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STRIKE-SLIP TECTONICS AND GRANITE PETROGENESIS

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Abstract. Transpression is a process that thickens the crust and therefore in obliquely convergent orogens as in normally convergent orogens there is the potential to generate granitic melts. Individual transcurrent shear zones may not only control the ascent paths, siting, and emplacement mechanisms of plutons, but they may also cause the genesis of the granitoids themselves. Two contrasting situations are examined. In the Hercynian shear zones of Iberia, thickening together with hydrous fluxing along shear zones created intracrustal wet melting of fertile Gondwanan sediments to produce syntectonic granites. In the northern part of the British Caledonides, the association of compositionally expanded granitoids with a major mantle component and transcurrent shear zones may be explained by melting of continental crust at the lower limits of crustal transpressional faults detaching into the Moho.

INTRODUCTION

It is becoming increasingly apparent that there is a spatial and, from structural and fabric studies, often a temporal coincidence of granitoid magmatism with zones of major active transcurrent shear in many orogenic belts. This is seen, for example, in the Hercynian shear zones of Iberia [Castro, 1985, 1986; Reavy, 1989] and Britanny [Nicolas et al., 1977; Strong and Hanmer, 1981], the Caledonian of the British Isles [Hutton, 1982, 1988; Hutton and McErlean, 1991; McCaffrey, 1989], Newfoundland [Hanmer, 1981], Saudi Arabia [Davies, 1982], and the Lachlan Fold Belt of Australia [Morand, 1988].

There are two ways of viewing this relationship: either the steeply inclined deep-reaching shear zones have provided a pathway for ascent and a mechanism of emplacement at high crustal levels [Hutton, 1988] for magmas that have been generated by some unrelated or loosely related tectonic process (e.g. subduction), or that transcurrent shearing in the continental lithosphere has not only controlled ascent, siting, and emplacement but has caused the genesis of the granitoid magmas. Using recent structural, tectonic, and petrogenetic data and ideas, we wish to explore this second possibility.

CRUSTAL SHEAR ZONES

Several recent studies of large transcurrent shear zones, exposed at a variety of crustal levels, have shown that they consist rarely of simple shear alone. Many are transpressional (simple shear and shortening across the zone) for short or considerably longer segments, and they may be locally transtensional (simple shear with a component of extension across the zone). Examples of granitoid emplacement in transpressional zones are the Main Donegal Granite [Hutton, 1982] and the Ox Mountains Granite [McCaffrey, 1989] of Ireland, the Serra da Freita pluton [Reavy, 1989], and the plutons of the South Armorican shear zone [Nicolas et al., 1977; Strong and Hanmer, 1981]. The presence within these intrusions of pre-full crystallization fabrics [Hutton, 1988a] associated with the transcurrent shear, synshear porphyroblasts in the thermal aureoles, and other features demonstrates that intrusion took place in active transcurrent shear zones, and therefore the granites are syntectonic with the shear zones in which they were emplaced. Transpression is demonstrated by steeply inclined strike parallel fabrics associated with noncoaxial nonplane strains in which K values typically vary between 0 and 1. This means that while undergoing transcurrent shear, the walls of the shear zone are squeezed together and the material in the shear zone is both shortened horizontally and extends or extrudes vertically [Sanderson & Marchini, 1984] (Figure 1). Such a process leads to thickening of the crust within the shear zone. In transpressional zones in the brittle upper crust the thickening commonly takes the form of an uplifted wedge bounded by oblique thrust faults at the highest levels linking to steep transcurrent faults at somewhat lower levels (so-called "flower" structures [Harding and Lovell, 1979]). The situation in the lower to middle crust is less well documented; our work in the Caledonides of western Ireland, however, indicates that similar structures occur within the ductile regime.

In the Ox Mountains inlier of western Ireland there exists a major NE-SW trending, generally steeply inclined, ductile transcurrent sinistral shear zone [Hutton and Dewey, 1986; Jones, 1989] (Figure 2). Syntectonic amphibolite facies mineral assemblages [Yardley et al., 1979] indicate that the main transcurrent deformation occurred at about a depth of 25 km. The shear zone is considered to be part of the exhumed sidewall of a branch of the Highland Boundary fault, a major Caledonian terrane boundary in the British Isles [Hutton and Dewey, 1986; Hutton, 1987]. Within the shear zone, the generally upright schistosity becomes concentrated into discrete planar zones of more intense mylonitic fabrics which form a large scale linked network (Figure. 2b). When viewed along the NE-SW-trending, gently plunging stretching lineation, the mylonitic belts splay downward from steeper attitudes at high levels to inclined and flat-lying attitudes at low levels (Figure 2c) in the NE; at the lowest structural level the Caledonian metasediments are thrust northeastward, directly along strike over pre-Caledonian basement. The outward splaying of the mylonite belts and the overthrusting of basement indicates that crustal thickening has occurred in this shear zone. The geometry of the mylonite belts is similar to that of many flower structures except that the form is inverted and the term "inverted flower structure" is proposed (C. S. Jones and D.H.W. Hutton, manuscript in preparation, 1992). The Ox Mountains data therefore show that crustal thickening in the ductile mid-lower crust (depths of 25 km) occurs in transpressional shear zones. Elsewhere in ductile shear zones, for example, Donegal [Hutton, 1982], Newfoundland [Hanmer, 1981], Brittany [Vigneresse and Brun, 1983] and Galicia [Courrioux, 1983], thickening of the crust is implied by the widespread occurrence of upright folds with subhorizontal or gently plunging hinges and $0 < K < 1$ strains (implying horizontal shortening and vertical thickening). In the remainder of this paper, we explore the possibility of granitoid petrogenesis under such conditions and consider two situations, one involving a mantle component, the other not.

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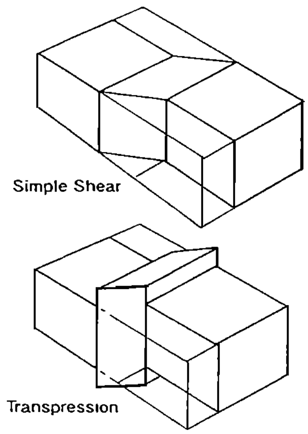

Fig. 1. Simple shear and transpression. In simple shear the shear zone walls do not change their horizontal separation. The material within the shear zone is deformed by volume conserving plane strain, and the vertical dimension remains unchanged in length. In transpression a component of horizontal shortening at right angles to the shear zone is added to the transcurrent shear. The walls of the shear zone converge, and the material within the shear zone is subjected to a flattening strain which results in a component of vertical extension.

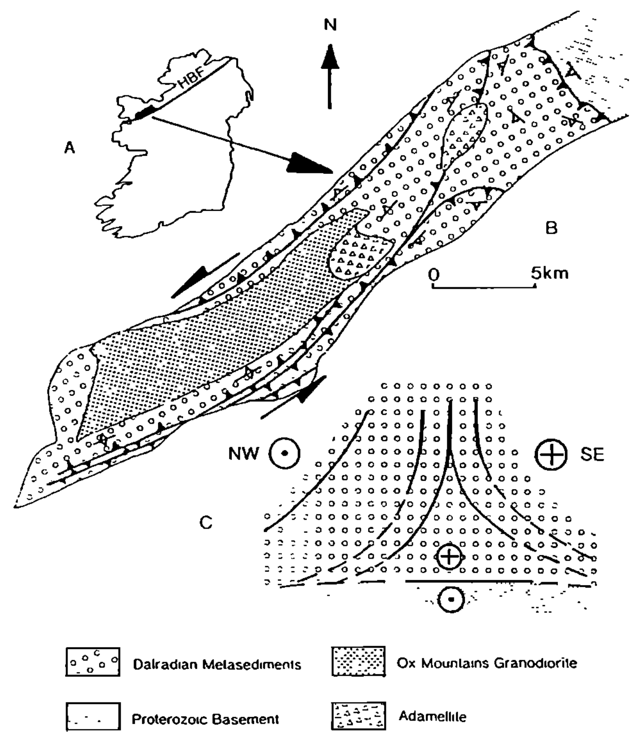

Fig. 2. The Caledonian Ox Mountains inlier in western Ireland. (a) Location of inlier adjacent to the Highland Boundary fault in Ireland. (b) Generalized map of the inlier. Solid lines with solid barbs are discrete shear zones and tectonic slides within the major shear zone. Barbs indicate dip directions. Short lines with open barbs indicate shear zone foliation dip and strike in metasediments and basement. (c) Schematic cross section of inlier with igneous rocks omitted. Solid lines are down plunge projections of discrete shear zones and slides. Dashed lines are extrapolations. Cross section is modified from C. S. Jones and D. H. W. Hutton (manuscript in preparation, 1992).

SHEAR ZONE GRANITES WITHOUT A MANTLE COMPONENT: THE IBERO-ARMORICAN PERALUMINOUS SUITE

The upper Palaeozoic Hercynian collision of the Ibero-Armorican arc was delimited in the north by the dextral south Armorican shear zone system in Brittany [Berthe et al., 1979] and in the south by the sinistral Coimbra-Cordoba shear zone in Iberia [Burg et al., 1981] (Figure 3a). Peraluminous two-mica leucogranites, mainly of metasedimentary derivation, are commonly intimately associated with the shear zones in Brittany and in the much larger area of Hercynian deformation in Iberia (Figures 3b and 3c). In Brittany, Hanmer and Vigneresse [1980] described how the Locronon and Pontivy leucogranites were emplaced syntectonically with regional Hercynian deformation, and Vigneresse and Brun [1983] and Guineberteau et al. [1987] further showed that many of the other two-mica granites in the Armorican shear zone system were also emplaced syntectonically with respect to ductile transcurrent deformation. In the Hercynian Iberian massif, Ponce de Leon and Choukroune [1980], Courrioux [1983], Castro [1985] and Reavy [1989] have shown that peraluminous metasedimentary-derived granites are intruded into major transpressive shear zones. The elongate plutons are commonly coincident with the high-grade cores of linear metamorphic belts in which the isograds are zoned parallel and toward the axes of the shear zones that contain the granites. This association characterizes Hercynian tectonics in much of the Iberian massif [Julivert et al., 1980].

The relationship between ductile shear and magma petrogenesis in such situations has been addressed by a number of authors. In eastern Brittany, Nicolas et al. [1977] proposed that frictional heating in the shear zone created the isograd zonation and produced the anatectic temperatures which generated the granite. Theoretical criticisms of frictional heating have been put forward by a number of authors [Yuen et al., 1978; Brun and Cobbold, 1980] on the grounds of inadequate rock viscosities, inadequate rates of movement, and inadequate duration of movement. Although it cannot be ruled out that such a process is likely to contribute to the heat budget in shear zones, other workers have invoked hydrous fluxing leading to a lowering of melting temperatures to account for the association [Strong and Hanmer, 1981]. Shear zones should facilitate fluid migration to potential melting zones in the crust, thereby increasing the degree of melting and enhancing melt segregation and melt migration. Strong and Hanmer [1981] argued that melting along a 30°C km^{-1} geotherm at 6 kbar could result from lowering of the melting temperature from the upper stability field of muscovite to the water-saturated granite solidus. The importance of fluids in promoting anatexis has been emphasized also by Wickham and Taylor [1985] and Wickham [1987] for granites in the Pyrenees.

In the Serra da Freita region of north central Portugal, Reavy [1989] has proposed that the transpressive Serra da Freita shear zone (Figure 3c) was the dominant control at all stages on the genesis of the Serra da Freita pluton. Geochemical and isotopic data such as overlapping values of high initial $^{87}Sr/^{86}Sr$ and high $\delta^{18}O$ for both granites and local schists indicate that the pluton was derived from greywacke-rich country rocks [Reavy et al., 1991] and it was

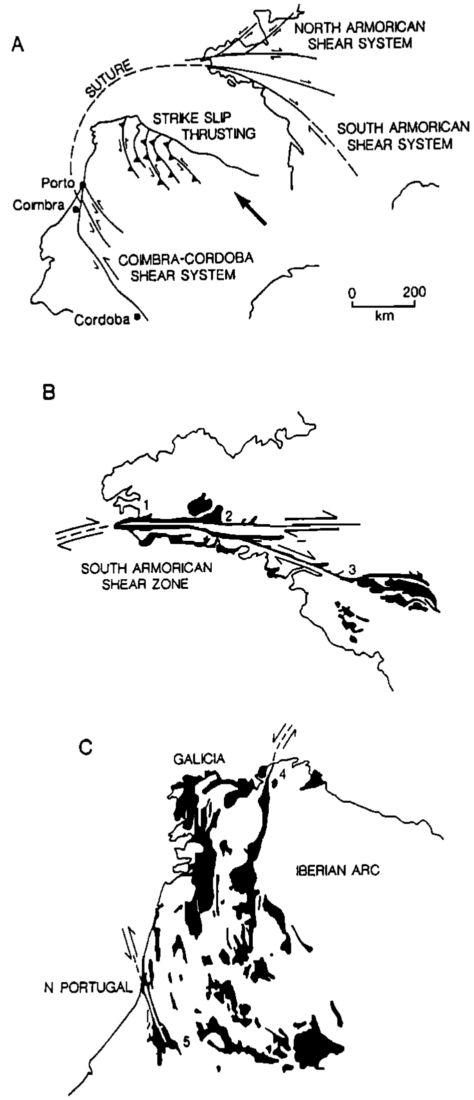

Fig. 3. The Ibero-Armorican Hercynides showing shear systems and associated granites. (a) A reconstruction of the Ibero-Armorican arc (modified from Burg et al. [1981]). (b) Granites associated with the South Armorican shear zone in Brittany. Areas mentioned in text are 1, Locronon; 2, Pontivy [Hanmer and Vigneresse, 1980]; and 3, Mortagne [Guineberteau et al., 1987]. (c) Granites associated with the Iberian arc in NW Spain and northern Portugal. Areas mentioned in text are 4, Puentedeume, Galicia [Ponce de Leon and Choukroune, 1980; Courrioux, 1983]; and 5, Serra de Freita, northern Portugal [Reavy, 1989].

considered that anatexis was achieved by a combination of geotherm disturbance following collision and crustal thickening, together with hydrous fluxing by fluids known to be enriched in boron and, probably, halogens [Reavy et al., 1992]. It is also likely that the shear zone was crucial in allowing the successive emplacement of batches of two-mica granite at high crustal levels relative to their source region and in controlling the final geometry of the consolidating pluton. In this situation therefore the existence of the transpressional shear zone allowed anatexis to occur within the crust without the need for the direct involvement of a mantle component as a heat source and, further, the shear zone facilitated ascent of melts to a higher level.

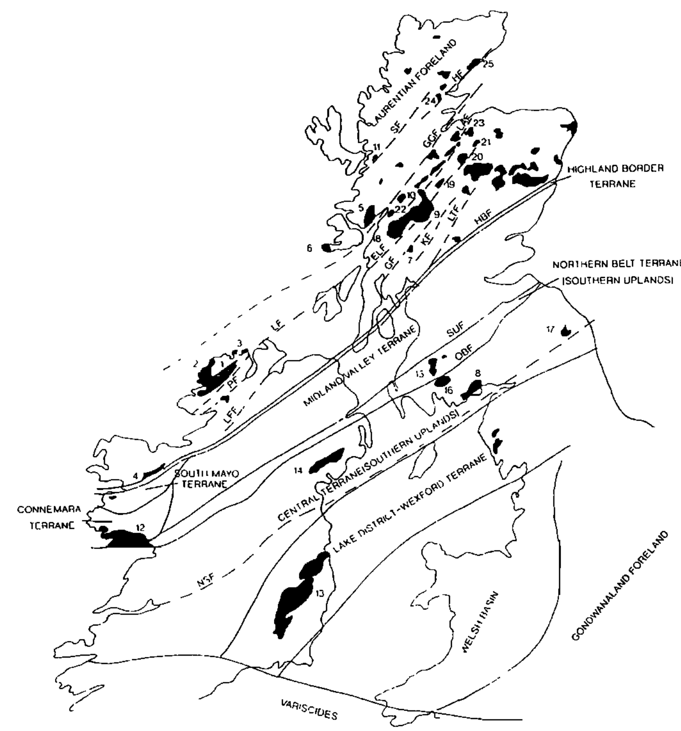

Fig. 4. The British Caledonides showing terranes, plutons, and Highland faulting patterns (modified from Hutton [1987] and Soper and Hutton [1984]). Faults (Scotland, from north to south) are SF, Strathconon fault; HF, Helmsdale fault; GGF, Great Glen fault; LAF, Laggan fault; ELF, Ericht Laidon fault; GF, Garabal fault; KF, Killin fault; LTF, Loch Tay fault; HBF, Highland Boundary fault; SUF, Southern Uplands fault; OBF, Orlock Bridge fault; and NSF, Navan-Silvermines fault. Plutons (in order of text) are 1, Main Donegal (Donegal); 2, Thorr (Donegal); 3, Fanad (Donegal); 4, Ox Mountains; 5, Strontian; 6, Ross of Mull; 7, Garabal Hill; 8, Criffell; 9, Rannoch Moor; 10, Strath Ossian; 11, Ratagain; 12, Galway; 13, Leinster; 14, Newry; 15, Loch Doon; 16, Fleet; 17, Cheviot; 18, Etive; 19, Strathspey; 20, Monadhliath; 21, Grantown; 22, Ballachulish; 23, Ardclach; 24, Fearn; and 25, Helmsdale.

In conclusion, it seems that many of the peraluminous two-mica granites associated with the collision of the Ibero-Armorican arc were generated by processes operating within shear zones, that is, that anatexis of thickened greywacke-rich crust was possible where fluids were concentrated into narrow transpressional shear zones. It seems very unlikely that this would have occurred in the absence of such a tectonic control. These conclusions are in accord with the theoretical models of England and Thompson [1986] who proposed that crustal thickening can lead to widespread anatexis without the involvement of mantle material, the volume of melt produced being critically dependent on the amount of available water in the system.

SHEAR ZONE GRANITES WITH A MANTLE COMPONENT: THE BRITISH CALEDONIDES

Unlike the peraluminous two-mica granites of Iberia and Brittany, the Caledonian plutons of Scotland and Ireland (Figure 4) display a wide spectrum of granitoid types with

Fig. 5. Features resulting from the coexistence of acid and basic magma. (a) Diorite showing chilled crenulate margins against host granite, Ross of Mull pluton, Scotland. (b) Complex contact produced by mingling between diorite and granodiorite, Ox Mountains pluton, Ireland. (c) Synplutonic dyke complex within the Prins Christian Sund pluton, southern Greenland. The complex, of noritic composition, is immediately to the left of the boat and contrasts with the lighter granodiorite into which it is intruded. (d) Intricate crenulated contact at the edge of the complex seen in Figure 5c. Note that the K-feldspars within the norite are strongly zoned.

large ranges in SiO2 and other major oxides. Hornblende and/or biotite granites, granodiorites, and diorites dominate, whereas tonalites and monzonites are subordinate, two-mica granites are very rare. The plutons are commonly internally zoned, either normally or reversely, or are composite. In many complexes, there is abundant field evidence that complex mixing and hybridization processes have produced very inhomogeneous intermediate compositions. Small volumes of mafic and ultramafic rocks (pyroxenites, hornblendites, and gabbros) commonly occur, especially when diorite forms a major component in any pluton. In particular, the importance of the "appinite" suite deserves consideration. These are coarse-grained hornblende- and/or biotite-bearing rocks of ultramafic to intermediate

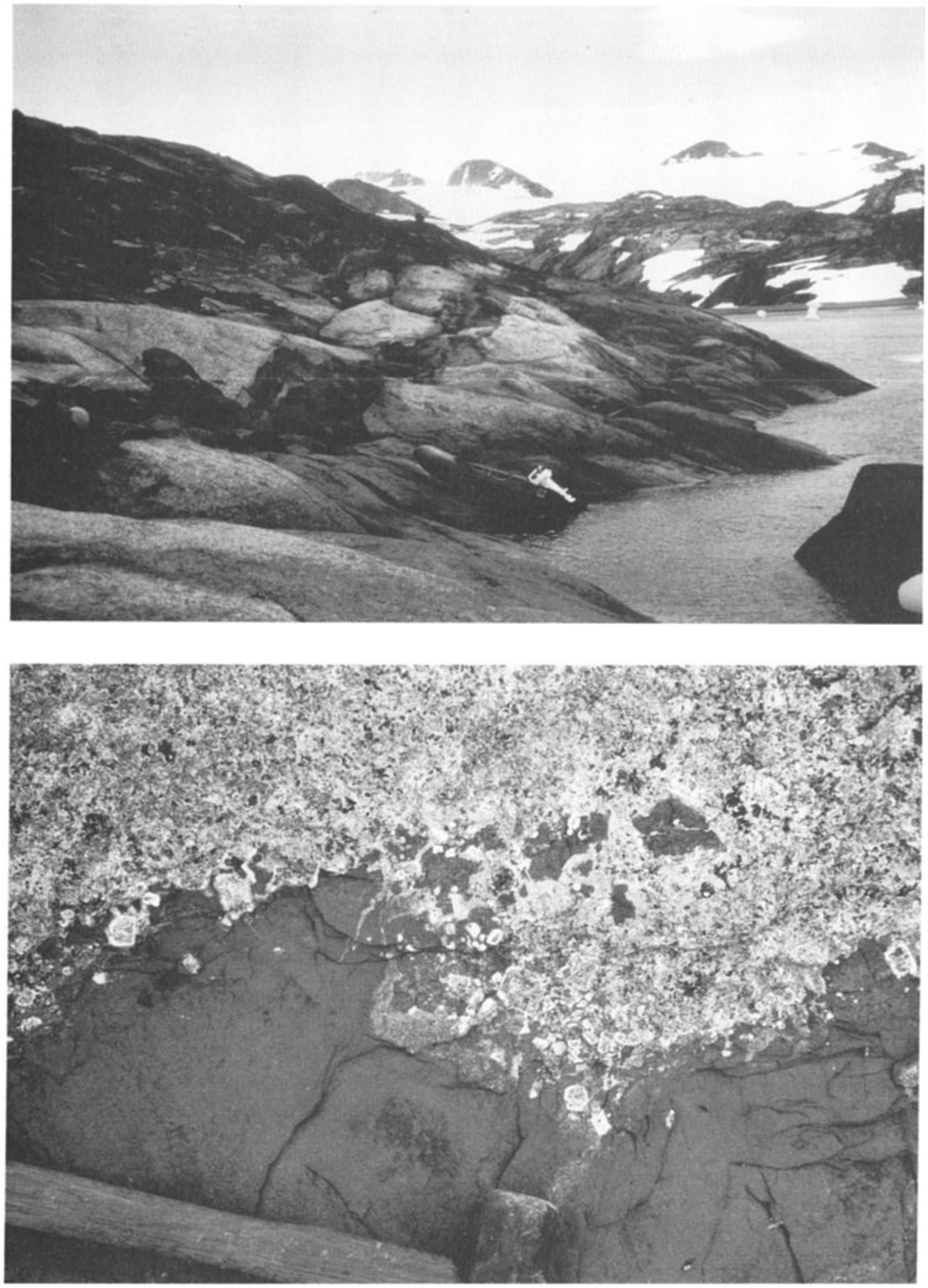

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Fig. 5. (continued)

composition; they are commonly, but not always, explosively emplaced in pipelike structures and have been interpreted as cumulates from volatile K-rich basaltic or andesitic magma [French, 1966; Hall, 1967]. They are usually regarded as being related to the lamprophyric group of minor intrusions which are considered [Hunter and Rock, 1987] as being sourced from deep levels.

The wide range of rock types present within these plutons argues for a mafic and, by inference, mantle component to the magmas. Many workers such as Harmon et al. [1984], Stephens and Halliday [1984] and Holden et al. [1987] have shown, mainly from combined isotopic methods, that the Caledonian plutons are crustal melts with varying but significant mantle inputs. Physical evidence for this mantle component may be seen in the common occurrence both in these rocks and in similar rocks worldwide of mafic or intermediate "enclaves" or "inclusions." The observations of Vernon [1984] (Australia), Frost and Mahood [1987] (Sierra Nevada), Holden et al. [1987] (Scotland), Hyndman and Foster [1987] (Idaho), Harrison et al. [1990] (Greenland), and our own unpublished data from Scotland (Ross of Mull, Garabal Hill, Crifell, Strath Ossian and Rannoch Moor plutons) and Ireland (Fanad, Ox Mountains and Thorr plutons (M. McErlean, personal communication, 1991))

(Figure 4) show that these inclusions commonly have ellipsoidal to spherical shapes, crenulate margins with lobes convex toward the granitoid host, fine-grained chilled margins, and are commonly associated with synplutonic diking (Figure 5). The occurrence of this phenomenon on such a global scale in plutons ranging from Proterozoic to Mesozoic in age strongly suggests to us that their presence is indicative of a fundamental process in granite genesis. The significance of these inclusions has been widely debated (see summary by Eberz and Nicholls [1988]); although many of these inclusions have been interpreted previously as being of xenolithic origin [e.g., Sabine, 1963], most workers now agree that these bodies represent uncrystallized basic to intermediate magma incorporated within uncrystallized granitoid host. The coexistence of acid and more basic magmas had of course been suggested much earlier, e.g. by Blake et al. [1965]; however, it is only comparatively recently that this process has been postulated as being of major significance in the plutonic environment and hence important in granite genesis. Holden et al. [1987] have shown for a number of British Caledonian plutons that the higher εNd values (typically, 1-2 εNd units) of the enclaves relative to their hosts can best be explained by a process in which the mafic inclusions represent synplutonic injections of mafic magma into a granitoid magma.

Therefore we follow Hyndman and Foster [1987] and others in suggesting that the mafic material represents high-temperature mantle-derived magma, which was injected into and partially melted the lower continental crust. The melts so formed then became incorporated variably with the mantle component to produce differing degrees of coexistence and hybridization. This, together with fractional crystallization, both at source and during emplacement, resulted in a complex spectrum of composition types, with both mantle and varying crustal geochemical and isotopic signatures and a range of mingling and hybrid textures present in the field. Therefore we suggest that much of the Caledonian magmatism in the Highlands and NW Ireland was the result of partial anatexis of lower continental crust which was initiated by mantle-derived mafic material.

Houseman et al. [1981] have suggested that during crustal shortening and thickening, the underlying mantle lithosphere must also thicken and shorten. Cold dense lithosphere is forced down into the hotter surrounding asthenosphere. They argue that this overthickened root becomes gravitationally unstable and is convectively and catastrophically removed, being replaced by hotter asthenospheric material. This results in rapid heating of the overlying crust and remaining lithospheric mantle, leading to regional metamorphism, rapid uplift of the crust and the generation of magmas. Clearly, magmas generated in this way will have a significant mantle component. In the following section, we explore the idea of how granites generated by lithospheric thickening can be applied to the British Caledonides.

In the British Caledonides, much of the granitic magmatism occurred in the interval 425-400 Ma (the so-called "Newer granites" of Read [1961]). Watson [1984] suggested that, within the Highlands, this was temporally coincident with regional sinistral strike-slip along NE-SW trending faults and shear zones. Evidence for syntectonic plutonism in shear zones based on critical, structurally based studies is best seen in Donegal [Hutton, 1982], the Ox Mountains [McCaffrey, 1989], at Strontian [Hutton, 1988b], and at Ratagain [Hutton and McErlean, 1991] (Figure 4). Elsewhere, the evidence is more circumstantial: the deformed Galway granite lies along the trace of the Southern Uplands fault in western Ireland, the elongate Leinster granite occupies a major shear zone in SE Ireland [Cooper and Bruck, 1983] and the Southern Uplands granites [Newry, Criffell, Doon, Fleet, and Cheviot] are emplaced within the transpressionally imbricated greywacke and shale stack of the Southern Uplands belt [Soper and Hutton 1984] (Figure 4). In Scotland, between the Great Glen and Highland Boundary faults, little detailed information exists to temporally link many of the granites with synplutonic faults and shear zones. However, a number of workers (especially Francis [1978] and Watson [1984]) have been so impressed by the strong spatial correlation that exists between granites and sinistral strike-slip faults, for example, the Etive, Rannoch Moor, Strathspey, Monadhliath, and Grantown plutons (18, 9, 19, 20 and 21 in Figure 4) and the Ericht-Laidon fault, and the near coincidence of the Laggan fault and the linear array of plutons between the Ballachulich, Ben Nevis, and Ardclach plutons (22 to 23 in Figure 4), to suggest that this implies a temporal and genetic linkage between faulting and granitic magmatism.

The tectonic environment of plutonism and 425-400 Ma sinistral strike slip has been related by Soper and Hutton [1984] and Hutton [1987] to the final closure of Iapetus where, between the two obliquely converging plates (Laurasia and Gondwana), the Caledonian terranes were accreted and, together with the forelands, deformed. It follows from this that the Caledonides during this period were subjected to a gross transpressional deformation, and therefore, like any normally convergent orogen, it was thickened. Faulting and other deformation are developed heterogeneously within the orogen. In some situations, for example, within slate belts such as the Southern Uplands, penetrative cleavages related to transpression are widely developed [Soper and Hutton, 1984]; however, transcurrent faults and shear zones are the typical expression of this event and they occur variously as terrane boundaries, within the terranes, and within the forelands (Figure 4).

The principal terrane bounding fault in the northern Caledonides is the Highland Boundary fault (HBF) of Scotland and Ireland which, as a major sinistral shear and fault zone, separates the Dalradian miogeoclinoral sequence to the north from the oceanic derived allochthonous terranes to the south. To the north of this, within the miogeocline and foreland, lie many of the Caledonian granites and their associated fault and shear zones. These, like the HBF itself, moved sinistrally in the period 425-400 Ma, and it seems therefore reasonable to physically link these secondary faults to the principal (plate) bounding fault. In Figure 6, a schematic cross section for a transpressionally thickened orogen such as the northern part of the British Caledonides is presented. This involves a listric, Moho-detaching, Highland Boundary fault, linked to secondary, foreland, steeply inclined faults (e.g., the Great Glen, Ericht-Laidon, Loch Tay, and Strathconan faults). Evidence for such a geometry of the main HBF is seen on seismic reflection profiles of the structure in the west of Ireland [Klemperer et al., 1991] where the plate boundary fault descends steeply northward from its outcrop trace in Clew Bay, bends northwards into the Moho, and continues parallel to this for some 70 km across strike before descending steeply into the mantle lithosphere. Thickening, as revealed by uplift in the Highlands between 425 and 400 Ma [Dewey and Pankhurst, 1970; Dempster and Harte, 1986] was synchronous with granite emplacement and faulting [Watson, 1984]. We consider that this thickening occurred across the entire orogen but, in the vicinity of the main faults and shear zones (such as the HBF in western Ireland, the Donegal Shear Zone, etc.) it was accentuated. At high crustal levels this is likely to have resulted in positive flower structures

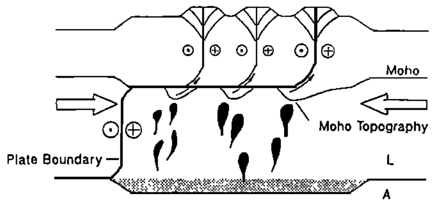

Fig. 6. Transpressionally thickened orogen such as the northern part of the British Caledonides. L is lithospheric mantle; A is asthenosphere. The heavy solid line with the Moho flat (the "plate boundary") (based on Klemperer et al. [1991]) and upper crustal flower structure is equivalent to the Highland Boundary fault and separates the foreland/miogeocline on the left from the accreted terranes (not differentiated) on the right. Second order linked transpressional faults within the foreland/miogeocline (thinner lines) are indicated. The lithospheric mantle keel (dotted) is destroyed by convecting asthenosphere and mantle diapirs which rise up to melt off the Moho topography created by transpression at the lower ends of the crustal shear zones. Granitic magmas thus formed rise up the shear zones to emplacement levels higher in the crust.

such as are seen in high crustal level transpressional zones [Harding and Lovell, 1979]. At lower crustal levels, following the Ox Mountains data, thickening also occurs, and we believe that this is capable of downwardly deflecting a horizontal datum (such as the Moho (Figure 6)) and thus creating a Moho topography. Convective removal of the lithospheric mantle keel [Houseman et al. 1981] will generate mantle melts, and we suggest that these will rise diapirically to the base of the crust, where they will begin to melt selectively the downward protuberances of the continental crust and thus remove the Moho topography. Following anatexis, mingling and/or mixing, and the generation of granitic magmas, these bodies will naturally rise up along their adjacent shear zones, and the shear zone kinematics will control the ascent and emplacement mechanisms. In this model therefore it is not so much the faults but the crustal thickening with which they are associated that causes the granitic magmatism.

CONCLUSIONS AND DISCUSSION

In this paper we have sought to show, for two contrasting areas of orogenic magmatism, that strike-slip transpression in oblique collision creates crustal thickening, which in turn is likely to be responsible for granitic magmatism. Further, we suggest that, in the northern part of the British Caledonides, intraplate transpressional faults may create a Moho topography that, when melted by and mixed with ascending mantle diapirs, will create compositionally expanded granitic melts that rise up the adjacent faults. Thus there may be a petrogenetic as well as a spatial/temporal relationship between transcurrent faults and granitoids.

The contrast in the types of granite produced in the Iberian Hercynides compared with the British and Irish Caledonides is, we believe, due to the different materials available as protoliths in their two respective crusts (see also Chappell and Stephens [1988]. In Iberia, one is dealing with a typical Gondwanan plate stratigraphy, that is, thick piles of low-grade Precambrian to lower Palaeozoic peraluminous metasediment. This "fertile" crust, when thickened and subject to hydrous fluxing, will generate syntectonic peraluminous two-mica leucogranites, anatectic temperatures being achieved totally intracrustally. In the British Caledonides (especially on the Laurentian margin), such material is generally absent and the crust is dominated by amphibolite and granulite facies gneisses and schists. It is unlikely that intracrustal melting, such as in Iberia, can take place here to any significant degree, and therefore an external energy source is needed to melt the continental crust. The melting of the lithospheric mantle keel and the rise of hot mantle diapirs to attack the corrugated base of the crust provides such a mechanism. A further implication of this model is that the type of granites being produced at a particular time will be a function of depth within the crust.

In the Portuguese situation, at the same time as the peraluminous two-mica leucogranites were being generated by anatexis of metasediments, a "Caledonian" situation may have been occurring much lower in or at the base of the crust. This would generate magma types similar to what has been documented here for the Caledonian in the British Isles. Such magmas, although generated syntectonically with the transpressive shear deformation, would be emplaced at higher levels later and would appear to be posttectonic. This could explain the apparent change in granite type with time documented by Julivert et al. [1980] for Iberia, where syntectonic upper crustal granites are followed by deeper-sourced magmas with mantle components.

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