HEAVY-MINERAL ASSEMBLAGES IN SANDSTONE INTRUSIONS: PANOCHE GIANT INJECTION COMPLEX, CALIFORNIA, USA

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ABSTRACT: Excellent exposure from part of the Panoche Giant Injection Complex in the San Joaquin Valley is used to examine provenance characteristics of sandstone intrusions with respect to two parent sandstone units that are known to feed the sand-injection complex. The succession is part of the Upper Mesozoic to Lower Tertiary Great Valley Group, and was deposited in a deepwater part of an evolving deep-water forearc basin. The section examined is mudstone-dominated, and the sand injection is constrained to have occurred in the Danian. Sandstones in the Dosados Member (Moreno Fm) are identified as the main parent unit on the basis of total heavy-mineral-assemblage compositions and varietal studies of selected minerals (tourmaline, garnet, titanite, apatite, and zircon). Fluidized sand is emplaced in turbulent flow conditions creating high-velocity inter-grain collisions. Evidence of comminution and diminution of minerals that are less hard than quartz is documented using indices for the relative hardness (TAH) and durability (TAD) of heavy minerals. Preferential settling of high-density zircon relative to lower-density tourmaline produces density-controlled variations of zircon:tourmaline upward through the injection complex. Heavy-mineral dissolution occurred in the most permeable sandstone intrusions and is believed to record the effects of mid-Eocene deep weathering, when subtropical climate prevailed in the study area. Detrital heavy-mineral assemblages, which are dominated by titanite and garnet, record erosion of the Sierran metamorphic terrane with mafic and alkaline plutonic rocks. Zircon with U/Pb ages of c. 140 to 160 Ma and c. 90 to 110 Ma, consistent with earlier independent analyses, record erosion of Sierran granitoids. On the paleo-

seafloor, enrichment of Ca-amphibole and epidote is indicative of Sierran provenance concurrent with sand extrusion. The presence of Na-amphibole in the Uhalde Sandstone supports earlier work that suggested sediment input from obducted seafloor to the west.

INTRODUCTION

Sandstone dikes, sills, and, more broadly, saucer-shaped intrusions, are commonplace in many sedimentary basins (Hurst and Cartwright 2007), although outcrop of giant sand-injection complexes has received limited attention (Hurst and Cartwright 2007; Hurst et al. 2011). Regionally developed injection complexes form when sand is fluidized and injected following focused hydraulic failure in the very shallow crust (typically shallower than 1.5 km). This requires a period of pore-fluid pressure that locally exceeded the lithostatic gradient, thus forming subhorizontal intrusions, and generally exceeded the fracture gradient of the host strata (Vigorito and Hurst 2010; Hurst et al. 2011). A pervasive turbulent-flow regime is inferred from theoretical considerations, the erosive modification of the fracture system, and the formation of internal structures during sand injection (Duranti 2007; Hurst et al. 2011).

Interest in sand injectites, and more specifically sandstone intrusions, has grown significantly since the oil industry became aware of their significance as reservoirs (Hurst et al. 2005) and as propagators of hydraulic continuity in otherwise low-permeability strata (Hurst et al. 2003). Knowledge grew initially from observations made on core samples (Dixon et al. 1995) and later using correlation between core and seismic-reflection data (Duranti et al. 2002). Sandstone intrusions are recognized as volumetrically significant reservoirs, particularly in deep-water clastic systems, and sometimes constitute entire oil fields (De Boer et al. 2007; Schwab et al. 2015). Deliberate exploration of sandstone intrusions, however, remains in its infancy (Szarawarska et al. 2010).

Heavy mineralogy has successfully supported subsurface correlation in sandstone-intrusion hydrocarbon reservoirs (Poulsen et al. 2007; Morton et al. 2014), by supplementing conventional subsurface data that cannot resolve the multiple or composite intrusions that typify them (Schwab et al. 2015; Hurst et al. 2015). There are, however, no outcrop studies of the heavy mineralogy of regionally-developed sand-injection complexes. Because many applications of heavy mineralogy to lithostratigraphy and provenance are concerned with the subsurface, they necessarily examine borehole data (Hurst and Morton 1985; Morton and Hallsworth 1994; Mange-Rajetzky 1995; Morton and Hurst 1995; Kazerouni et al. 2011; Kilhams et al. 2014; Morton et al. 2014). Such studies avoid the potential effects of post-emplacement weathering, but inevitably limit the examination of spatial variations to 1D borehole sections.

The Panoche Giant Injection Complex (PGIC), located on the northwestern margin of the San Joaquin Valley, California (Figure 1), is a regionally developed complex of sandstone intrusions exposed over an area of approximately 400 km^2 (Vigorito et al., 2008). Sand was injected through more than 1200 m (undecompacted thickness) of predominantly low-permeability mudstone, in which sills, saucer-shaped intrusions, and wings, together with dikes, form a 200 to 250 m-thick, locally sandstone-rich, sill zone (Vigorito and Hurst, 2010). A paleo-seafloor of Danian age consisting of sand extrusions and carbonate seeps forms the top of the PGIC (Schwartz et al. 2003; Vigorito et al. 2008).

The exceptional exposure of the PGIC enables an immutable physical association to be established between parent depositional units and sandstone intrusions. Furthermore, the PGIC affords the opportunity to examine the provenance of sand within an injection complex and to assess the relative contribution to sand injection made by the two potential parent units identified by Vigorito et al. (2008), Vigorito and Hurst (2010), and Vigorito and Hurst (in press). Concurrently, the examination of parent units enables consideration of regional-scale provenance.

Fluidization of sand during injection is dominated by turbulent flow (Duranti 2007; Hurst et al. 2011), during which inter-granular collisions are common (Scott et al. 2009). Hence, the hardness of minerals relative to quartzo-feldspathic minerals (the most abundant constituents of fluidized sand) may affect their durability and persistence. A further variable is the chemical stability of heavy-mineral assemblages, which controls their persistence during burial diagenesis (Morton 1987; Milliken and Mack 1990; Morton and Hallsworth 2007; Walderhaug and Porten 2007). Since similar mineral stability relationships exist during weathering (Morton and Hallsworth 1999), a single source terrane can produce different depositional heavy-mineral assemblages (Hurst and Morton 2001; Hurst and Morton 2014), as previously suggested for the Great Valley area (Allen 1948).

Here, we use the combination of physical and chemical stability of heavy minerals to derive information about the process of sand fluidization and injection, the local provenance of sandstone intrusions, regional provenance of depositional sandstone, and possible pre- and post-depositional stability caused by weathering and/or diagenesis.

GEOLOGICAL SETTING

The sedimentary strata that host the Panoche Giant Injection Complex (PGIC) were deposited in a late Mesozoic forearc basin that is locally up to 12 km thick, and termed the Great Valley Group or Sequence (Figure 1; Bailey et al. 1964; Ingersoll, 1979 1982;). Sandstone in the Great Valley Group (GVG) is predominantly litharenitic, and mudstone is predominantly smectitic with varying amounts of biogenic silica (Ingersoll 1982; Hurst unpublished data). Exposure of the GVG along the western margin of the San Joaquin Basin forms a monocline, and sand injectites, of which the PGIC is best known (Vigorito and Hurst 2010; 2017), are present in several stratigraphic units. The PGIC is emplaced into Upper Cretaceous to Lower Paleocene mudstone-rich units of the upper part of the Panoche Fm (Uhalde Sandstone of Bartow and Nielsen 1990) and the Moreno Fm (Figure 1B, C; Hurst et al. 2007; Vigorito et al. 2008).

A tripartite architecture of (depositional) parent units, an intrusive complex, and an extrusive complex is defined in the PGIC, which comprises depositional sandstone, sandstone intrusions, and sandstone extrusions (Vigorito et al. 2008; Hurst et al. 2011). Within the intrusive complex, there are lower and upper dike zones, between which is a sill zone where most sandstone intrusions occur (Figure 1C and Vigorito and Hurst 2010). This architecture is present throughout the PGIC and probably occurs in varying proportions in other sand injection complexes (Vigorito and Hurst 2010).

Most applications of heavy mineralogy to lithostratigraphic correlation are subsurface studies and typically examine stratiform hydrocarbon-reservoir sandstones that are sampled in boreholes (Hurst and Morton 1988; Mange-Rajetzky 1995; Morton and Hurst 1995; Morton et al. 2010; Kilhams et al. 2014). Sampling of the PGIC was designed to characterize each part of the tripartite architecture so that relationships between the component parts can be evaluated; the sampling frequency is similar to that employed in borehole studies. The non-stratiform discordant character of sandstone intrusions and their intrusive origin present challenges when determining and correlating lithostratigraphic units (DeBoer et al. 2007; Hurst et al. 2015), whereby minerals from older, deeper strata are reworked, fluidized, and emplaced into younger, shallower strata.

This study focuses on Moreno Gulch, the northernmost continuous exposure of the PGIC in the Panoche Hills (Figure 1; Ingersoll 1979; Fig. 3 in Vigorito and Hurst 2010). Almost continuous exposure is present from (depositional) parent units in the upper part of the Uhalde Sandstone upward through the intrusive complex and onto a paleo-seafloor where sand extrudites occur (Figure 2; excursion 1 in Vigorito and Hurst 2017). Genetic relationships between parent units, sandstone intrusions, and sand extrudites can thus be mapped with confidence (Vigorito et al. 2008; Vigorito and Hurst 2010). Because the paleo-seafloor supported cold-carbonate seep communities, the macrofauna allow timing of sand extrusion, and the underlying sand injection is therefore constrained as Danian, 61.7 to 65.5 Ma (Schwartz et al. 2003; Vigorito et al. 2008).

HEAVY MINERALOGY

Twenty-three samples were taken from exposures in Moreno Gulch, three from depositional medium- to coarse-grained sandstones of the Uhalde Sandstone located in the uppermost ~ 1 km of the Panoche Fm. (Bartow and Nilsen, 1990), six from the frequently intensely modified (by sand fluidization) parent units of the fine- to medium-grained Dosados Mbr, eleven from sandstone intrusions (three from sills, three from low-angle dikes, and five from high-angle dikes), and three from sand extrudites (Figure 2B). In the PGIC, sandstone intrusions are predominantly fine- to medium-grained sand, with which the 63 to 125 µm mean-diameter fraction of heavy minerals examined in this study is approximately hydraulically equivalent.

The heavy-mineral assemblages are rich and diverse, with seventeen mineral species recorded (Figure 3; Table 1). However, just five minerals (apatite, garnet, titanite, tourmaline, and zircon) collectively account for 89% (mean of 23 samples) of the assemblages. Andalusite, anatase, epidote, calcic amphibole, rutile, and staurolite together comprise a further ~ 11%. Chrome spinel, chloritoid, diaspore, gahnite (zinc spinel), kyanite, monazite and sodic amphibole (glaucophane and ferroglaucophane proved by electron-microprobe analysis) are distinctive but scarce components.

Apatite, which is notoriously susceptible to dissolution during weathering (Morton, 2012 and references therein; Hurst and Morton, 2013), is present in variable amounts, from 0% to > 10%. Some samples from the Uhalde Sandstone, the Dosados Mbr, and the extrudites contain apatite without evidence of dissolution, and in these cases apatite:tourmaline ratios and apatite geochemical data are considered reliable indicators of provenance. There are major variations in abundance of many other heavy-mineral species between samples (Figure 3): titanite varies from 0 to 71%, zircon from 9 to 83%, garnet from 1 to 29%, tourmaline from 1 to 24%, epidote 0 to 21%, and calcic amphibole from 0 to 25%.

Some parent units, including those in the Dosados Mbr, are intensely deformed by sand fluidization (Vigorito and Hurst 2010) and contain consistently high amounts of titanite and garnet. By contrast, overlying and adjacent sandstone intrusions rarely contain significant amounts of titanite, garnet is less common, and zircon and tourmaline are significantly more abundant. In the extrudites, titanite is abundant, and one sample contains common calcic amphibole, which is rare elsewhere in the PGIC. These striking differences between the heavy-mineral assemblages in sandstone intrusions compared with the parent units from which they were derived and sand extrudites that they fed give the impression that the units may not be genetically related. However, given the demonstrable outcrop evidence that supports genetic relationships between the units (Figure 2; Vigorito et al. 2008), the variations in heavy mineralogy are more likely attributable to processes involved in the emplacement of sand such as hydrodynamic segregation and mechanical comminution during sand fluidization, injection, and extrusion, and/or post-emplacement diagenesis and weathering.

Once emplaced, sandstone intrusions act as preferred conduits for fluid migration (Jenkins, 1930; Hurst et al., 2003), which may enhance cementation (Jonk et al. 2005) and the diagenetic modification of minerals. The relative significance of these processes is considered later, but first we assess whether or not the heavy-mineral data are consistent with outcrop mapping (Vigorito et al. 2008) that suggests a genetic relationship between parent units, sandstone intrusions, and the extrudites.

MINERAL-CHEMICAL CHARACTERISTICS

Because individual mineral groups are less likely to be modified by hydraulic and postdepositional processes than the entire heavy-mineral suite (Mange and Maurer 1992; Morton and Hallsworth 1999), varietal-mineral studies are particularly amenable to the objective comparison of the provenance characteristics of sandstones. Varietal studies were therefore applied to evaluate the possible common provenance of the contrasting heavy-mineral assemblages from selected representative examples from Moreno Gulch. To establish genetic links between parent units in the Uhalde Sandstone and, or, the Dosados Mbr of the Moreno Fm, and sandstone in the intrusive complex and the extrudite complex, parameters that are unlikely to be significantly modified by mechanical abrasion, hydrodynamic segregation or diagenesis are required. To achieve this, we apply major-element compositional analysis of tourmaline and garnet populations by electron microprobe analysis (EMPA), trace-element compositional analysis of titanite, and apatite populations by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS), and U/Pb age determinations of detrital zircon populations by laser-ablation magnetic sector-field inductively coupled plasma mass spectrometry (LA-SF-ICPMS).

Tourmaline

Tourmaline in the PGIC (Figure 4) falls mainly in field F on provenance-discriminant Al-Fe-Mg ternary diagrams (Henry and Guidotti 1985). Field F comprises Fe^{3+}-rich quartz-tourmaline rocks (such as skarns) together with calc-silicates and metapelites. Subsidiary amounts of tourmaline fall in field E (Al-poor metasediment) and field D (Al-rich metasediment). Granitic tourmaline (field B) is scarce. By plotting the relative proportions of tourmaline from fields D, E, and F (Figure 4) we show that the intensely remobilized depositional sandstone of the Dosados Mbr has tourmaline populations very similar to those of the sandstone in the intrusive and extrudite complexes. Depositional sandstone in the Uhalde Sandstone has higher proportions of field D tourmaline (Al-rich metasedimentary origin). From the similarity of tourmaline compositions from the intrusive and extrudite complexes with those from depositional sandstone in the Dosados Mbr, we infer the latter to be the main parent unit. Tourmaline from the Uhalde Sandstone is less similar, indicating that the Uhalde Sandstone is less likely to have contributed significant sand to the sandstone intrusions.

Garnet

Two distinct groups are present in the garnet populations, one comprising andradite-grossular (high-Ca, low-Mg) compositions and the other comprising spessartine-rich (high-Mn, low-Ca types) that plot near the Fe+Mn pole (Figure 5). Using the terminology of Mange and Morton (2007), these groups correspond to types D and Bi respectively. Garnet assemblages in the Dosados Mbr, the intrusive complex, and the extrudites are closely comparable (Figure 6), with the

Type D component constituting 84 to 94% of the populations. The similarity between the garnet assemblages in these samples supports a common provenance. The Uhalde Sandstone contains fewer Type D garnets (76 to 78%), suggesting that the Uhalde Sandstone is less likely to have contributed significant sand to remobilization during sand injection, supporting the evidence from the tourmaline data. Sample MG05-CC from within the intrusive complex has significantly fewer Type D garnets than other samples from the intrusive complex. The reason for this anomaly is discussed later in the text.

Titanite

Trace-element and rare-earth-element data were acquired from titanite populations in sandstones of possible parent units (Uhalde Sandstone and Dosados Mbr), the intrusive complex, and the extrusive complex. The four populations are closely comparable; all titanites are enriched in light rare earth elements (La, Ce, Pr) and have relatively low Y concentrations (Figure 7). By comparison with data presented by Fleischer (1978), most of the titanites have compositions that correspond to alkaline or mafic-intermediate sources, with comparatively little input from granitoids. The similarity of titanites in all samples indicates that sandstones in both the Uhalde Sandstone and the Dosados Mbr could have been the parent units for the overlying intrusive and extrudite complexes.

Apatite

Apatite compositions reflect the composition of their sources (Fleischer and Altschuler 1986; Belousova et al. 2002) and are excellent provenance indicators (Morton and Yaxley 2007). However, because of the susceptibility of apatite to dissolution in pre- and post-depositional weathering environments, it is not always preserved. In the PGIC, apatite is generally scarce (Figure 3), but was recovered and analyzed from three samples: one each from the Uhalde Sandstone, the Dosados Mbr, and the extrusive complex. Consistent with the evidence from the detrital titanite, most of the apatite has compositions that suggest derivation from alkaline and mafic or intermediate sources (Figure 8). There are differences in relative contributions from alkaline and mafic/intermediate sources, with the Uhalde Sandstone sample having significantly fewer apatites of alkaline origin (42%) compared with the Dosados Mbr (67%) and the extrusive complex (75%). These data are consistent with the interpretation that the Dosados Mbr was remobilized to generate the sand extrudites, and implying a similar relationship with sandstone in the intrusive complex. On the basis of the apatite data, the Uhalde Sandstone appears to be a less likely source of sand for the intrusive complex, consistent with the tourmaline and garnet data.

Zircon

Zircon age spectra from all samples almost exclusively comprise grains younger than 200 Ma (Figure 9). All samples have bimodal populations with a main group peaking at ~ 90 to 110 Ma and a subsidiary group peaking at ~ 140 to 160 Ma.

The youngest zircon ages in the four samples are closely comparable, 80 Ma in the Uhalde Sandstone, 77 Ma in the Dosados Mbr, 80 Ma in the intrusive complex, and 77 Ma in the extrudite complex. Similar age spectra in sandstone from the Dosados Mbr and the Uhalde Sandstone preclude differentiation between their local provenances but demonstrate that they were originally derived from similar source terranes.

PROCESSES CONTROLLING VARIATIONS IN PGIC HEAVY-MINERAL ASSEMBLAGES

Extensive outcrop data demonstrate that the parent units for the PGIC occur in the uppermost few hundred meters of the Uhalde Sandstone and in the lower part of the Dosados Mbr. Sandstone dikes emanate from, connect and crosscut depositional parent units, and demonstrate the physical continuity between parent units and the overlying intrusive complex (Vigorito et al., 2008; Vigorito and Hurst 2010; Vigorito and Hurst 2017). Outcrop data do not provide unequivocal evidence of the precise origin of the injected sand, since significant quantities of sand could be derived from either the Uhalde Sandstone, the Dosados Member, or both. On the basis of varietal data from tourmaline, garnet, and apatite, Dosados Mbr sandstone is the more likely parent unit for sandstone in the intrusive complex, whereas the Uhalde Sandstone was less significant. Distribution of sodic amphibole is also consistent with the interpretation of the varietal data, as it is present consistently in the Uhalde Sandstone samples but has sporadic presence elsewhere (one Dosados Mbr sample and five of the fourteen intrusive and extrudite samples). We conclude that differences in heavy mineralogy between the Uhalde Sandstone and the Dosados Mbr sandstones reflect minor changes in provenance, which allow us assign the Dosados Mbr sandstone as the main parent unit for the intrusive complex and extrudites.

The consistent trends recorded from the varietal minerals, tourmaline, garnet, and apatite, contrast with the major differences in heavy-mineral assemblages between the parent units, the intrusive complex, and the extrudites (Fig. 3). Heavy-mineral assemblages vary because of (i) hydrodynamic fractionation; (ii) mechanical breakdown, (iii) postdepositional diagenetic modification, and (iv) postdepositional weathering. These factors are discussed below.

Hydrodynamic Fractionation

The hydrodynamic behavior of heavy minerals is controlled mainly by grain size and density, with grain shape potentially important (Komar, 2007; Garzanti et al., 2008). During the fluidization and injection of sand, structures such as flow banding and laminae form (Scott et al., 2009), and may cause the selective concentration of heavy minerals (Kazerouni et al., 2011). In this study, the influence of grain size on the interpretation of heavy mineralogy is reduced by analysis of a single size fraction (63 to 125 µm mean diameter) and by comparing ratios of heavy minerals with contrasting density within this size range

(Table 2). One can thus evaluate the effects of hydrodynamic fractionation. In this context the zircon:tourmaline index (ZTi) is particularly useful because both are ultrastable during weathering and diagenesis (Morton and Hallsworth 1999) but lie at the opposite ends of the density range in heavy-mineral assemblages (zircon 4.6 to 4.7 g cm^{-3}, tourmaline 3.06 g cm^{-3}).

Outcrop mapping supported by heavy mineralogy demonstrates that depositional sandstone in the Dosados Mbr was intensely deformed during a single episode of sand fluidization and acted as the parent for the overlying sandstone intrusions and extrudites (Vigorito et al. 2008; Vigorito and Hurst 2010). Thus, it is reasonable to expect that in the absence of hydrodynamic fractionation, ZTi values similar to those in the parent units would pervade into the overlying sandstone intrusions and extrusions. This is not the case. A gradual ZTi increase upward in the intrusive complex, with highest values in the shallowest high-angle dikes, records an enrichment of zircon relative to tourmaline (Figure 10). Similar high ZTi values are retained in the extrudites. This trend is interpreted as recording density segregation and sedimentation of the denser zircon relative to tourmaline as the fluidized sand moved upward through the fracture system that hosts the sandstone intrusions.

During sand injection the highest pore-fluid pressure relative to the hydrostatic gradient occurred at the lithostatic equilibrium surface (LES, Vigorito and Hurst 2010), at the base of the Sill Zone (Figure 1C). Above this, the main focus of hydraulic fracturing of the host mudstone strata occurred, supra-lithostatic pore-fluid pressure was exceeded, sandstone dikes are short, have irregular geometry and are randomly oriented, and there is abundant evidence for rapid emplacement of sand in turbulent flows (Vigorito and Hurst 2010; Hurst et al., 2011). Increased zircon relative to tourmaline is a record of the fluidized sand being increasingly unable to sustain the transport of zircon relative to tourmaline in the upper part of the intrusive complex, where close-to-vertical dikes predominate. This behavior of zircon relative to tourmaline is indicative of lower buoyancy in the upper dike zone relative to the sill zone and implies that pore-fluid pressure decreased toward the paleo-seafloor during sand injection. The difference in ZTi between the Uhalde Sandstone and the Dosados Mbr is a function of a slight change in provenance, with some possible modification caused by changes in hydraulic conditions during deposition, as suggested by their different grain sizes.

Other differences in heavy mineralogy, for example the extreme depletion of titanite in sandstone intrusions compared with the parent units and extrudites, cannot be ascribed to hydrodynamic fractionation. Since titanite has a density of 3.5 g cm^{-3}, intermediate between the density of tourmaline and zircon, it will inevitably be less profoundly affected by hydrodynamic processes compared with the proportion of tourmaline relative to zircon. Furthermore, had hydrodynamic fractionation caused the extreme depletion of titanite, it would be difficult to explain how the mineral reappears in such abundance in the extrudites, which were derived from the underlying intrusive complex.

Mechanical Stability

Mechanical stability is evaluated using two previously untested parameters termed total assemblage hardness (TAH) and total assemblage durability (TAD). Mineral hardness is measured in controlled experimental conditions and records the force at which a single grain fractures under uniaxial force. TAH is determined by assigning a hardness value for all minerals present, multiplying this by the percentage abundance of each mineral, and summing the values to give a measure of the overall hardness of the assemblage; high TAH values indicate enrichment of the hardest heavy minerals. Hardness values are taken from the Mohs hardness scale (from Deer et al., 1992) with midpoint values used where a range is given. Mineral durability describes the resistance of grains to mechanical degradation during transport. TAD is determined by assigning an arbitrary number to each mineral dependent upon its position in the relative stability scheme of Thiel (1940, 1945): 1 for kyanite (least stable) and 10 for tourmaline (most stable). Several minor minerals (anatase, andalusite, chrome spinel, monazite, and sodic amphibole), which in total make up < 7% of the assemblages, were not included in the study by Thiel (1940, 1945); therefore, the relative proportions of the remaining minerals were recalculated to 100% excluding these minor minerals.

Parent units in the Uhalde Sandstone and the Dosados Mbr have uniform TAH with a mean value of 692 (range 699 to 706) (Figure 10). Sills and low-angle dikes have a combined mean of 700 (range 696 to 711). High-angle dikes have the highest TAH values with a mean of 713 (range 704 to 717). Extrudite samples have TAH virtually identical to the parent units (mean = 690, range 664 to 703). The distinctly lower TAH (664) in one extrudite sample is due to the abundance of calcic amphibole. The slightly higher and variable TAH values within the intrusive complex could be regarded as evidence that fluidization and injection of sand causes preferential loss of less mechanically stable grains. Titanite, which is the only major heavy mineral in the PGIC that is significantly less hard than quartz and feldspar (Figure 11), is abundant in parent units but is scarce or absent in the intrusive complex (Figure 10). The depletion of titanite is therefore the main factor behind the increase in TAH in the intrusive complex. Titanite is, however, chemically unstable, and the depletion in titanite and consequent high TAH in the intrusive complex could be a function of titanite dissolution, rather than mechanical modification of the assemblage. Furthermore, if titanite depletion is due to mechanical processes, it is difficult to explain how it reappears in abundance in the extrudites.

Heavy-mineral durability produces a surprising trend with sandstone intrusions containing the lowest TAD values in the PGIC (Figure 10). This indicates that the proportion of durable minerals in the intrusive complex is lower relative to the parent units and extrudites. This pattern is strongly influenced by the abundance of titanite, which is the most abundant heavy mineral in the depositional sandstones (Figure 3) but is scarce in the sandstone intrusions. In studies of heavy-mineral durability (Friese, 1931; Thiel 1940, 1945), titanite was determined to be one of the heavy minerals most resistant to mechanical abrasion. As discussed above, it is difficult to argue for mechanical loss of titanite in the injection complex since the mineral reappears in abundance in the extrudites.

Borehole samples from the Clair oil field (west of Shetland, UK) revealed that the apatite:tourmaline index (ATi) is reduced by mechanical processes because of the relatively low durability of apatite (Morton, 2012). Extrudites have lower ATi than the Dosados Mbr parent units (26 to 48, compared with 45 to 59 in samples that have not been affected by weathering; Table 2, Figure 10). The reduced apatite relative to tourmaline in the extrudites is therefore attributed to mechanical depletion in the intrusive complex, since other factors such as hydrodynamics, diagenesis and weathering can be excluded.

Chemical Stability (Burial Diagenesis and Weathering)

Three indices are used to evaluate the overall stability of the heavy mineralogy: the zircon tourmaline rutile (ZTR) maturity index (Hubert 1962; Table 2), the total assemblage stability during diagenesis (TAS_D), and the total assemblage stability during weathering (TAS_W). TAS_D and TAS_W are newly introduced indices determined by assigning a relative-stability value to each heavy mineral, multiplying this by the abundance of each mineral in the sample, and summing the values to give a measure of the overall stability of the assemblage (Table 2). For TAS_D, stability values are assigned according to the relative-stability pattern for heavy minerals during burial diagenesis (Morton and Hallsworth 2007). Minerals that do not undergo burial-related dissolution (zircon, rutile, tourmaline, anatase, monazite, and chrome spinel) are assigned high stability values (8), and minerals with low stability, such as calcic amphibole, are assigned low values (1). Accordingly, assemblages containing large proportions of stable minerals have high TAS_D values, whereas those containing abundant unstable minerals have low TAS_D. TAS_W is calculated in the same way, using a generalized order of stability for heavy minerals during weathering (Morton 2012).

ZTR, TAS_D, and TAS_W show that the intrusive complex contains much higher abundances of stable minerals than the parent units and the extrudites (Figure 10). ZTR is slightly higher in the high-angle dikes compared with the sills and low-angle dikes, which is largely because the sills and low-angle dikes tend to contain more garnet (higher GZi) than the high-angle dikes (Figure 10). SEM images confirm that titanite and garnet in sandstone intrusions are considerably more corroded than in parent units (Figure 12). We infer that the sandstone intrusions, especially high-angle dikes, have undergone significantly greater dissolution and ultimately removal of unstable minerals, most notably apatite and titanite, but also epidote and garnet, when compared with the parent units and extrudites.

A direct relationship exists between stability of the heavy-mineral assemblages and mean porosity and permeability (Figure 13), which show that sandstones with higher porosity and permeability underwent the greatest amount of heavy-mineral dissolution, a phenomenon that is long established when comparing cemented and uncemented depositional sandstone (Bramlette 1941) or sandstone and adjacent mudstone (Blatt and Sutherland 1966). High porosity and permeability, and high TAS_D and TAS_W are characteristic of the sandstone intrusions, whereas the extrudites have low values. Parent units in the Dosados Mbr have intermediate porosity and permeability, and the underlying Uhalde Sandstone has the lowest porosity and permeability but slightly higher TAS_D.

Persistence of fully expandable smectite in adjacent mudstone (Hurst unpublished data) implies that burial diagenetic temperatures never exceeded 60° C (Nadeau 2011); the presence of opal-A and -CT in the biosiliceous Marca Mbr may indicate an even lower thermal maximum (~ 40° C). Thus, all mineral dissolution occurred at low diagenetic temperatures. The relationship between sandstone porosity, permeability and mineral dissolution suggests that fluid flux is the significant mechanism that determined mineral stability.

DISCUSSION

Fluidization and Mineral Modification

When sand is fluidized and injected turbulent flow is implicated, the fluid velocity is significantly in excess of minimum fluidization velocities, estimated at 0.1 to 0.7 m s^{-1}, and likely in excess of 1 m s^{-1} (Duranti and Hurst 2004; Duranti 2007; Hurst et al. 2011). While flowing, the fluidized sand constitutes a fluid column in the complex geometry of a fracture network that forms a permeable conduit in a matrix of predominantly low-permeability compacting mud and mudstone. In the case of the PGIC, the fluid column in which most of the heavy minerals were transported is up to ~ 700 m high (from near the base of the Dosados Mbr) and continues for at least a further ~ 500 m into the Panoche Fm (Vigorito and Hurst 2010).

Hydrodynamic fractionation of individual heavy minerals concentrated denser grains relative to less dense grains, and preferential comminution of less hard grains changed their relative abundance. Comminution of heavy-mineral grains is significant during sand fluidization and injection because of flow turbulence (Reynolds numbers from 1×10^3 to 3×10^5, Allen 1985), during which high-velocity intergranular collisions damage or disintegrate grains. For example, microfracturing of quartz is typical of sandstone intrusions (Scott et al. 2009). Because heavy minerals form a very small fraction of sand, their persistence is significant only in terms of hardness and durability relative to the major granular components present, which in the case of the study area consist of quartz, feldspar, and lithic grains (Ingersoll 1982; Scott et al. 2013). Although apatite, titanite, and andradite-grossular are similarly less hard than quartz (Figure 11), we only have direct evidence that apatite was depleted by mechanical processes during sand injection, owing to the subsequent partial or total dissolution of titanite and andradite-grossular. Hence, although we might expect concurrent diminution of titanite and andradite-grossular by abrasion, we can hypothesize only that it may have happened. Because quartz is hard relative to many heavy minerals (Figure 11), the abrasive effect of the quartz content of a fluidized sand directly influences heavy=mineral durability.

Disaggregation and abrasion are not known to significantly affect heavy-mineral assemblages in depositional systems, even along extremely long transport pathways (Garzanti et al. 2012). Flows with similarly high Reynolds numbers to fluidized injected sand are unusual in sedimentary environments but other possible candidates for high levels of mechanical abrasion capable of modifying heavy-mineral assemblages, and producing microfractured quartz, may occur in subglacial tunnels or aeolian sand storms. Documentation of experimental mineral durability is sparse (Friese 1931; Thiel 1940, 1945; Dietz 1973), and the effects are undocumented from fluidized sand. Although cleavage is widely known to compromise the durability of kyanite, relationships between the hardness (Mohs scale) and the durability of other minerals, particularly with respect to cleavage, is undocumented.

Post-Emplacement Modification

Dissolution of heavy minerals in sandstone is caused either during burial (Morton and Hallsworth 2007; Walderhaug and Porten 2007) or by near-to-surface alteration in meteoric water (Morton 2012). Evidence of mineral dissolution is clear in the intrusive complex, which, although derived from Dosados Mbr sandstone, has significantly lower proportions of low-chemical-stability grains (higher TAS_D, TAS_W, and ZTR, Figure 10). Burial diagenetic temperature is discounted as a significant cause of mineral dissolution because of the low-temperature burial history of the strata (< 60° C), and thus the fluid flux of either connate or meteoric fluids controlled mineral stability. Furthermore, the evidence for apatite depletion in the intrusive complex rules out burial-related dissolution, since apatite is stable under such circumstances but is highly unstable during weathering (Morton and Hallsworth 1999; Morton 2012).

Sandstone intrusions create permeable conduits through otherwise low-permeability strata and thereby focus the upward drainage of connate fluids from adjacent compacting fine-grained strata (Hurst et al. 2003). Because strata in the Great Valley Group are largely marine (Ingersoll 1982), the connate fluids are unlikely to have caused significant heavy-mineral dissolution. When exposed or close to Earth's surface, the same system of permeable conduits facilitates seepage of meteoric water into the injection complex, thereby promoting dissolution of unstable minerals (amphibole, apatite, epidote, and titanite) in the intrusive complex relative to the parent units (Figures 3 and 12). Because the permeability and porosity of the sandstone intrusions are significantly higher than that of the parent units and sand extrudites (Figure 13), meteoric-water influx enhanced their weathering relative to the other sandstones.

Introduction of the measurements of total assemblage stability TAS_D and TAS_W supplements the ZTR index (Hubert 1962), because they utilize all available mineral-stability data from the heavy-mineral assemblage. This gives greater insight when establishing the overall chemical stability of the assemblage compared to ZTR, which measures only the frequency (%) of zircon, tourmaline, and rutile. TAS_D and TAS_W are less sensitive to changes caused by sudden, possibly anomalous, perturbations of the content of zircon, tourmaline, or rutile, for example due to hydrodynamic fractionation. Improved understanding of relationships between burial temperature and dissolution of specific minerals will further enhance the value of the TAS_D index. Mineral dissolution clearly had a major influence on determining the present-day mineral abundances and the associated mineral textures in this study (Figure 13) and will apply equally well to minerals undergoing diagenetic dissolution. The extrudites do not share the heavy-mineral dissolution characteristics of the sandstone intrusions; an intermediate level of modification by dissolution is preserved. Although heavy minerals in the extrudites were derived from the underlying intrusive system, the early (seafloor) carbonate cementation (Schwartz et al., 2003) prevented significant mineral dissolution related to influx of meteoric water.

Andradite-grossular (Ca-rich) garnets are potentially less durable than other garnets since they are less hard (Figure 11). As they undergo abrasion, finer-grade particles (higher ratios of surface area to mass) will be introduced, and this will increase their overall rate of dissolution. Ca-rich (andradite-grossular) garnets are known to be less stable than Ca-poor varieties during burial diagenesis (Morton 1987; Smale and van der Lingen 1989; Milliken and Mack 1990; Morton and Hallsworth 2007) and a similar pattern is observed in the PGIC where sandstones with low GZi (Figure 10) have lower contents of Type D (andradite-grossular) garnet compared with Type B (almandine-spessartine) garnet (Figure 5). An extreme manifestation of this is sample MG05-CC, which has the lowest GZi (5.2) of all samples with garnet geochemical data, and also has markedly lower abundances of Type D garnet (Figures 5 and 6). The relative stability of Ca-rich and Ca-poor garnets during weathering is not well documented, but the evidence from the PGIC suggests a pattern similar to that established during diagenesis.

Andradite-grossular garnets are comparatively rare detrital components of sandstone, and hence their stability in sedimentary systems is rarely evaluated. In the PGIC, there appears to be a relationship between GZi and the Fe/Ca ratios in the andradite-grossular component (Figure 6), with lower GZi values associated with lower Fe/Ca. This relationship suggests that in the andradite-grossular group, garnet stability is controlled by the Fe^{3+} content, with Ca-rich garnets more stable than Fe^{3+}-rich types. Although this inference requires verification, the data offer new information on the relative stability of detrital-garnet compositions during weathering.

At least three regionally significant periods of tectonically controlled unconformity occurred following formation of the sand-injection complex in the Danian, which kept older strata close to the Earth’s surface (Johnson and Graham 2007). During the middle Eocene a warm, moist, subtropical climate prevailed in the Great Valley, and in the neighboring paleo Sierra Nevadan mountains deep weathering occurred. Kaolinitic regoliths formed and were eroded (Mulch et al. 2006; Mix et al. 2016) and the quartzose Domengine Sandstone was deposited along the paleo-shoreline (Todd and Monroe 1968; Sullivan and Sullivan 2012). In combination, the Moreno Fm and PGIC were kept close to Earth’s surface and were susceptible to ingress of meteoric water during the middle Eocene.

Provenance

Two aspects of provenance are significant in the context of the PGIC: the origin of the sand injected into the intrusive complex and the character of the source terrane from which depositional sandstone was derived, including that which was injected. The first of these is the main focus of this study because relationships between parent unit and intrusive complex have never before been constrained. Typically they are inferred where outcrop is discontinuous (Scott et al. 2009) or where features mapped on seismic data may allow strong inferences to be made (Huuse et al. 2005; Wild and Briedis 2010; Jackson et al. 2011).

Origin of injected sand From outcrop mapping, two depositional parent units, the Uhalde Sandstone (Panoche Fm) and the Dosados Member (Moreno Fm), are known to have provided sand to the PGIC, as both feed into dikes and are connected to the PGIC (Figure 1C; Vigorito and Hurst 2010; Vigorito and Hurst 2017). Which of these units is the main source of sand injected into PGIC cannot be differentiated using granular characteristics or thin section petrography. Dosados Mbr sandstone and the overlying sandstone intrusions have very similar varietal data compositions, specifically from garnet, tourmaline, and apatite (Figures 4, 5, 6, and 8) and a common provenance is assigned. In the Uhalde Sandstone, garnet, tourmaline, and apatite compositions are less similar, and thus the Uhalde Sandstone does not appear to have a quantitatively significant presence in the PGIC. The huge Panoche Fm aquifer was almost certainly the main source of aqueous fluid that fluidized and mobilized sand in the Dosados Mbr (Vigorito and Hurst 2010).

The upper part of the Dosados Mbr, which co-hosts the intrusive complex with the Tierra Loma Mbr (Vigorito et al. 2008), is confirmed as the main parent unit for the PGIC. Similar spatial relationships were constrained using heavy mineralogy in the Eocene of the Greater Forties area, North Sea, where thin laterally discontinuous sandstones immediately below the sandstone intrusions were identified as the parent units rather than the thick and deeper Paleocene Forties Fm (Morton et al. 2014). Interpretation of 3D seismic data led to similar parent-intrusion relationships (Huuse et al. 2005; Jackson et al. 2011) but were unconstrained with respect to provenance.

Provenance of source terrane Paleo-Sierra Nevada and Klamath terranes are the predominant source for the litharenitic coarse-clastic sediment in the Great Valley Group (GVG; Ingersoll 1982). Our zircon U/Pb data identify two phases of granitoid intrusion, c. 140 to 160 Ma (mid-Jurassic to earliest Cretaceous) and c. 90 to 110 Ma (mid-Cretaceous) (Figure 9). These correspond to ages of plutonic events in both in the central (Cecil et al. 2010) and the northern (Cecil et al. 2012) areas of the Sierra Nevada Batholith, and are similar to zircon U/Pb data from GVG outcrops of similar age and older Cretaceous strata elsewhere in the San Joaquin Valley (DeGraaff-Surpless et al. 2002; Sharman et al. 2015). Quartz dioritic, granodioritic, and tonalitic affinities with largely metaluminous compositions represent the great majority of the plutonic rocks in the Sierra Nevada Batholith (Bateman 1992; Cecil et al. 2012), which are ideal candidates as a source for zircon. The scarcity of pre-Mesozoic zircons in the PGIC suggests that there was little recycling of zircon from pre-existing sediment and metasediment, which contain a wide range of mid-Proterozoic to Archean zircons (see compilation by Cecil et al., 2010), despite their relatively widespread distribution along the western margin of the Sierra Nevada Batholith.

In the depositional sandstone of the Uhalde Sandstone and the Dosados Member, zircon is not abundant, and is subordinate to titanite and garnet (Figure

3). Most components of the heavy-mineral assemblage support a predominance of nongranitic source terrane. The bimodal garnet population comprises an andradite-grossular group together with a group of Fe+Mn-rich (almandine-spessartine) garnets (Figure 5). The latter can be reconciled with a granitic origin (Mange and Morton 2007) but the andradite-grossulars suggest erosion of skarns. Skarns are documented from the Sierra Nevada and are known to contain ugrandite garnets (Kerrick 1977) that are comparable with the andradite-grossular in the PGIC.

Tourmaline is dominated by Type F (*sensu* Henry and Guidotti 1985), which may be associated with skarns, but Types D and E are also common (Figure 6) and are typically derived from metasediments (Henry and Guidotti 1985). Tourmaline from Li-rich and Li-poor granitoids is very scarce.

Mineral-chemical data from titanite (Figure 7) and apatite (Figure 8) indicate that mafic and/or alkaline rocks were their main sources, with only minor input from granitoids. Quite probably titanite and apatite were eroded from pre-Cretaceous plutons in the Sierra Nevada, which are more heterogeneous than the more silicic mid-Cretaceous plutons and include both mafic and alkaline compositions (Miller 1978; Bateman 1992).

Ca-amphibole, epidote, and Na-amphibole, all of which have significance with respect to provenance, are preserved with varying abundance in depositional sandstone and the sand extrudite but are scarce in the intrusive complex (Figure 3). In the uppermost sand-extrudite sample (MG05-B, Table 1), Ca-amphibole (> 25%) and epidote (> 20%) are the second and third most common heavy minerals behind titanite (> 32%); Ca-amphibole is very scarce in all other samples. This marked change to an assemblage with large proportions of these chemically and mechanically unstable minerals is indicative of an input of depositional sand concurrent with sand extrusion, with a provenance different from that of the Uhalde Sandstone or Moreno Formation. Although Sierra Nevadan plutonic rocks contain Ca-amphibole (Bateman 1992), the substantial change in abundance of this mineral, along with epidote, is indicative of a change in source terrane relative to the other samples. Their presence in a single extrudite sample may be due to preferential preservation, but given their rarity in older depositional sandstone this seems unlikely.

The trace amounts of Na-amphibole (glaucophane) in the Uhalde Sandstone suggest a sediment contribution from blueschist, which is not readily reconciled with Sierra Nevada provenance. Ophiolite in the poorly exposed Smartville terrane (northern Sierras) may be a possible eastern source of Na-amphibole, but its presence there is unknown (W.G. Ernst and J. Liou, personal communication 2015). A westward derivation from erosion of obducted oceanfloor is favored, and is consistent with evidence from 3D seismic-reflection data from the northern part of the San Joaquin Valley (Mitchell et al. 2010), which provides independent evidence of emergence and erosion of the Franciscan subduction complex during the Mesozoic.

Although detrital-zircon U/Pb ages are related to the erosion of granitoid batholiths in the Sierras (DeGraaff-Surpless et al. 2002; Sharman et al. 2015), they fail to differentiate between sandstone from the Uhalde Sandstone (Panoche Fm) and the Dosados Mbr (Moreno Fm) (Figure 9). In contrast, tourmaline, garnet, and apatite differentiate the lithostratigraphic units (Figures 4, 5, 6, and 8) and contribute substantially to enhancing the understanding of Sierran provenance by identifying several predominantly metamorphic source terranes and pre-Cretaceous intrusives.

Our study is from a single canyon in the Upper Cretaceous to Lower Paleocene section of the Great Valley Group (GVG), and uses a sampling density similar to that used in subsurface lithostratigraphic studies (Hurst and Morton 1988; Mange-Rajetzky 1995; Morton and Hurst 1995; Morton et al. 2010; Hurst and Morton 2014). Reconstruction of source area lithology, geochronology, and source-to-sink relationships generally cannot be achieved using a single provenance technique, and here we demonstrate the success of an approach that integrates results from a number of different but complementary techniques.

CONCLUSIONS

Heavy mineralogy, and specifically varietal data, are demonstrated as robust lithostratigraphic tools that identify the spatial relationships between parent units and intrusive complexes. Varietal data allow the potentially confusing effects of post-intrusional mineral dissolution to be reconciled, and provide insights into heavy-mineral modification during injection and source terrane provenance. The excellent exposure of the PGIC, where physical relationships between parent units and sandstone intrusions are visible, allows confident application of these methods to situations with limited exposure, particularly the subsurface.

Sandstone in parent units, the intrusive complex, and sand extrudites are differentiated by their heavy-mineral assemblages. Varietal analysis of tourmaline, garnet, and apatite compositions identify sandstone in the Dosados Mbr as the main parent unit for sandstone intrusions in the PGIC. Hydraulic sorting causes ratios of ultrastable zircon and tourmaline (ZTi) to increase upward in the injection complex as the denser zircon settles preferentially. Mechanical depletion modified the parent heavy-mineral assemblages during sand injection, with titanite, apatite, and Ca-garnet (andradite-grossular) having marked diminution upward caused in part by their low durability relative to quartz. Differences in mineral durability are accentuated in turbulent flow because of common interparticle collisions. New indices to quantify total-assemblage hardness (TAH) and total-assemblage durability (TAD) are successfully deployed. Post-emplacement leaching of the more soluble heavy minerals was analyzed using the total-assemblage stability during diagenesis (TAS_D) and total-assemblage stability during weathering (TAS_W), which supplement the ZTR index as a measure of heavy-mineral chemical stability. Mineral dissolution was caused almost entirely by weathering, and was most pronounced in the most permeable sandstone. The weathering is inferred to have occurred during the middle Eocene when a subtropical climate prevailed in the Great Valley. Leached sandstone in the intrusive complex has resistate-mineral assemblages dominated by zircon and tourmaline.

A common Sierran provenance with zircon U/Pb dates of c. 140 to 160 Ma (mid-Jurassic to earliest Cretaceous) and c. 90 to 110 Ma (mid-Cretaceous) is confirmed for depositional sandstone in the Panoche and Moreno formations. Zircon is a subordinate depositional mineral relative to titanite and garnet, which together with the other heavy minerals record derivation from Sierran metamorphic terrane and, mafic and alkaline plutonic rocks. Additional provenance indications are identified in the sand extrudite (Danian) on the basis of a sudden influx of volumetrically significant Ca-amphibole and epidote. Although consistent with Sierran provenance, the abundances of Ca-amphibole and epidote are far greater than in the parent units, and demonstrate that, at least in part, the sand extrusions have a depositional origin. Traces of blueschist-sourced Na-amphibole in the Uhalde Sandstone are indicative of minor westward derivation of sand from obducted ocean floor.

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FIGURE CAPTIONS

Fig. 1. A) Geological setting of the Great Valley Group. B) Outcrop of the Moreno and Panoche formations with the sampling area, Moreno Gulch marked. C) Lithostratigraphy of the Panoche Giant Injection Complex (PGIC) and the host strata from the Panoche and Moreno formations in the Moreno Gulch area (Vigorito et al. 2008). Upper and Lower Dike Zones and Sill Zone are as defined in Vigorito and Hurst (2010). LES is the lithostatic equilibrium surface (Vigorito and Hurst 2010).

Fig. 2. A) View ~ northeast along Moreno Gulch taken from the location of parent sandstone units (approximately at the site of samples MG05- T,U,V) showing a sill complex of stepped and saucer-shaped sills with erosional upper margins. Strata dip into the field of view, and a bedding surface (broken yellow line) illustrates bedding discordance of adjacent intrusions. Sample MG05-Z was taken from the thickest (~ 8 m) sill in the foreground. A swarm of nearly vertical dikes (right area of view) that thin and bifurcate upward toward the paleo-seafloor (not visible) form the lateral (southern) margin of the sill complex. B) Location of samples shown in Tables 1 and 2. Strata dip at ~ 30° to the northeast: thus, strata are younger from left to right. Image from Google Earth.

Fig. 3. Variations in modal heavy-mineral contents in the Panoche Fm, Dosados Mbr, the intrusive complex and the extrudite complex of the PGIC.

Fig. 4. Tourmaline populations from the PGIC plotted on Al-Mg-Fe provenance-discriminant ternary diagrams devised by Henry and Guidotti (1985). Lower ternary diagram compares the relative abundances of tourmalines falling into fields D, E and F within the sample set. Tourmaline geochemical data were acquired using a Link Systems AN10000 energy-dispersive X-ray analyzer attached to a Cambridge Instruments Microscan V electron microprobe at the University of Aberdeen.

Fig. 5. Garnet populations from the PGIC plotted on Fe^{2+}+Mn-Ca-Mg ternary diagrams with all Fe calculated as Fe^{2+}. Garnet geochemical data were acquired using a Link

Systems AN10000 energy-dispersive X-ray analyzer attached to a Cambridge Instruments Microscan V electron microprobe at the University Aberdeen, UK. ●, $X_{Mn} < 5\%$, ○, $X_{Mn} > 5\%$, ▲, Fe/Al > 0.1.

Fig. 6. Comparison of garnet populations in the PGIC. Upper plot shows relationships between abundance of Type D garnet and GZi (garnet:zircon index). Lower plot compares GZi with Fe/Ca ratios of garnets in the Type D group (i.e., excluding the Type B component).

Fig. 7. Titanite compositions in sandstones (open circles) from the PGIC plotted on the La+Ce+Pr vs Y/(Y + total rare earth elements) diagram devised by Fleischer (1978). Also shown are average compositions of titanites from alkaline pegmatites, alkaline rocks (including syenites), basic rocks (gabbros and pyroxenites), granodiorites (including diorites, monzonites and adamellites), granites, granitic pegmatites, and gneisses and migmatites (from Fleischer, 1978). Titanite compositions were acquired by LA-ICPMS at Cardiff University, UK.

Fig. 8. Rare-earth-element compositions of detrital apatites in sandstones from the PGIC. Fields of acidic, mafic to intermediate, and alkaline apatites are taken from Fleischer and Altschuler (1986). Bar chart shows relative abundances of apatites falling into the acidic, mafic to intermediate and alkaline fields. Apatite compositions were acquired by LA-ICPMS at Cardiff University, UK.

Fig. 9. Zircon age spectra from PGIC sandstones determined by LA-SF-ICPMS, following methods described by Frei and Gerdes (2009). Relative-probability histogram plots were generated using the AgeDisplay program (Sircombe, 2004). The entire population is plotted in light gray, with zircons having 90 to 100% concordance (figures denoted by "n") being superimposed in dark gray areas. Concordance for these samples is calculated as 100 * $^{238}U/^{206}Pb$ age / $^{207}Pb/^{235}U$ age.

Fig. 10. Comparisons between parameters controlled by hydrodynamics (ZTi), mechanical stability (TAH, TAD) and chemical stability during diagenesis and weathering (TAS_D, TAS_W, ZTR, GZi, ATi) in sandstones of the PGIC.

Fig. 11. Representation of the relative durability of the major and minor heavy minerals present in this study relative to quartz and feldspar, which are the main framework grains present. The vertical axis is Mohs hardness scale and minerals less hard than feldspar (F) and less hard than quartz (Q) are inferred to have very low and low durability, respectively. Ap = apatite, Sp = titanite, Ep = epidote, Gt = garnet, ad/gs = andradite-grossular garnet, St = staurolite, To = tourmaline, Zr = zircon, Cr = chrome-spinel, An = andalusite, Ru = rutile, At = anatase, Ca = calcic amphibole, and Mo = monazite.

Fig. 12. Scanning electron micrographs comparing titanite and garnet surface textures in the Dosados Mbr parent beds with those from the intrusive complex. A) Titanite from Dosados Mbr sample MG05-R, showing evidence for incipient corrosion in the form of shallow scattered etch pits. B) Fe^{2+}-Mn garnet (Type B) from Dosados Mbr sample MG05-R, displaying very little evidence for corrosion. C) Fe^{3+}-Ca garnet (Type D) from Dosados Mbr sample MG05-R, virtually unetched. D) Titanite from injectite sample MG05-Z (sill), showing advanced corrosion with development of deep etch pits and holes. E) Fe^{2+}-Mn garnet (Type B) from injectite sample MG05-K (high-angle dike), showing well-developed surface facets and etch pits. F) Fe^{3+}-Ca garnet (Type D) from injectite sample MG05-K (high-angle dike), showing advanced corrosion textures.

Fig. 13. Relationships between porosity-permeability characteristics (from Scott et al., 2013) and heavy-mineral-assemblage stabilities, showing that samples with greater porosity and permeability have more stable heavy-mineral assemblages. Porosity is estimated from point counts of petrographic sections (300 points) and permeability measured using a probe permeameter (Halvorsen and Hurst, 1990; Hurst et al., 1995). Because samples are very poorly consolidated, estimates of porosity may have been compromised (lowered) during sample preparation.