Evolution and chronology of the Pangong Metamorphic Complex adjacent to the Karakoram Fault, Ladakh: constraints from thermobarometry, metamorphic modelling and U-Pb geochronology

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Abstract

Sillimanite and staurolite grade metamorphic rocks exhumed along the Pangong fault, the NE branch of the right-lateral Karakoram strike-slip fault in northern Ladakh, NW India, show multiple episodes of metamorphism and fabric development. Debate has centred on whether these metamorphic rocks were formed as a result of shear heating during strike-slip faulting, or whether they are exhumed earlier metamorphic rocks unrelated to movement on the Karakoram fault. Here we constrain the burial and exhumation history of the Pangong Metamorphic Complex combining the pressure-temperature evolution with accessory phase geochronology. Sillimanite grade metamorphism in graphitic pelites was superseded by the preserved P-T conditions of a Bt+Ms+St+Grt+Qtz+Fsp assemblage at 585-605°C and 6.05-7.25 kbar, equivalent to ca 20-25 km of burial. Laser ablation monazite U-Pb geochronology reveals that sillimanite grade metamorphism occurred at 108.0±0.6Ma in rocks immediately adjacent to the Pangong strand of the Karakoram fault, implying that most metamorphic rocks along the Karakoram fault were not formed by shear heating during Miocene strike-slip faulting. This age correlates closely with the ages of the Hunza granite-granodiorite batholith, and the K2 orthogneiss in northern Pakistan, and confirms that some high-grade metamorphism occurred before collision and accretion of the Kohistan arc and the Indian Plate to Asia; protracted high-grade metamorphism, and accompanying crustal thickening lasted at least 100 Myr along the South Asian plate margin. Our P-T and geochronology results also demonstrate the continuity of Cretaceous metamorphism across the Karakoram fault.

Abstract End

The Karakoram terrane is the western extension of the Qiangtang terrane of central south Tibet (Fig. 1A; Searle *et al*, 1989, Searle, 1991, Kapp *et al*, 2003). Whereas the Qiangtang terrane mainly exposes supracrustal rocks on the Tibetan plateau, the southern Karakoram is mostly comprised of deep crustal metamorphic rocks and leucogranites. The Karakoram Metamorphic Complex (KMC) consists of staurolite, kyanite and sillimanite grade metamorphic rocks and anatectic granites that extend across northern Pakistan and Ladakh into western Tibet (Fig. 1B). A ~700 km long granite batholith comprised mainly of Tertiary leucogranites (Baltoro granites) in Pakistan extends east to the Karakoram fault. Along the NE side of the Karakoram fault, the Nubra-Siachen leucogranites are interpreted to be the continuation of the Baltoro granites (Phillips, 2004).

The Karakoram fault (Fig. 1) is a major right-lateral strike-slip fault that bounds the SW margin of the Tibetan plateau (Searle, 1996, Tapponnier *et al.*, 2001). The Karakoram metamorphic complex is important, not only for determining the timing of metamorphism and crustal thickening along the Asian plate margin but also for determining the timing and magnitude of motion along the Karakoram fault. Whereas some authors propose that the Karakoram fault cuts the entire crust, has high (10-32 mm a^{-1}) slip rates and moved synchronously with generation of leucogranites (Tapponnier *et al.*, 2001, Lacassin *et al.*, 2004a, 2004b, Valli *et al.*, 2007), others propose that the fault is purely an upper crustal feature which cuts across earlier formed metamorphic and granitic rocks and has modest (<10mm a^{-1}) long-term slip rates (Searle, 1996; Searle *et al.*, 1998, Phillips *et al.*, 2004, Phillips & Searle 2007, Searle & Phillips 2004, 2007).

1. Previous Geochronology of the Karakoram

Searle & Tirrul (1991) defined four major phases of metamorphism based on regional structural mapping, preliminary P-T data, and U-Pb dating of the Miocene (25-15Ma) Baltoro granite batholith (Parrish & Tirrul, 1989, Schärer *et al.* 1990, Searle *et al.*, 1992) in northern Pakistan. The KMC, together with the Cretaceous Hunza batholith (Crawford & Searle, 1992), and the Miocene Baltoro batholith, represent the exhumed southern margin of the Asian plate that is now sutured against the western Himalaya (Indian Plate). Fraser *et al.* (2001) carried out more comprehensive U-Pb dating of metamorphic and granitic rocks in both the Hunza and Baltoro regions of Pakistan and defined multiple episodes of metamorphism and crustal anatexis ranging from 63-4 Ma.

These authors obtained a U-Pb zircon age of 105.7±0.5 Ma from the Hunza batholith. U-Pb monazite dating suggests that peak sillimanite grade metamorphism occurred at 63.3±0.4 Ma and 44.0±2.0 Ma, with major phases of leucogranite dyke intrusion (Hunza dykes) at 52-50 Ma and 35.0±1.0 Ma (Fraser *et al*., 2001). The youngest metamorphic episodes include staurolite grade metamorphism in Hunza at 16.0±1.0 Ma and sillimanite - K-feldspar grade migmatitic gneiss domes at 5.4±0.2 Ma (Dassu gneisses) in the Baltoro region (Fraser *et al*., 2001). Although the KMC is laterally continuous, significant differences are apparent between the western (Hunza), central (Baltoro) and eastern (Nubra-Pangong, Ladakh) regions. The central region has belts of Cretaceous orthogneiss (e.g. Hushe gneiss, Muztagh gneiss, K2 gneiss; Searle, 1991, Crawford & Searle, 1992, Searle *et al*., 1992) that have been subsequently metamorphosed, but the area is dominated by the Miocene Baltoro batholith (Searle, 1991, Searle *et al*., 1992). The Hunza region is dominated by the Mid-Cretaceous Hunza Plutonic Unit but has numerous sets of leucogranitic dykes intruding both the batholith and the KMC to the south (Searle, 1991, Crawford & Searle, 1992, Fraser *et al*., 2001).

In the Pangong region of northern Ladakh (Figs. 1B & 2A) the right-lateral Karakoram fault splays into two branches, a south-western strand (Tangtse fault) and a north-eastern strand (Pangong fault). In this region orthogneisses and amphibolites have been intruded by later leucogranite sheets (e.g. Tangtse and Muglib granites), and extensive dyke-sill networks (Weinberg & Searle, 1988, Searle *et al*., 1998, Phillips, 2004; Phillips *et al*., 2004; Weinberg & Mark, 2008). A tract of staurolite grade schists, the Pangong Metamorphic Complex, occurs immediately adjacent to the Pangong fault and extends to the NNE into unmapped Chinese territory away from the Karakoram fault (Fig. 2). The same staurolite schists occur in between the two strands of the Karakoram fault.

Along the Tangtse fault Phillips *et al.* (2004) constrained the timing of ductile strike-slip shearing by U-Pb monazite (ID-TIMS) dating of early sills aligned parallel to and containing the strike-slip fabrics (15.7±0.5 Ma), and later narrow dykes that cross-cut the ductile strike-slip shear fabrics (13.7±0.3 Ma). Later brittle faults cut all the granitic and metamorphic rocks and dextral strike-slip S-C fabrics are superimposed onto all rocks along the shear zone. In contrast, Lacassin *et al*. (2004a, 2004b) interpreted all the leucogranites as syn-kinematic and hence used the U-Pb zircon age (~23 Ma) to constrain timing of right-lateral strike-slip motion along the Karakoram fault. In southwest Tibet, Valli *et al.* (2007) also proposed that U-Th-Pb leucogranite ages of ~25-22 Ma constrained the onset of deformation along the south-eastern segment of the Karakoram fault. Rolland *et al.* (2008) suggested that granulite and amphibolite facies metamorphism and generation of the Tangtse leucogranite were all formed during strike-slip shearing.

The temporal relationship between metamorphism, leucogranite formation and strike-slip shearing is the key to understanding the timing and evolution of strike-slip shear. Metamorphism could be syn-kinematic with respect to strike-slip shear (Lacassin *et al*., 2004a, 2004b, Valli *et al*., 2007, Rolland *et al*., 2008), or metamorphism could be pre-kinematic, with later strike-slip fabrics superimposed onto the already metamorphosed rocks (Searle *et al*., 1998, Phillips *et al*., 2004, Phillips & Searle, 2007, Searle & Phillips, 2004, 2007). In this paper we first describe the field relationships along this part of the Karakoram strike-slip fault and outline the differences of interpretation regarding the relative timing constraints between pre- and syn-shearing fabrics. We then present new P-T determinations, together with pseudosection modelling and new U-Pb age data that constrain the age of peak metamorphism in rocks immediately adjacent to the Karakoram fault.

2. The Pangong Metamorphic Complex

The Pangong Metamorphic complex (PMC) is a >10km wide band of steeply dipping sequence of metapelites, psammites, metacarbonates and amphibolites. It runs alongside the Pangong strand of the Karakroam fault between Muglib and Pangong Lake and then extends northeast across the lake into an unmapped area (Fig. 2). Similar staurolite schists are also present SW of the Pangong fault. NW-SE trending upright folds within the shear zone are oblique to the strike of the Pangong fault (~140^{o}) but fold axes and metamorphic fabrics swing into alignment (see stereonets in Fig. 2) with the high-strain mylonite zones along the two bounding faults (Phillips & Searle, 2007). Dextral C-S fabrics, mylonite zones and horizontal or shallow (20-40^{o}) plunging stretching lineations (Phillips & Searle, 2007) are ubiquitous. Microstructures indicate that the strike-slip fabrics are clearly younger than the regional schistosity. The Pangong fault also cuts the Muglib leucogranite and its surrounding migmatite envelope and therefore must have slipped after their formation (Fig. 3).

Pelites typically consist of the assemblage Qtz+Ms+Bt+Grt+Pl±St. Large euhedral staurolite porpyroblasts, up to 1cm long, occasionally show twinning and are pre-kinematic with relation to the dominant fabric, defined by muscovite and biotite, which wraps around them. Garnets show a pre-existing deformation fabric that consists of inclusion trails of quartz and muscovite. Garnet rims are sometimes embayed and show intergrowths of plagioclase, muscovite and chloritised biotite. Rare laths of fine-grained sillimanite occur within these intergrowths. White marble bands intercalated with the pelites are coarse-grained dolomitic and contain diopside and quartz, whilst the psammites consist of the assemblage Qtz+Bt+Ms+Pl±Grt. Prominent black bands within the marbles and pelites are amphibolites containing the assemblage: Hbl+Pl+Bt+Qtz+Grt.

3. Petrography and Mineral chemistry

The pelites of the PMC, of which six samples were specifically studied in thin section, are uniform in mineralogy and consist of the assemblage Qtz+Ms+Bt+Pl+Grt±St with accessory graphite and ilmenite. There location is shown in figure 2. Garnet and staurolite are common in the pelitic schists, occurring as 0.5–5mm euhedral to subhedral porphyroblasts in mica-rich layers. In four of the samples, garnets are texturally zoned, typically with a sharp break separating a sector-zoned core from an outer zone containing inclusions that define a tectonic fabric. In some cases the break is also marked by an annular ring of sillimanite inclusions (Fig. 4A, B). The break appears to mark a change in the garnet growth mechanism, from sector zoning with matrix displacement (Rice & Mitchell, 1991) to replacement growth. The outer zones may contain staurolite inclusions, corresponding to the matrix assemblage. Because sillimanite is not found in the matrix, we infer that these garnets have a two-stage growth history, the sector-zoned cores formed during an M1 event that culminated at sillimanite grade, and the outer zones grew during a second phase of metamorphism (M2) at staurolite grade. Such a history is similar to that of the Hunza valley section through the KMC, where protracted sillimanite-grade metamorphism (‘M1-a, b, c’) was followed by an M2 staurolite-grade event (Fraser *et al.*, 2001). An early foliation S1, defined by graphitic inclusion trails, is conspicuous in staurolite and the outer zones of some garnets (Fig. 4 c, d, e, f). This is regarded as a composite event, where often the initial S1 schistose fabric is locally micro-folded within the porphyroblasts. Porphyroblast growth over straight or folded S1 is pre-kinematic with respect to the strong matrix foliation S2, which is flattened around garnet and staurolite and is discordant to the internal fabrics.

Minerals were analysed with a JEOL JSM-840A scanning electron microscope in the Department of Earth Sciences, Oxford, equipped with an Oxford Instruments Isis 300 energy-dispersive analytical system. Accelerating voltage was 20 kV, with a beam current of 6 nA, and a live counting time of 100 seconds. It was calibrated with a range of natural and synthetic standards, and a ZAF correction procedure was used. Two feldspar-bearing graphitic schists were investigated: P19 with the assemblage Grt-St-Bt-Ms-Pl-Qtz, and P21 containing Grt-Bt-Ms-Pl-Qtz. Mineral analyses are listed in Table 1.

Biotite varies little within and between samples, with X_{Mg} (= molar Mg/(Mg+Fe)) of 0.50 (P19) and 0.45 (P21), and Ti content of 0.21 (P19), 0.23 (P21 near garnet) and 0.27 (P21 away from garnet). The presence of accessory ilmenite implies that biotite is saturated with respect to Ti. Sample P19 contains plagioclase of composition $an_{28\pm2}$ (oligoclase), whereas P21 is more calcic at $an_{45\pm2}$ (andesine).

Staurolite from P19 was homogeneous and has X_{Mg} = 0.19 and a Si content of 3.90 apfu. This lies within the range of typical values; between 3.7 and the theoretical maximum of 4. Muscovite shows a relatively small amount of phengite substitution, and a moderate amount of Na substitutes for K as a paragonite component. Sample P21 shows a homogeneous spatial distribution of muscovite composition (6.12 apfu Si and 0.13 apfu Na), but for P19 there appears to be a small systematic difference between muscovites close to and distant from garnet. Muscovites adjacent to garnet show lower Si (6.09) and higher Na (0.22) compared to matrix values away from garnet (6.18 and 0.19 respectively). These features may reflect later stages of equilibration in the neighbourhood of the garnet porphyroblasts and are consistent with a slightly higher temperature of equilibration.

The garnet composition profiles in figure 5 were generated from 256-channel line scans run for about 30 minutes, background-corrected and calibrated against spot analyses from the same profile. Garnets are compositionally zoned, with Mn-enriched cores and a rimward increase in Mg. Ca profiles are more varied, and P21 shows a Ca-rich outermost mantle. The textural break in the garnet (Figs. 4 & 5) usually corresponds to a disturbance in the zoning profile, although the outer zone commonly resumes at a similar composition to that inside the break. The preservation of steep local gradients in composition suggests that the garnets have not undergone significant diffusional modification, and thus largely preserve a record of equilibrium growth. The fluctuations near the textural discontinuity, however, may reflect disequilibrium processes analogous to those described by Chernoff & Carlson (1997).

4. P-T conditions and metamorphic modelling

Samples P19 and P21 were selected for use in the determination and modelling of P-T conditions of the PMC through time as they show a detailed record of garnet growth, attributable to changing conditions through multiphase metamorphic history. They also contain plagioclase, allowing the use of Ca-bearing equilibria between feldspar and garnet for geobarometry and P-T modelling. The only record of the M1 sillimanite grade event lies in the preservation of sector zoned garnet cores and sillimanite inclusions, and the matrix appears to have completely re-equilibrated during M2. Therefore, P-T conditions for M1 cannot be estimated. Peak M2 staurolite-grade conditions can be determined on the assumption that the garnet rim composition was in equilibrium with staurolite (in P19) and with the matrix assemblage of Bt+Ms+Pl+Qtz. Calculations were made using the current version (v5.5) of the self-consistent thermodynamic database of Holland & Powell (1998) and the computer program THERMOCALC (Powell & Holland, 1988, 1994).

In practice, many temperature sensitive equilibria are also sensitive to the composition of metamorphic fluid, and in graphitic rocks the water activity is expected to be significantly less than unity (Ohomoto & Kerrick, 1994). P-T estimates that are independent of water activity can be derived from THERMOCALC runs that do not include H_2O as an phase component, and also from independent temperature estimates derived from H_2O-free equilibria, such as the garnet–biotite Fe-Mg exchange thermometer (Holdaway, 2000) and the temperature calibration of Ti saturation in biotite (Henry *et al*., 2005). Table 2 lists the results of these H_2O-dependent and H_2O-free determinations which are then shown in figure 6.

The best estimate of M2 staurolite-grade conditions is taken as the intersection of the Holdaway garnet-biotite geothermometer (Holdaway, 2000) and the H_2O-free average P-T ellipse (Fig. 6), giving 585°C, 6.05 kbar for P19 and 605°C, 7.25 kbar for P21. Comparison with the H_2O-dependent results indicates $X(H_2O) < 1$, but the actual fluid composition is poorly constrained. The H_2O-dependent P-T result falls within the ±25°C uncertainty band of the exchange thermometer over the range 0.8–0.2 $X(H_2O)$ for P19 and 0.85–0.3 for P21. These results represent conditions predating the development of the matrix foliation that parallels the Pangong fault strand and can be compared with lower P-T syn-kinematic conditions of 460 ± 92^{o}C and 3.3 ± 2.3kbar calculated by Rutter *et al.* (2007) for calc-silicate mylonites adjacent to the fault. Although poorly constrained, the syn-kinematic results are consistent with a decompression and cooling history from M2, suggesting that pre-kinematic metamorphism in the PMC was terminated by Karakoram fault motion and subsequent transpressional unroofing.

5. Pseudosection modelling

We attempt to constrain the pre-kinematic P-T evolution of these samples using pseudosections to further quantify the metamorphism of the PMC. Bulk composition was determined by combining mineral microprobe analyses (Table 1) with volume percentages of minerals, determined from image analysis of thin section BSE images (Table 3). The garnet contribution to bulk composition was calculated from a three dimensional spherical model of garnet, combined with the compositional linescans. This ensured accuracy in the analysis of the components that are important for calculation of pressure-temperature equilibria (Mn, Ca, Fe, and Mg). Although this method of bulk composition determination may lead to reasonable errors in, for example, Si and Al compositions, these will not significantly affect the resulting pseudosection.

Pseudosections were drawn for sample P19 following the principles outlined in Walker *et al.* (2001) using THERMOCALC v.3.23 in phase diagram mode of Powell *et al.* (1998). The model system $CaO-NaO-MnO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O$ (CNMnKFMASH) was used so that all garnet end members along with muscovite and plagioclase could be modelled. Pseudosections were drawn at $aH_2O=0.75$ (Ohomoto & Kerrick, 1977). Paragonite, $NaAl_2(Si_3Al)O_{10}(OH)_2$, was included to take account of the Na content of muscovite. Initially a complete, unfractionated bulk rock composition was used for modelling (Table 3). As Ti was not being considered in the model system ilmenite was discarded from the bulk composition calculations. Pseudosections are shown in figure 7.

The M2 P-T conditions of 585°C and 6.05kbar determined for P19 lie within the field for the observed mineral assemblage (Gt+St+Bi+Pl+Qtz+Ms), showing consistency between model and observation (Fig. 7) although garnet fractionation has not yet been taken into account. However, the purpose of modelling the unfractionated composition is to attempt to constrain conditions for the M1 stage of metamorphism. The area of interest in the pseudosection is contoured in terms of spessartine, grossular and pyrope mole fraction (Fig. 7). The garnet composition at the textural break, corresponding to the most evolved stage of M1 metamorphism, was estimated at mole fractions of 0.055 spessartine, 0.04 grossular and 0.12 pyrope (Fig. 5). The isopleths representing this composition intersect within their uncertainty in the stability field of Grt+Bt+Sil+Pl+Ms+Qtz at about 5 kbar, 625°C (Fig. 7). The predicted amount of garnet at these conditions is 16% by volume; however the amount of garnet represented by the observed core zones account for only about 3% by volume. A possible explanation for the discrepancy is that much of the garnet formed during prograde M1 metamorphism was subsequently resorbed. Any textural evidence to support this has clearly been lost. Nevertheless, although the possibility remains that the most evolved M1 garnet composition has been lost, we take 625°C and 5 kbar as the best indication of M1 conditions.

The evolution of the system during the M2 metamorphism can be modelled by fractionating the M1 cores, i.e. by removing 3% by volume of garnet corresponding to the mean core composition from the bulk rock, and investigating the growth of 12% of new garnet to reach the final assemblage (Fig. 8). The fractionation of garnet from the system barely affects the position of the field boundaries on the pseudosection, but does affect the modal proportions of minerals within phase fields. We therefore contoured the phase field of interest relating to the M2 assemblage (Gt+St+Bi+Pl+Qtz+Ms) in terms of garnet and staurolite modal percent (by volume). An adequate match to the volume and composition of newly-grown garnet is found in the P-T region of the M2 conditions determined by geothermobarometry (Fig. 8), in the presence of about 7% of staurolite, slightly more than the 5% observed.

The P-T evolution between M1 to M2 is likely to be complex and is not recorded by these rocks. Considering metamorphism was protracted through time in the Karakoram crust elsewhere in the region (Fraser *et al*., 2001), metamorphism here may also be separated in time to some greater or lesser degree. *– not quite sure what you mean by this sentence but don't think you can have 'protracted through time', protracted infers an extended time. And what do you mean by 'metamorphism here may also be separated in time to some greater or lesser degree'? Metamorphism separated in time? Do you mean different metamorphic events or similar metamorphic events occur at different times across the Karakoram?* Other P-T paths determined in this area have revealed shallow cooling P-T paths (Rolland *et al.,* 2008) which could be akin to the M1-M2 pressure-temperature evolution. However the preservation of compositional growth profiles in garnets suggest that elevated temperatures of >700^{o}C were not incumbent on these samples for a very long (>>10Ma) period of time (Carlson 2006).

6. U-Pb geochronology

Occasional monazite and zircon were found in sample P21, but monazite was much more abundant in sample P19. Multistage monazite growth has been used to date multiple metamorphic events in rocks both in the Himalaya (Kohn *et al*., 2005) and the Karakoram (Fraser *et al*., 2001, Foster *et al*., 2004) and was therefore used here as the primary target for dating metamorphic geochronology (Parrish, 1990). However a number of potential complications in the interpretation of metamorphic monazite ages can occur and the petrological and chemical characterisation of monazite is therefore imperative (Kohn *et al.* 2005).

Monazites are mostly small (20-30μm), highly poikilitic anhedral grains in the matrix but in sample P19 occasional grains are also present in the inner and outer zones of garnet. Because of the abundance of monazites and their occasional inclusion in garnet (e.g. monazite 6, Fig. 9), sample P19 was used for geochronology analysis. Grains found in the sillimanite bearing cores of garnets are particularly significant as they become chemically isolated from the matrix upon inclusion; matrix grains are subject to further metamorphic reactions or stages of metamorphism. Monazite 6 is therefore interpreted to solely relate to the sillimanite grade metamorphism.

6.1. Trace element mapping

Of particular importance to metamorphic monazite and the correct interpretation of ages is zoning of yttrium content, which is often related to the episodic growth of monazite during protracted metamorphism (Foster *et al*., 2000, 2002). Monazite can be linked to silicate reactions and subsequent trace-element balance. Element maps derived from $Ce_{L\alpha}$, $Y_{L\alpha}$, $Th_{L\alpha}$ and $U_{L\alpha}$ X-ray spectra were composed of selected grains from sample P19 and are shown in figure 9. Sample monazites have largely uniform chemical patterns, with many showing variability in Th over a small range, and two grains exhibiting some faint zoning with Y enriched in various patches (e.g. monazite 8). Many of the monazite grains appear to be microporphyroblasts, with hints of an internal fabric defined by the distribution and shape of tiny quartz inclusions, and the shape of compositional domains, especially of Th. The fine scale of this fabric suggests very early growth of monazite in the metamorphic history, consistent also with the presence of petrographically similar monazite inclusions (e.g. monazite 6, Fig. 9) in the sector-zoned cores of garnets.

Y systematics can be complex as the element can be hosted by a number of minerals, principally garnet, monazite, allanite and xenotime (Spear & Pyle, 2002). In sample P19 allanite and xenotime are absent, and so Y is principally partitioned between garnet and monazite (Pyle & Spear, 1999). Therefore in these samples we propose that the garnet growth is intrinsically linked to the monazite petrogenesis. Major element zoning in garnets shows little evidence of diffusional homogenisation, and so Y contents are also assumed to be largely un-homogenised. The Y contents of two garnets in P19 were mapped, and show a faint Y zoning (Fig. 10) that corresponds to the textural break relating to the evolution from M1 to M2. It is therefore interpreted that during the M1 event garnet cores were Y deficient, whilst during M2 garnet growth Y was more concentrated in garnet and deficient in the matrix and monazite Y budget. The ragged edges of many of the monazites (Fig. 9) implies that a stage of monazite dissolution may have occurred, releasing Y which was then enriched in M2 stage garnet rims as seen in figure 10.

6.2. LA-MC-ICP mass spectrometry

In order to exploit the textural configuration of the seven monazites in sample P19, *in-situ* dating of monazite was undertaken on petrographic thin sections. Spatial resolution needs to be on the same scale as the zoning of monazites. As such, we used laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS), performed at the NERC Isotope Geosciences Laboratory, UK. A Nu Plasma MC-ICP-MS (Nu Instruments, Wrexham, UK) and a UP193SS laser ablation system (New Wave Research, UK) were used to analyse the samples with an ablation spot size of 15 or 20µm. Laser fluence was kept at 2-3J.cm^{-2}. Procedures for U-(Th)-Pb dating were the same as those reported in Cottle *et al.* (2009). Reference material Manangotry monazite was used for U-Pb normalisation of monazite with secondary normalisation to FC-1 monazite. U-Pb data are presented in Table and plotted on a Tera-Wasserburg plot in figure 11. The position of each laser ablation spot is annotated on figure 9. Down hole ablation depth is of the order 10-15µm.

The data produced are all wholly discordant, and are open to multiple interpretations. All the monazites appear to contain common-Pb. On a Tera-Wasserburg plot (Fig. 11), the majority of analyses fell on a single common Pb trajectory. Two analyses *(of what zones? Any different to the other analyses??)* were grouped at a younger ^{206}Pb/^{238}U age. One of these analyses came from a grain (monazite 13) which also yielded a data point lying on the common-Pb trajectory defined by the majority of other points. With no distinct chemical zoning (Fig. 9), Pb loss might be invoked as a possible cause of the deviation of these analyses from the major population. The ragged edges often associated with Y depletion (e.g. monazites 13 & 14 – *is it possible to label at least some of the data points on Fig.11 to relate them to your monazite numbers? Then people can compare the different forms of these two points with the others.*) and protracted and multiphase nature of metamorphism in these samples adds weight to this possibility, although Pb loss in monazite is considered unlikely on the timescales and temperatures involved (Cherniack *et al.*, 2004) and is therefore discounted. An alternative and more likely interpretation is that further isotopic resetting of these monazites may have occurred during later metamorphic events, at ~85-90Ma. Importantly, we also do not see any systematic age differences between those crystals included in garnet (cores) and those in the matrix. Therefore we interpret the majority of these monazites to represent a single age population, pertaining to the sillimanite grade event (local M1) of the garnet cores. Subsequent metamorphism has corroded the rims of these monazites and reset these monazites to a younger age. The limited period of time between M1 and M2, suggested by the preservation of compositional growth profiles in garnet, points to an M2 signature for these younger (approximately 85-90Ma) monazites. This corrosion of monazite rims has also released Y, which appears to be subsequently enriched in the outer rims of garnets. We attribute the common-Pb component of many of these analyses to the ablation of inclusions which was unavoidable in these crystals. With only two data points at younger ages this was not deemed reliable enough to provide any further conclusive analysis on age.

To interpret an age for the older population of monazites a regression line was anchored at a common-Pb ^{207}Pb/^{206}Pb ratio of 0.836±0.006 to reflect an appropriate range of probably common-Pb compositions (Stacey & Kramers, 1975). This assigned uncertainty was therefore factored into the uncertainty calculation for the regression thereby propagating through to the quoted final age and uncertainty of 108.0±0.6Ma (MSWD=1.4).

This interpreted monazite age of 108.0±0.6Ma is similar to the crystallization age of 105.7±0.5Ma (Fraser *et al.* 2001) for the Hunza Plutonic unit, an Andean-type hornblende–biotite granodiorite that forms much of the Karakoram batholith in Pakistan (Searle, 1991, Crawford & Searle, 1992). We therefore suggest that the age of Pangong peak metamorphism M1 determined here correlates with the Cretaceous phase of crustal thickening, metamorphism and magmatism along the south Asian margin (M_0/D_0 of Searle & Tirrul, 1991).

7. Discussion and Conclusions

7.1. Age of metamorphism in the Eastern Karakoram

Well-constrained P-T-t paths are an integral part of understanding tectonic events that have occurred in exhumed continental collision zones. We interpret our U-Pb age of 108.0±0.6Ma on the Pangong metamorphic complex as dating peak sillimanite grade (M1) metamorphism in the Eastern Karakoram. This P-T evolution is demonstrated from the modelling of garnet growth, which shows M2 (Pangong) metamorphism at a similar crustal level on a cooler peak geotherm. There is a close correlation between U-Pb ages of metamorphism in the PMC and plutonism at Hunza across the Karakoram fault. We suggest that the KMC was continuous from north Pakistan into the Pangong metamorphic complex in Ladakh, before being offset by later Miocene dextral motion along the Karakoram fault. The cretaceous sillimanite-grade metamorphism could have been the result of crustal thickening and heating related to Andean-type tectonism along the South Asian active continental margin.

Further sillimanite-grade metamorphism is also dated in Hunza Karakoram at ca. 65 Ma (Fraser *et al*., 2001) which was subsequently partially overprinted by tertiary (<50 Ma) high-grade kyanite and sillimanite metamorphism (Searle & Tirrul, 1991, Fraser *et al*., 2001). In both the Hunza and the Pangong regions a younger lower grade staurolite event has been recorded and it is possible that the two events could well be correlated. In Hunza the staurolite-grade metamorphism has been dated at 16.0±1.0 Ma (Fraser *et al*., 2001), whereas in Pangong we have been unable to find datable U-bearing minerals in our samples unequivocally pertaining to this event. Staurolite grade conditions may have been prevalent not long after our second dated metamorphic event in the PMC, at ca. 85-90Ma (Fig. 11). The fact that the Karakoram fault cuts fabrics relating to the staurolite grade event in the PMC, allows us to speculate that the fault may not have been active before 16Ma.

Correlation of metamorphism in terms of time and P-T evolution along the strike of the KMC between Hunza and Pangong, combined with mapped offsets of Miocene

Baltoro leucogranites (Searle, 1991, Searle & Crawford, 1992, Searle *et al.*, 1998, Phillips *et al.*, 2004, Searle & Phillips, 2007), means that the overall geological offset of the Karakoram fault in this area cannot be more than 120-150 km and could be considerably less (see Fig. 1). Sillimanite grade metamorphism appears to have been widespread across the KMC including Pangong in Cretaceous times suggesting regional scale geological correlations are possible. Our correlations of the PMC, in agreement with studies on other parts of the Karakoram fault (e.g. Murphy *et al.* 2000), support these modest offset amounts and do not support the larger proposed offsets of 1000 km (Peltzer & Tapponier, 1988), 250-300 km (Lacasssin *et al.*, 2004a, 2004b) or 280-400 km (Valli *et al.* 2007) proposed for the Karakoram fault in Ladakh and Pakistan.

7.2. Relationship between metamorphism and strike-slip faulting

Our sample with a U-Pb age of 108.0±0.6Ma was collected from a location immediately adjacent to *(- adjacent to what??)*, on the NE margin of the Pangong strand of the Karakoram fault (Figs. 1 & 2). Similar staurolite schists also occur SW of the Pangong fault in the middle of the Karakoram shear zone. The age data from the PMC show that metamorphism along the Karakoram fault was not related to strike-slip shearing or to shear heating along the fault. Along the Pangong strand of the Karakoram fault, both the brittle fault and ductile dextral shear fabrics abruptly cut the Muglib granite and migmatite-gneiss complex. Leucosomes from the Muglib intrusion have a U-Pb age of ~15 Ma (Phillips *et al.* in prep.), showing that the Pangong fault must have initiated after this time (Fig. 3). The structural and U-Pb (ID-TIMS) dating work of Phillips *et al.* (2004) clearly shows that the ductile fabrics associated with right-lateral shearing along the Tangtse strand of the Karakoram fault also occurred during or after 15.7±0.5 Ma (age of leucogranite dykes parallel to the shear fabric) and before 13.7±0.3 Ma (age of undeformed leucogranite dykes cross-cutting the dextral shear fabrics) at this locality. Our structural and geochronological studies show that sillimanite grade metamorphism in the PMC is cretaceous in age. This demonstrates that metamorphism was not a result of strike-slip shearing (Lacassin *et al.*, 2004a, 2004b, Valli *et al.*, 2007, Rolland *et al.*, 2008), but was earlier than, and unrelated to the strike-slip faulting (Searle *et al.*, 1998, Phillips *et al.*, 2004, Phillips & Searle, 2007, Searle & Phillips, 2004, 2007). Since the age of metamorphism along the Karakoram fault, both at K2 (Searle & Phillips, 2007, Searle *et al.*, 1990) and Pangong (this paper), is Cretaceous and shows no temporal connection to the fault, there is now no metamorphic or thermochronological evidence to support a deep crustal or lithospheric scale to the Karakoram strike-slip fault in northern India and Pakistan.

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Figure Captions

Fig. 1. (a) Tectonic map of the Himalaya-Karakoram system showing location of study area (Fig. 2) and major tectonic boundaries; after Searle & Phillips (2007) (b) Sketch map of the central and eastern Karakoram in North Pakistan, Ladakh and SW Tibet showing the spatial extent of the Baltoro granite batholith, Cretaceous Karakoram granitoids (e.g. K2 gneiss, Arganglas diorites) and metamorphic complexes including the Karakoram Metamorphic complex (KMC) and Pangong metamorphic complex (PMC).

Fig. 2. (a) Map of the Pangong area of the Karakoram fault, showing sample localities, geology and faults in the area of the PMC, and (b) cross-section A-A' showing the relationship of the two strands of the Karakoram fault, the Tangtse and Pangong faults, after Phillips & Searle (2007).

Fig. 3. Photograph of the northern strand of the Karakoram fault (Pangong fault) abruptly truncating the Muglib leucogranite and its migmatite envelope to the SW and the staurolite grade metamorphic rocks to the NE. U-Pb ages are from Phillips *et al.*, 2004 .

Fig. 4. Photomicrographs of samples from the PMC; a; Euhedral garnet porphyroblast with a ring of sillimanite inclusions, b, Garnet porphyroblast with a sector zoned core and type 2 inclusion trails. Outer zone of garnet is being invaded by later staurolite, c, d; Pre-kinematic (S1) inclusion trails in garnet and staurolite porphyroblasts, wrapped by a secondary (S2) matrix fabric, e, f; complexly deformed inclusion trails in pre-kinematic staurolite wrapped by a matrix fabric)

Fig. 5. Backscatter electron images and compositional profiles of garnets from P19 and P21 plotted in terms of mole fractions of the divalent cation garnet end members.

Fig. 6. Best pressure-temperature estimates for (a) St-Grt-mica schist P19 and (b) Grt-mica schist P21, defined by the intersection (shaded) of the garnet-biotite geothermometer and the H_2O-independent average P-T ellipse calculated with THERMOCALC.

Fig. 7. CNMnKFMASH pseudosections drawn for sample P19 at an $aH_2O=0.75$ for a total bulk composition. M1 and M2 events are shown. The area of interest (peak

conditions for M1 and M2) is contoured in terms of Mn, Ca and Mg garnet end members and volume mode percentage garnet. The end member isopleth values corresponding to the textural break exhibited by the garnets are drawn in bold, and copied as dashed lines onto the volume mode percentage garnet pseudosection to determine a point on the P-T path relating to M1.

Fig. 8. CNMnKFMASH pseudosections calculated for sample P19 at an $aH_2O=0.75$ for a garnet fractionated bulk composition after M1 stage. Garnet (solid line) and staurolite (dashed line) volume modal percent contours are added to assess the validity of modelling and P-T determination.

Fig. 9. $Ce_{L\alpha}$, $Y_{L\alpha}$, $Th_{L\alpha}$ and $U_{L\alpha}$ X-ray spectra compositional maps of analysed monazite grains from P19. Circles on the Y maps represent geochronology ablation spots, numbered as in Table 4. Monazite 6 is included in a garnet core.

Fig. 10. $Y_{L\alpha}$ X-ray spectra maps of two garnets from sample P19. The textural break in garnet growth is shown, with Y enrichment outside of this.

Fig. 11. U-Pb Tera-Wasserburg plot of LA-MC-ICP mass spectrometry data of monazites from sample P19. The common-Pb regression was plotted through the larger population of data points and anchored at the upper intercept shown *(- change the plot to show 0.836 +/- 0.006 not 0.83-0.842, the latter suggests the regression is poorly constrained and drawn in by eye).* Uncertainty ellipses are at 2σ.

Table Captions

Table 1. Representative SEM-EDS mineral analyses from samples P19 and P21. See text for analytical conditions.

Table 2. Results of geothermometry and THERMOCALC average P-T calculations

Table 3. Bulk composition calculations for sample P19. Average garnet composition was determined from the profiles in figure 4. Modal proportions were then combined with averages of mineral analyses in table 1 to determine bulk composition.

Table 4. Results of LA-MC-ICP mass spectrometry for sample P19. Results are plotted in figure 11. – *change table header to LA-MC-ICP-MS data not LA-MC-PIMMS*

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