Keywords: Gander Zone, fault zones, rheology, reactivation, transpression.

The siting of major zones of shearing and faulting in the crust is likely to be determined by processes operating at different scales. At a regional scale, faulting will be controlled ultimately by the position and relative movement of deep lithospheric blocks in response to plate vectors. At a local scale, the actual site of deformation is likely to be controlled by focusing and partitioning of strain due to rheological weakening processes (e.g. Handy 1989). Many deformation zones display evidence for long lived structural histories and reactivation. It is now widely accepted that close associations also exist between major faults and shear zones in orogenic belts and the emplacement of granitoid magmas (e.g. Hutton 1988; Hutton & Reavy 1992; D'Lemos *et al.* 1992). If crustal-scale faults and shear zones act as magma pathways, then it is likely that the syn-tectonic emplacement of magma will lead to a profound rheological weakening (e.g. Hollister & Crawford 1986). Strain localization is to be expected due to the presence of magma, heating of the wall-rocks and, on a longer time scale, due to a long lived thermal perturbation in that part of the lithosphere. Such processes may also control the siting of subsequent reactivation episodes along faults and shear zones. In this study from the northeastern Gander Zone of the Newfoundland Appalachians, we attempt to explain strain partitioning, kinematic evolution and fault zone reactivation by invoking both regional-scale controls and processes related to syn-tectonic magma channelling at different crustal depths.

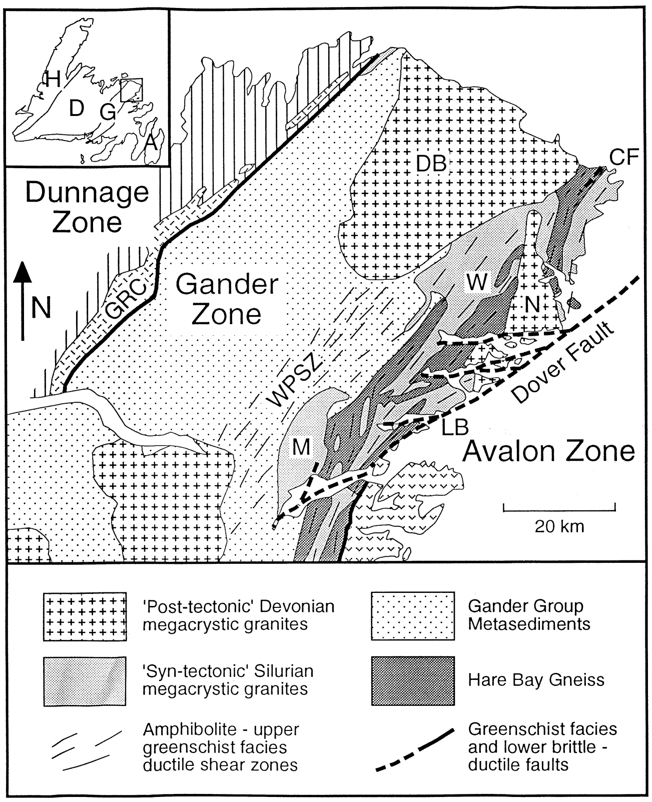

Fig. 1. Simplified geological map of the northeastern Gander Zone, Newfoundland, and location of main tectonostratigraphic zones (inset). H, Humber Zone; D, Dunnage Zone; G, Gander Zone; A, Avalon Zone; GRC, Gander River Complex; WPSZ, Wing Pond Shear Zone; N, Newport Granite; DB, Deadman's Bay Granite; CF, Cape Freels Granite; LB, Lockers Bay Granite; W, Wareham Granite; M, Middle Brook Granite.

Geological background

The Gander Zone of northeastern Newfoundland (Fig. 1) represents part of a Gondwanan-derived continental fragment accreted to Laurentia during Iapetus closure (e.g. Williams *et al.* 1988). The Iapetus suture in Newfoundland lies within the Dunnage Zone, the eastern part of which was obducted onto the Gander Zone during the Arenig. The western margin

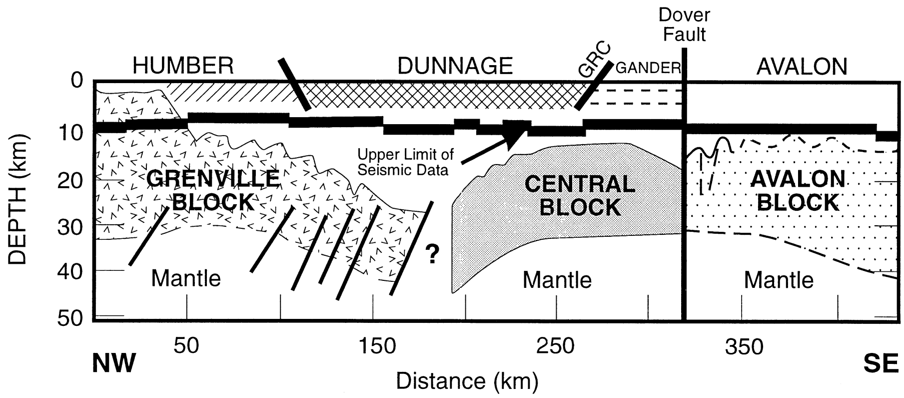

Fig. 2. Cross-section showing underlying crustal blocks in relation to tectonostratigraphic zones in Newfoundland based upon offshore deep seismic profiles (after Marillier *et al.* 1989). GRC, Gander River Complex.

of the main Gander Zone outcrop in NE Newfoundland is marked by an overlying allochthonous unit of ultrabasic and volcanic melanges (Gander River Complex) emplaced initially on east-vergent thrusts, and subsequently reworked during Silurian orogenesis (Colman-Sadd & Swinden 1984). The present-day eastern margin of the NE Gander Zone is the Dover Fault Zone, a major brittle–ductile structure (Blackwood & Kennedy 1975; Holdsworth 1994) which, based upon interpretation of offshore deep-seismic profiles (Marillier *et al.* 1989; Stockmal *et al.* 1990), cuts down to the Moho and separates two lower crustal blocks of different seismic character (Fig. 2). The Avalon Zone east of the Dover Fault comprises a characteristic Gondwanan Neoproterozoic tectonostratigraphy and Palaeozoic cover (O'Brien *et al.* 1983).

Four major lithological units occur within the Gander Zone of NE Newfoundland (Fig. 1).

Gander Group metasedimentary rocks are typified by greenschist facies pelite and psammite which, in the west of the region, exhibit east vergent recumbent folds with local development of later upright structures (Kennedy & McGonigal 1972; Blackwood 1977; O'Neill 1991). Towards the east, the metamorphic grade of the metasediments increases and early structures are transposed to form steep penetrative fabrics (Hanmer 1981; Holdsworth 1994).

The Hare Bay Gneiss (and its correlatives; Blackwood 1977; Holdsworth 1994) comprises amphibolite-facies paragneiss, migmatite and metamorphosed igneous units. A progressive metamorphic transition from Gander Group metasediments into paragneiss (Square Pond Gneiss and part of Hare Bay Gneiss of Blackwood 1977), stromatic migmatite and diatexite is observed at several localities and supported by Sm:Nd isotopic data (D'Lemos & Holdsworth 1995). Metagranitic and metabasic rocks, intruded after at least one phase of folding in host metasediments (Hanmer 1981; Holdsworth 1994; Schofield *et al.* 1996) were metamorphosed and deformed at amphibolite facies and subsequently folded prior to or during emplacement of the later megacrystic granites.

Foliated megacrystic granites and associated intrusives form a number of elongate plutons and sheets (kilometres wide and tens of kilometres long), which post-date early fold structures in host units, but share a common, typically strongly developed sub-vertical foliation and associated sub-horizontal stretching lineation. These bodies were emplaced during the Silurian to earliest Devonian syntectonically with respect to the development of the dominant NE–SW regional structural grain.

Later megacrystic granites are typically large plutons that lack penetrative foliations, cross-cut the regional structural grain and develop overprinting metamorphic aureoles demonstrating emplacement after penetrative regional deformation. However, moderate to weakly developed magmatic fabrics, porphyroblast–fabric relationships in aureoles and large-scale pluton geometries indicate that, although post-tectonic with respect to Silurian ductile deformation, the bodies were emplaced syn-tectonically with respect to Devonian brittle–ductile deformation (D'Lemos *et al.* 1995). Sm:Nd data show that the Silurian and Devonian granites were not derived from adjacent migmatites, but from a deep crustal source contaminated to variable degrees by mid-crustal wall rocks (D'Lemos & Holdsworth 1995).

Timing, conditions and kinematics of deformation

The *c.* 25 km-wide zone west of the Dover fault is characterized by microtextures and mineral assemblages which record transpressional high strain over a range of *PT* conditions (Hanmer 1981; Holdsworth 1994). Moving eastwards, early recumbent folds and associated greenschist-facies fabrics of the western Gander Zone are progressively transposed into the steeply dipping *c.* 10 km wide sinistrally transpressive Wing Pond Shear Zone (O'Neill 1991). The shear zone fabrics are associated with the syn-tectonic growth of andalusite which is partially replaced by kyanite and wrapped by a sillimanite and staurolite-bearing fabric which defines the peak metamorphic assemblage at *c.* 5 kbar and 600°C. A 2 km wide zone of later greenschist-facies mylonite developed at the eastern margin of the Wing Pond Shear Zone is metamorphically overprinted by the Middle Brook Granite (Fig. 1).

East of the Wing Pond Shear Zone, deformation is localised within several high strain zones developed in the Hare Bay Gneiss and strongly partitioned into migmatites and syntectonic granite bodies. Upright foliations and sub-horizontal stretching lineations are associated with first sinistral, and later mainly dextral, kinematic indicators. Peak metamorphism derived from mineral reactions, cordierite geobarometry and hornblende–plagioclase geothermometry reveal high temperature–moderate pressure conditions (*c.* 740°C at 4.5 kbar). The Wareham Granite, intruded during Silurian migmatization of the Hare Bay Gneiss, exhibits magmatic, pre-rheologically critical melt percentage (see Tribe & D'Lemos 1996) to high-temperature sub-solidus fabrics. Fabrics associated with the emplacement of the syn-tectonic Locker's Bay and the Cape Freels granites overprint the primary migmatitic banding and peak migmatization in the

Hare Bay Gneiss indicating that these plutons are slightly younger than the Wareham Granite. The Cape Freels Granite carries a NE trending, sub-horizontal, pre-rheologically critical melt percentage L-fabric indicating emplacement during local transtension synchronous with development of aureole migmatites and contact porphyroblasts. Subsequent down-temperature fabric development toward regional upper greenschist facies temperatures during sinistral shear was progressively partitioned toward the pluton margins (Schofield *et al.* 1996). Upper greenschist-facies sinistral mylonites within the aureole are overprinted by lower temperature dextral mylonites. Internally, the Locker's Bay Granite is dominated by sub-solidus fabrics which develop grain scale sinistral S–C fabrics and narrow anastomosing sinistral shear zones, while marginal regions are widely affected by later low temperature dextral shearing. Both plutons indicate emplacement during sinistral strike-slip deformation at upper greenschist facies conditions, and subsequent lower greenschist facies (dextral) reworking (Schofield *et al.* 1996).

The Dover Fault Shear Zone comprises a 2 km wide zone of NE-trending dextral ductile deformation and widespread dynamic recrystallisation associated with retrograde greenschist facies metamorphism which overprints high temperature, largely sinistral, fabrics in the Hare Bay Gneiss and syntectonic granites (Holdsworth 1994 and references therein). Wide mylonite belts (*c.* 1 km) or discrete arrays of anastomosing shear zones are developed with sub-vertical foliations and gently plunging mineral lineations associated with dextral shear-sense indicators. Linked systems of later, steep brittle faults severely disrupt the pre-existing shear zone architecture proximal to the Gander–Avalon boundary. Individual fault zones are marked by narrow veins of epidotic cataclasite or broader zones of breccia. Shear fibres and slickenlines have dominantly shallow plunges suggesting strike-slip displacement. Brittle shear sense criteria suggest dextral displacements along major fault traces, whilst conjugate strike-slip arrays in intervening fault blocks are consistent with a moderate NW–SE shortening. Ductile fabrics associated with the Dover Fault Shear Zone overprint the Locker's Bay Granite, but are cross-cut by the Devonian Newport Granite. The Newport Granite is cross-cut by subsequent brittle faulting along the trace of the Dover Fault (Holdsworth 1994; D'Lemos *et al.* 1995).

Regional controls on siting of deformation

The contrasting stratigraphy and tectonothermal evolution of the Avalon and Gander zones indicate significant palinspastic separation prior to Siluro-Devonian deformation (Williams *et al.* 1988). Marked contrasts in isotopic characteristics of granites which have passed through, and presumably been contaminated by, the underlying basement blocks (Fryer *et al.* 1992; D'Lemos & Holdsworth 1995) and regional studies of detrital zircon populataions from sedimentary sequences (Nance & Murphy 1995 and references therein; van Staal *et al.* 1996) indicate that Avalonian and Gander blocks initially occupied markedly different positions along the peri-Gondwanan margin. The Dover Fault thus corresponds to a fundamental boundary between two distinct, rifted-off blocks of Gondwanan crust (Avalon and Central lower crustal blocks of Marillier *et al.* 1989; Stockmal *et al.* 1990). We suggest that during the Silurian, the Avalon block was translated obliquely northward against the Gander block resulting in sinistral transpression with deformation focused along the Gander-Avalon boundary. A wide (tens of kilometres) shear zone developed, which in the mid-crust which became the site of syn-tectonic granite emplacement, above average heat flow and amphibolite-facies metamorphism.

A change in plate motion vectors late in the orogenic cycle resulted in regional dextral transpression. We suggest that the siting and kinematics of deformation were again controlled by the position and geometry of the basement block margins and focused at the Gander–Avalon suture. Reactivation of the shear zone, currently exposed levels of which had by that time been exhumed to mid- to upper crustal levels, led to the inception of the km's wide brittle-ductile greenschist facies dextral Dover Fault Shear Zone, which truncates the earlier zone of ductile deformation. The easternmost part of the Silurian ductile shear zone, and the presumed original Gander–Avalon suture, would have been displaced southwards relative to present day co-ordinates. Dextral movements continued up to and after emplacement of Devonian plutons into extensional fault jogs (D'Lemos *et al.* 1995). The final brittle displacements at upper crustal levels were associated with E–W-trending dextral fault zones, many of which may be Carboniferous to Mesozoic features (Williams *et al.* 1995).

Local controls on siting of deformation

Field and isotopic evidence (D'Lemos & Holdsworth 1995) shows that during the Silurian, voluminious granite magma was generated at depth beneath the eastern margin of the Gander Zone, possibly as a consequence of transpressional thickening and subsequent advective heating during thinning of the lithosphere subjacent to the Gander–Avalon contact. We suggest such magma presence greatly weakened the lithosphere and that displacements were transmitted into the lower to mid-crust generating shear zones (Fig. 3). A combination of magma buoyancy and magma over-pressure in the deforming lower crustal section aided magma separation and movement upward and along shear zones. Kilometre-scale magma conduits developed (megadyke systems; D'Lemos *et al.* 1992), in part preserved as the sheets of Silurian syn-tectonic granite, through which large volumes of granite magma ascended (Fig. 3). The high-temperature–moderate-pressure metamorphism spatially and temporally closely associated with the Silurian syntectonic granites exceeds that typically associated with kilometre-scale plutons and may be further evidence for significant magma flux. Considerable (unrecorded) transcurrent movement may have been accommodated by the magma-filled conduits. Cooling and crystallization lead to development of penetrative solid state fabrics (Tribe & D'Lemos 1996; Schofield *et al.* 1996). Deformation progressively partitioned into zones of maximum anisotropy (e.g. pluton margins), and finally ceased as deformation shifted to other sites where magma was being actively emplaced, and the process repeated. We suggest that the magma being transported (ascending) through the mid-crust was incorporated into assembling plutons in the upper crust. Subsequent exhumation removed the Silurian upper crustal section, but we draw parallels with the preserved Devonian upper crustal section comprising brittle-ductile fault systems and discordant plutons. We view these Devonian plutons as the likely forms of intrusions formed above the megadyke feeders (Fig. 3). Emplacement at high levels was largely passive (D'Lemos *et al.* 1995) and facilitated by movement on faults whose location was controlled by the upward transmission of displacements from underlying shear zones. Some such high level plutons (e.g. Newport Granite)

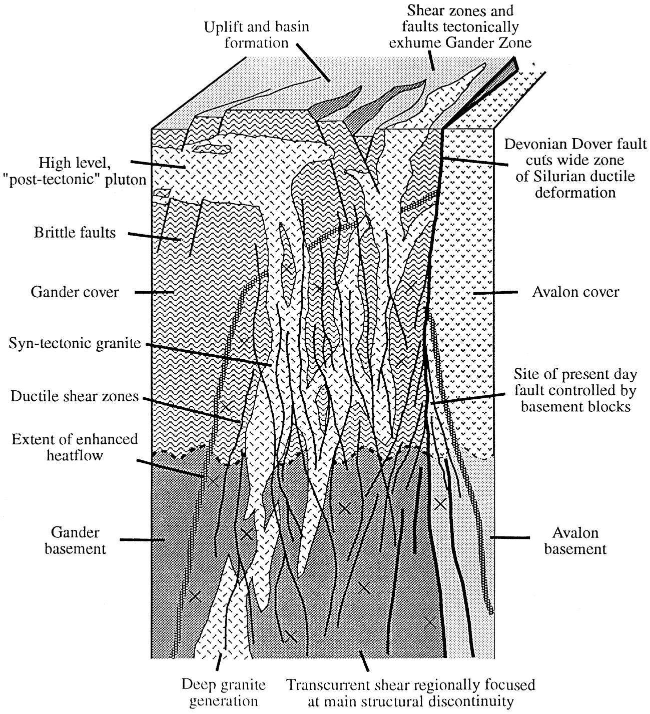

Fig. 3. Cartoon depicting relationships between shear zone and fault development, magma ascent and emplacement, metamorphism and position of crustal blocks in a mid to upper crustal section (after D'Lemos *et al.* 1992).

filled vertical transtensive side-wall rip-outs in fault systems while others (e.g. Deadman's Bay Granite) form broad laccoliths (D'Lemos *et al.* 1995).

Reactivation and overprinting to produce the relatively narrow zones of intense brittle–ductile shear is attributed to greater strain partitioning at the higher structural levels and lower ambient temperatures during the Devonian following Silurian exhumation. Reactivation was apparently focused into zones of strong rheological anisotropy (e.g. around granite contacts, at boundaries between mafic complexes and hosts) or preferentially accommodated by softened, phyllosilicate-rich fault rocks (e.g. previously mylonitized migmatite). Micaceous mylonites and phyllonites reworked at lower temperatures are associated with muscovite recrystallization while latest brittle–ductile and brittle faults are hydrothermally altered. These observations suggest that fluid ingress and associated weakening may have had an important effect on late-stage strain localization.

Conclusions

We consider the development of shear and fault zones within a *c.* 25 km wide zone of transpressive deformation in the north-eastern Gander Zone was controlled by processes operating at two scales. At a regional scale, siting and reactivation was governed by the location and geometry of the fundamental basement contact between Avalon and Gander crustal blocks and their relative translation in response to plate-scale movements. The down temperature record of overprinting tracks the exhumation of the Gander margin through time. At a local scale, Silurian ductile deformation and magma ascent was largely controlled by softening due to a positive feedback loop between shearing, magma presence and enhanced metamorphism. Brittle–ductile reactivation was sited at pre-existing compositional anisotropies and in units rheologically weakened during earlier deformation. Upper-crustal fault zones may also have been controlled by the location of shear zones and sheeted plutons at depth. Thus, reactivation of faults and shear zones at various crustal levels may have been intricately linked to the pathways of magma migration through time.

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