Shallow laccolithic emplacement of the Land’s End and Tregonning granites, Cornwall, UK: Evidence from aureole field relations and P-T modeling of cordierite-anthophyllite hornfels

Jonathan M. Pownall1*, David J. Waters1, Michael P. Searle1, Robin K. Shail2, and Laurence J. Robb1
1Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK
2Camborne School of Mines, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Cornwall Campus, Penryn TR10 9EZ, UK

ABSTRACT

The Land’s End and Tregonning-Godolphin granites of the >250 km-long Permin Cornubian Batholith are heterogeneous medium- to coarse-grained peraluminous biotite-, tourmaline-, and lithium-mica granites traditionally thought to be emplaced as massive magmatic diapirs. Although S-type characteristics are dominant (quartz + biotite + muscovite + tourmaline ± topaz ± lithium-micas in the melt, numerous greisen and pegmatite veins, Sn-W mineralization), some characteristics of evolved I-type granites are also exhibited (hornblende-bearing enclaves, elevated εNd, Cu mineralization, batholithic dimensions). Here, we present an investigation focusing on the contact metamorphism and deformation of the aureole rocks adjacent to the Land’s End and Tregonning granites as an approach to better determine the method of granite emplacement and the depth at which it occurred. New 1:5000-scale geological maps are presented for ~15 km of coastal exposure of the granites and their aureoles. We propose that the granites were emplaced non-diapirically by intrusion of sills that amalgamated to form a sheeted laccolith-type body. Granite contacts cleanly truncate all faults, folds, and cleavages generated during both Variscan convergence and subsequent latest Carboniferous–Early Permian (end-Variscan) extension, and it is likely that granite was emplaced during continuation of this extensional episode. There is evidence for stopping of the country rocks by an outward-migrated sill and dyke network, and uplift and doming of the host rocks can be partially attributed to laccolith inflation. Host meta-silstones of the Devonian Mylor Slate Formation formed a contact aureole of cordierite + biotite + chlorite ± andalusite “spotted slates.” Several interspersed pillow basalts and dolerites, previously affected by hydrothermal alteration, underwent isochemical contact metamorphism to form cordierite- and orthoamphibole-bearing hornfels, including cordierite-anthophyllite rocks that are present in Kenidjack cliff, NW Land’s End aureole. THERMOCALC P-T modeling and pseudosection construction for these rocks in the large Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2-Fe2O3 (NCKFMASHTO) chemical system indicates contact metamorphism occurred at 1.5 ± 1.0 kbar and 615 ± 50 °C. This ultra-low pressure metamorphism equates to a likely emplacement depth of 5–6 km for the adjacent granite sheets. The Cornubian Batholith is highly composite and likely comprises an amalgamation of discrete shallow-seated sheeted laccoliths that are dyke-fed from a common lower-crustal/upper-mantle melt region to result in the batholith’s mixed S-type/I-type character.

INTRODUCTION

Hypotheses for the emplacement of granitoids have been frequently led by the two extreme end-member concepts for granite genesis: (1) the diapirc emplacement of igneous-derived “I-type” granites typified by the Andean batholiths (e.g., Pitcher, 1979; Petford and Atherton, 1996); and (2) the replacement of sheeted complexes of crustal-melt- (or sedimentary-) derived “S-type” granites typified by the Himalayan leucogranites (e.g., Harris and Massey, 1994; Harris et al., 1995; Searle, 1999; Searle et al., 2009). The I- and S-type distinction was initially proposed by Chappell and White (1974) and is still widely utilized. Andean-type granites are characterized by long, linear granites of batholithic proportions, intrusive hornblende- and biotite-bearing gabbro-granodiorite-granite-tonalite fractionation sequences with extrusive andesite-ryholite-dacite volcanics, and abundant Cu-Mo-Pb-Zn-Au mineralization. Crustal-derived Himalayan-type leucogranites are less voluminous, tend to be peraluminous (containing garnet, muscovite, biotite, and tourmaline), are associated with regional high-grade metamorphic-migmatite belts, have no extrusive volcanic component, and are in many cases associated with Sn-W mineralization. However, there are increasing numbers of granitoid bodies that have been found, compositionally, to fit neither of these examples or that represent a hybrid between the two types. Examples include the Baltoro Batholith in the Pakistani Karakoram, which comprises subduction-related I-type diorites, granodiorites and granites intruded by large-scale post-collision S-type two-mica ± garnet leucogranites (Searle et al., 2010), and the Main Range Tin granites of the Malay...
Peninsula, which include both I-type granodies and S-type biotite granites (Searle et al., 2012). Furthermore, the concept of granite diapirism has, in recent years, faced increasing scrutiny (Petford, 1996; Clemens, 1998; Petford and Clemens, 2000; Petford et al., 2000), and several plutons traditionally viewed as diapirc—including both S-type bodies such as the Monte Capanne granite on Elba, Italy (Farina et al., 2010; Rocchi et al., 2010) and I-type bodies such as the Mount Kinabalu granite in Borneo (Cottam et al., 2010)—have been re-interpreted, often as incrementally emplaced laccoliths or lopoliths (cf. Pollard and Johnson, 1973; Jackson and Pollard, 1988; Cruden, 1998).

Most approaches in determining emplacement style have been concerned with mapping internal granite fabrics as defined by phenocryst alignment, anisotropy of magnetic susceptibility (AMS), or geochemical trends, and the systematic dating of different granite facies. These methods have proved very successful in unravelling the emplacement history for many sheeted, composite or laccolith-type bodies (e.g., Morgan et al., 1998; de Saint-Blanquat et al., 2001; Michel et al., 2008; Clemens and Benn, 2010; Cottam et al., 2010; Farina et al., 2010; Rocchi et al., 2010; Leuthold et al., 2012). However, the effect of pluton emplacement on host rocks—specifically contact metamorphism and deformation (or lack thereof)—has sometimes received less attention. The study of aureole rocks can provide great insight into the details of pluton emplacement that cannot easily be discerned from focusing exclusively on the granite itself (as demonstrated by Paterson et al., 1991; Pattison and Harte, 1997; Ciavarella and Wyld, 2008). In particular, the depth of granite emplacement can be determined by calculating the pressure of peak aureole metamorphism. Also, the timing of emplacement relative to host-rock deformation can be inferred so that, for instance, it can be determined whether granite emplacement was a cause, an effect, or of no consequence to a specific tectonic episode.

Here, we present an investigation of the metazzoaric aureoles of the Land’s End and Tregonning granites of the Cornubian Batholith, South-west England (Fig. 1). Despite the Cornubian granites being a prominent component of Britain’s geological history, relatively little has been published on the field relations with their aureole rocks (Rattey and Sanderson, 1984; Hughes et al., 2009), and the majority of recent studies have instead focused on the granites’ mineralogical and geochemical characteristics and ore genesis (e.g., Floyd et al., 1993; Chappell and Hine, 2006; Müller et al., 2006). Some of the older interpretations for the formation of the Cornubian Batholith, as summarized in Floyd et al. (1993), have essentially assumed “large-tank” magmatism and the forced emplacement of individual plutons as massive “hot Stokes” diapirs (e.g., Pitcher, 1979; Marsh, 1982; Bate- man, 1984; Mahon et al., 1988; England, 1990; Paterson and Vernon, 1995). However, as previously mentioned, a paradigm shift (summarized by Petford et al., 2000) from diapirc ascent processes (c.f. Ramberg, 1981; Weinberg and Podladchikov, 1994) to dyke-controlled ascent and emplacement mechanisms has largely taken place, and the more recent interpretations for Cornubian Batholith emplacement do not invoke granite diapirism as the primary process (Salmon and Powell, 1998; Powell et al., 1999; Kratínová et al., 2003, 2010; Bouchez et al., 2006; Taylor, 2007; Hughes et al., 2009).

We firstly describe field relations observed during detailed (1:5000) mapping along coastal sections of the margins of the Land’s End and Tregonning granites and their aureole; secondly, we discuss a petrological and structural study of the aureole rocks; and thirdly we present P-T estimates of three cordierite-anthophyllite hornfelses from Kenidjack, NW Land’s End aureole. We use the field relationships and P-T estimates of the aureole rocks to determine the style of granite emplacement and the depth at which it occurred. P-T pseudosections are calculated using the computer program THERMOCALC (Powell and Holland, 1988, 2008) in the recently enhanced Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O-TiO2-Fe2O3 (NCKFMASHTO) system for cordierite-orthoamphibole assemblages (Diener et al., 2007, 2008). An additional aim of this study is therefore to contribute to the understanding of cordierite-orthoamphibole rock petrogenesis by determining the peak P-T conditions of their formation in this classic locality (Tilley and Flett, 1929; Tilley, 1935; Chimner and Fox, 1974).

Although this study is primarily concerned with the Land’s End and Tregonning granites, the ideas and approach detailed herein could be applied to all granites of the Cornubian Batholith. We hope to further clarify the petrogenesis and emplacement of the Land’s End and Tregonning Granites in relation to Variscan orogenesis. In a wider sense, we hope to (1) illustrate the use of aureole geobarometry in deciphering granite emplacement depth, and (2) further demonstrate some of the insights that can be drawn from the study of metamorphic aureole deformation and aureole-granite contact relations.

**GEOLOGICAL SETTING: THE VARISCAN OROGEN**

The European Variscides formed through the collision of Laurussian and Gondwanan continental fragments after closure of the Rheic Ocean (Late Devonian to Early Carboniferous) and are represented in several large massifs stretching from Iberia to Bohemia (Fig. 1A). Remnants of Rheic oceanic crust and mantle, or that of associated marginal ocean basins to the north, are only sporadically preserved (e.g., the Mid-Devonian Lizard complex in Cornwall; Kirby, 1979; Shail and Leveridge, 2009). The orogen comprises distinct E–W trending tectonostratigraphic terranes of the Rheonohercy-nian, Saxothuringian, and Moldanubian rift-oceanic basins separated by Palaeozoic and Precambrian basement (Kossmat, 1927; Matte, 1986; Franke, 1989; Nance et al., 2010). Early Devonian to Early Carboniferous passive margin sedimentary rocks were affected by Carboniferous inversion and crustal shortening and thickening involving folding and NNW-vergent thrusting (Shackleton et al., 1982; Coward and McClay, 1983; Leveridge et al., 1984). In the Early Permian, widespread lower crustal anatexis led to ascent and emplacement of granites into the upper crust. Published emplacement depths for granitoids along the orogen are far from uniform (Table 1), although Vigneresse (1999), using gravity surveys conducted across the whole Variscan belt, estimated that a consistent 6–8 km of erosion has occurred since their emplacement.

Southwest England represents part of the western Rheonohercynian passive margin of the Variscan Orogen (Warr, 2000; Shail and Leveridge, 2009) and comprises a series of rift-generated basins (Culm, North Devon, Tavy, South Devon, Looe, and Gramscatho basins) infilled with deep-marine argillaceous sedimentary and rift-related igneous rocks (Fig. 1B). The southernmost of these basins, the Gramscatho Basin, includes the Mylor Slate Forma-

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Figure 1. Geological setting of the Cornubian granites within the European Variscides. (A) The Variscan belt of Europe during the Early Carboniferous, modified from Matte (1986) and Franke (1989). (B) The Western Rhenohercynian of SW England, after Shail and Leveridge (2009). (C) Geological map of SW Cornwall, simplified from Goode et al. (1984) (British Geological Survey; 1:50,000). Yellow boxes indicate areas mapped—see Plate 1.
and $D_3$ SSE-verging folding ($F_3$) and axial planar cleavage development ($S_3$), which are variably associated with low-angle detachments, that developed during post-convergence extensional reactivation of Variscan thrusts (Alexander and Shail, 1995; Shail and Leveridge, 2009; Fig. 2).

A SYNOPSIS OF PREVIOUS WORK

Cornubian Batholith Morphology

The Cornubian Batholith is exposed in southwest England over a distance of ~200 km in seven large unroofed plutons (from west to east, the Isles of Scilly, Land’s End, Tregonning-Godolphin, Carnmenellis, St. Austell, Bodmin Moor, and Dartmoor granites) that are hosted by Devonian and Carboniferous sedimentary and igneous rocks of the Rhenohercynian passive margin. Granite magmatism was a protracted event spanning some 20 m.y. during the Early Permian (from 294 to 274 Ma) with assembly times for individual plutons lasting up to 4.5 m.y. (Chen et al., 1993; Chesley et al., 1993). The Land’s End granite (Fig. 3) is the youngest of the major plutons, emplaced between 277 ± 2 and 274.5 ± 2 Ma (Chen et al., 1993; Clark et al., 1993, 1994).

The Cornubian Batholith was originally modeled as a flat-bottomed body that occupies the upper 12 km of a 27-km-thick crustal section based on interpretation of a −50 mGal Bouguer anomaly and seismic refraction data (Bott et al., 1958, 1970). The batholith was also interpreted to widen with depth (e.g., Willis-Richards and Jackson, 1989), whereupon its base is possibly bound by a major late-Variscan thrust at 10–15 km depth (Brooks et al., 1984). High-resolution gravity modeling by Taylor (2007) recently showed that the individual plutons

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Pluton</th>
<th>Massif</th>
<th>T (°C)</th>
<th>P (kbar)</th>
<th>Depth (km)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradshaw and Stoyel (1968)</td>
<td>(whole batholith)</td>
<td>Cornubian</td>
<td>n.d.*</td>
<td>1</td>
<td>3</td>
<td>Fluid inclusion studies of quartz and fluorite veins in granites.</td>
</tr>
<tr>
<td>Floyd (1971)</td>
<td>(whole batholith)</td>
<td>Cornubian</td>
<td>580</td>
<td>1</td>
<td>3</td>
<td>Tentative estimate of thickness (3–4 km) and density (2800 kg m$^{-3}$) of eroded sedimentary cover. Temp. of 350°C calculated at 5 km dist.</td>
</tr>
<tr>
<td>Charroy (1986)</td>
<td>Carnmenellis Granite</td>
<td>Cornubian</td>
<td>530–600</td>
<td>0.5–2.5</td>
<td>1.5–3.0</td>
<td>Calculation of phase equilibria during crystallisation of granite</td>
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<tr>
<td>Chen et al. (1993)</td>
<td>(whole batholith)</td>
<td>Cornubian</td>
<td>n.d.*</td>
<td>0.5–5</td>
<td>1–2</td>
<td>High-resolution gravity modeling by Taylor (2007) recently showed that the individual plutons</td>
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<tr>
<td>Kita Ib. Granite</td>
<td>Cornubian</td>
<td>500–770</td>
<td>0.8–5.2</td>
<td>3.8–4.2</td>
<td>3.4</td>
<td>Indicated by stability of aureole mineral assemblages</td>
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<tr>
<td>Klein et al. (2008)</td>
<td>(whole batholith)</td>
<td>Cornubian</td>
<td>n.d.*</td>
<td>3.2</td>
<td>1.2</td>
<td>Indicated by stability of aureole mineral assemblages</td>
</tr>
<tr>
<td>Žák et al. (2011)</td>
<td>Mrákotía granite</td>
<td>Bohemian</td>
<td>&gt;2.5</td>
<td>&lt;2.5</td>
<td>&lt;9</td>
<td>Indicated by presence of magmatic andalusite</td>
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<td>Tartèse and Boulvais (2010)</td>
<td>Lizio Granite</td>
<td>Amorican</td>
<td>n.d.*</td>
<td>3–4</td>
<td>1–2</td>
<td>P-T range indicated by stability of aureole mineral assemblages</td>
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<tr>
<td>Tartèse and Boulvais (2010)</td>
<td>Questembert Granite</td>
<td>Amorican</td>
<td>n.d.*</td>
<td>3–4</td>
<td>1–2</td>
<td>P-T range indicated by stability of aureole mineral assemblages</td>
</tr>
</tbody>
</table>

Figure 2. Summary of deformational episodes ($D_1$ to $D_3$) for the rocks of the SW Grams-catho Basin. Schematic diagrams illustrate the field relations between different fold generations ($F_1$ to $F_3$) and associated cleavages ($S_1$ to $S_3$). $S_1$ and $S_3$ are axial-planar to $F_1$ and $F_3$, respectively. $S_1$ has developed parallel to original bedding. The limbs of the isoclinal $F_1$ folds are roughly parallel to $S_1$ and thus difficult to identify in the field. Modified after Rattey and Sanderson (1984) and Hughes et al. (2009).
have pronounced tabular forms in cross section, but that they are far thinner than originally envisaged, in some cases just 3–4 km top to bottom (one-third that previously predicted). Furthermore, these smaller estimates for Cornubian pluton thicknesses would make their aspect-ratio closely comparable to several well-documented sheeted (laccolithic or lopolithic) granitoid bodies (McCaffrey and Petford, 1997; Cruden and McCaffrey, 2001). Vertical or steep conduits have also been identified, which would feed such laccolith-type plutons (Taylor, 2007).

**Cornubian Batholith Petrogenesis**

The Cornubian biotite granite suites have a typical S-type geochemical signature indicating derivation from a (meta-)sedimentary protolith (cf. Chappell and White, 1974, 2001; Chappell and Hine, 2006). However, there is also a mantle (I-type) component, notably prevalent in the Dartmoor granite, as inferred from whole rock geochemistry (Stone, 1997, 2000a, 2000b), Sm-Nd isotopes (elevated $\varepsilon_{Nd}$; Darbyshire and Shepherd, 1994), and the presence of hornblende-bearing microgranite enclaves (Stimac et al., 1995). Alongside peraluminous coarse-grained porphyritic biotite granites and two-mica granites, there is a co-genetic suite of lithium mica granites (Stone, 1992) and tourmaline granites (Lister, 1978a, 1978b) that shows B enrichment, and late stage, chemically distinct topaz and fluorite granites that show enrichment in F, Li, and P$_2$O$_5$ (Floyd et al., 1993; Manning, 1981; Manning et al., 1996; Williamson et al., 2010). The Cornubian Batholith is remarkably heterogeneous, and even within individual plutons there is a great deal of chemical and textural variation resulting from successive intrusive phases and magma mingling (e.g., Knox and Jackson, 1990; Salmon, 1994; Manning et al., 1996; Salmon and Powell, 1998). Exley et al. (1983) and Floyd et al. (1993) set out a granite classification scheme, types A to F, of which “Type-B”—coarse-grained megacrystic biotite granite—comprises over 90% of the suite. “Type-E” granite—equigranular lithium-mica (zinnwaldite and lepidolite) granite—represents the second most voluminous granite and is largely confined to the Tregonning and St. Austell plutons and the Meldon aplite dyke along the northwestern margin of the Dartmoor granite (Stone, 1984). To explain the petrogenesis of these different granite facies, Floyd et al. (1993) proposed what is now known as the “St. Austell Model,” which shows the internal composition and zonation of a typical Cornish granite (Fig. 4). In this model, the early Type-B coarse megacrystic granite was intruded first by biotite granite and then by Type-E equigranular
Li-mica granite with a metasomatic halo forming “Type-D” megacrystic Li-mica and tourmaline granite. Alternatively, the so-called “1980s model” (Floyd et al., 1993; Fig. 5) considered that granitic magma was generated in the lower crust by heat derived from the mantle and later evolved by assimilation of upper-crustal components and differentiation of Li-mica granites, becoming increasingly more hydrated during the late stages until mineralized veins intrude through the carapace.

The Metamorphic Aureole

Emplacement of the Cornubian granites caused contact metamorphism of the enveloping Mylor Slate Formation. Early work by de la Beche (1839), Allport (1876), Phillips (1876), and Reid and Flett (1907) described the metasedimentary rocks (“killas”) and concordant metabasic igneous rocks (“greenstones”) that form the aureole, and outlined the respective increases in metamorphic grade toward the granite contact, thus identifying the effect of contact metamorphism. A certain group of greenstones, the cordierite-anthophyllite hornfelses of Kenidjack, just north of Cape Cornwall, have long been discussed (Tilley and Flett, 1929; Tilley, 1935; Vallance, 1967; Floyd, 1968; Chinner and Fox, 1974), as they are considered some of the best examples of this assemblage, aside from the classic cordierite-anthophyllite gneisses (COGs) of Orijärvi, Finland (Eskola, 1914; Schneiderman and Tracy, 1991). We targeted these rocks for P-T determination of peak aureole metamorphism (owing to their useful low-variance multiphase mineral assemblages, and to the unsuitability, commonly through late hydrothermal alteration, of pelitic hornfelses) as a way to quantify granite emplacement depth. Therefore, it is important to better understand how the petrogenesis of the Land’s End cordierite-anthophyllite rocks relates to granite emplacement.

Tilley and Flett (1929) first proposed that the Kenidjack cordierite-anthophyllite rocks formed by weathering of parental basalts; however, Tilley (1935) later revised this theory in order to account for Fe and Mg enrichment by invoking metasomatism. However, both these interpretations were later dismissed by Valance (1967) and Chinner and Fox (1974), who argued for formation by isochronal thermal metamorphism of pre-altered basalts. Floyd (1975) described Ca2+ mobility as being a key control on formation of the more “exotic” hornfelses from variably altered parental basalts, with chlorite-rich basalts metamorphosing to anthophyllite-bearing hornfelses, calcite-rich basalts forming hornblende-plagioclase hornfelses, and mobilised Ca later forming calc-silicate skarns through metasomatism.

Previous Theories Linking Cornubian Granite Emplacement to Host-Rock Deformation and Metamorphism

There has likewise been debate over the emplacement mechanisms and emplacement depths of the granites and the relationship between emplacement and host-rock deformation. Several early emplacement models assumed forceful diapiric intrusion of massive granitoid plutons (e.g., Booth, 1966; Rattey, 1980; Rattey and Sanderson, 1984; Goode and Taylor, 1988; Floyd et al., 1993), leading some to argue that S1 and F1 structures “are attributed to the same deformation event associated with the diapiric rise of the batholith” (Rattey and Sanderson, 1984, p. 91). Following this hypothesis, Rattey and Sanderson (1984) argued that ductile host-rock deformation, occurring in response to forceful en masse intrusion of hot buoyant granite, caused an S1 cleavage development parallel to the diapir roof, and F1 folds that verge away from the granite margins with a “Christmas tree” profile (Fig. 5). However, more recent work concludes that the regional D3 event predated granite emplacement and is instead related to the latest Carboniferous-Early Permian extensional reactivation of Variscan thrusts (Shail and Wilkinson, 1994; Alexander and Shail, 1995, 1996; Shail and Alexander, 1997; Le Boutillier, 2003; Hughes et al., 2009; Shail and Leveridge, 2009). Such an extensional episode may have been the cause, rather than an effect, of granite generation and emplacement (Shail et al., 2003). The concept of diapirc emplacement may also be negated by more recent field studies of relationships between different granite types, which suggest the granites are largely composite bodies comprising discrete sheetlike intrusions often with sharp planar contacts (Salmon, 1994; Salmon and Powell, 1998; Powell et al., 1999; Müller et al., 2006). Nevertheless, examples of small-scale diapiric structures have been reported (Powell et al., 1999), and attributed to instances when a fluid magma has been injected into a similarly fluid granite host.

Previously, P-T estimates of the Cornubian granites upon emplacement are wide ranging and often poorly constrained (see Table 1). Here, we present the first THERMOCALC P-T estimate for Cornubian granite aureole rocks in order to determine the depth of granite emplacement to better evaluate the emplacement mechanism. First, we present the field relationships of each region mapped in detail.

FIELD RELATIONSHIPS AND AUREOLE PETROGRAPHY

Four coastal sections were selected for mapping on the basis that they clearly display granite contact relations and aureole lithologies. Mapping was conducted at 1:5000 during June–August 2009 by JMP. As shown in Figure 1C, they are the: (1) 7-km-long “St. Just aureole,” from Cape Cornwall to Porthers Cove, encompassing both metapelites and metabasites, including pillow basalts, calc-silicates, and the cordierite-anthophyllite hornfelses of Kenidjack and Botallack; (2) areas around the Porthmeor granite cupolas and Land’s End granite contact in the vicinity of Great Zawn; (3) Tater-du peninsula, south Land’s End granite; and (4) Tregonning granite coastal exposure from Praa Sands to the granite sheets at Megiliggar Rocks.

In this section, we present an account of the key field relations for both the Land’s End and Tregonning aureoles. In addition to this, a more comprehensive area-by-area report on the mapped regions can be found in Appendix 1. For our new geological map, see Plate 1, which is available at its full size (1:5000) online. A schematic vertical section summarizing aureole stratigraphy, which can be used as
The metamorphic aureole of
The Land’s End Granite
at Cape Cornwall - Portmerion Cove - Great Zawn - Porthmeor Cove - Tater-du
The Tregonning Granite
at Pendeen Watch - Mothdrigg Rocks
Penwith Peninsula, Cornwall, England

Jonathan Pownall
Bath Spa College, School of Environments, Bath Spa University
Bath, UK
28th June - 9th August 2009

Plate 1. Geological map (1:5000) of the Land’s End and Tregonning granite aureoles. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00802.S1 or the full-text article on www.gsapubs.org to view the full-sized PDF file of Plate 1.
a key to maps presented later in the paper, is shown in Figure 6.

### Land's End Granite Aureole

All aureole rocks mapped as part of this study are assigned to the Devonian Mylor Slate Formation, which comprises both metapelites and concordant basic sills and lavas (Goode et al., 1984; Goode and Taylor, 1988). Metapelites are best exposed at the north (Pendeen Watch) and south (Cape Cornwall; Fig. 7) of the St. Just aureole, with only small isolated bodies occurring near Botallack and Levant. The entire Tregonning granite coastal aureole is also metasedimentary. Basalts were extruded through the sediments and are mostly exposed in the center of the St. Just aureole with some having later developed cordierite-anthophyllite and hornblende-plagioclase assemblages.

### Aureole Rock Petrography and Contact Relations

#### Metapelites

The metapelites are typically dark gray, fine-grained, strongly foliated (S1), remarkably hard, and can be described as “spotted hornfels” (or “spotted slates” if poorly indurated) due to the abundance of small (<3 mm) dark patches of cordierite and/or andalusite visible in hand samples (Fig. 8B). The peak assemblage comprises Crd+Bt+Ms+Chl+Pl+Qtz ± And ± Ilm with occasional apatite, pyrite, and corundum. The cordierite is markedly poikiloblastic, and incorporates fine-grained quartz and feldspar of the siltstone protolith. The hornfelses are micaceous; biotite is abundant and aligned to cleavage although muscovite is scarcer. Cordierite spots often have pinitised rims (retrogression to muscovite and clays). Andalusite poikiloblasts were found to be rarer than cordierite; chalcedony was never observed. Abundant quartz veins and vugs result from hydrothermal fluids generated late during Variscan convergence; elsewhere they postdate regional D3 structures but are deformed by D4 structures.

#### Metabasic rocks

Metamorphosed pillow basalts (Fig. 9A) and dolerite sills (Fig. 9B) are interbedded with metapelites as members of the Mylor Slate Formation. An excellent demonstration of the field relationship between these two lithologies is provided by the small dolerite sill within the folded metapelites of Priest’s Cove (Fig. 8C). However, in most instances where basalt and (altered) metasedimentary beds are intricately interbanded, the exact contact plane is difficult to pinpoint (Fig. 10). The clearest indicator of such contact zones is the atypical pink-gray appearance of the metapelites at close proximity to basalt (Fig. 9B and 9C). In many localities, these altered metapelites contain large (up to 10 mm diameter) euhedral cordierite poikiloblasts, rather than amorphous spots, with biotite and ilmenite inclusions. These rocks have undoubtedly been altered by basalt and dolerite emplacement and subsequent metasomatism, and thereby represent a minor basalt “aureole” that has later been overprinted by subsequent thermal metamorphism during granite emplacement (also noted by Flett, 1903; Mitropoulos, 1984). At the contact at The Avarack (Fig. 9D), where sediment was deposited onto cooled basalt with an extinct hydrothermal system, no alteration is seen and the contact is of very different character. The (meta-)basalts and dolerites display gradational contacts with cordierite-anthophyllite rocks (described separately next), strongly suggesting they are the protolith for such later-developed assemblages. Both the hornblende-plagioclase and cordierite-anthophyllite hornfelses contain early-formed ilmenite trains, suggesting that both lithologies may share similar metamorphic histories.

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**Figure 6.** Schematic vertical section of lithologies mapped, displaying crosscutting field relations. Please use this diagram as a key to the maps included throughout the paper. *—Turner et al. (1979); †—abbreviation by Goode and Taylor (1988); §—granite classification of Exley et al. (1983).
Cordierite-Anthophyllite hornfelses. Following Tilley and Flett (1929), a band of cordierite-anthophyllite facies rocks from Kenidjack Castle to The Crowns, Botallack has been remapped (Figs. 11 and 12). These rocks are derived from metamorphosed basalts with which they share a gradational contact. They are best displayed at the quarries at Kenidjack Cliff and at the small promontory between De Narrow Zawn and Zawn a Bal. At these localities, the cordierite forms large (typically 1 cm but up to 8 cm) spherical poikiloblasts that have weathered out from the matrix, forming the characteristic nodular texture termed “ball-rock” by Tilley (1935) (Fig. 13A). In more marginal localities, such as above Wheal Edward Zawn (Fig. 11B, sample 12D; Fig. 12B, sample 12L), the rock has a banded appearance comprising blue-gray cordierite-rich and brown-gray anthophyllite-bearing horizons. More homogenous varieties also exist at closer proximity to metabasalts. These hornfelses have a pronounced foliation, concurrent with the surrounding S1 fabric, which is defined by aligned trains of biotite and ilmenite. At Tater-du (Fig. 14), cordierite-cummingtonite assemblages were observed.

Calc-silicate rocks. Calc-silicate assemblages mapped on the St. Just aureole include a sheeted garnet-magnetite-sphene-chlorite-vesuvianite skarn at The Crowns, a garnet-apatite skarn at Carn Vellan, and a massive hornblende-diopside-sphene-axinite(-pyrite) skarn on Trewellard South Cliff. Similar to the cordierite-anthophyllite rocks, these calc-silicate skarn deposits occur discordantly within metabasalts and associated assemblages and were suggested by Alderton and Jackson (1978) to have formed by metasomatic introduction of basalt-sourced Ca by granite-derived fluids during late stages of emplacement.

Granite-Aureole Field Relations
The land’s End granite and its contact relations with aureole rocks were studied at Priest’s Cove, Porth Ledden, and Portheras Cove (Figs. 7 and 15). The typical facies present is a buff-pink, medium to coarse-grained, two-mica granite characterized by large, often-aligned euhedral orthoclase megacrysts (e.g., Vernon, 1986; Vernon and Paterson, 2008), which also contains minor tourmaline, cordierite, apatite, zircon and monazite (Müller et al., 2006)—an Exley et al. (1983) Type-B granite. Splits of black tourmaline needles are especially abundant along marginal zones of the granite, including sills and dykes.

In all instances, the fabric of the aureole rocks (D1 to D3) is cleanly truncated by the contact with the Land’s End granite and radiating aplite dykes (Figs. 16 and 18). At several localities such as Carn Veslan (Fig. 17), intense D3 chevron folding is clearly crosscut by granite intrusions (Fig. 18A), and the deformation is therefore shown to predate granite emplacement.

At Portheras Cove (Fig. 15B) and Great Zawn (Fig. 18), the granite-aureole contact is unfaulted and forms a stepped profile revealing sheetlike granite geometries. Granes often display both horizontal jointing, which is aligned with the S1 fabric of the adjoining hornfelses, and vertical jointing, which runs parallel to the steps in the contact, suggesting the granite was in part accommodated by the stoping of roughly cuboid blocks of country rock that broke off along and perpendicular to the S1 plane of weakness. Sills and dykes extending from the leading edge of the granite, as seen at Portheras Cove, Great Zawn, and Megiliggar Rocks (see section on the Tregonning granite) can therefore be considered precursors for pluton growth. Granite dykes also crosscut D1-deformed quartz-veined metapelites at several localities between Porth Ledden and Portheras Cove (Fig. 16E). Wide, heavily tourmalinized quartz veins have often developed along vertical joints in the granite that have likely arisen through late-stage fluid migration. Prime examples of stopped blocks can be found at Porth Ledden (Fig. 15A), where a number of small hornfels xenoliths and a large hornfels block (> 10 m long) border the pluton margin.

At Porthmeor Cove are two small granite cupolas whose emplacement has been independent of the main Land’s End granite (Figs. 17 and 19); see Appendix 1 for details.

Structure of the St. Just Aureole
It can be concluded that the structure of the aureole rocks is broadly consistent over the region mapped. F3 folds dominate, with only a few recognized F2 structures. F2 folds were not knowingly observed but have been described by Hughes et al. (2009). F3 fold axes are roughly parallel to the steps in the contact, suggesting that the granite was in part accommodated by the stoping of roughly cuboid blocks of country rock that broke off along and perpendicular to the S1 plane of weakness. Sills and dykes extending from the leading edge of the granite, as seen at Portheras Cove, Great Zawn, and Megiliggar Rocks (see section on the Tregonning granite) can therefore be considered precursors for pluton growth. Granite dykes also crosscut D1-deformed quartz-veined metapelites at several localities between Porth Ledden and Portheras Cove (Fig. 16E). Wide, heavily tourmalinized quartz veins have often developed along vertical joints in the granite that have likely arisen through late-stage fluid migration. Prime examples of stopped blocks can be found at Porth Ledden (Fig. 15A), where a number of small hornfels xenoliths and a large hornfels block (> 10 m long) border the pluton margin.

At Porthmeor Cove are two small granite cupolas whose emplacement has been independent of the main Land’s End granite (Figs. 17 and 19); see Appendix 1 for details.
parallel to the line of intersection of $S_1$ and $S_3$ planes. A dominant primary cleavage ($S_1$) is usually bedding-parallel as a consequence of isoclinal $F_1$ folding; it is often intersected by a strong secondary cleavage ($S_3$), axial-planar to the $F_3$ folds. It should be noted that $F_3$ fold axis azimuths at Cape Cornwall (~015°) progressively become more eastward-directed moving northward to Pendeen Watch (to ~045°); this has been ascribed to post-folding rotation across NW–SE strike-slip faults by Hughes et al. (2009).

The regional structure is revealed by compilation of $S_1$ and $S_3$ orientations (Fig. 20C), and can be generalized as a broad anticlinal structure with fold axis aligned roughly parallel to the granite/aureole contact plane of the NW pluton margin (with slight northward plunge). Although the data show relatively poor correlation, it can still be argued that the aureole shows signs of doming uplift around the margin of the granite, which could have been caused by inflating emplacement. Other studies (Alexander and Shail, 1995, 1996) show that $D_3$ structures have similar orientations to the east of the pluton. Therefore, $D_3$ deformation seems very unlikely to have been driven by a diapir-induced radial strain field as would be expected if the Rattey and Sanderson (1984) model of forceful diapiric intrusion were correct.

The nature of the contact between metabasic and metapelitic rocks is roughly parallel to original bedding. However there is a discrepancy between $S_1$ (35° dip) and the average dip of the contact plane (10°). This may be accounted for by two factors: (1) that the basalt was partly intruded as a sequence of parallel sills with an upwards-stepping leading edge; and (2) extensive simple shearing of the whole region by $D_3$, manifested as the observed downward-stepping of the ESE-verging $F_3$ folds, has widened the angle between measured $S_1$ and the actual original depositional surface (maximum strain ~70%). Cross-sections are presented in Figure 21.

**Tregonning Granite Aureole**

The entire Tregonning coastline was mapped at 1:5000 (see Plate 1); however, there are only three regions where the aureole rocks are exposed: east Praa Sands, Rinsey Cove, and Megiliggar Rocks. In all instances, the aureole comprises exclusively metapelites.
At Megiliggar Rocks (Figs. 22 and 23; previously described by Stone, 1975, 1992), several thick granite sheets intrude the metapelites, thinning away from the Tregonning granite with a dip of ~20° (Fig. 23A). The formation is upthrown by a major fault to the west, and so provides insight into granite–country-rock relations at depth. One major sheet branches, then remerges further east entrapping a slice of hornfels, demonstrating mechanisms of country-rock isolation and sill amalgamation. Stepped contacts in association with xenoliths demonstrate that a stoping mechanism operated within individual sheets (Fig. 23B); xenoliths may result from failed bridge structures due to growth of adjacent en echelon intrusions. The interior of the sheets, best exposed on intersection with the wave-cut platform, display massive, homogeneous fabrics and angular jointing, and are indistinguishable from the granites of the main plutons. This suggests it is plausible for the plutons to have formed from amalgamation of granite sheets. Megiliggar Rocks may therefore represent an arrested stage of pluton construction, exhibiting mechanisms of sill-intrusion and amalgamation, accommodated by isolation and stoping of the country-rock, plus roof uplift.

**DEPOSITION AND DEFORMATION OF THE MYLOR SLATE FORMATION**

Deep-marine sedimentation within the Devonian Gramscatho basin was punctuated by episodes of basaltic volcanism resulting in intrusion of basic sills and extrusion of pillow basalts. Gabbros were emplaced prior to D1 deformation and are likely associated with the basalts. Dolerite sills within the sedimentary rocks (Figs. 8C, 9B, 14B), and likewise bodies of sedimentary rock encapsulated within the basalts, demonstrate that basalt horizons are not laterally extensive. These field relationships partially account for the discrepancy between the average basalt-metapelite contact angle and the S1 dip to which both were originally orientated, assuming a stepped leading-edge of successive basalt sheets that have since been sheared by D3.

A hydrothermal system associated with this seafloor volcanism has evidently caused...
fluid transport through surrounding sediments forming alteration zones characterized by soft, pink cordierite-rich metasedimentary rocks and extensive quartz-veining. This zone represents a minor basalt aureole (strictly a metasomatic adinoite) that has subsequently been overprinted by granite-related contact metamorphism and incorporated into the main Land’s End aureole. Widespread quartz veining present throughout the metasedimentary rocks may be related to this hydrothermal event, to granite emplacement, or to regional metamorphism predating granite emplacement. Quartz veins are affected by D₃ deformation and therefore cannot be sourced from a granite intrusion that postdates D₃, folding; a significant portion likely originated during early-Variscan regional metamorphism. These extensive F₃-defining quartz veins (plus associated S₃, axial-planar cleavage) are cleanly truncated at all observed granite contacts, and there are no perceivable effects of granite emplacement on aureole fabrics at outcrop scale (Fig. 1A).

It is concluded that D₃ deformation predates granite emplacement and must instead be caused by post-convergence extension as summarized by Shail and Leveridge (2009) and Hughes et al. (2009). We therefore reject the hypotheses of Rattey (1980) and Rattey and Sanderson (1984) that D₃ was caused by granite emplacement. Nevertheless, the structural data presented earlier indicate a broad antiformal structure for hornfels overlying the granite roof, and we therefore acknowledge that granite emplacement has caused host-rock deformation, albeit overprinting D₃, in the form of regional (long-wavelength) uplift and doming (D₄).

**THERMOBAROMETRY OF THE KENIDJACK CORDIERITE-ANTHOPHYLLITE ROCKS**

Cordierite-orthoamphibole rocks, as previously mentioned, comprise an unusual metamorphic assemblage characterized by Ca-poor amphiboles and bulk compositions rich in Fe+Mg+Al. Such assemblages may be derived from either an igneous or sedimentary protolith and thus are often regarded simply as “allochemorphic metamorphic products” (Vallance, 1967, p. 84). The classic cordierite-orthoamphibole gneisses (COGs) of the Orijärvi region, Finland (Eskola, 1914), have in recent years been restudied in light of new analytical techniques (e.g., Schneiderman and Tracy, 1991; Smith et al., 1992); however, the cordierite-anthophyllite hornfelses of Kenidjack have only once been re-analyzed (Chinner and Fox, 1974) since the original studies by Tilley and Flett (1929) and Tilley (1935).

Five cordierite-anthophyllite rocks were collected from Kenidjack, St. Just aureole (samples 10A, 12D, 12L, 12X, and 17E; Fig. 24); three (10A, 12D, and 12L) of these were selected for thermobarometry in order to constrain the emplacement depth of the adjacent Land’s End Granite.

**Cordierite-Anthophyllite Hornfels**

**Mineral Chemistry**

Polished thin sections of the three samples were analyzed at the University of Oxford using a JEOL JSM-840A Scanning Electron Microscope (SEM) fitted with a Link ISIS energy-dispersive microprobe system (EDS) for quantitative analysis. Operating conditions were a 20.0 kV accelerating voltage, 5.00 nA beam current (with 2 µm beam diameter for spot analysis), 15 mm working distance, and a 100 second live counting time. Calibration was by natural and synthetic standards, and a ZAF correction procedure was applied. Spot analyses were always performed at >250 x magnification to ensure high-resolution control of beam location and minimal deviation from perpendicular beam incidence. Averaged microprobe analyses are presented in Table 2, and bulk compositions (mol% in NCKFMASHTO) are presented in Table 3.

Orthoamphibole is present throughout (at ~15 vol% abundance) as radiating sprays of acicular crystals (Figs. 13C and 13D), whose compositions (Fig. 25) plot close to the anthophyllite endmember (low Al; low Fe; low Na). Cordierites are large (~1 cm in 10A), spherical, and extremely poikiloblastic containing biotite, plagioclase, quartz, and ilmenite, and account for ~25 vol%. In 12X, cordierite is pseudomorphed by bytownite. Fine-grained biotite is present throughout but mainly confined to the matrix and has medium-high X(Mg) (~0.7 average) and fairly high Ti. The rest of the matrix comprises plagioclase and quartz. Plagioclase compositions vary widely between oligoclase and labradorite. Ilmenite trains are present throughout both cordierite poikiloblasts and the matrix and account for around 3 vol% of the rock (Fig. 13B). Accessory minerals include pyrite (fairly abundant in 10A) andapatite.

**Ti-in-Biotite Geothermometry**

The biotite Ti-saturation geothermometer of Henry et al. (2005) has been applied to
Figure 11. (A) Photograph of Kenidjack Cliff taken from The Crowns overlaid with geological boundaries. (B) Geological map of Kenidjack taken from Plate 1. See Fig. 21 for cross-sections A and B; see Fig. 6 for key to lithologies. Locations of photographs in other figures are marked in green. MHW and MLW indicate the mean high and low water marks, respectively, and the intertidal zone is shaded in a paler color. The limit of exposure is indicated with the white line.
Figure 12. (A) Photograph of Botallack Cliff taken from above Wheal Edward Zawn overlaid with geological boundaries. (B) Geological map of Botallack taken from Plate 1. See Fig. 21 for cross-sections C and D; see Fig. 6 for key to lithologies. Locations of photographs in other figures are marked in green. MHW and MLW indicate the mean high and low water marks, respectively, and the intertidal zone is shaded in a paler color. The limit of exposure is indicated with the white line.
all five cordierite-anthophyllite hornfelses and three metapelites (for comparison) and yielded temperature estimates as shown in Figure 26. It must be noted, however, that the Henry et al. (2005) geothermometer is calibrated for graphitic, peraluminous metapelites that contain ilmenite or rutile and have equilibrated at ~4–6 kbar, for which an error of ± 24 °C is quoted. This pressure is higher than calculated for the rocks in this instance, nevertheless the geothermometer is still the most suitable available, and produces a useful (although poorly constrained) temperature estimate of 615 ± ~50 °C of the cordierite-anthophyllite hornfelses, complementary to the P-T pseudosections. For comparison, the three analyzed metapelites yield notably higher (arguably implausibly high?) temperature estimates of 680 ± 50 °C.

Construction of THERMOCALC P-T Pseudosections

We used the computer program THERMOCALC (Powell and Holland, 1988, 2008) to produce P-T pseudosections for three cordierite-anthophyllite rocks in the NCKFMASHTO system, as presented in Figure 27. The recent compilation of activity composition (a-X) codings for cummingtonite-grunerite, anthophyllite, and gedrite (Dale et al., 2005; Diener et al., 2007) now allow geologically realistic modeling of cordierite-orthoamphibole rocks in large chemical systems such as NCKFMASHTO (Diener et al., 2008).

Calculations were performed with THERMOCALC 3.33 (tc333.exe; Powell and Holland, 1988, updated October 2009), using the Holland and Powell (1998) internally consistent thermodynamic data set (tc-ds55.txt) and the NCKFMASHTO system a-X codings (tc-NCKFMASHTOi.txt) for garnet, biotite and silicate melt (White et al., 2007), chloritoid, cordierite, epidote, staurolite and talc (Holland and Powell, 1998), clinino- and orthoamphibole (Diener et al., 2007), clinopyroxene (Green et al., 2007), orthopyroxene (White et al., 2002), chlorite

Figure 13. Cordierite-anthophyllite hornfelses. (A) Photograph of outcrop at Kenidjack exhibiting large weathered-out cordierite “knots” aligned to strong ilmenite-defined S1 foliation (250/41°NW). Length of visible hammer is ~9 cm. (B) Photomicrograph (PPL) of sample 10A (from same locality as A) sectioned through a large cordierite poikiloblast (left). (C) Photomicrograph (XPL) of sample 12L from South Botallack displaying large anthophyllite burst. (D) Back-scattered electron (BSE) image of sample 10A displaying anthophyllite needles within bt+pl+qtz matrix.
Figure 14. Tater-du, south Land’s End Granite. (A) Photograph of Rosemondress Cliff overlain with geological boundaries. Locations of other photos are indicated in green. (B) Metapelite horizons (Mp*) within metabasalts (Mb). Pencil for scale. (C) Thin-section (XPL) of altered metapelite bearing sapphire (corundum; crn) and cordierite (crd) poikiloblasts. (D) Geological map of Tater-du taken from Plate 1. See Fig. 6 for key to lithologies. MHW and MLW indicate the mean high and low water marks, respectively, and the intertidal zone is shaded in a paler color. The limit of exposure is indicated with the white line.
Figure 15. Panoramic photographs of the Land's End granite–aureole contact of the St. Just aureole at (A) Porth Ledden, and (B) Portheras Cove. Locations of photographs shown in Figure 16 are indicated in green.
Figure 16. Land’s End granite–aureole contact relations, St. Just aureole. See Figs. 7 and 15 for locations. (A) Contact at Porth Ledden between coarse megacrystic granite and spotted hornfels. (B) Wide, vertical granite dyke intruding hornfels alongside contact at Porth Ledden. (C) Granite sill intruding Porth Ledden foreshore near contact. (D) Close-up of contact at Porth Ledden. (E) Granite dyke crosscutting deformed quartz veins in hornfels, east of Wheal Edward Zawn. (F) Small isolated hornfels body sharing subhorizontal contact with aplite and pegmatite sheets at Portheras Cove.
Figure 17. Geological map of Great Zawn and Porthmeor Cove taken from Plate 1. The Porthmeor Cupolas are enlarged at the bottom right. The positions of cross-sections F–F' and G–G' (top left) are indicated. See Fig. 6 for key to lithologies. Locations of photographs in other figures are indicated in green. MHW and MLW indicate the mean high and low water marks, respectively, and the intertidal zone is shaded in a paler color. The limit of exposure is indicated with the white line.
(Holland et al., 1998), muscovite–paragonite (Coggan and Holland, 2002), plagioclase–K-feldspar (Holland and Powell, 2003), spinel–magnetite (White et al., 2002), and ilmenite–hematite (White et al., 2000). Pseudosections were plotted using Drawpd 1.15 (dr115.exe, www.metamorph.geo.uni-mainz.de/thermocalc/documentation/drawpd/index.html). Bulk compositions in terms of NCKF-MASHTO oxides, as input to THERMOCALC, are presented in Table 3.

The observed mineral assemblage (Anth+Crd+Bt+Pl+Ilm+Qtz) occupies a large field on each of the three calculated P-T pseudosections, spanning ~0–3 kbar and 500–720 °C. In order to more precisely pinpoint the modeled rocks in this large P-T space, orthoamphibole compositional isopleths were calculated and plotted.

Fe³⁺

The effect of Fe³⁺ on phase equilibria and pseudosection construction has become a much-discussed topic now that large systems incorporating ferric Fe, such as NCKF-MASHTO, have been devised (Diener et al., 2008; Powell and Holland, 2008; Diener and Powell, 2010). Fe²⁺O and Fe³⁺O₃ cannot be distinguished by SEM-microprobe and so the percentage of Fe as Fe³⁺ must be estimated. In the analyzed samples, the oxide mineral assemblage can be used to indicate the likely oxidation ratio. Ilmenite is the only Fe-bearing oxide, and in all analyses of fresh material, its Fe+Mn+Mg content is within error of its Ti content, suggesting a negligible content of Fe³⁺. For the model calculations, therefore, the additional O content of the bulk composition was set at the arbitrarily low value of 0.01.

Natural and Model Amphibole Compositions

Our strategy in comparing the natural to the calculated amphibole compositions is outlined in Appendix 2.

Thermodynamic Basis for Pressure Sensitivity of Orthoamphibole Composition

The tschermak substitution governing anthophyllite–gedrite relations (the y(anth) parameter) in a cordierite-orthoamphibole
rock can be expressed as $3\text{Anth} + 7\text{Crd} = 7\text{Ged} + 17\text{Qtz}$. This equilibrium is associated with a large volume change of about $-10\%$ as estimated from Mg end-member data (Holland and Powell, 1998), assuming water is approximately conserved, and so the equilibrium should have promise as a geobarometer. Anthophyllite–sodicanthophyllite relations are controlled by the edenite substitution (as monitored by the $a(\text{anth})$ parameter), such as in the equilibrium $\text{Anth} + \text{Ab} = \text{Na-Anth} + 4\text{Qtz}$, a principle that forms the basis for the Holland and Blundy (1994) hornblende-plagioclase geothermometer. Combination of both substitutions leads to sodicgedrite, equivalent to the Ca-amphibole pargasite. Linear trends in natural orthoamphibole compositions when these two substitutions are plotted against each other (Schumacher, 2007) suggest they are partially coupled. In the calculated diagrams (Fig. 27), both sets of isopleths have shallow P-T slopes.

The end-member data that underpin thermodynamic modeling in this system are constrained to differing extents. Anthophyllite properties are well constrained, but the fundamental thermodynamic properties of gedrite (entropy, volume, and specific heat capacity) that are included in the Holland and Powell (1998) DS5 data set are described as “estimated.” The Na-amphibole end-members have been developed by analogy with Ca-amphibole end-members (Diener et al., 2007), and constructed by summations from anthophyllite, assuming similar mixing behavior to that in Ca-amphiboles and then by fitting Darken’s Quadratic Formalism (DQF) adjustments where necessary to reproduce certain natural compositions (Powell, 1987; Will and Powell, 1992).
Mixing parameters for the amphibole solid-solution model were refined by Diener et al. (2007) and by Diener and Powell (2012) mainly from natural occurrences of coexisting amphibole species with similar \( a(\text{anth}) \) and \( y(\text{anth}) \) values to the Land’s End anthophyllites (Stout, 1972; Clark, 1978; Spear, 1980, 1982; Miyake, 1984; Schneideman and Tracy, 1991; Frimmel, 1996), and successfully reproduce the relevant miscibility gaps. This mixing model affects the distribution of compositional isopleths, especially in the neighborhood of miscibility gaps, but should have only a second-order effect on the overall sensitivity to pressure, which rests on the molar volumes of amphibole end-members. It is known from earlier studies that cell parameters and molar volumes are smaller for gedrites and sodic gedrites than for members of the anthophyllite-ferroanthophyllite series (Deer et al., 1997). Therefore, a sensitivity to pressure may be predicted using this calibration. Moreover, an assemblage in which orthoamphibole coexists with cordierite, quartz, and sodic plagioclase should, on the basis of the equilibrium given above, saturate the orthoamphibole in both gedrite and sodic gedrite components.

Model Predictions

Application of the updated Holland and Powell data set (DS5.5) together with the orthoamphibole solution model of Diener et al. (2007, 2008) and Diener and Powell (2012) shows encouraging trends. Firstly, the calculated changes in modal proportions with pressure along an isotherm approximate to \( \text{Crd} + \text{Pl} = \text{Oam} + \text{Qtz} \) (actually \( 1\text{Crd} + 0.59\text{Pl} = 0.51\text{Oam} + 4.45\text{Qtz} \) between 1 and 5 kbar at 620 °C), with the amphibole evidently increasing in Na and Al. Secondly, the calculated amphibole compositions quite closely follow the trend of natural anthophyllite-gedrite amphiboles in the compilation by Schumacher (2007), although the anthophyllites of this study lie a little to the high-Na, low-Al side of this array.

Nevertheless, in the absence of precisely measured thermodynamic properties for gedrite and one or more of the sodic end-members, it does not yet appear possible to provide an absolute calibration for a geobarometer based on Al- and Na-saturated orthoamphibole compositions. We therefore rely on the existing Holland and Powell (1998) end member data and the refined activity models of Diener and Powell (2012) to constrain pressure in the aureole.

P-T Estimates for the Land’s End aureole

The Na and Al contents of the Kenidjack anthophyllite compositions offer a number of criteria for comparison with the P-dependent model isopleths in Figure 27. As outlined in Appendix 2, the total Na (\( \text{ed} = \text{Na} \)) and tschm Al (tsch = \( \frac{1}{2}(\text{Al}-\text{Na}) \)) provide maximum limits for the calculated parameters \( a(\text{anth}) \) and \( y(\text{anth}) \), and should place maximum limits on pressure (see Table 4). Alternatively, one can match the observed and calculated values of total Na, total Al, and tsch (see Appendix 2). These values are not so readily contoured from the output of model calculations, but are listed for the 615 °C isotherm in Table 4, and indicated on the summary diagram Fig. 27E. In practice, because of the relatively high Na, low Al character of Kenidjack anthophyllites, the limits imposed by Al content fall at lower pressure than those from Na, and in some cases lie at negative pressure. It is nevertheless clear that the Land’s End assemblages equilibrated at very low pressure, and that the mean of the Na- and Al-based indicators is in the region of 1.5 kbar. The uncertainty on the pressure of calculated isopleths, derived from the uncertainties of the end member thermodynamic data, is around 1 kbar in the temperature range of interest.

We therefore propose that the most likely depth of emplacement for the granite adjacent to the modeled cordierite-anthophyllite rocks is between 5 and 6 km, corresponding to a pressure of 1.5 kbar at a likely density of < 2800 kg m\(^{-3}\) for the upper crust, although this depth carries a rather large uncertainty. This is the first P-T estimate of a Cornubian granite aureole to employ modern thermobarometry in a “geologically realistic chemical system” (Diener et al., 2007, p. 644).

PETROGENESIS OF THE KENIDJACK CORDIERITE-ANTHOPHYLLITE ROCKS

The mechanisms behind cordierite-orthoamphibole mineral assemblage development, which notably may arise from a number

Figure 20. Stereonets (equal-area lower-hemisphere projections) of (A) \( S_1 \) cleavage planes, St. Just aureole; (B) \( S_2 \) cleavage planes, St. Just aureole; (C) Poles to \( S_2 \) (black squares) and \( S_3 \) (red squares) with \( \pi \)-girdle (dotted great circle) and pole to \( \pi \)-girdle (pink dot) describing regional fold-axis orientation; (D) \( F_3 \) fold axes of the St. Just aureole (orange squares) and Great Zawn (green crosses), oriented parallel to the \( \pi \)-girdle pole (pink dot; 19° plunge, 014°N azimuth), the average \( S_1 - S_3 \) cleavage-intersection lineation.
Figure 21. Cross-sections of the St. Just aureole drawn roughly perpendicular to the granite contact, from south (A–A’) to north (E–E’). Dotted lines indicate contacts are inferred. See Plate 1 for locations; see Fig. 6 for key to lithologies. The sea is shown in pale blue.
of different protoliths, are contentious (e.g., Robinson et al., 1982; Schumacher, 2007; Dieren et al., 2008). There have been three main proposed formation methods to account for the low Ca+Na, high Mg+Al+Fe+K bulk composition: (1) Mg and Fe enrichment of volcanics by metasomatism (Eskola, 1914; Tilley, 1935); (2) Ca and Na depletion of metasediments and metavolcanics by extraction of granitic melt (Grant, 1968); and (3) either pre-metamorphic enrichment in Mg and Al by diagenesis of sediments or evaporites (e.g., Reinhardt, 1987), alteration of basalts (e.g., Vallance, 1967; Chinner and Fox, 1974; Moore and Waters, 1990; Peck and Smith, 2005), or hydrothermal alteration in the presence of sulphides (e.g., Chinner and Fox, 1974; Moore and Waters, 1990; Peck and Smith, 2005), or hydrothermal alteration in the presence of sulphides (e.g., Chinner and Fox, 1974; Moore and Waters, 1990; Peck and Smith, 2005).

The cordierite-anthophyllite hornfelses at Kenidjack occur exclusively within the (meta-)basalts with which they share gradational contacts and grade from homogeneous (17E) to banded (12D,12L) to poikiloblastic (10A) textures toward their interior. Formation from basalt thus seems the only plausible origin. Anthophyllites are Al-poor and therefore close to “pure” end-member composition. Parallel S̆-aligned trains of ilmenite occur throughout all samples (Fig. 13B), consistently at ~3 vol% abundance. They are seemingly the first product of metamorphism and occur throughout the cordierite-anthophyllite as well as the hornblende-plagioclase hornfelses. It can therefore be assumed that both assemblages share a common origin, with the hornblende-hornfelses representing (as suggested by Tilley, 1935) the more typical contact facies. An X(Fe³⁺) of <10% is also sufficient to account for possible deprotonation substitutions in the amphibole. The above evidence supports the theory of Vallance (1967) and Chinner and Fox (1974) of formation from previously hydrothermally altered basalt by isochronal thermal metamorphism. We conclude that the Kenidjack cordierite-anthophyllite rocks formed at very low pressure (1.5 ± 1.0 kbar) and moderately high temperatures (615 ± 50 °C). This result is similar to that calculated for the cordierite-cummingtonite rocks of the Stillwater gabbroic complex, Montana (~2 kbar, ~600 °C, Labotka and Kath, 2001), and not too dissimilar from the cordierite-cummingtonite rocks of the Gold Brick District, Colorado (~3 kbar, 550 ± 70 °C, Earley and Stout, 1991), the cordierite-anthophyllite-cummingtonite rocks of the Lar Deposit, Manitoba (3–4 kbar, 550–700 °C, Elliott-Meadows et al., 2000), and the classic COGs of Orijärv, Finland (~3 kbar, 550–600 °C, Schneiderman and Tracy, 1991), all calculated using conventional thermobarometry. Notably, however, the Al content of anthophyllite coexisting with cordierite in these last two studies is greater than at Kenidjack, lending further support to the low calculated pressure in the Land’s End aureole.

**DISCUSSION**

The deformation and metamorphism of the Land’s End and Tregonning aureoles and field relations along the granite-aureole contacts (see Fig. 28) demonstrate that: (1) the plutons are not associated with any observable small-scale wall-rock deformation, with F̃ folds cleanly truncated by sharp, planar granite contacts suggesting that granite intrusion has exploited brittle fractures in the host-rock; (2) sheetlike granite geometries can be inferred from stepped granite-hornfels contact relations and sills extending from the pluton’s leading edge; (3) no evidence exists to suggest D̃ deformation represents a cylindrical diapir-induced shear-zone as F̃ fold vergence in the host rocks is typically to the SE throughout the region rather than being directed radially outwards from the pluton; and lastly (4) aureole thermobarometry indicates the Land’s End Granite was emplaced at a shallow crustal level (5–6 km depth).

These insights tie in with many of the arguments that have questioned the viability of granite diapirs, namely: (1) the inherent “space problem” of forcefully intruding large volumes of melt into the solid crust (e.g., Pitcher, 1979); (2) dubious or nonexistent field evidence for expected wall-rock features, such as a cylindrical shear zone, pluton-up kinematic indicators, rim-synclines, and evidence for diapir “tails” (Clemens, 1998; Cruden, 1998; Petford et al., 2000); and (3) the tabular shape of many granitoid bodies that have been shown to comprise sill-like structures (McCaffrey and Petford, 1997; Cruden, 1998), both identified in the field (e.g., Michel et al., 2008; Horsman et al., 2009; Rocchi et al., 2010) and by newer geophysical interpretations (e.g., Vigneresse et al., 2010; Evans et al., 1993; Taylor, 2007). Furthermore, several additional arguments against granite diapirs are also supported by features of the Land’s End granite, albeit in a less direct way. Firstly, the shallow emplacement of the granite demonstrated here would have occurred well into the brittle regime. It
Figure 23. (A) Photograph of Megiliggar Rocks at high tide displaying the spectacular granite sheets—the leading edge of the laccolith—dipping away from the center of the pluton. (B) Close-up view of the uppermost granite sheet displaying small-scale intra-sheet stoping. (C) Cross-section of the Tregonning Granite. See Plate 1 for line of section.
has been argued that heat output required of an ascending diapir to soften and deform the wall rocks would be too great to allow ascent to such high structural levels, and that any diapir would have suffered thermal death in the earlier stages of ascent (e.g., Mahon et al., 1988). Also, it may be argued that the textural and chemical heterogeneity of the Cornubian granites, as demonstrated by the close associations of fine-grained- and (megacrystic) coarse-grained granites as well as chemically different Li-mica and tourmaline granites, would not have been attainable after the degree of convective overturning necessary to facilitate diapirc ascent (Clemens, 1998).

Plentiful evidence exists for stoping around the margins of the Land’s End and Tregonning granites, although its overall contribution to accommodation remains unknown. Some have voiced doubts over stoping as a volumetrically significant pluton accommodation process (Glazner and Bartley, 2006) and the observed examples of stoped blocks may arguably be only late-stage phenomena. Alternatively, stopping may well have been a very significant process and operated throughout pluton assembly, as argued by Žák et al. (2006) in the instance of the Central Bohemian Pluton, Czech Republic.

Although a diapiric emplacement mechanism for the plutons of the Cornubian Batholith would seem unlikely, examples of centimeter-scale diapiric structures, present within or between granite sheets, have been identified in Cornwall (e.g., Treen Cliff, south Land’s End granite; Powell et al., 1999) although they appear to be secondary processes that do not contribute widely to pluton growth or host-rock deformation. Some authors have defended the role of such small-scale diapirs that operate in the visco-elastic regime (e.g., Miller and Paterson, 1999).

As an alternative to a diapiric mechanism, there is clear evidence to suggest that networks of dykes facilitated the vertical transport and emplacement of the Land’s End and Tregonning granites. The clearest example is at Megiliggar Rocks where several major subhorizontal granite sheets extend from the pluton margin and intrude the host-rock (Fig. 22, 23), demonstrating the processes of sill intrusion and amalgamation, as well as host-rock stopping and uplift. Furthermore, the granite cupolas at Porthmeor Cove (Fig. 19) demonstrate that dyking is intrinsically related to their emplacement.

The majority of authors now consider dykes to be the most viable mechanism for vertical transport of felsic magmas in the mid to upper crust (Lister and Kerr, 1991; Clemens and Mawer, 1992; Petford et al., 1993; Petford, 1996), with granite emplacement occurring by transition to horizontal flow and subsequent injection, amalgamation and inflation of sills. Dykes are thought to propagate by elastic fracturing of the country rock, but with a critical width that must be surpassed in order for the dyke to avert freezing and be self-propagating (Clemens and Mawer, 1992). This critical
TABLE 2. SEM-MICROPROBE ANALYSES OF 3 CORDIERITE-ANTHOPHYLLITE HORNIFELS FROM KENIDJACK, LAND'S END AUREOLE

<table>
<thead>
<tr>
<th></th>
<th>10A</th>
<th>12D</th>
<th>12L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>crd</td>
<td>anth</td>
<td>bt</td>
</tr>
<tr>
<td>SiO₂</td>
<td>49.72</td>
<td>55.54</td>
<td>38.55</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.05</td>
<td>0.10</td>
<td>1.64</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.02</td>
<td>0.19</td>
<td>0.04</td>
</tr>
<tr>
<td>MnO</td>
<td>0.02</td>
<td>0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>MgO</td>
<td>10.44</td>
<td>18.62</td>
<td>15.74</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.50</td>
<td>0.33</td>
<td>0.41</td>
</tr>
<tr>
<td>CaO</td>
<td>0.02</td>
<td>0.19</td>
<td>0.04</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.01</td>
<td>0.02</td>
<td>7.93</td>
</tr>
</tbody>
</table>

**Note:** Only phases considered by and input to THERMOCALC are listed (minor accessory phases are ignored); quartz has not been analysed. Analyses performed by a JEOL JSM-840A SEM with Link ISIS EDS system at the University of Oxford, UK.

*p.f.u. = per formula unit, based on the number of oxygen anions given in brackets.

†Volume% abundances are careful estimates.
TABLE 3. CORDIERITE-ANTHOPHYLLITE HORNFELS BULK COMPOSITIONS (MOL% ABUNDANCE OF OXIDES CONSIDERED IN NCKFMASHTO SYSTEM)

<table>
<thead>
<tr>
<th>mol%</th>
<th>10A</th>
<th>12D</th>
<th>12L</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>59.918</td>
<td>58.024</td>
<td>57.755</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>9.709</td>
<td>10.771</td>
<td>9.063</td>
</tr>
<tr>
<td>CaO</td>
<td>1.368</td>
<td>1.199</td>
<td>1.320</td>
</tr>
<tr>
<td>MgO</td>
<td>13.769</td>
<td>15.487</td>
<td>17.387</td>
</tr>
<tr>
<td>FeO</td>
<td>9.687</td>
<td>9.182</td>
<td>9.660</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.634</td>
<td>1.385</td>
<td>1.383</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.316</td>
<td>1.637</td>
<td>1.035</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.587</td>
<td>2.302</td>
<td>2.387</td>
</tr>
<tr>
<td>O</td>
<td>0.011</td>
<td>0.011</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Figure 25. Amphibole compositions plotted in edenite-tschermakite space (projected along the glaucophane vector, gl = Na + Li; diagram modified from Schumacher, 2007). Blue lines divide the space into compositional fields for the four endmembers based on nomenclature of Leake et al. (1997). Dashed lines show aluminum isopleths (³Al). The analyses plot very close to the “pure” anthophyllite endmember due to low Al content. Amphiboles in 17E are split between anthophyllites contained in late veins and gedrites in the main bulk of the rock. Many of these gedrite analyses plot outside of the theoretical composition space and may therefore be altered. Anthophyllites of 12X are partly altered to actinolite+talc and so plot further toward the gedrite endmember.

Figure 26. Temperature estimates of the cordierite-anthophyllite hornfelses and three metapelites (for comparison) using the Ti-in-biotite geothermometer of Henry et al. (2005). X(Mg) = Mg/(Mg+Fe). Average temperature estimates for the cordierite-anthophyllite hornfelses are as follows: 10A—615 °C; 12D—613 °C; 12L—616 °C; 12X—601 °C; 17E—460 °C. Error is estimated at ± ~50 °C. Metapelites 10G, 20Q, and 21K are from Kenidjack Cliff, Portheras Cove, and Wheal Edward Zawn, respectively.
THERMOCALC P-T pseudosections for (A) 10A, (B) 12D, and (C) 12L in NCK-FMASHTO. Darker shades indicate higher variances. Key for all small numbered fields is given in (D). The target field (anth+cd+bt+pl+ilm+qtz) is contoured with $a(anth)$ isopleths (dashed white lines) and $y(anth)$ isopleths (dotted white lines). The $y(anth)$ isopleths representing the suprasolvus extension of the anthophyllite-gedrite transition is marked by a black dashed line. The $a(anth)$ isopleths relating to the measured value of the rock is indicated as a thick solid white line, labeled “P,” and marks the pressure estimate (offset by $P_{\text{MAX}}$ and $P_{\text{MIN}}$ error bounds at a distance of 1σ). The thick vertical solid white line labeled “T” marks the temperature estimate calculated by the Henry et al. (2005) Ti-in-biotite geothermometer (offset by $T_{\text{MAX}}$ and $T_{\text{MIN}}$ error bounds). The P-T estimate for each rock is therefore indicated by the P and T lines intercept (green dot) with the error bounds shown by the green boundary line. (E) Comparison of valid P-T windows for 10A, 12D, and 12L. The region within the green border is common to all, and therefore represents the final P-T estimate based on utilization of $a(anth)$ as a geobarometer. Note that lower pressures are indicated by all other approaches used (summarized in Table 4) and therefore this result represents a maximum estimate for pressure of contact metamorphism and granite emplacement depth.
Figure 27 (Continued.)

D
1) anth+ged+cd+cli+bt+pl+ilm+qtz
2) anth+cd+cli+bt+pl+ilm+qtz
3) ms+cd+cli+bt+pl+ilm+qtz
4) cli+bt+pl+ilm+qtz
5) pa+cd+cli+bt+pl+ilm+qtz
6) ged+pa+cd+cli+bt+pl+ilm+qtz
7) ged+cli+bt+pl+ilm+qtz
8) ged+pa+cli+bt+pl+ilm+qtz
9) anth+cd+bt+pl+ilm+qtz+liq
10) ged+cd+opx+bt+pl+ilm+qtz+liq
11) anth+cd+opx+bt+pl+ilm+qtz+liq
12) anth+cd+opx+bt+pl+ilm+qtz
13) cd+pa+cli+bt+pl+ilm+qtz
14) ged+cd+pa+cli+bt+pl+ilm+qtz
15) ged+cd+bt+pl+ilm+qtz+liq
16) ged+cd+opx+bt+pl+ilm+qtz
17) opx+cd+bt+pl+ilm+liq
18) ab+ms+cli+bt+pl+ilm+qtz
19) pa+ms+cli+bt+pl+ilm+qtz
20) pa+cli+bt+pl+ilm+qtz

E

12L
12D
10A
Both features are likely attributed to country-rock uplift and doming by granite emplacement. It must be concluded that there is a regional scale inflatative emplacement dynamic in addition to emplacement by sill propagation as observed at local scale.

It is therefore proposed that the Land’s End and Tregonning granites are laccolithic, with inflation of sheets manifested as a broad doming of the aureole. Successive intrusion and coalescence of dyke-fed granite sheets seems to have formed a tabular intrusion (as shown by Taylor, 2007), typically with a large width:height ratio, to produce a laccolith geometry with a flat base and domed roof (cf. Pollard and Johnson, 1973; Jackson and Pollard, 1988). Melt would have ascended from its source, via feeder dykes or by pervasive flow, until the drop-off in overburden pressure favored the lateral intrusion of sills rather than the vertical intrusion of dykes (cf. Hutton, 1997). Further intrusion and amalgamation of the sheets, and migration of the pluton by stoping of country rock, would have then occurred until country-rock uplift (due to sill inflation) became the preferential accommodation mechanism (see Fig. 29).

Emplacement postdated faults, folds, and cleavages generated during both Variscan convergence and subsequent latest Carboniferous–Early Permian end-Variscan extension (D1–D3). Emplacement of the granites during continued extension would partially answer the “space problem” of granite accommodation, and indeed there is evidence to suggest that extensional structures exerted a strong control on granite emplacement (Shail and Wilkinson, 1994).

Further support for the feasibility of shallow tabular laccoliths is lent by post-1980s geological interpretations. For example, Evans et al. (1993), after conducting a high-resolution seismic survey of the Lake District Batholith, northern England, interpreted sub-horizontal reflectors as country-rock slivers or basalts interspersed throughout a sheeted complex with a “cedar tree” profile. Importantly for this study, Taylor (2007) has recently re-interpreted several plutons of the Cornubian Batholith as shallow tabular bodies with geometries in accordance with the Cruden and McCaffrey (2001) power-law relationship for laccolithic plutons. Furthermore, rapid melt ascent through dykes of up to 10 cm s$^{-1}$ ($10^4$ to $10^8$ times faster than calculated for diapiric ascent; Clemens, 1998) has been shown to allow laccolith assembly by rapid emplacement of discrete magma pulses

### Table 4. P-T Estimates for 3 Cordierite-Antophyllite Hornfelses from Kenidjack, Land’s End Aureole

<table>
<thead>
<tr>
<th>Rock</th>
<th>Pressure estimates by various geobarometers$^*$ (kbar)</th>
<th>Ti-in-Bt Temperature$^+$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a(\text{anth})^\beta$</td>
<td>$\text{Na}_{\text{total}}$</td>
</tr>
<tr>
<td>10A</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>12D</td>
<td>2.4</td>
<td>1.9</td>
</tr>
<tr>
<td>12L</td>
<td>3.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>

$^*$calculated for the 615°C isotherm (average Ti-in-Bt geothermometry result).

$^+$using the Henry et al. (2005) geothermometer.

$^\beta$utilised on P-T pseudosections of Figure 27.

---

**Figure 28.** A schematic cross-section summarizing all observed field relations along the St. Just aureole of the Land’s End granite.
of all the plutons, with chemically and texturally nubian Batholith confirms this feature is typical (Shail, 1999). Geochronology of the wider Cor-
megacrystic “St. Just wedge” (Salmon and Clark et al., 1993, 1994), joined by the poorly 274.5 ± 2 Ma St. Buryan lobe (Chen et al., 1993; Buchez et al., 2006; Taylor, 2007; Hughes et al., 2009) that a diapirc emplacement mechanism for the granites is unlikely, and instead there is evidence for shallow laccolithic emplacement of the plutons.

The aureole protolith comprised pillow-basalts emplaced upon argillaceous ocean-floor sediments that have both undergone partial alteration by a seafloor hydrothermal system prior to contact metamorphism by the Land’s End granite. During contact metamorphism, some basalts are inferred to have formed cordierite-anthophyllite and hornblende-plagioclase assemblages. In contrast, calc-silicate hornfelses formed through granite-associated metasomatism. Field relations show D3 deformation occurred prior to granite emplacement during end-Variscan NNW–SSE extension. On a small scale, granite emplacement has caused no discernible wall-rock deformation, with pre-existing aureole fabrics (D1–D2) undeformed and cleanly truncated. However, on a regional scale, granite emplacement has caused a broad uplift and doming of the host-rocks. We propose that the Land’s End and Tregonning granites are laccolith-type bodies emplaced, at least at the current exposure level, by intrusion of dyke-fed sills, which caused at least partial stoping of country-rock blocks. Accommodation of the granite was partly achieved by slight roof uplift driven by laccolith inflation. The “space problem” of granite accommodation is also partially solved by the granites’ likely emplacement during continued end-Variscan extension.

THERMOCALC P-T pseudosections suggest the cordierite-anthophyllite hornfelses of Kenidjack reached peak contact metamorphism at 1.5 ± 1.0 kbar and 615 ± 50 °C, indicating a likely emplacement depth of 5–6 km for adjacent granites exposed near present-day sea-level. Furthermore, the roof of the granites, now eroded, would have been emplaced at even shallower depth.

The Land’s End biotite granites are likely dyke-fed by a common lower-crustal/upper-mantle melt source, and the Tregonning lithium-mica granites were later generated by metasomatism of the crustal residuum (or of more basic granitoids) by volatiles exsolved from the same region (Stone, 1992). It would seem likely that other plutons of the Cornubian Batholith were similarly emplaced as dyke-fed shallow-crustal laccoliths, with differing fractionation paths of segregated melts during magma ascent accounting for the chemical disparity observed between biotite granites of different plutons.

This shallow emplacement depth is consistent with the typical S-type granite, as is the peraluminous composition; however, certain aspects, such as the batholithic dimensions of

(cf. Glazner et al., 2004), as elucidated by recent geochronological studies (e.g., Coleman et al., 2004; Michel et al., 2008; Cottam et al., 2010; Howard et al., 2011), and by work on the plumbing of magma chambers within volcanic systems (Lipman, 2007; Annen, 2009, 2011). U-Pb dating of the Land’s End granite shows that granite magmatism was indeed a protracted event and caused the emplacement of at least three distinct bodies of Exley et al. (1983) Type-B granite—the 277 ± 2 Ma Zennor lobe and the 274.5 ± 2 Ma St. Buryan lobe (Chen et al., 1993; Clark et al., 1993, 1994), joined by the poorly megacrystic “St. Just wedge” (Salmon and Shail, 1999). Geochronology of the wider Cornubian Batholith confirms this feature is typical of all the plutons, with chemically and texturally distinct intrusions incrementally emplaced over a ~20 m.y. period (Chen et al., 1993; Chesley et al., 1993).

Elvan dykes (quartz porphyry) and an exposed rhyolite at Kingsand Beach (Plymouth) provide limited evidence for associated acid volcanism (e.g., Darbyshire and Shepherd, 1985; Floyd et al., 1993).

CONCLUSIONS

Field relations observed during mapping of the aureole rocks of the Land’s End and Tregonning granites (shown schematically in Fig. 28) have supported the findings of recent studies (Salmon and Powell, 1998; Powell et al., 1999; Kratinová et al., 2003, 2010; Buchez et al., 2006). During continued end-Variscan extension, with pre-existing aureole fabrics (D1–D2) undeformed and cleanly truncated. However, on a regional scale, granite emplacement has caused a broad uplift and doming of the host-rocks. We propose that the Land’s End and Tregonning granites are laccolith-type bodies emplaced, at least at the current exposure level, by intrusion of dyke-fed sills, which caused at least partial stoping of country-rock blocks. Accommodation of the granite was partly achieved by slight roof uplift driven by laccolith inflation. The “space problem” of granite accommodation is also partially solved by the granites’ likely emplacement during continued end-Variscan extension.

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The Land’s End biotite granites are likely dyke-fed by a common lower-crustal/upper-mantle melt source, and the Tregonning lithium-mica granites were later generated by metasomatism of the crustal residuum (or of more basic granitoids) by volatiles exsolved from the same region (Stone, 1992). It would seem likely that other plutons of the Cornubian Batholith were similarly emplaced as dyke-fed shallow-crustal laccoliths, with differing fractionation paths of segregated melts during magma ascent accounting for the chemical disparity observed between biotite granites of different plutons.

This shallow emplacement depth is consistent with the typical S-type granite, as is the peraluminous composition; however, certain aspects, such as the batholithic dimensions of

Figure 29. The Land’s End laccolith: a semi-schematic cross-section. Granite at the present-day exposure level (green line) is drawn at 5.5 km palaeodepth as calculated by THERMOCALC thermobarometry (mean value) of adjacent aureole rocks. Dips of uppermost granite sheets are inferred from observed tilt of aureole S1 fabrics. The laccolith has been drawn so its thickness (3 km) is consistent with other Cornubian granites calculated by Taylor (2007), and so that its aspect-ratio is in agreement with the Cruden and McCaffrey (2001) estimate for typical laccolith geometries. The depth of the lowermost crust (27 km) was suggested by Bott et al. (1970). This proposed emplacement mechanism accounts for granite accommodates by regional-scale roof uplift and by localized stoping; however, no ductile deformation is required at outcrop scale, thus D3 aureole structures (which predated granite emplacement) are cleanly truncated.
the Cornubian granite system and the mantle melt-contribution, have more of an affinity with I-type granites. We further suggest that while representing useful first-order petrogenetic concepts, the two end-member I- and S-type granite facies cannot be applied in this instance, and that Cornish granites are a hybrid between typical I-type and typical S-type. The proposed shallow-crustal tabular intrusions concur with the most recent geophysical interpretations by Taylor (2007), and we hope our P-T estimates can further quantify this proposal.

**APPENDIX 1: AREA-BY-AREA FIELD OBSERVATIONS FOR THE LAND’S END AND TREGONNING GRANITE AUREOLES**

In addition to the key field observations described in the main text, here is a more thorough area-by-area account of the aureole rocks of the Land’s End and Tregonning granites.

### The Land’s End Granite Aureole

**Priest’s Cove**

A mineralized subvertical faulted contact along Saveall’s Lode, Priest’s Cove, marks the southernmost extent of the St. Just aureole hornfelses. Granite is fine-grained than at localities further north and locally hosts abundant quartz, tourmaline, and hematite veins. It is thought to be part of the St. Just Wedge (Salmon and Shail, 1999) and has been termed the Carn Gloue Granite (Salmon and Shail, 1999; Müller et al., 2006). The fabric of the hornfelsed metapelites adjoining the fault is cleanly truncated with no evidence to suggest it postdates faulting. The metapelites are intruded by thin planar aplite dykes that crosscut F3 folds. The metapelites are heavily deformed and display tight F1 chevron folds (Fig. 8C). Growth of metamorphic minerals, and resultant hornfelsing of the sediment (a possible grain-size inversion; Hughes et al., 2009) appears to have been preferential along certain beds. A dominant primary cleavage (S1) is usually bedding-parallel as a consequence of isoclinal F1 folding; it is often intersected by a strong secondary cleavage (S2), axial-planar to the F1 folds. Cordierite growth is aligned to S2. Cleavage relationships are fairly consistent around Cape Cornwall (S1 ~210/30°NW; S3 ~150°). Cleavage is often well developed and is plane-exposed (Fig. 8D), with crenulation relations with S1 displayed.

**Botallack**

At Botallack (Fig. 12), there is an isolated metapelite lens within metabasalts (300 x 100 m). Its outer margin is altered, but it grades inwards to a spotted hornfels similar to that mapped elsewhere in the region. Mapping by Goode et al. (1984) (British Geological Survey 1:50,000 geological map, Penzance sheet) and Goode and Merriman (1987) show both this feature in addition to a second smaller body to its south, but no field evidence could be found for this second feature; it is claimed location are large outcrops of hornblende-plagioclase hornfels. The metapelites within this feature are, in general, even more fine-grained than elsewhere, and contain smaller cordierite spots. Features originating from original bedding are often better preserved, and later-developed cleavages (often which crenulate S1) are better displayed. Fold geometries and cleavage orientations are consistent with the rest of the coast. Clear examples of minor dolerite sills are seen to the east of Wheal Edward Zawn at the contact with underlying metapelites (Fig. 9B).

### Porthleden

At Porthleden (Figs. 7 and 15), the contact between the roof of the granite and the overlying hornfels, typically dipping at 30–40°, is well exposed (Fig. 16A). Along the granite margin, there are a number of small hornfels xenoliths, as well as a large (15 x 8 m) dyke-bound hornfels block. Such inclusions of intact country rock, at one time isolated by sill- and dyke-intrusions that exploited brittle host-rock fractures, demonstrate that stopping at least in part accounted for granite accommodation in such regions. A number of large sills, which could be considered precursors for pluton growth, intrude hornfelses in the Porthleden

### Levant

At Carn Vealn, Levant, another isolated metapelite body is present, although it is too small to contain typical spotted hornfelsite. However; all of the metapelites has been subject to some degree of contact alteration with the enveloping basalts. The metabasic rocks are predominantly extrusive to the north, in the Levant region, and many of the best-displayed pillow lavas can be found here. Many basalts mapped as extrusive further south, such as those forming the natural arch at Stamps-an-Jowl Zawn, display only the characteristic weathering pattern emanating from crisscrossing hydrothermal veins (Fig. 9A).

### Porters Cove

At Porters Cove, the granite-hornfels contact is unfaulted and forms a stepped profile in the cliff, revealing sheeplike granite geometries. Along the foreshore, the contact is orientated roughly horizontal, and several small remnant patches of hornfels overlying the sheet are exposed at low tide (Fig. 16F). Hornfels just west of the contact is intruded by three ~0.5 m wide granite dykes, which possibly would have preceded the emplacement of further sheeted granites had emplacement continued.

### Great Zawn

At Carn Veslan (Fig. 17), granite-truncated F1 folds within a 10 x 8 m relict patch of hornfels provides convincing evidence that D3 preceded granite emplacement (Fig. 18A). Further east, above Great Zawn itself, the stepped contact between the granite sheets and overlying metapelite is well exposed, in this instance displaying a northwestern dip (Fig. 19B). Granites display both horizontal jointing, which is aligned with the S1 fabric of the adjoining hornfelses, and vertical jointing, which runs parallel to the steps in the contact, suggesting the granite was in part accommodated by the stepping of roughly cuboid blocks of country rock that broke off along and perpendicular to the S1 plane of weakness. Wide, heavily tourmalized quartz veins have developed along vertical joints in the granite, which may have arisen through late-stage fluid migration.

East of Great Zawn, the granite is emplaced within an extremely hard, coarse-grained Cpx+Pl+Ab+Ms+Chl ± Ap ± Ilm meta-gabbrro. This gabbro dome is encircled by overlying metapelites in map view so that its shape in cross-section can be inferred. No evidence could be found for metagabbro at Carn Veslan Cliff as mapped by Goode et al. (1984). The most significant feature at Great Zawn, which appears to be undocumented in the literature, is the contact relation between granite and metagabbro: toward the narrow zawn beneath Carn Moyle (Fig. 18C), the small, angular end-profile of the granite is underlain by and surrounded by metagabbro. The straight, extremely clean planar contacts, which differ from the intermingled contacts further west, almost certainly failed to accommodate the granite intrusion. The structure of this granite intrusion differs from the two “satellite” granite cupolas on the other side of Porters Cove (Floyd et al., 1993), which is connected to the main Land’s End granite to the west. Nevertheless, it likely shares a very similar joint-controlled passive emplacement mechanism. From this intrusion, several major granite dykes radiate to the northeast, and can be followed for 300 m toward the Porthmeor Cove Cupolas before reaching the sea. The granite in this vicinity is especially tourmaline-rich, and a few small tabular xenoliths (quite possibly stoped blocks of country rock) bear an almost complete tourmaline and quartz replacement (Fig. 15D).

### The Porthmeor Cupolas

The Porthmeor Cupolas, described by Stone and Exley (1984) and mentioned by Reid and Flett (1907), Hall and Jackson (1975), Floyd et al. (1993), and Müller et al. (2006), are thought to be the only two examples of “satellite” stocks in Southwest England (see Fig. 19). The dominant granite facies present in both cupolas is the same as the main pluton (coarse-grained biotite granite; Type-B). The north cupola, emplaced exclusively in metapelites, is exposed mainly in cliff section as a tall granite dome with sharp, angular contacts. A network of fine-grained aplite sills connects it to the smaller but more accessible south cupola,
which is intruded into both metapelites and metagabro. Both cupolas and associated sills and dykes cleanly crosscut all country-rock structures, demon- strating a non-forceful emplacement mechanism. Dykes extend from the corners of the south cupola, as if they once isolated a large block that has since subsided into the underlying granite (Fig. 19B). The roof complex of the south cupola granite, developed beneath a slightly domed roof contact, comprises a banded leucogranite-pegmatite sequence. The other significant lithological variations are occasional darker horizons rich in biotite. Dykes emanating from the granite display several crosscutting relations: in one instance, a thick, coarse-grained granite dyke intruded outward from the eastern corner crosscuts a fine grained leucogranite dyke, causing a 1.5 m sinistral offset (Fig. 19B). This is evidence for an earlier dyking stage before emplacement of the cupula. Apart from slight roof doming, there is no evidence to suggest that either cupula was emplaced by forceful diapiric intrusion, and no perceivable country-rock deformation, apart from uplift of blocks along dyke-exploited joints, can be discerned.

**Megilgarr Rocks**

See main text and Figure 23 for description.

**APPENDIX 2: METHODOLOGY FOR DEVISING MODEL AMPHIBOLE FROM NATURAL COMPOSITIONS**

Amphiboles are defined by the general formula $A_{12}M_{2}X_{10}O_{22}(OH)_{2}$, where $T$ and $M$ to $M$ denote tetrahedral and octahedral sites, respectively. $X$-sites represent sites between the bases of tetrahedral chains that can remain vacant or accept large cations. Two equilibria concerned with the Kenidjack orthoamphiboles are: (1) Edenite substitution, $Si^{4+}A_{1}Na^{+}Al$ (where $’A’$ denotes a site vacancy), which relates anthophyllite, $Mg_{2}Si_{2}O_{5}(OH)_{4}$, to sodic- anthophyllite, $NaMgAlSi_{2}O_{5}(OH)_{4}$; and (2) Tschermak substitution, $Mg_{2}AlSi_{2}O_{8}(OH)_{2}$, which relates anthophyllite to gedrite, $Mg_{2}Al_{2}Si_{2}O_{8}(OH)_{4}$, and gedrite (gedinite) compositions can therefore be described in terms of their edenite (ed) and tschermakite (tsch) coupled-substitution vectors, defined by Schumacher (2007) as $tsch = [Al – Na] / [K + Ca]$. Equation 1 and $Na^{+} + [K + Ca]$, where superscripts “T” and “A” denote tetrahedral- and $A$-sites, respectively, and the element symbols represent cations per formula unit. The equivalent proportion parameters in the Diener et al. (2007) and related models, for use with THERMO-CALC in the simplified system NCFMASHO, are $y(anth) = \frac{1}{2}tsch$, and $y(anth) = \frac{1}{2}tsch$ and $A$ where $Na^{+}$ and the amount of $Al$ involved in tschermak substitution, $TAl$, orthoamphibole compositions can be modeled. Comparisons between natural and model amphibole compositions is not straightforward, as both Na and Al can divide between multiple sites, with Na divided between A and M4 sites, and Al between M2 and tetrahedral sites. Uncertainties in determining $X(Anthony)$ and a(anth) are: (a) the existence of Na and Mg substitutional mechanisms and site allocation strategies. Added to this is the generally unknown oxidation state of Fe. From a calculation of cations per formula unit from a microprobe analysis on the basis of 23 oxygens, tetrahedral Al is most simply derived by subtracting Si cations from 8. However, the uncertainty on Al derived in this way depends on the precision of the Si analysis and will be large at low Al contents. Na(+)K in the A-site is the simplest base, being fixed by the excess over 15 cations per formula unit, and it is uncertain that Na then depends on the precision of the entire analysis and will be large at low Na contents. These sources of uncertainty and bias need to be considered for the Kenidjack amphibole compositions in which both the Na and Al contents are very low, even in relation to the calculated amphiboles at low pressure. Cation totals on the basis of 23 oxygens are lower than required to force all Na onto A sites, and imply a finite amount of glauconaphane substitution, which for almost all analyses is within error of 0.1 atoms of Na p.f.u. in M4 sites. However, under low-pressure conditions, Na is expected to reside in the A site, and the calculated amphibole compositions have <0.02 Na in M4. Allocating some Fe as Fe$^{2+}$, while keeping the oxygen total at 23, lowers the cation totals further, increasing the proportion of Na assigned to M4 sites. However, low cation totals cannot be attributed to systematic underestimation of Si, since Si contents are close to 8 cations p.f.u. and in many analyses give barely sufficient tetrahedral Al to account for an edenite substitution for Na if this is assumed to be dominantly in the A site. In contrast, factors that would cause an overall increase in the cation total, such as the presence of a deprotonation (oxy-) substitution coupled to Fe$^{3+}$ or Ti (cf. in hornblende: Deer et al., 1997, p. 276; Dyar et al., 1993), further decrease the estimated tetrahedral Al content of the natural amphiboles. The possibility exists, therefore, of a systematic analytical bias affecting the relative proportions of the major cations Mg, Fe, and Si.

In consequence, our strategy in comparing the natural to the calculated amphibole compositions is to use the Na and Al contents directly, without an explicit formula recalulation, and to maximize the estimated proportion of edenite by assuming all Na resides on the A site (i.e., $ed = Na$) and that of tschermakite by assuming that all Al not accounted for by Na-edenite is accommodated by the tschermakite substitution (i.e., $tsch = \frac{1}{2}(Al – Na)$). Because both parameters increase with pressure in the model calculations, this should place a maximum pressure constraint on the cation totals in the amphibole.

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