Phase equilibria and microstructural constraints on the high-$T$ building of the Kohistan island arc: The Jijal garnet granulites, northern Pakistan

Freya R. George1 | Dave J. Waters2,3 | Simon J. Gough2,4 | Michael P. Searle2 | Jacob B. Forshaw5

1Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MA, USA
2Department of Earth Sciences, University of Oxford, Oxford, UK
3Museum of Natural History, University of Oxford, Oxford, UK
4Brunei Shell Petroleum Company Sendirian Berhad, Panaga, Brunei
5Department of Geoscience, University of Calgary, Calgary, Canada

Abstract
The Kohistan island arc represents a >50 km thick and completely exposed Late Cretaceous–Eocene Neo-Tethyan island arc sequence between the Indian and Eurasian plates in the western Himalaya. At the base of the Kohistan Arc, the Jijal Complex exposes a continuous sequence from ultramafic upper mantle rocks to mafic rocks of the lower crust across the Moho transition zone. In the shallower mafic section of the Jijal Complex, widespread garnet–clinopyroxene gabbros are uniform in assemblage but show a spectrum of microstructural variation involving two distinguishable styles of garnet growth. Uncertainty surrounds the genetic origin of these equilibria across the sequence which have been variably proposed to derive either from (a) dehydration melting of amphibole-bearing precursor rocks, (b) subsolidus recrystallization of gabbronorite, or (c) primary magmatic crystallization. Owing to extensive high-$T$ re-equilibration, compositional records of magmatic precursors and the pre-peak evolution across the complex have been erased. However, quantitative textural analysis evidences a progressively increasing departure from microstructural randomness from deep to shallow levels of the upper Jijal Complex. This is interpreted to reflect the increased propensity for shallow garnet–clinopyroxene gabbros to have been derived from solid-state recrystallization of a cumulate gabbronorite precursor, resulting in the development of coronitic garnet microstructures. In the deepest portions of the mafic sequence, both cumulate textures and thermodynamic modelling attest to the basal levels of the Kohistan arc crust at ~10–14 kbar crystallizing primary magmatic garnet and clinopyroxene from low H$_2$O (<6 wt%) basaltic–andesitic melts. Granulite facies metamorphism and re-equilibration across the whole upper Jijal Complex—shown via phase equilibrium modelling to be associated with over-accretion in the mid-arc crust and a pressure increase of 2–3 kbar to 850–1,050°C and 11–14 kbar—was followed by a period of approximately isobaric cooling across ~200°C and amphibolitization. Compositions of low-volume leucosome-hosted garnet indicate melting occurred prior to, or during,
INTRODUCTION

The Kohistan Terrane in northern Pakistan is one of the best-preserved profiles through a complete section of island-arc crust and uppermost mantle in the World (e.g. Bard et al., 1980; Jagoutz et al., 2019; Jan & Howie, 1981; Petterson, 2010). Situated within the Neo-Tethyan Indus–Tsangpo suture zone and bound by the Shyok suture zone (SSZ) to the north and the Indus suture zone (ISZ, or Main Mantle Thrust, MMT) to the south (Figure 1a), the arc sequence is commonly interpreted to have been thrust south onto the leading margin of the Indian plate prior to the closure of Neo-Tethys ocean and India–Eurasia collision (e.g. Bard, 1983; Bouilhol et al., 2013; Khan et al., 1997). The >50 km thick Kohistan Arc exposes a stratigraphic profile from supracrustal sedimentary rocks and andesites, dacite and rhyolites (Chalt, Shamran volcanic Groups), through thick amphibolites and metagabbros (Kamila Complex) to lower crust gabbronorites (Chilas Complex) and basal mafic–ultramafic mantle rocks (Jijal Complex) (Figure 1b). The upper structural levels in the north contain abundant Late Cretaceous to Early Eocene (c. 75–42 Ma) subduction-related calc-alkaline granitoids of the Kohistan Batholith that intruded into the Chalt Volcanic Group and metasediments of the Gigit Complex.

The mafic–ultramafic Jijal Complex at the base of the arc has been studied extensively (e.g. Dhuime et al., 2007, 2009; Garrido et al., 2006, 2007; Gough, 2002; Jan & Howie, 1981; this re-equilibration period and melt reintegration simulations suggest that dehydration melting of amphibole-bearing precursors played only a minor role in the genesis of the Jijal garnet–clinopyroxene gabbros. By combining field relationships, petrological and textural analysis, interpretations of mineral compositions, and phase equilibrium modelling, we therefore provide detailed constraints on crustal thickening and the thermal evolution of the lowermost arc crust.

KEYWORDS
arc metamorphism, garnet granulite, Jijal Complex, Kohistan island arc
Khan et al., 1993; Ringuette et al., 1999). The southernmost ultramafic rocks of the Sapat complex and the lower part of the Jijal Complex are widely interpreted to represent the deepest tholeiitic cumulates of the arc (Boulihol et al., 2011, 2015). Therefore, the Jijal Complex of Kohistan provides unparalleled access to the deepest levels of an island arc that are very rarely exposed elsewhere. The origin and relative history of the overlying garnet-bearing mafic unit, however, remains poorly resolved. Specific problems include (a) whether or not any igneous basal-arc cumulate contributions were garnet bearing, (b) the significance of variation in garnet texture and morphology from deep to shallow crustal levels, and (c) the relative contribution of igneous and metamorphic processes in controlling these microstructures and assemblages. Based on geochemical, experimental, and textural assessment, these laterally continuous assemblages have been interpreted as having crystallized from a primary mantle melt (e.g. Alonso-Perez et al., 2009; Jagoutz et al., 2006, 2007; Kausar & Picard, 1998; Miller et al., 1991; Yamamoto, 1993). Alternatively, their formation has been related to solid-state metamorphic recrystallization (e.g. Ringuette et al., 1999), dehydration of hornblende gabbronorites (Yamamoto & Yoshino, 1998), or dehydration melting (Garrido et al., 2006) during granulite facies overprinting.

In this contribution, we combine field relationships, petrological and textural analysis, interpretations of mineral compositions, and phase equilibrium modelling (using both THERMOCALC and alphaMELTS) of mafic rocks from the Jijal Complex to obtain refined constraints on crustal thickening and thermal evolution. Our results are consistent with early emplacement of magmatic gabbroic assemblages containing some primary garnet above basal ultramafic cumulates, followed by emplacement of principally gabbronorite plutonic bodies (the Sarangar Gabbro). Magmatic over-accretion in the deepest regions of the arc (Patan, Jijal, and Kamila complexes) led to burial and heating, with resultant subsolidus crystallization of coronitic metamorphic garnet and some partial melting in hornblende-bearing lithologies. Peak metamorphic conditions at this time coincided with an episode of total chemical re-equilibration, followed by isobaric cooling at depth, amphibitization and the development of localized ductile shear zones, before final exhumation.

2 | GEOLOGICAL SETTING OF THE KOHISTAN ISLAND ARC

The Cretaceous–Eocene Kohistan–Dras island arc in northern Pakistan and western Ladakh (India) is a large intra-oceanic island arc formed within the Neo-Tethys, bounded by the SSZ to the north and the ISZ to the south (e.g. Bard et al., 1980; Coward et al., 1982; Jagoutz & Schmidt, 2012; Jan & Windley, 1990; Tahirkheli, 1983). Early models proposed that the Kohistan Arc first collided with Asia at c. 90 Ma along the SSZ, with subsequent collision of both terranes with India along the ISZ at c. 50 Ma (e.g. Borneman et al., 2015; Coward et al., 1982; Searle et al., 1999; Treloar et al., 1989). The age of closure of the SSZ is very poorly constrained, whereas the age of closure of the ISZ in Ladakh is well constrained as c. 50 Ma from palaeomagnetic data (Jagoutz & Kelemen, 2015; Martin et al., 2020) and structural and stratigraphic constraints, most notably from the ages of final marine sediments (Green et al., 2008). More recent data have supported the contention that there were two Cretaceous–Eocene north-dipping subduction systems in the Himalayan Neo-Tethys, one beneath the Kohistan Arc and the other beneath the Trans-Himalayan granite batholith along the southern margin of Asia (e.g. Martin et al., 2020; Searle & Hacker, 2019). In this scenario, obduction of ophiolite complexes and the Kohistan Arc south onto the Indian plate margin occurred during the latest Cretaceous–early Palaeocene, and final closure of Neo-Tethys occurred at c. 50–45 Ma.

The ISZ along the southern margin of Kohistan is a large-scale ductile shear zone that has emplaced the arc over regional metamorphic rocks of the Greater Himalayan series (Searle & Khan, 1996). The upper parts of the Kohistan terrane in the north have been intruded by numerous calc-alkaline biotite- and hornblende-bearing granites, granodiorites and diorites belonging to the large >2,000 km long Trans-Himalayan batholith (Kohistan, Ladakh, and Gangdese granites) forming an Andean-type continental margin along the southern margin of the Eurasian plate. U–Pb dating of magmatic phases (Boulihol et al., 2013; Heuberger et al., 2007; Jagoutz et al., 2019; Schaltegger et al., 2002) has constrained this long-lived period of magmatism throughout Kohistan from at least 120 Ma, possibly back into the Late Jurassic. In Pakistan, the batholith was intruded during at least three discrete phases (c. 102–85 Ma, 85–40 Ma, and c. 30 Ma), and comprises numerous complex and/or composite intrusions (e.g. Coward et al., 1982; Khan et al., 2009; Petterson & Windley, 1985; Tahirkheli, 1983). Volumetrically minor post-collisional garnet-bearing leucogranites (Indus confluence dykes) are also present. Crustal contamination of arc magmatism only occurred after c. 50 Ma (Boulihol et al., 2013).

Intra-arc extension led to the intrusion of the largely gabbronoritic Chilas Complex at c. 85–80 Ma (e.g. Burg et al., 1998), into both metasediments and metavolcanics of the Gligit Complex to the north and the southerly Kamila Amphibolite Complex (Treloar et al., 1996). Unconformably overlying these youngest Kohistan-wide units is more localized Cretaceous–Eocene volcano-sedimentary successions, including the Yasin Formation, the Shamran/Teru Formation, and the Dir Group (Sullivan et al., 1993).
Here, we briefly describe the geology and field relationships of rocks from the deepest levels of the Kohistan Arc, notably the Jijal Complex. The reader is directed to Tahirkheli (1983), Bard (1983), Sullivan et al. (1993), Khan et al. (1998), Searle et al. (1999), Schaltegger et al. (2002), Petterson and Treloar (2004), Jagoutz et al. (2006), Jagoutz & Klein (2018), Heuberger et al. (2007), Dhuime et al. (2009), Petterson (2010, 2019), Burg (2011), Bouilhol et al. (2011, 2015), and Jagoutz and Schmidt (2012) for thorough descriptions of the Kohistan Arc.

2.1 The Sapat and Jijal complexes

Along the hangingwall of the ISZ, the deepest structural units of the Kohistan Arc comprise several laterally discontinuous mafic–ultramafic complexes, including the Tora-Tiga, the Sapat, and the Jijal complexes (Searle et al., 1999; Figure 1a). The 2 km thick Sapat Complex is dominantly an ultramafic mantle fragment (primary harzburgite, dunite, clinopyroxenite), overlain by a crustal-scale gabbroic complex containing km-size pyroxenite sills and dykes (Bouilhol et al., 2011, 2015). U–Pb zircon dating of a range of lithologies suggests that the Sapat Complex gabbros were intruded at 106–99 Ma (Bouilhol et al., 2011).

Similar to the structural and field relationships in the Sapat Complex, the Jijal Complex can be divided into two: an ultramafic upper mantle section, and a mafic lower crustal sequence (Figures 1b and 2). The ultramafic unit comprises primary websterite, dunite, peridotite, pyroxenites, and wehrlites (Garrido et al., 2006, 2007; Jan & Howie, 1981) with depleted rare earth element (REE) signatures, no high-field strength element (HFSE) anomalies, and large-ion lithophile element enrichments (Dhuime et al., 2007). Sm–Nd isochron clinopyroxene ages from the basal ultramafic rocks yield an age of 117 ± 7 Ma, interpreted as dating primary crystallization during incipient subduction (Dhuime et al., 2007).

The appearance of plagioclase in assemblages towards shallower levels of the Jijal Complex is interpreted as the expression of the petrological Moho in Kohistan (Bard, 1983; Burg et al., 1998). These upper levels comprise clinopyroxene–garnet gabbros (commonly described as garnet granulites in the literature), with lenses and pods of two-pyroxene gabbros and subordinate amphibolites, garnetites, and hornblendites (Garrido et al., 2006, 2007; Jan & Howie, 1981; Searle et al., 1999). Mafic units exhibit enriched REE signatures and negative HFSE anomalies (Khan et al., 1998). Their whole-rock trace element geochemistry reflects their cumulate origin (Garrido et al., 2006), although Dhuime et al. (2007) interpreted the negative HFSE...
anomaly as reflecting a significant subduction component. Gabbronorites in the upper Jijal Complex have been dated at c. 118–117 Ma (Sm–Nd mineral isochrons; Yamamoto & Nakamura, 1996), comparable to the age of the ultramafic section. Sm–Nd isochrons of clinopyroxene–garnet gabbros yield ages of c. 96–91 Ma, thought to reflect a secondary granulite facies metamorphic event and cooling through 700–800°C at 30–40 km depth (Anczkiewicz & Vance, 2000; Yamamoto & Nakamura, 2000). Plagioclase-absent garnet hornblendites have been dated at 83 ± 10 Ma (Sm–Nd mineral isochrons; Yamamoto & Nakamura, 2000), although this date is poorly constrained (MSWD = 12).

Consistent with the decreasing metamorphic grade and depth from south to north in the Kohistan Terrane, estimates of conditions of metamorphic overprinting of these basal units vary considerably: 810–825°C, 10–12 kbar (Padron-Navarta et al., 2008); 700–800°C, 6–12 kbar (Yoshino & Okudaira, 2004); 700–950°C, >10 kbar (Yamamoto & Nakamura, 1996); and 949°C, 17 kbar (Jan, 1979).

2.2 | Sarangar Gabbro

The Jijal Complex mafic rocks are directly overlain to the north by the Sarangar Gabbro, the southernmost subdivision of the Patan–Kiru–Kamila Metaplutonic Complex (Burg et al., 2005; Dhuime et al., 2009; Figures 1 and 2). The Sarangar gabbro is a 3 km thick sheet that largely comprises retrogressed two-pyroxene gabbros and hornblende bodies less than 100 m thick that separate garnet–clinopyroxene gabbros of the upper Jijal Complex to the south from gabbros and diorites of the basal Kamila unit to the north (Patan, Kiru sequences of Dhuime et al., 2009). The southern contact exposes its intrusive nature into the Jijal garnet-bearing gabbros. The northern contact with the Kamila Metaplutonic Complex is partially obscured by well-developed ductile shear zones with strong foliations and north-plunging lineations consistent with their development during intrusion, and late south-directed shearing (Burg et al., 2005; Searle et al., 1999; Zeilinger, 2002). U–Pb zircon geochronology yielded an age of 98.9 ± 0.4 Ma (Schaltegger et al., 2002) for the Sarangar Gabbro.

2.3 | Kamila Metaplutonic Complex

Overlying the Jijal Complex and a continuation of the Sarangar gabbro is the Patan–Kiru–Kamila Metaplutonic Complex (variably known as the Kamila Complex, the Southern Amphibolites, or the Patan–Dasu Metaplutonic Complex). The complex is a 10–45 km wide unit comprising now-metamorphosed basalts and basaltic–andesitic volcanic and plutonic bodies. U–Pb ages on zircon range from c. 110 Ma to c. 75 Ma (see compilation in Burg, 2011). The complex is divided into the most southerly Patan sheared gabbros and diorites (which incorporates the Sarangar Gabbros), the Kiru Amphibolites (interlayered gabbros, tonalites, and diorites), and the most northerly Kamila Amphibolites which include ortho-amphibolites, metapelites, and metavolcanics (Dhuime et al., 2009; Garrido et al., 2006; Zeilinger, 2002).

3 | LITHOLOGICAL DESCRIPTIONS

Samples from the Jijal Complex and Sarangar gabbro were collected along the Karakoram Highway, approximately perpendicular to the strike of the contacts between units (Figure 2), allowing the change in texture, mineral content, and composition to be tracked with changing depth within the mafic regions of the basal arc. A full list of samples is provided in Table S1. Despite extensive late-stage hydration and retrogression to amphibolite facies across the upper Jijal Complex and variable nomenclature and unit classification in the literature, two major petrological subdivisions are defined in this study: garnet–clinopyroxene gabbros and gabbronorites (i.e. two-pyroxene gabbros), each associated with localized amphibolites and hornblendites. As described, all rocks have been subject to high-T conditions but the prefix ‘meta’ is not used in the following discussion to preclude premature inferences of the primary origins of peak mineral assemblages.

3.1 | Petrographic constraints

3.1.1 | Garnet–clinopyroxene gabbros

Preserved garnet–clinopyroxene gabbros comprise garnet, clinopyroxene, plagioclase, and quartz (Figure 3a–d). Plagioclase is variably saussuritized to fine clinzoisite needles, from incipient along grain boundaries to almost complete (Figure 3a,c,d,f). Accessory rutile mantled by titanite is present both as inclusions in garnet and clinopyroxene and in the matrix. Ilmenite often contains exsolution lamellae of titanohematite and inclusions of magnetite. Garnet–clinopyroxene gabbros are commonly associated with cross-cutting leucocratic veins, which act as host to coarse, ~1 cm garnet distinct from those in the host rock (Figure 3e). These garnet contain inclusions of saussuritized plagioclase and exsolved Fe–Ti oxides and are abundant in the middle of a reaction zone between gabbronorites and garnet–clinopyroxene gabbros.

Despite the almost ubiquitous presence of the same assemblage across the upper Jijal Complex, there are significant textural disparities between garnet–clinopyroxene gabbros from deeper and shallower structural levels. In the
southern four kilometres (e.g. samples SG22-25, SG27, SG31, and SG35 in Figure 2), garnet–clinopyroxene gabbros contain equigranular garnet and clinopyroxene, which appear to be in textural equilibrium with intercumulus plagioclase (Figure 3a,b). Quartz is heterogeneously distributed at the thin section scale. Idiomorphic to hypidiomorphic garnet is coarse, with crystals up to 5 mm in diameter. Clusters of garnet and clinopyroxene define a cumulate foliation and a lineation that is defined by the shape-preferred orientation of clinopyroxene and garnet (Figure 3a). This textural variety of garnet will hereafter be known as ‘Type 1’ garnet.

In the upper ~1.5 km of the Jijal Complex (e.g. samples SG37, KH6, and SG39), garnet–clinopyroxene gabbros contain skeletal garnet associated with elongate quartz, which together form 0.5–1 mm wide symplectitic coronae around clinopyroxene (Figure 3c). The internal rim of coronitic garnet in contact with quartz is lobate to embayed, whereas the external interface with plagioclase is idiomorphic, and clinopyroxene is rarely in contact with plagioclase. The simplified overall reaction interpreted to control this microstructure is:

\[
\text{clinopyroxene} + \text{anorthite} = \text{garnet} + \text{quartz}
\]

This textural variety of garnet will henceforth be known as ‘Type 2’ garnet. Type 2 garnet has been previously documented by Ringuette et al. (1999), and Yamamoto and Yoshino (1998) who also found orthopyroxene in the cores of analogous coronas, which has not been identified in the samples studied here. In the middle portion of the upper Jijal Complex (e.g. sample SG35), Type 1 garnet is present alongside Type 2 garnet (Figure 3d), and some Type 1 exhibits secondary Type 2 overgrowths. Discerning outcrop-scale transitions between these microstructural varieties has not been possible.

In both Type 1 and 2 garnet–clinopyroxene gabbros, replacement of the primary mineral assemblage by symplectites of hornblende and quartz and/or epidote and quartz ranges from negligible to complete (Figure 3f). Chloritization along cracks in garnet is common, and clinopyroxene rims in Type 2 samples are variably altered to actinolite across ~100 μm. Hydration fronts associated with Type 2 samples exhibit complete amphibolitization of coronitic garnet, and pervasive hydration of largely anhydrous peak assemblages is also evidenced locally by domains containing epidote, hornblende, scapolite, clinozoisite, and paragonite.

3.1.2 | Gabbronorites (i.e. two-pyroxene gabbros)

Previous work by Yoshino et al. (1998) has identified a single orthopyroxene-out boundary corresponding to the mapped contact between the Jijal Complex and Sarangar Gabbro. However, gabbronorites are increasingly common towards the northern limit and within the Jijal Complex itself. They contain granoblastic clinopyroxene and orthopyroxene, abundant plagioclase and minor quartz, ilmenite, and hematite (e.g. sample KH7). Texturally late blue–green amphibole often replaces clinopyroxene, and samples exhibit a cumulate foliation defined by elongate mafic layers (Figure 3a). There is good field evidence for the replacement of this Jijal two-pyroxene gabbro by garnet–clinopyroxene gabbro along bands and elongate patches (e.g. see also figure 4 of Yamamoto and Yoshino (1998); figure 3 of Yamamoto and Nakamura (2000)), and a direct reaction front between garnet–clinopyroxene gabbros containing Type 2 garnet and the Jijal gabbronomite can be observed in sample SG40 (Figure 3g). In some works, this unit is known as a hornblende gabbronomite (Yamamoto & Nakamura, 2000; Yamamoto & Yoshino, 1998); however, in this study we have not documented significant (>2%) primary amphibole in these samples.

The overlying units mapped as the Sarangar Gabbro in the Kamila Amphibolite Belt exhibit sheared but discernibly intrusive contacts with the Jijal Complex. The region comprises a similar gabbronomite to that of the Jijal Complex which has been variably retrogressed to an assemblage comprising hornblende and plagioclase (Figure 4b,c), with or without garnet porphyroblasts. Pristine gabbronomite in the Sarangar Gabbro (e.g. KH13, KH16) is generally coarser grained than equivalent assemblages in the Jijal Complex.

3.1.3 | Garnet hornblendite

Plagioclase-free garnet hornblendites (e.g. samples KH30, SG33, and SG34) contain hornblende, garnet, ilmenite,
and hematite with or without clinopyroxene, and have been mapped as metre- to kilometre-scale lenses and pods, exhibiting both intrusive and intruded relationships with the surrounding garnet–clinopyroxene gabbro (Figure 1, and figure 3a of Yamamoto & Yoshino, 1998). Garnet hornblendites and subordinate garnetite bodies are aligned subparallel to the palaeo-Moho, and the layering present in garnet–clinopyroxene gabbros is truncated at the contact between the lithologies.

Coarse hornblende plates (~0.5 cm) form an interlocking texture with Fe–Ti oxides concentrated along grain boundaries and at triple junctions, and hematite exsolution lamellae are parallel to the hornblende cleavage (Figure 4d). When present, clinopyroxene is either disseminated through coarse hornblende, or concentrated along discrete horizons. In some samples (KH30, SG34), clinopyroxene and garnet are contained within localized thin section scale enclaves (Figure 4d). As previously described, leucocratic veins are commonly found in the vicinity of garnet–hornblendite lenses (e.g. sample KH4).

3.2 | Textural characterization

To more accurately describe the microstructural variations within garnet–clinopyroxene gabbros across the upper Jijal Complex, statistical analysis of the frequency of grain contacts using a method modified after Kretz (1969) and Ashworth and McLellan (1985) was applied. This method permits assessment of the frequency of contacts and tests the hypothesis that certain grain contacts occur more commonly than expected for a random distribution in particular reaction-controlled assemblages.

Parallel line traverses were taken using an X–Y stage across thin sections and the phase entered and exited at each grain boundary was successively recorded for at least 500 contacts. Like contacts (e.g. garnet–garnet) were ignored, and traverses sampled the entire thin section area to account for any small-scale microstructural variability. For each pair of phases, the normalized difference between the observed number of transitions and those expected from a random distribution was calculated. To test the null hypothesis,
the chi-squared ($\chi^2$) test was applied to determine whether the distribution departs significantly from that expected for a random phase distribution. Chi-squared results are then visualized as multiples of the statistically critical value, known as the ‘order index’ (OI), with higher values indicating a greater deviation from randomness. A second index arises by considering an ideal corona formed by Reaction 1, in which the mineral sequence should be Cpx–Qz–Grt–Pl, as in the extreme example in SG39 (Figure 3c). The ‘reaction corona index’ (RI) is derived from the sum of favoured transitions (i.e. cpx–qz, qz–grt, and pl–grt,) minus the sum of transitions prohibited by this ideal corona sequence (i.e. cpx–pl, cpx–grt, and pl–qz). All samples can then be compared to the most coronitic sample SG39 in order to qualitatively assess the extent of the transition between Type 1 and Type 2 samples. Results for SG25 and SG39 are summarized in Figure 5, and full calculations and results are presented in Table S2.

Statistical analyses highlight a relatively well-defined array from the base to the top of the upper Jijal Complex that reflect the qualitative observation of the predominance of Type 1 and Type 2 garnet in the deepest and shallowest levels respectively. Both the OI and RI increase up-section (Figure 5). Samples SG22 to SG30b, representing the southernmost ~5 km of Jijal all have OI ~1, indicating a near-random association of minerals. Towards the shallow levels, there is a progressive increase in the OI over ~2 km, consistent with a departure from randomness and preference for organized grain contacts. Microstructures within the assessed sample containing coarse vein-related garnet (KH4) fall off this systematic trend and exhibits an ordered texture that is interpreted to be unrelated to corona formation.

This trend of garnet microstructures from south to north is interpreted to reflect two overlapping generations of garnet: a ‘cumulate’ garnet (Type 1) in textural equilibrium with other phases in the deepest units of the Jijal Complex, and a secondary, ‘metamorphic’ garnet (Type 2) generated by Reaction 1, in the shallowest outcrops of the complex.

**FIGURE 5** Results of grain transition probability textural analysis. (Top) Normalized differences between observed transitions and the expected transitions for a random distribution and $\chi^2$ values for microstructure. Critical value at 95% confidence level with nine degrees of freedom. Green denotes grain transition more abundant than expected in the random case, red denotes less favourable transitions. (Bottom) Reaction corona index versus order index, highlighting the array from a random texture in the south to an ordered coronitic texture in the north [Colour figure can be viewed at wileyonlinelibrary.com]
4.1 Analytical techniques

Mineral compositional data (both point analysis of individual phases and compositional line traverses of garnet) were acquired for all samples using a JSM-JEOL-840A scanning electron microscope (SEM) fitted with an Oxford Instruments Isis 300 energy-dispersive spectrometer (EDS) in the Department of Earth Sciences at the University of Oxford, UK. The accelerating voltage was 20 kV, with a beam current of 6 nA at a working distance of 15 mm. The live counting time was set to 100 s. Calibration was to a range of natural and synthetic standards, and a ZAF correction procedure was applied to all acquired analyses. The strength of the beam current was monitored regularly using a Faraday Cup inserted into the electron column and was calibrated every 120 min using a cobalt metal standard. Maintenance of a uniform beam current in this way ensures that reproducibility for elements heavier than Na approaches that of a wavelength dispersive spectroscopy technique (Waters & Charnley, 2002). Accumulated count compositional profiles across garnet were determined along 256-channel line scans for ∼30 min. Profiles were background corrected and calibrated against at least six full-point analysis taken along the profile.

4.2 Effective bulk composition

Effective bulk compositions were calculated by combining point-counted volume estimates from thin sections (Table 1) with representative compositional analysis of mineral phases (Table 2). Rutile, quartz, and ilmenite–hematite were assumed to be pure phases. Where applicable, Fe$^{3+}$ was determined using the software AX (Holland & Powell, 2009). Results are presented in Table 3. By avoiding the use of bulk-rock compositions derived via X-ray fluorescence this method enables selection of the most appropriate assemblage which represents that interpreted to be present during near-anhydrous peak metamorphism, without including hydro retrograde phases (e.g. St-Onge et al., 2013). The bulk composition of the studied mafic sequence is relatively narrow, has low total alkali and SiO$_2$ contents, and falls within the range of the most primitive Jijal compositions determined by Dhuime et al. (2009, their figure 6).

4.3 Major phase compositions

The average jadeite component in clinopyroxene from garnet–clinopyroxene gabbros increases slightly from shallow to deep levels: SG39, SG35, and SG25 contain 7%, 13%, and 14% respectively. Clinopyroxenes are largely unzoned, but slight increases (<2%) in the jadeite component from core-to-rim of a given crystal may reflect plagioclase breakdown or a systematic change in the oxidation state towards the end of clinopyroxene crystallization. Consistent with trends documented by Yoshino et al. (1998), octahedral and tetrahedrally coordinated Al in clinopyroxene increase by 2%–5% in mineral rims. Unaltered plagioclase has X$_{An}$ =0.34–0.55 in garnet–clinopyroxene gabbros (increasing from deep to shallow levels in the complex) and X$_{An}$ = 0.65 in KH7.

Garnet in all analysed samples show comparable patterns of core-to-rim compositional variation, despite differing microstructural styles (Figure 6). Cores contain 31%–37% pyrope (X$_{Pp}$) and 17%–26% grossular (X$_{Grs}$), while rims contain 26%–31% pyrope and 25%–31% grossular. The spessartine content (X$_{Sp}$) in all garnet is negligible and unzoned, and almandine (X$_{Alm}$) core contents (45%–50%) decrease by ~5%–10% towards outer rims. Representative line profiles through Type 1 and Type 2 garnet are presented in Figure 7.

Large Type 1 and Type 2 garnet (Figure 7a–c) contain compositionally homogeneous cores characterized by relatively high X$_{Pp}$ (~30%–35%) and low X$_{Grs}$ (~15%–25%) contents. Towards garnet rims X$_{Pp}$ and X$_{Grs}$ decrease and increase, respectively, over ~50–500 µm. In smaller garnet, the central plateau is less well defined, but compositional trends meet to form bowl- or dome-shaped profiles with central minima and maxima equivalent to core compositions in larger grains. In both large and small grains, core maxima/minima vary slightly between crystals of the same sample, potentially related to non-central sectioning effects. Many coronitic Type 2 garnet in SG39 display similar zoning patterns (Figure 7c). However, some are fully homogenized with <10 µm-wide diffusional rims, and others exhibit linear asymmetric zoning with increases in X$_{Grs}$ of ~4%–6% towards

|       | Grt | Cpx | Opx | Hbl | Pl  | Qtz | Rt  | Ilm |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| SG25  | 41.4| 11.0| 0   | 0   | 38.5| 6.7 | 2.5 | 0   |
| KH30  | 21.0| 22.9| 0   | 52.3| 0   | 0   | 0.4 | 3.4 |
| SG35  | 37.0| 20.0| 0   | 0   | 39.7| 3.0 | 0.3 | 0   |
| KH7   | 0   | 25.2| 13.9| 0   | 53.2| 3.3 | 0.0 | 4.3 |
| SG39  | 19.4| 33.8| 0   | 0   | 34.2| 10.8| 1.8 | 0   |

TABLE 1 Mineral modes (vol.%) used to calculate effective bulk compositions
### TABLE 2
Representative core mineral compositions of peak assemblages (except garnet, average core–rim compositions) in samples SG25, SG35, SG39, and KH7

| Sample | SG25 | | | SG35 | | | | SG39 | | | | KH7 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mineral No. Analyses | Grt | Cpx | Pl | Grt | Cpx | Pl | Grt | Cpx | Pl | Cpx | Opx | Pl | Cpx | Opx | Pl |
| SG25 34 | 37.81 | 50.07 | 59.60 | 39.62 | 49.91 | 58.36 | 39.59 | 51.32 | 54.33 | 48.73 | 48.84 | 51.43 | 0.42 | 0.06 | 0.02 |
| SiO₂ | 0.11 | 0.59 | 0.01 | 0.08 | 0.66 | 0.02 | 0.07 | 0.59 | 0.01 | 0.42 | 0.06 | 0.02 |
| TiO₂ | 20.87 | 7.82 | 23.87 | 21.84 | 7.04 | 25.41 | 22.05 | 5.15 | 29.27 | 8.09 | 6.02 | 30.56 |
| Al₂O₃ | 21.42 | 8.32 | 0.29 | 20.94 | 7.79 | 0.06 | 20.90 | 7.23 | 0.07 | 10.69 | 23.63 | 0.10 |
| MnO | 0.49 | 0.05 | 0.02 | 0.48 | 0.05 | 0.01 | 0.51 | 0.04 | 0.01 | 0.33 | 0.75 | 0.01 |
| MgO | 7.32 | 10.13 | 0.02 | 9.06 | 11.03 | 0.02 | 7.93 | 12.45 | 0.00 | 10.23 | 19.75 | 0.00 |
| CaO | 9.37 | 19.89 | 7.35 | 8.43 | 20.67 | 7.80 | 8.68 | 22.45 | 11.31 | 20.15 | 0.36 | 13.17 |
| Na₂O | 0.00 | 2.27 | 7.59 | 0.03 | 1.76 | 7.02 | 0.22 | 0.99 | 5.11 | 1.21 | 0.02 | 3.97 |
| K₂O | 0.00 | 0.03 | 0.10 | 0.04 | 0.03 | 0.25 | 0.01 | 0.00 | 0.11 | 0.01 | 0.01 | 0.13 |
| Total | 97.38 | 99.16 | 98.85 | 100.51 | 99.09 | 98.94 | 99.96 | 100.25 | 100.24 | 99.85 | 99.44 | 99.39 |
| Si | 2.97 | 1.86 | 2.69 | 2.99 | 1.86 | 2.62 | 3.01 | 1.90 | 2.45 | 1.82 | 1.85 | 2.36 |
| Ti | 0.01 | 0.02 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.02 | 0.00 | 0.01 | 0.00 | 0.00 |
| Al | 1.93 | 0.34 | 1.27 | 1.94 | 0.31 | 1.37 | 1.98 | 0.22 | 1.56 | 0.36 | 1.67 | 0.00 |
| Fe³⁺ | 0.11 | 0.06 | 0.01 | 0.08 | 0.06 | 0.00 | 0.02 | 0.03 | 0.00 | 0.07 | 0.27 | 0.00 |
| Fe²⁺ | 1.30 | 0.19 | 0.00 | 1.25 | 0.17 | 0.00 | 1.34 | 0.19 | 0.00 | 0.27 | 0.75 | 0.00 |
| Mn | 0.03 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 |
| Mg | 0.86 | 0.56 | 0.00 | 1.02 | 0.62 | 0.00 | 0.90 | 0.69 | 0.00 | 0.57 | 1.11 | 0.00 |
| Ca | 0.79 | 0.79 | 0.36 | 0.68 | 0.83 | 0.38 | 0.71 | 0.89 | 0.55 | 0.81 | 0.01 | 0.64 |
| Na | 0.00 | 0.16 | 0.67 | 0.00 | 0.13 | 0.62 | 0.03 | 0.07 | 0.45 | 0.09 | 0.00 | 0.35 |
| K | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 |
| Sum | 8.00 | 4.00 | 5.00 | 8.02 | 4.00 | 5.01 | 8.01 | 4.01 | 5.01 | 4.02 | 4.02 | 5.01 |
| Oxygen | 12 | 6 | 8 | 12 | 6 | 8 | 12 | 6 | 8 | 6 | 6 | 8 |
| X_Mg | 0.38 | 0.75 | — | 0.45 | 0.78 | — | 0.40 | 0.78 | — | 0.00 | — | — |
| X_Jd | — | 0.14 | — | 0.13 | — | 0.07 | — | 0.09 | — | — | — |
| X_An | — | 0.34 | — | 0.39 | — | 0.55 | — | 0.65 | — | — | — |

Note: $X_Mg = Mg/(Mg+Fe^{3+}); X_Jd = Na/(Na+Ca); X_An = Ca/Ca+Na.$
the garnet–plagioclase grain boundary. Large centimetre-scale garnet associated with feldspathic veins in sample KH4 contain similar symmetrical core-to-rim zoning but are compositionally dominated by the core plateau (Figure 7d).

Given the compositional similarities between garnet of a variety of textural forms from across the upper Jijal Complex and the prevalence of homogeneous core compositions, it can be inferred that assemblages containing a large proportion of the current garnet (including both Type 1, Type 2, and coarse vein-related garnet) underwent extensive chemical equilibration at high temperatures. As a consequence, garnet contain no compositional record of pre-peak prograde events (such as igneous or metamorphic crystallization). Interpretation of the development of these assemblages relies therefore on the preserved microstructural record and inferences made with phase equilibrium modelling.

Rim compositions are interpreted as diffusional closure profiles acquired during cooling from conditions of plateau equilibration. In order to account for the rimward elevation in $X_{\text{Grs}}$, some garnet growth by net-transfer reaction must also have been involved, in addition to diffusional modification and Fe–Mg exchange.

### 5 | METAMORPHIC MODELLING

Phase equilibrium modelling has been conducted for samples from the south, middle, and north of Jijal garnet–clinopyroxene gabbro body (SG25, SG35, and SG39 respectively) and one Jijal gabbronorite (KH7). Given major element garnet core compositions that have equilibrated at high temperatures and diffusional rims that are associated with some net-transfer garnet-forming reaction, the apparent cooling path from peak to closure temperature can be constrained, providing a framework for the post-peak evolution of the Kohistan basal arc crust.

Phase equilibria for each of the modelled samples were constructed using THERMOCALC v.3.45 (Powell et al., 1998) and the internally consistent data set of Holland and Powell (1998; ds55, update 4 August 2004). Calculations were completed in the 10 and 9 component systems NaO–CaO–K$_2$O–FeO–MgO–Al$_2$O$_3$–SiO$_2$–H$_2$O–TiO$_2$–O$_2$ (NCKFMASHTO) and NaO–CaO–K$_2$O–FeO–MgO–Al$_2$O$_3$–SiO$_2$–TiO$_2$–O$_2$ (NCKFMASHTO). The following activity–composition ($a$–$X$) models were used: melt, biotite, and garnet (White et al., 2007); amphibole (Diener et al., 2007); high-$T$ clinopyroxene (Holland, pers. comm. to DJW, 2013); orthopyroxene and magnetite–spinel (White et al., 2002); plagioclase and K-feldspar (Holland & Powell, 2003); epidote (Holland & Powell, 1998); and ilmenite–hematite (White et al., 2000). Quartz, rutile, titanite, and an aqueous fluid were modelled as pure phases. Calculations have also been completed using the new $a$–$X$ relations for silicate melt, augite, and amphibole

| Sample | Lithology | SiO$_2$ | TiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | FeO | MnO | MgO | CaO | Na$_2$O | K$_2$O | Mg# |
|--------|-----------|--------|--------|------------|------------|-----|-----|-----|-----|-------|-------|-----|
| SG25 Grt–Cpx gabbro | 48.92 | 3.31 | 19.02 | 1.28 | 11.10 | 0.23 | 5.07 | 8.45 | 2.68 | 0.03 | 44.6 |
| SG35 Grt–Cpx gabbro | 49.46 | 0.39 | 19.52 | 0.95 | 9.96 | 0.21 | 6.30 | 10.44 | 2.70 | 0.08 | 46.2 |
| KH7 Gabbronorite | 48.62 | 2.35 | 18.25 | 0.43 | 9.58 | 0.21 | 5.73 | 11.96 | 2.95 | 0.03 | 51.2 |
| SG39 Grt–Cpx gabbro | 50.53 | 2.35 | 18.25 | 0.43 | 9.58 | 0.21 | 5.73 | 11.96 | 2.95 | 0.03 | 51.2 |
| Derived andesite$^a$ | 57.20 | 0.95 | 18.84 | 1.73 | 8.43 | 0.30 | 2.95 | 7.43 | 2.95 | 1.48 | 66.3 |
| Average arc basalt$^b$ | 50.53 | 0.91 | 15.74 | 0.95 | 7.58 | 0.45 | 15.74 | 7.58 |

**Note:** Mg# as molar Mg/(Mg+Fe$^{2+}$). $^a$From Alonso-Perez et al. (2009). $^b$From Kelemen et al. (2005).
designed for phase equilibria of basic and intermediate lithologies (ds62, update 6 February 2012, Green et al., 2016) in thermocalc version 3.47 and are included in Figure S3. These results are discussed in Section 7.1. Mineral abbreviations follow Whitney and Evans (2010), and phase diagrams are shaded to reflect the variance of each divariant field, with darker shades indicating higher variance.

Effective bulk-rock compositions used for phase diagram construction were derived from the approach described in Section 4.2 and are presented in Table S4. Despite anhydrous peak assemblages in SG25, SG35, and SG39, small amounts of \( \text{H}_2\text{O} \) (0.2 mol.%) were included in the bulk compositions for calculation of peak metamorphic conditions that just saturate the solidus, enabling the location and behaviour of amphibole stability to be tracked without significantly affecting the phase relations and compositions of solid assemblages. Fully anhydrous phase equilibria calculated using ds5 are included in Figure S5 and are the basis of cooling path models in Section 5.2. Given the lack of graphite observed in the assemblages, the activity of \( \text{H}_2\text{O} \) was set to 1.

**FIGURE 6** Average core and rim \( X_{\text{Grossular}} \) and \( X_{\text{Pyrope}} \) content for 12 garnet–clinopyroxene gabbro samples. Each datapoint represents the mean analysis of numerous garnet within a single sample.

**FIGURE 7** Representative garnet porphyroblast compositional line profiles. (a–d) Rim-to-rim garnet composition profiles for samples SG25, SG35, SG39, and vein-related garnet KH4 respectively. (e–h) Corresponding garnet BSE images showing the exact location and length of transects [Colour figure can be viewed at wileyonlinelibrary.com]
5.1 Peak metamorphic conditions

5.1.1 Approaches

First-order estimates of the conditions of peak metamorphism were determined by identifying the stable divariant field representing peak mineral assemblages. The high temperatures experienced by these rocks mean that more specific $P$–$T$ conditions of equilibration cannot be reliably estimated using conventional thermobarometry alone, as the chemical composition of coexisting phases may not be in equilibrium as a consequence of diffusional modification (e.g. Frost & Chacko, 1989; Pattison & Bégin, 1994). Instead, $P$–$T$ conditions of garnet core re-equilibration (interpreted as equalizing peak conditions) are constrained using the average ($\pm 1\sigma$) of $X_{\text{Grs}}$ and $X_{\text{Prp}}$ compositions in the cores of garnet across the sample suite.

**FIGURE 8** Calculated $P$–$T$ phase diagram for samples (a) SG25, (b) SG35, and (c) SG39, (d) KH7. The observed assemblages are highlighted in red, and applicable garnet isopleths and vol.% isolines are shaded. Results of application of garnet–clinopyroxene thermometer of Ravna (2000) are denoted in purple in (a)–(c), with associated errors of $\pm 50^\circ$C. Results of application of clinopyroxene–orthopyroxene thermometer of Wells (1977) are denoted in navy in (d), with associated errors of $\pm 70^\circ$C [Colour figure can be viewed at wileyonlinelibrary.com]
The jadeite content of clinopyroxene is also used as a monitor of peak \( P-T \) conditions. Mineral modal abundances are not used owing to their potential modification during growth along the cooling path.

5.1.2 Results

Figure 8a–c show the combined results of thermobarometric analysis of each of the three garnet–clinopyroxene gabbro samples: SG25, SG35, and SG39. As expected given the similarities between their bulk compositions, topologies of all diagrams are similar, with high-variance fields containing the peak mineral assemblage of garnet+clinopyroxene+plag ioclase+quartz+rutile melt occupying a wide range of temperatures at pressures broadly exceeding \( \sim 9-10 \) kbar.

The anti-correlated nature and near parallelism of \( X_{\text{Grs}} \), \( X_{\text{Prp}} \), and jadeite isopleths means that there is a large uncertainty on their position and thus the precise conditions of garnet core re-equilibration. No single set of \( P-T \) conditions are able to reproduce the observed mineral compositions and modal abundances for any given sample. Similarly, garnet core compositions are non-unique across a range of temperatures. However, best estimates of reasonable conditions for core (re-)equilibration are \( 11-15 \) kbar, 900–1,000\(^\circ\)C for SG25, 11–14 kbar and 875–975\(^\circ\)C for SG35, and 10–14 kbar and 800–900\(^\circ\)C for SG39. The range of pressures is consistent with those previously reported (Yamamoto, 1993; Yamamoto & Yoshino, 1998), and potentially evidence a slight decrease in pressure (on the order of \( 1-3 \) kbar) from the base to the top of the garnet–clinopyroxene gabbro sequence. Ilmenite is present in all garnet–clinopyroxene gabbros but is part of equilibrium assemblages at pressures too low to be simultaneously consistent with both isopleth intersections and the documented presence of rutile. Ilmenite may, therefore, be metastably preserved in the peak assemblage.

These estimates from phase equilibria are consistent with temperature estimates obtained using the garnet–clinopyroxene thermometer of Ravna (2000), which decrease from 954 ± 50\(^\circ\)C to 836 ± 50\(^\circ\)C in the deepest (SG25) to shallowest (SG39) garnet–clinopyroxene gabbros respectively. Although not modelled in detail here, local leucocratic vein ing interpreted to derive from amphibole dehydration melting is particularly prevalent in deeper regions of the upper Jijal Complex (Yamamoto & Yoshino, 1998), and places conditions of re-equilibration above the solidus, at temperatures >700\(^\circ\)C (Palin et al., 2016).

Sample KH7, a gabbronorite representative of the Jijal gabbros collected within coronitic garnet–clinopyroxene gabbros (Figure 3b) has also been modelled (Figure 8d). The topology is comparable to that of the garnet–clinopyroxene gabbros, and the observed mineral assemblage is stable at a similarly wide range of temperatures at pressures \( 1-2 \) kbar lower than the garnet–clinopyroxene gabbro divariant field. The two-pyroxene thermometer of Wells (1977) yields an average temperature of last equilibration at \( \sim 870 \pm 70\(^\circ\)C, consistent with those peak temperatures estimated for the rest of the sequence.

5.2 Cooling path

5.2.1 Approaches

In contrast to approximately equilibrated high-\( T \) garnet cores, chemical zoning trends at garnet rims document post-peak cooling and diffusional closure. The changing Ca content of garnet in these high-variance assemblages cannot be achieved only via closed-system cation exchange, so the development of rim compositions was most likely accompanied by some garnet growth. Moreover, euhedral garnet rims developed against plagioclase in mixed Type 1 and 2 samples suggest that the development of post-peak equilibration rim compositions must have incorporated some growth on pre-existing garnet, in addition to low-\( T \) diffusional closure.

Rather than use poorly constrained input parameters to attempt to produce a reaction–diffusion model, we locate an array of pressures and temperatures at which the rim compositions are satisfied. To track the \( P-T \) path implied by the zoning, paths for SG25 have been simulated by extracting garnet compositions and modifying the THERMOCALC RBI matrix to approximate chemical fractionation of the effective bulk composition. For simplicity, modelling has been conducted in a fully anhydrous system in two steps: homogeneous core development at peak conditions and subsequent overgrowth of the ‘rim’ compositions. Given the large uncertainty on conditions of core (re-)equilibration (Section 5.1), paths were calculated from two disparate \( P-T \) points (Core 1 at 11.2 kbar and 900\(^\circ\)C and Core 2 and 14 kbar and 1,100\(^\circ\)C), which bracket the approximate limits of the range of possible high-\( T \) homogenization conditions. Rocks equilibrated at Core 1 peak conditions are modelled to contain 77%–91% of final garnet volume and at Core 2 conditions, 67%–79%.

Along these two-step paths, average rim compositions are modelled to variably equilibrate with the interior of garnet by varying the degree of garnet fractionation from the bulk along the two-step \( P-T \) path, after the method described by St Onge et al. (2013). A 100% fractionation scenario approximately simulates no equilibration between the core and rim compositions, whereas lesser degrees of garnet fractionation permit increasing degrees of diffusional exchange. The former scenario is unlikely to be realistic, given the efficacy of diffusional modification at high temperature (e.g. Caddick et al., 2010), and zero fractionation is inconsistent with compositionally zoned garnet. To constrain which output path is
most appropriate, other criteria, including predicted mineral modes at the end of the modelled path and phase compositions were calculated. For each calculated scenario, constraints were compared with the observed assemblage.

5.2.2 | Results

Despite the variability in potential core isopleth intersections, the final conditions of fractionated rim equilibria form a regular $P$–$T$ locus from high to low $P$–$T$, so that for a given amount of fractionation, paths from diverse starting conditions tend to converge (Figure 9a). Thus, encouragingly, the final result (i.e. the annealing temperature), is not particularly sensitive to the chosen starting point of high-$T$ equilibration, useful given the relatively poor constraints on such high-$T$ metamorphic conditions.

For both starting conditions, 80%–100% fractionation (i.e. 20%–0% garnet recycled) tends to drive pressure (and in one instance temperature) upwards. Conversely, the zero fractionation end-member generates the longest $P$–$T$ path, driving rim isopleth intersections down to unrealistically low $P$–$T$s. Comparison of predicted mineral modes and compositions at different degrees of fractionation with those observed allowed determination of the most likely degree of fractionation (Figure 9b,c). Intermediate degrees of fractionation (~70%, i.e. 30% of previously grown garnet available for re-equilibration with new garnet growth) best matches the criteria defined by mineral modes and compositions. For this 70% fractionation, the amount of newly grown garnet in the single step is 9%–23% and 21%–33% of the final total from Core 1 and Core 2 respectively.

These results imply that the most probable $P$–$T$ path recorded by garnet involves approximately isobaric cooling of the upper Jijal Complex at between 11 and 14 kbar from peak conditions of chemical (re-)equilibration at 850–1,000°C. These pressures have little difference from the regions of isopleth intersection uncertainty for equilibrated garnet cores, indicating little early decompression from peak conditions. Cooling proceeds to temperatures ~620–670°C, consistent with expected diffusional closure temperatures from major cations in garnet (e.g. Caddick et al., 2010). Given similarities in bulk chemical compositions and garnet zonation between garnet–clinopyroxene gabbros within the whole of the upper Jijal Complex, the obtained cooling path is considered applicable to all samples.

5.3 | Melt reintegration

5.3.1 | Approaches

Garnet–clinopyroxene gabbros of the upper Jijal Complex have in the past been interpreted to derive from dehydration
melting of primary hornblende-bearing gabbronorites, now preserved as rare relics in the complex (Garrido et al., 2006). In such cases, garnet–clinopyroxene gabbros are restitic. The preserved hornblende content in such samples varies dramatically from 0.3 to 8.2 vol.% (Yamamoto & Yoshino, 1998), and nomenclature/recognition varies significantly (with some authors grouping these with gabbronorites sensu stricto). In our samples, negligible primary hornblende has been documented in gabbronoritic samples. Despite this poor constraint on the amount of hornblende in a precursor lithology (which may well vary across the complex), the potential contribution of dehydration melting of hornblende gabbronorites along a prograde path has been investigated via progressive reintegration of melts in equilibrium with the restitic solids (e.g. Diener et al., 2008; Indares et al., 2008; Korhonen et al., 2013).

Melt reintegration from the approximately anhydrous bulk of sample SG25 (Table 3) was performed in a series of steps along a schematic and geologically reasonable prograde $P$–$T$ path. Following the approach described in Korhonen et al. (2013), the system was modelled as ‘conditionally open’, whereby the upper bound at which melt is taken to exist as a connected network and can drain from the rock system is ~6–7 vol.% (e.g. Rosenberg & Handy, 2005; Yakymchuk et al., 2013). Accordingly, a value of 6 mol.%—which is approximately equivalent to 6 vol.% on a one-to-one oxygen basis—is used as the inverse step size for the reintegration of melt until the final reintegration. For the final

![Composite summary of $P$–$T$ phase diagrams calculated during inverse melt reintegration modelling. Rightmost panel as in Figure 8a, and melt is reintegrated in each step at the 1 mol.% isopleth down-$T$ along a schematic $P$–$T$ path approximately consistent with Padron-Navarta et al., (2008) with ~25°C/kbar (path defined by yellow circles). The leftmost phase diagram (<769°C) is derived after 12 mol.% melt reintegration. The solidus and the water-saturated solidus are highlighted in pale blue, and dashed dark blue, respectively [Colour figure can be viewed at wileyonlinelibrary.com]](image-url)
reintegration, only enough melt is added to just saturate the solidus. However, melt is unlikely to drain fully and may be retained on grain boundaries (Sawyer, 2001), so for each step reintegration occurs where 1 vol. % melt is present as part of the equilibrium assemblage. At this point, 5 vol. % melt with a composition in equilibrium with the assemblage at these P–T conditions is reintegrated into the bulk composition, resulting in 6 mol. % melt in the total system. At each stage, the reintegrated bulk composition is used to construct a new phase diagram for the subsequent down-temperature integration step.

5.3.2 | Results

Figure 10 summarizes the results of three melt reintegration steps in sample SG25, using modified bulk compositions presented in Table S4. Melt reintegration was also performed in a single step melt increment (as in Bartoli, 2017) and along different P–T paths (not shown) to test the sensitivity of the approach to these central assumptions. While the size of the integration steps determines how many drainage events are inverted, results differ very little from those described given the only minor shifts in melt composition with small changes in P–T.

Starting with the peak assemblage containing 1 vol. % melt and approximate peak conditions as constrained in Section 5.1 (11 kbar and 877°C), 5 mol. % melt was reintegrated into the bulk composition following the method described above. The topology of the resulting phase diagram is broadly similar to that modelled at peak—with most pressure-sensitive equilibria having shifted negligibly. The second integration step is modelled at 7 kbar and 777°C, conditions in equilibrium with 1 vol. % melt, ~3 vol. % augite, ~14 vol. % orthopyroxene, ~66 vol. % plagioclase, ~3 vol. % ilmenite, ~12 vol. % hornblende, and <1 vol. % quartz. This relatively steep decrease in pressure was chosen to bring the assemblage in line (at least in terms of phases present if not their abundance) with the documented hornblende-bearing gabbroonites and is consistent with the P–T path of Padron-Navarta et al. (2008) along which dehydration melting is proposed to have occurred. During the third and final integration step, the composition of the melt was calculated at 6.5 kbar and 769°C, in a simulated assemblage containing 1 vol. % melt, ~1 vol. % augite, ~3 vol. % orthopyroxene, ~66 vol. % plagioclase, ~4 vol. % ilmenite, ~25 vol. % amphibole, and <1 vol. % quartz. Reintegration of only 2 mol. % melt was required to elevate the H2O-saturated solidus to between 710 and 750°C (Figure 10, leftmost panel).

Thus, reintegration of only ~14 mol. % melt is required to saturate the solidus. At this point the bulk chemical composition of the system approximates that of a plausible protolith composition potentially represented by the combined range of compositions of KH7 (Table 3) and the suite of hornblende-bearing two-pyroxene gabbros presented by Yamamoto and Yoshino (1998; their table 1). According to Figure 9, the down-T extension of the postulated prograde P–T path with a bulk of this composition would result in a H2O-saturated subsolidus protolith assemblage at ~6 kbar comprising 63–66 vol. % plagioclase, <2 vol. % biotite, two clinopyroxenes totalling ~25–30 vol. %, <4 vol. % ilmenite, and <1 vol. % quartz; no such lithology has been documented in the Jijal Complex.

Alternatively, a possible prograde evolution may have involved suprasolidus emplacement of a primary amphibole-bearing gabbroonite already into mid-crustal levels at conditions of ~6–7 kbar and >750°C, with progressive dehydration melting on burial and pressure increases of ~4–5 kbar. In this scenario ~5–10 vol. % trondhjemitic melt would be removed from the restite during melting to 877°C, and a potential amphibole-bearing gabbroonite protolith with the recalculated bulk composition would be expected to contain 12–23 vol. % amphibole. While this may be plausible, modes of ortho and clinopyroxene contents are dramatically underpredicted by these models.

6 | IGNEOUS MODELLING

Despite its anomalous thickness more comparable to continental arc batholiths such as the Sierra Nevada, the Kohistan Arc is broadly interpreted to represent juvenile igneous crust, derived mainly from partial melting in an intraoceanic arc setting (e.g. Bard, 1983; Tahirke, 1979). The Chilas Complex and Southern Plutonic Complex and Kohistan Batholith have been shown to have formed along distinct liquid lines (Jagoutz et al., 2011), and recent work by Jagoutz and Schmidt (2013) demonstrated that mafic/ultramafic cumulates at the base of Kohistan can be extracted from primitive melts, with the section in the vicinity of the petrological Moho representing gravitationally unstable cumulates that would be expected to founder. However, the relative contribution of high-P igneous crystallization of primitive melts to the development of garnet-clinopyroxene metagabbro assemblages, in particular, remains uncertain. As discussed by Jagoutz et al. (2006) and Münntener and Ulmer (2018), deep-seated cumulates are often not controlled by simple crystallization mechanisms (e.g. fractional or equilibrium crystallization), but are complex systems with various degrees of trapped melts, intercumulus liquids and magma mixing. However, by sampling the bulk composition and modal phase proportions of instantaneously fractionating solids along a cooling path, a first-order assessment of whether the cumulate textures in the deepest levels of the Upper Jijal Complex may have been produced via magmatic crystallization during arc development can be made.
The MELTS algorithm (Asimow & Ghiorso, 1998; Ghiorso & Sack, 1995) was executed through the alphaMELTS package v1.9 (Smith & Asimow, 2005). As with metamorphic THERMOCALC modelling, crystallization simulations were performed in the NCKFMASHTO system. No trace element compositions were incorporated. Simulations were conducted with 5°C step intervals along isobaric $P$–$T$ paths, at pressures that broadly bracket the baric conditions of lower crustal pressures and garnet core re-equilibration determined in Section 5.1, 8–14 kbar.

Two hydrous bulk compositions were used for crystallization models (Table 3): (a) an average primitive oceanic arc basalt of Kelemen et al. (2003) which is comparable to the calculated composition of primitive calc-alkaline–tholeiite arc melts in Kohistan of Jagoutz and Schmidt (2013); and (b) a derivative andesitic melt, initially derived from a series of crystallization experiments on natural arc-derived compositions by Kägi (2000) and remixed experimentally by Alono-Perez et al. (2009). Fractionated intermediate andesites may contribute significantly to the growth of average andesitic–dacitic arc crust (Mg# 0.43–0.55) and are often in equilibrium with mantle harzburgites at lower crustal depths (e.g. Müntener et al., 2001). This evolved composition prohibits extensive crystallization of an ultramafic component. Oxygen fugacity in the melt was fixed via Fe$_2$O$_3$–FeO ratios.

### 6.1 Results

Instantaneous solid bulk compositions modelled during fractional crystallization of an average arc basalt from above the
liquids to the high-\( T \) conditions of annealing at ~800°C are presented in Figure 11; corresponding phase proportions are also shown. Results for derived andesite starting compositions are presented in Figure S6. To assess whether fractionated material could plausibly accumulate in the lower upper Jijal Complex, predicted solid compositions are compared to the average bulk composition of Jijal garnet–clinopyroxene gabbros containing Type 1 garnet (Table 3), recalculated to omit late crystallized plagioclase and quartz. Accordingly, recalculated volumetric proportions of garnet and clinopyroxene are 65%–79% and 21%–35%. Owing to likely chemical re-equilibration of all solid assemblages as discussed in Section 5.1, primary chemical compositions predicted by the thermodynamic routine are not presented.

For low \( \text{H}_2\text{O} \) and pressure simulations, orthopyroxene is saturated at the solidus, and as \( \text{H}_2\text{O} \) wt% and pressure increase olivine is stabilized at the solidus. At all pressures and \( \text{H}_2\text{O} \) contents, crystallization of this early high-Mg phase is followed by a ~100–175°C interval of augite fractionation (with or without simultaneous fractional fractionation of <7vol.% orthopyroxene). Subsequently, simultaneous fractionation of garnet and augite occurs over a thermal interval of 150–200°C, forming ~65–85% and 10%–35% of the solid assemblage respectively. At liquid \( \text{H}_2\text{O} \) contents ≤4 wt%, higher volumes of augite are stabilized, whereas at ≥6 wt% \( \text{H}_2\text{O} \), augite makes up only ~12% of the garnet-bearing assemblage.

At high pressures and \( \text{H}_2\text{O} \) contents, exhaustion of MgO in the remaining bulk is followed by a period in which garnet is the only major crystallizing phase, whereas at low pressures and \( \text{H}_2\text{O} \) contents, exhaustion of MgO leads to the loss of clinopyroxene and stabilization of plagioclase in garnet-bearing assemblages. In all simulations, spinel fractionation begins at ~1,000–1,050°C, and forms less than ~1 vol.% of the solid assemblage. At 2 wt% \( \text{H}_2\text{O} \) and <10 kbar, spinel forms only in an assemblage containing garnet and feldspar, whereas at higher \( \text{H}_2\text{O} \) contents, it is modelled to fractionate with garnet and clinopyroxene for much of the isobaric path. Spinel has not been observed in Jijal garnet–clinopyroxene gabbros. However, preservation of primary magmatic spinel is relatively uncommon owing to the propensity for spinel to be compositionally altered during metamorphism (e.g. Guice et al., 2021), and the widespread prediction of accessory spinel does not negate the general applicability of the results. At 14 kbar and ≥4 wt% \( \text{H}_2\text{O} \), late fractionated solids contain titanite in equilibrium with garnet below ~860°C, and at 10–14 kbar and 2–4 wt% \( \text{H}_2\text{O} \) corundum and oxides are in equilibrium with feldspar and minor garnet.

Derived andesite compositions can also produce the observed assemblage (Figure S6). In this case, augite is always saturated at the solidus. As in more primitive basaltic compositions, garnet and augite (with or without spinel) fractionate at a wide range of \( P-T-X(\text{H}_2\text{O}) \) conditions. Garnet and augite vol.% are lower (50%–75%) and higher (25%–35%), respectively, than the basaltic case, and are therefore similarly aligned with the recalculated modal abundances. Plagioclase-bearing assemblages are stabilized at higher temperatures.

Comparison of the effective mafic-corrected bulk composition to those predicted to be extracted during fractional crystallization confirms that the cumulate garnet–clinopyroxene assemblage in Jijal gabbros can be attributed to simple fractional crystallization of an average primitive basaltic melt or derived andesite. Simultaneous garnet and augite fractionation is predicted at a wide range of pressures, temperatures, and initial \( \text{H}_2\text{O} \) contents, precluding precise constraints on the conditions of lower crustal crystallization. In both the andesitic and basaltic case, progressive increase in the FeO and Al\( _2\)O\(_3\) and depletion of SiO\(_2\) and CaO of the fractionating solids at the onset of garnet fractionation and increase in the SiO\(_2\) and decrease in FeO at the cessation of garnet-augite fractionation define the start and end of the relevant crystallization interval. Combined with constraints from the stable solid assemblages, matching the recalculated bulk composition to that of the predicted bulk solid in this region broadly restricts the conditions of simultaneous garnet–clinopyroxene crystallization from an average island arc basalt to ~900–1,250°C, depending on the \( \text{H}_2\text{O} \) of the liquid and the pressure of crystallization. At \( \text{H}_2\text{O} \) ≤4 wt% where the relative modal abundances are best matched, this interval ceases at ~1,000°C. Towards higher pressures the interval of co-crystallization with spinel is reduced, potentially pointing to higher pressure conditions for extraction of the observed solids.

If garnet–clinopyroxene gabbros—regardless of whether their present assemblage was derived from igneous or metamorphic processes—equilibrate at high temperature and undergo isobaric cooling, additional subsolidus garnet growth (potentially between 10 and 20 vol.%) may be expected as discussed in Section 5.2. This may preclude crystallization from basaltic liquid compositions containing ≥4 wt% \( \text{H}_2\text{O} \), which predominantly crystallize garnet during garnet–clinopyroxene co-crystallization. However, documented occurrences of garnetite in the Jijal Complex (e.g. Yamamoto & Nakamura, 2000) may be linked to fractional crystallization of these melts.

Results of MELTS major element modelling therefore suggest that the observed cumulate assemblages can be produced via magmatic crystallization at a wide range of lower crustal conditions, from both primitive and more derived melts. In the former case, widespread garnet–clinopyroxene fractionation and the predicted compositional evolution allow crystallization of Jijal gabbros across a range of lower crustal pressure (8–14 kbar), likely from a low \( \text{H}_2\text{O} \) content (≤4 wt%) melt. Here we have only considered crystallization of mafic phases, but simulations are also consistent with late intercumulus feldspar crystallization from residual liquids after cumulate garnet and clinopyroxene fractionation.
DISCUSSION

7.1 Choice of thermodynamic database for metamorphic models

With the recent publication of $a$–$X$ relations for metabasic phases comprising silicate melts with trondhjemitic–tonalitic composition, augitic clinopyroxene, and potassic and Ti-bearing amphibole (Green et al., 2016) a relative refinement to the reproduction of metabasic granulitic assemblages might be expected. Results of modelling in Section 5 using ds62 and Thermocalc version 3.47 are provided in Figure S3.

The positioning of univariant lines using the two databases is broadly comparable and at near-equivalent $P$–$T$, although solidi are shifted down temperature ~75–100°C with ds55 compared to ds62. The latter serves to slightly reduce the apparent intersection of the isopleths due to the decrease in temperature of $X_{Prp}$ content at subsolidus conditions. Gridding the anhydrous SG35 Grt+Cpx+Pl+Qz+Rt field from 9 to 15 kbar and 750–1,050°C (Figure 12) for both sets of models indicates that the observed garnet compositions only partially intersect those calculated, and that core compositions are better matched by ds55. However, some of the most Mg-rich and Ca-poor garnet compositions still cannot be matched using the older $a$–$X$ models. Overall, ds62 and ds55 produce comparable and within-error compositional constraints on the conditions of peak chemical re-equilibration. Given the near-anhydrous bulk composition and limited stabilization of hornblende-bearing assemblages of the modelled samples, this is not unexpected. As detailed by Forshaw et al. (2019), only when sufficient H$_2$O stabilizes high modal abundances of hornblende do significant discrepancies appear in the amphibole and pyroxene modes predicted by ds62.

However, problems arise with the prediction and convergence of mineral modes and compositions on the cooling path using ds62. The modelled isopleth intersections of the garnet rim compositions fail to converge on the observed Grt–Cpx–Pl modes along any cooling path from either core, and consistently underpredict clinopyroxene and garnet volumes (by ~4%–12%) and overpredict plagioclase volumes (by ~11%–13%). While both models underpredict Al cpfu in clinopyroxene, clinopyroxene Al cpfu in ds62 is approximately half that in ds55; the resulting deficit may be counterbalanced by the increased mode of plagioclase using ds62 (47%–51%) compared to ds55 (41%–43%). Similarly, $X_{Mg}$ and $X_{Mn}$ in clinopyroxene and $X_{An}$ in plagioclase fail to adequately converge using any amount of fractionation along cooling paths in ds62.

In both sets of models $X_{Fe^{3+}}$ is overpredicted in garnet. Core Fe$^{3+}$ values in SG25 are ~0.06 cpfu, overpredicted by both ds55 and ds62 as 0.10–0.13 and 0.13–0.15 respectively. However, average rim Fe$^{3+}$ in SG25 (equivalent to the core at 0.06 cpfu) is well predicted by ds55 across the suite of fractionation scenarios (0–0.06 cpfu), whereas fractionation only slightly decreases Fe$^{3+}$ content from rim to core in ds62 (0.10–0.11 cpfu). The older model does not consider Fe$^{3+}$ in clinopyroxene, whereas ds62 does a relatively good job of predicting absolute Fe$^{3+}$ in augite along the range of starting conditions and potential cooling paths (0.054–0.066 cpfu compared to the measured ~0.064 cpfu). However, progressively worsening underprediction of clinopyroxene vol.% with increasing proportions of garnet recycling in ds62 may preclude enough Fe$^{3+}$ accommodation in clinopyroxene, with the remainder going into garnet.

7.2 Formation of the Jijal Garnet Gabbros

Mafic gabbros at the base of arc crust in Jijal are akin to gabbroic rocks exposed in oceanic arc plutonic complexes such as the Tanzawa Complex in Japan (Kawate & Arima, 1998) and to the evolved gabbroic rocks from the Talkeetna Complex in Alaska (Debari & Sleep, 1991; Greene et al., 2006). In Kohistan, three hypotheses have been proposed to account for the widespread presence of garnet–clinopyroxene gabbros: (a) solid-state metamorphism of garnet-free precursor gabbros and subsolidus garnet growth (Ringuette et al., 1999); (b) in-situ lower crustal igneous crystallization of mantle-derived melts (e.g. Jagoutz et al., 2011; Miller et al., 1991; Ringuette et al., 1999); and (c) dehydration/dehydration melting of amphibolite-bearing arc plutonic rocks, forming
restitic garnet–clinopyroxene gabbros (Garrido et al., 2006; Yamamoto & Yoshino, 1998). Discriminating between these scenarios has proven contentious, and here we consider our textural and modelling results with reference to these hypotheses.

### 7.2.1 High-P cumulate crystallization

Regardless of the systematics of the source, the original plutonic origins of these units are undisputed (e.g. Jagoutz & Kelemen, 2015; Müntener & Ulmer, 2018), and are evidenced by the widespread preservation of cumulate microstructures in the Upper Jijal Complex. Whole-rock trace element geochemistry of the garnet–clinopyroxene gabbros has been interpreted to at least partially reflect their cumulate nature (Garrido et al., 2006), although the nature of this magmatic source is contentious with respect to its subduction versus mantle component (e.g. Dhuime et al., 2007; Ewing & Müntener, 2018). Rutile Hf(i) varies between 11.4 ± 3.2 and 20.1 ± 5.7 across 2 km of variably retrogressed garnet–clinopyroxene gabbros (Ewing & Müntener, 2018), and isotope systematics from the Sarangar Gabbro are indistinguishable at Hf(i) = 14.2 ± 0.2 (Schaltegger et al., 2002). Within the relatively low precision achievable for rutile isotope systematics, this indicates a single source for magmas that make up the assessed mafic section (although sampling of Ewing and Müntener 2018 excluded the northernmost coronitic samples). Dhuime et al. (2007) showed that this source may be distinct from the magmatic source from which the ultramafic section of the Jijal Complex, potentially precluding the possibility that the mafic and ultramafic sections are related to each other via progressive fractionation of a single batch magma. Conversely, petrochemical models of Jagoutz and Schmidt (2013) demonstrated that integration of deep cumulates and overlying andesitic bulk Kohistan crust reproduced the major and trace element composition of the bulk arc basalts.

However, the question remains whether any primary garnet existed in the source, either providing nuclei for granulite facies overprinting and garnet growth or forming primary assemblages comparable to those presently observed which (re-)equilibrated at ~850–1,000°C and ~11–14 kbar during metamorphism.

Experimental constraints on crystal fractionation of water-undersaturated andesites, derivative andesites, and basaltic andesites have been obtained by Müntener et al. (2001) and Alonso-Perez et al. (2009) respectively. At pressures of 8 kbar, Alonso-Perez et al. (2009) showed that crystallization of hydrous andesite with 4–8 wt% H₂O formed garnet- and plagioclase-rich assemblages. At pressures of 12 kbar, the fractionating assemblage is highly sensitive to H₂O content: above 8 wt% precludes clinopyroxene crystallization between 1,000 and 800°C; at 6 wt%, liquidus garnet is followed by clinopyroxene and trace amphibole; at 4 wt% both garnet and clinopyroxene are liquidus phases followed by clinopyroxene and then plagioclase. Consistent with MELTS modelling presented here, clinopyroxene is generally only stable at temperatures exceeding 900°C.

In line with constraints derived from experiments and trace element simulations, first-order equilibrium thermodynamic results obtained in this study indicate that a portion of the observed garnet–clinopyroxene gabbroic sequence may represent the fractionated crystallites formed during locally isobaric cooling at a broad range of lower crustal pressures from >8 to 14 kbar. For primitive basaltic parental magmas, H₂O contents <4 wt% are preferred. A hydrous derived andesite containing 2–6 wt% H₂O between 8 and 14 kbar is expected to simultaneously fractionate garnet and clinopyroxene at >900°C. These models may also account for the development of garnetite bodies within the upper Jijal Complex. In general, the relative scarcity of hornblende-rich rocks is consistent with the low melt H₂O content. It is important to note, however, that these results derive from isobaric crystallization simulations, whereas natural liquids may be locally isobaric but largely result from polybaric crystallization (e.g. Melekhova et al., 2015).

Final solid assemblages are likely mixtures of mafic cumulate assemblages and feldspar derived from in situ residual melt crystallization. If mafic and ultramafic sections are indeed derived from different sources (Dhuime et al., 2007; Garrido et al., 2007), garnet-bearing mafic assemblages may be unrelated to underlying ultramafics via fractional crystallization of basaltic magmas. In this case, modelled stabilization of liquidus olivine along low-P cooling trajectories in melts with low H₂O contents perhaps precludes such compositions as a parental source of garnet–clinopyroxene gabbros, but these discrepancies might be a consequence of further differentiation, partial assimilation, and mingling processes (e.g. Müntener & Ulmer, 2018).

Crystallization models yield solids that contain the required high volumes of garnet, precluding the ubiquitous need for significant subsolidus garnet growth during granulite facies metamorphism in at least the deepest levels of the lower crust. However, in solids containing less magmatic garnet than now documented (derived, e.g. from andesitic liquids with 2–4 wt% H₂O and at lower pressures), cumulate garnet may have served as effective nuclei for additional garnet growth, yielding samples containing both Type 1 magmatic and Type 2 metamorphic garnet. These results are at odds with Garrido et al. (2006), who suggest, based on REE modelling and constraints of Müntener et al. (2001) that neither primitive basalts nor derived andesites can account for Jijal garnet–clinopyroxene gabbros. Given relatively limited shortening in lower crustal exposures at the base of the arc and the pronounced transition between Type 1 and Type 2
garnet morphologies, and assuming Type 2 assemblages experienced negligible textural reorganization/equilibration, as much as 60%–70% of the Jijal garnet–clinopyroxene gabbronorite yielded assemblages containing ∼80% of the total final volume of garnet. This value may be significantly higher in the case that slightly deeper samples underwent textural reorganization/equilibration, with sluggish transport kinetics in these anhydrous rocks even at peak temperatures yielding coronitic and strongly diffusion-limited microstructures.

7.2.2 | Solid-state metamorphic reaction

There is widespread agreement that granulite facies metamorphism was ubiquitous across the deepest levels of Kohistan (e.g. see references in Petterson, 2010). However, the contribution of garnet exclusively formed by subsolidus metamorphic transformation to the assemblages in the mafic Jijal sequence has not been extensively documented (see Garrido et al., 2006; Ringuette et al., 1999). Petrographic and statistical assessment of microstructures in this study has indicated a systematic deviation in the departure from randomness that relates to position at the base of the Kohistan Arc. Moving from deepest to shallowest structural levels (i.e. south to north geographically), primary cumulate phase associations (Figure 3a,b) with statistically random microstructures give way to progressively non-random textures, with the middle of the sequence containing texturally igneous garnet alongside metamorphic garnet and overgrowths (Figure 3d), and the shallowest extent of the sequence culminating in the exclusively coronitic and highly non-random microstructures (Figure 3c). These microstructures demonstrably preserve evidence of solid-state Reaction 1, with sluggish transport kinetics in these anhydrous rocks even at peak temperatures yielding coronitic and strongly diffusion-limited microstructures.

The dry Jijal gabbronorite that is present in discontinuous pods in the upper portion of the Upper Jijal (e.g. KH7) records maximum equilibrated conditions of <10 kbar and 800–950°C. The loss of orthopyroxene and ilmenite and the growth of garnet via Reaction 1 in the gabbronorite/two-pyroxene gabbro upon pressure increases of ∼2–3 kbar (burial by ∼7–10 km) can be documented along reaction fronts bounding bodies of the two lithologies in the field, and was the primary mechanism by which metamorphic garnet–clinopyroxene gabbros developed in at least the shallowest 1.5 km of the Jijal Complex (∼20% of the total thickness). This value may be significantly higher in the case that slightly deeper samples underwent textural equilibration during or subsequent to solid-state reaction. This transformation of the gabbronorite yielded assemblages containing ∼80% of the total final volume of garnet.

Metastable preservation of this precursor to garnet–clinopyroxene gabbros may be linked to heterogeneous fluid transfer prior to granulite facies peak conditions. Re-equilibration may have been facilitated by CO₂ rich fluids, as evinced by the presence of metasomatic sulphate-type scapolite in some garnet–clinopyroxene assemblages (Yoshino & Satish-Kumar, 2001). The transformation was evidently isochemical with respect to major elements, given the widespread similarity in bulk compositions, and the preservation of cumulate aspect ratios in coronitic metagabbros (e.g. see Yamamoto & Nakamura, 1996) attests to the bulk of the reaction occurring prior to significant deformation across the basal levels of Kohistan. The suggestion that this reaction front represents the formation of garnet–clinopyroxene gabbros at the expense of hornblende-bearing gabbronorites via the breakdown of primary igneous hornblende only (e.g. Bard, 1983; Yamamoto & Nakamura, 2000) seems unlikely, as all amphiboles in studied gabbronorite assemblages are secondary.

Gabbronorites of the Sarangar unit—geochemically and texturally distinct from the Jijal gabbronorites but with a comparable mineral assemblage and metamorphic facies—did not undergo any transformation. Owing to the extensive amphibolite facies shear zones associated with the unit, its precise position during burial is unclear. However, its presence constrains the approximate pressure of the contact between the two to the narrow pressure conditions across which modelling indicates transformation occurs, at 10–11 kbar.

In addition to the formation of garnet–clinopyroxene gabbros from the in situ transformation of the Jijal gabbronorites, secondary subsolidus growth of the remaining 15–25 vol.% garnet is anticipated to have occurred during cooling from peak temperatures. Garnet growth along this cooling path may also have added volume to primarily igneous garnet, which is underpredicted in some MELTS models. While Type 2 garnet overgrowing Type 1 garnet is preserved in many cases, the lack of distinct metamorphic texture in some deeper samples may relate to variation in the reactions driving subsolidus syn-cooling growth between samples, or to the fact that at greater depths the slight increase in temperature would have facilitated more efficient kinetics, inhibiting the formation of transport-limited microstructures.

7.2.3 | Dehydration melting

As is the case for petrogenesis of lower crustal garnet–clinopyroxene gabbros in Milford Sound, New Zealand (e.g. Daczko et al., 2001), dehydration melting of amphibole-bearing gabbronorites is commonly invoked as the principal mechanism by which restitic garnet–clinopyroxene gabbros formed throughout the upper Jijal Complex (Garrido et al., 2006). Similarly, garnet hornblendites—which exhibit lithological contacts parallel to the palaeo-Moho and which are isotopically distinct from surrounding garnet–clinopyroxene granulites (Dhuime et al., 2007)—are
interpreted have formed as a consequence of dehydration melting of a precursor garnet-free hornblende interbedded within the dominant and primary gabbronorites. Based on their major and trace element signatures, and potentially similar ages of high-\textit{P} metamorphism (c. 97 Ma) and granitic bodies (97–36 Ma), granitic melts produced by melting of both lithologies have been proposed as a source for bodies of the Patan–Dasu Metaplutonic Complex to the north of the Jijal Complex (Garrido et al., 2006; Schaltegger et al., 2002).

By fully reintegrating melt in equilibrium with the observed assemblage, results of this study indicate that a potential protolith assemblage may have contained less than \textasciitilde 20 vol.% amphibole. Progressive dehydration melting of this precursor from \textasciitilde 6 to 8 kbar to approximate peak conditions is modelled to produce a maximum 14 vol.% melt. However, the suggestion that these melts form the Patan–Dasu Metaplutonic Complex seems implausible given the large volumes of melt required (or conversely, exceedingly large volumes of precursor with low-degree melts), and the significant melt migration required in this scenario. Moreover, given that down temperature extrapolation of this bulk composition to H$_2$O-saturation yields modelled assemblages outside the reasonable realm of possibility (i.e. entirely lacking orthopyroxene), the degree of melting may not have been as significant.

Reintegration of only 10 mol.% melt into the restitic bulk maintains the calculated stability of hornblende–gabbronorites at \textasciitilde 6–7 kbar and \textasciitilde 765°C (second from left panel in Figure 10), contrary to the total loss of orthopyroxene at temperatures less than 765°C when additional (i.e. >10 mol.%) melt is reintegrated (as in leftmost panel of Figure 10). However, even with this low degree of melting, precursor gabbronorites would contain \textasciitilde 5% pyroxene. This combined with the high modes of amphibole (~12%–26%) required to produce low-volume melts is inconsistent with any preserved amphibole-bearing gabbronorites which are documented to contain only up to 8 vol.% primary hornblende (Yamamoto & Yoshino, 1998).

Despite the inability of melt reintegration models to adequately elucidate dehydration melting the presence of low-degree leucocratic veins that cross-cut garnet–clinopyroxene gabbros do attest to some anatexis, in addition to the unrelated leucosome in the vicinity of hornblendite pods. Garrido et al. (2006) also suggest from their geochemical modelling that the amount of peritectic garnet formed by hornblende melting is relatively small (<5%), consistent with the sparse distribution of this garnet-bearing leucosome in the field. Primary and suprasolidus amphibole-bearing gabbronorites may therefore have formed the precursor to some garnet–clinopyroxene gabbros, but constraints on this as a potentially widespread and volumetrically significant rock-forming process are still lacking in the Jijal Complex.

7.3 Tectono-metamorphic evolution at the base of an arc

It is clear from combined constraints presented in this and other studies that the formation of the garnet-bearing granulitic assemblages may require contribution from all three garnet-forming processes: igneous crystallization, dehydration melting, and solid–solid reactions resulting from a pressure increase during burial. Thus, a model that links the formation of the Jijal Complex with the wider crustal evolutionary framework (cf. Petterson, 2010) and previous metamorphic and geochronological studies is presented and summarized in Figure 13.

From c. 120 Ma to c. 105 Ma, northwards-directed subduction of the palaeo-Tethys at a boundary between old and young crust (Dhuime et al., 2009) initiated magmatism and arc volcanism in the Jijal Complex. The ultramafic–mafic transition now exposed is widely recognized to reflect the upper mantle–lower crustal Moho transition zone during this period (e.g. Garrido et al., 2006; Jan, 1988; Khan et al., 1998; Yamamoto, 1993; Yoshino & Okudaira, 2004), below which some fractionated ultramafic hornblende cumulates probably crystallized (Garrido et al., 2006). While potentially genetically and geochemically distinct from the underlying mantle sequence (e.g. Dhuime et al., 2007, 2009), coeval intrusion of more evolved and layered basaltic–andesitic melts is evidenced by the predominance of 118–117 Ma Sm–Nd isochron ages in the plagioclase-bearing gabbronorites in the upper Jijal Complex (Yamamoto & Nakamura, 1996). These metastable precursors to garnet–clinopyroxene gabbros (like KH7) were emplaced and
equilibrated (with respect to their major elements) at <10 kbar. At its basal levels (10–12 kbar) MELTS modelling presented in this study indicates that early crustal accumulation may also have proceeded via emplacement of an orthopyroxene-free assemblage. This assemblage, derived from a range of basaltic–andesitic melts at low H2O contents, potentially contained a significant proportion of cumulate garnet and clinopyroxene, with later interstitial crystallization of feldspar from residual liquids.

Given low internal strain in the mafic Jijal sequence, and the relatively sparse distribution of late shear zones, it is likely that the vertical thickness from the petrological Moho to the top of the shallowest Jijal gabbronorites was similar to that observed today, on the order of 5–7 km. While the original position of the upper contact is ambiguous as a consequence of the intrusion and shearing associated with the emplacement of the Sarangar Gabbro, this thickness represents not much more than a few kbar of pressure at ~10–14 kbar. Despite poor constraints on the upper pressure limit of primary crystallization from MELTS, this is consistent with the relatively limited range of peak granulite facies re-equilibration from the base to the top of the Jijal Complex magmatic bodies (Figure 7). In that context, primary assemblages containing garnet, clinopyroxene, and feldspar may have both fractionated and re-annealed during the subsequent period of granulite facies conditions at very similar P–T conditions. Previous higher pressure estimates of >17–20 kbar for the crystallization of mafic precursors (e.g. Jan, 1979; Ringue et al., 1999) seem unlikely.

Subsequent to emplacement of the layered bodies that comprise the upper Jijal Complex, the Sarangar Gabbro was intruded at c. 99 Ma (Schaltegger et al., 2002). This unit annealed in the two-pyroxene granulite facies together with the older and deeper Jijal gabbronorites. Pristine examples of these units are preserved in the otherwise highly retrogressed Sarangar Gabbro where deformation is reduced.

Shallow intrusion of gabbro and diorites (i.e. the Patan, Kiru, and parts of the Kamila magmatic sequence) resulted in progressive tectonic thickening and over-accumulation of younger units and burial of earlier bodies in the roots of the growing arc edifice. While the latter may also have had a heating effect (e.g. Waters, 1990), in-situ solid-state replacement of the Jijal gabbronorite assemblages by coronitic garnet–clinopyroxene granulites requires a 2–3 kbar pressure increase. This implies initiation of burial of the whole upper Jijal Complex by a further ~7–10 km to peak re-equilibration conditions of 850–1,050°C and 11–14 kbar after the 99 Ma crystallization of the Sarangar Gabbro, at 96–91 Ma (Anczkiewicz & Vance, 2000; Yamamoto & Nakamura, 2000). These peak temperatures are consistent with recent Zr-in-rutile thermometry of Nakazawa et al. (2020). As discussed by Yoshino and Okida (2004), in the absence of an unusually high geothermal gradient in Kohistan the maintenance of these high temperatures at the base of the crust, relatively distal to an intraplate heat source, may be compensated by an additional heating component derived from simultaneous magmatic underplating at the base of the crust.

Following Garrido et al. (2006), this pressure increase may have also resulted in dehydration melting of hornblende-bearing plutonic bodies, leading to the formation of mafic and ultramafic restites in the Jijal Complex (<5 vol.% and small volumes of LREE-enriched melts (probably a carbonic fluid and/or trondhjemitic melt) that accumulated in shallower levels of Kohistan. The lack of primary chemistry preserved in coarse restitic garnet in the Jijal Complex (Figure 4d) indicates that melting occurred prior to or concurrent with high P–T peak equilibration in the rest of the complex, at c. 98–91 Ma (Anczkiewicz & Vance, 2000; Yamamoto & Nakamura, 2000).

The maximum extent of burial along anticlockwise P–T paths is constrained by conditions of compositional re-equilibration of garnet (and presumably other phases) in the granulite facies, at ~11–14 kbar and 850–1,050°C. This pressure is notably lower than the ~15–21 kbar estimates of Jan (1979) and Ringue et al. (1999) and indicates a depth to the petrological Moho of ~45 to 50 km at c. 98–95 Ma. If, as is indicated by Melts modelling, a large proportion of the assemblage was already present in the deepest portions of the Upper Jijal Complex at incipient burial, little reaction may have occurred, thus requiring chemical re-equilibration only. For the likely case in which solid-state reaction occurred upon burial, reaction textures are not preserved anywhere but in garnet–clinopyroxene gabbros containing both Type 1 and Type 2 garnet.

Broadly consistent with the shape of the inferred path of Ringue et al. (1999), metamorphic modelling in this study indicates peak metamorphic conditions were followed with a period of approximately isobaric cooling to ~12 kbar and 700–750°C. This cooling to upper amphibolite facies conditions at or c. 91 Ma (Yamamoto & Nakamura, 1996) was unlikely to have been accompanied by significant deformation or exhumation.

Following cooling, a major episode of intra-arc shortening deformation occurred in the southern Kamila Complex, probably associated with the collision of Kohistan with Eurasia (cf. Petterson, 2010). This resulted in the development of SSW-directed reverse-sense shearing over the southern Kamila and northernmost Jijal Complex and thrust northeastern Kamila units over the southern Kamila (Sarangar Gabbro) and Jijal Complex (Gough, 2002). Deformation and ductile shearing was accompanied by widespread hydration under amphibolite–epidote–amphibolite facies conditions.

P–T constraints from mylonites indicate that development of anastomosing shear zones began after cooling of ~200°C without significant deformation or exhumation and continued to ~600°C and 7 kbar (Zeilinger, 2002).
Hornblende-plagioclase thermometry of Gough (2002) indicates that amphibolite facies recrystallization occurred at temperatures of 550–670°C, serving to almost entirely overprint the granulate facies assemblage of the Sarangar Gabbro/Southern Kamila amphibolites. Hydration was most likely much less pervasive in the Jijal Complex granulites as a consequence of its preservation as a relatively undeformed unit. Intrusion of garnet–hornblende pods into the Jijal Complex at 83 ± 10 Ma (Yamamoto & Nakamura, 2000) accompanied this amphibolite overprint. Mica and hornblende K–Ar and Ar–Ar cooling ages, U–Pb zircon and Sm–Nd mineral isochrons for Kohistan (e.g. Treloar et al., 1989; Yamamoto, 1993; Yamamoto et al., 2005; Yamamoto & Nakamura, 1996, 2000) together suggest that southern Kohistan and possibly the bulk of the terrane cooled through the 500°C isotherm c. 80 Ma.

8 | CONCLUSIONS

The Jijal Complex along the base of the Kohistan arc in northern Pakistan provides evidence of contiguous magmatic–metamorphic processes at the base of an evolved and long-lived island arc. Jijal garnet–clinopyroxene gabbros are uniform in assemblage but show a spectrum of microstructural variation involving two distinguishable styles of garnet growth. Mineral compositions record a stage of thorough equilibration at garnet-granulite conditions and ~45–50 km depth and c. 96 Ma, at temperatures high enough to remove any earlier igneous or metamorphic record. Thus, inferences presented here on the genetic origins of these lithologies rely heavily on their microstructures and phase equilibrium modelling.

The shallow upper portions of the Jijal Complex were likely derived from solid-state recrystallization of precursor gabbronorites, with additional metamorphic garnet grown along isobaric cooling paths to ~700°C. This transformation may not always be preserved in the form of undeformed coronitic microstructures. Conversely, in the deepest portions, major element modelling of a texturally distinct ‘primary’ garnet is interpreted to originate at least partially from high-P fractional crystallization of basaltic–andesitic melts with relatively low H2O contents. Dehydration melting of amphibole-bearing precursors is considered to contribute only minor volumes of gabbroic material to the sequence. The Jijal Complex therefore provides a unique snapshot into overlapping igneous and metamorphic processes driving intra-oceanic arc maturation processes and crustal evolution.

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ORCID

Freya R. George https://orcid.org/0000-0002-0505-9998
Jacob B. Forshaw https://orcid.org/0000-0003-2988-7832

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

Table S1 Sample list
Table S2 Microstructural statistics
Figure S3 DS6 phase equilibria
Table S4 THERMOCALC bulk compositions
Figure S5 Anhydrous phase equilibria
Figure S6 Andesitic crystallization models

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