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Evolution of the Eastern Karakoram Metamorphic Complex, Ladakh, NW India, and its relationship to magmatism and regional tectonics

David Wallis *, R.J. Phillips, G.E. Lloyd

School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

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ABSTRACT

The eastern Karakoram terrane, NW India, records crustal evolution in the core of the Himalayan–Tibetan orogen. Recent debate has centred on whether prograde metamorphism, anatexis and leucogranite emplacement were the result of localised shear heating and magma advection within the Karakoram Fault Zone (KFZ) or instead predate the KFZ and were the result of regional tectonometamophic events. Inclusions within andalusite porphyroblasts that grew during 15.7 Ma leucogranite emplacement have fabrics that are random or discordant to the KFZ matrix foliation, indicating that the KFZ initiated after this time. Therefore, earlier anatexis and metamorphism are the result of regional metamorphic events. Amphibole–plagioclase thermobarometry on a c. 17 Ma migmatite melanosome, later exhumed within a transpressional zone of the KFZ, shows that melting occurred at 688 °C and 522 MPa. Amphibolites record an older kyanite-grade metamorphic event that occurred at 677–736 °C and 875–1059 MPa. Metapelites also record a kyanite-grade event which is constrained by Ti-in-biotite thermometry to have occurred at 622 °C and >650 MPa. The tectonometamorphic history of the eastern Karakoram correlates closely with that of the central Karakoram away from the KFZ. This correlation supports the interpretation that metamorphism and anatexis were regional in extent and also indicates a limited offset of <150 km on the KFZ.

1. Introduction

Understanding the evolution of the continental crust during the orogenic cycle, the pressure–temperature paths experienced by metamorphic rocks and their relationship to magmatic and deformation processes are fundamental but challenging issues. The complex histories of rocks in continental collision zones must be deciphered to place constraints on the evolution of an orogen. The Karakoram–Qiangtang terrane in the Himalayan–Tibetan orogen (Fig. 1a) provides an opportunity to investigate the former south Asian active margin, which later became the core of the orogen, and hence holds key information on crustal evolution in these tectonic settings. The Karakoram terrane in Pakistan is relatively well studied and has yielded much information on its complex history (e.g. Foster et al., 2004; Fraser et al., 2001; Palin et al., 2012; Villa et al., 1996). However, surface exposures of its correlative, the Qiangtang terrane in Tibet, consist predominantly of supracrustal and early Mesozoic metamorphic lithologies, which record little information on mid- to lower-crustal processes around the time of India–Asia collision (Pullen et al., 2011). The eastern Karakoram in Ladakh, NW India, geographically links the central Karakoram with the Qiangtang terrane and contains exposures of basement lithologies exhumed from a range of depths. However, metamorphism in this region remains relatively less studied and has potential to further our understanding of these key terranes.

The Karakoram terrane in the Hunza and Baltoro regions of Pakistan has experienced five metamorphic events (M_0–M_4). M_0 is represented in Hunza by Early Cretaceous andalusite-grade contact metamorphism during subduction prior to closure of the Shyok suture (Palin et al., 2012). Late Cretaceous closure of the Shyok suture resulted in regional sillimanite-grade M_1 metamorphism in Hunza, culminating in Eocene migmatisation following closure of the Indus suture during India–Asia collision (Foster et al., 2004; Fraser et al., 2001). Oligo-Miocene kyanite-grade M_2 metamorphism in Hunza and Baltoro was closely followed by an M_3 staurolite-grade event during the mid-Miocene in Hunza (Fraser et al., 2001; Palin et al., 2012; Villa et al., 1996). M_4 Mio-Pliocene sillimanite-grade metamorphism is represented by migmatisation in the Bullah and Dassu domes in the Baltoro (Fraser et al., 2001).

In the eastern Karakoram, the Karakoram Fault Zone (KFZ) cuts through medium-high grade metamorphic rocks of the Karakoram terrane and is spatially associated with exposed migmatite and large volumes of leucogranite (Phillips, 2008). Recent debate has centred on whether prograde metamorphism resulted from shear heating and/or fault-guided magmatic advection within the KFZ (Rolland and Pêcher,

Abbreviations: KFZ, Karakoram Fault Zone; EKMC, Eastern Karakoram Metamorphic Complex; PTZ, Pangong Transpressional Zone; PMC, Pangong Metamorphic Complex.

* Corresponding author.
E-mail address: eedw@leeds.ac.uk (D. Wallis).

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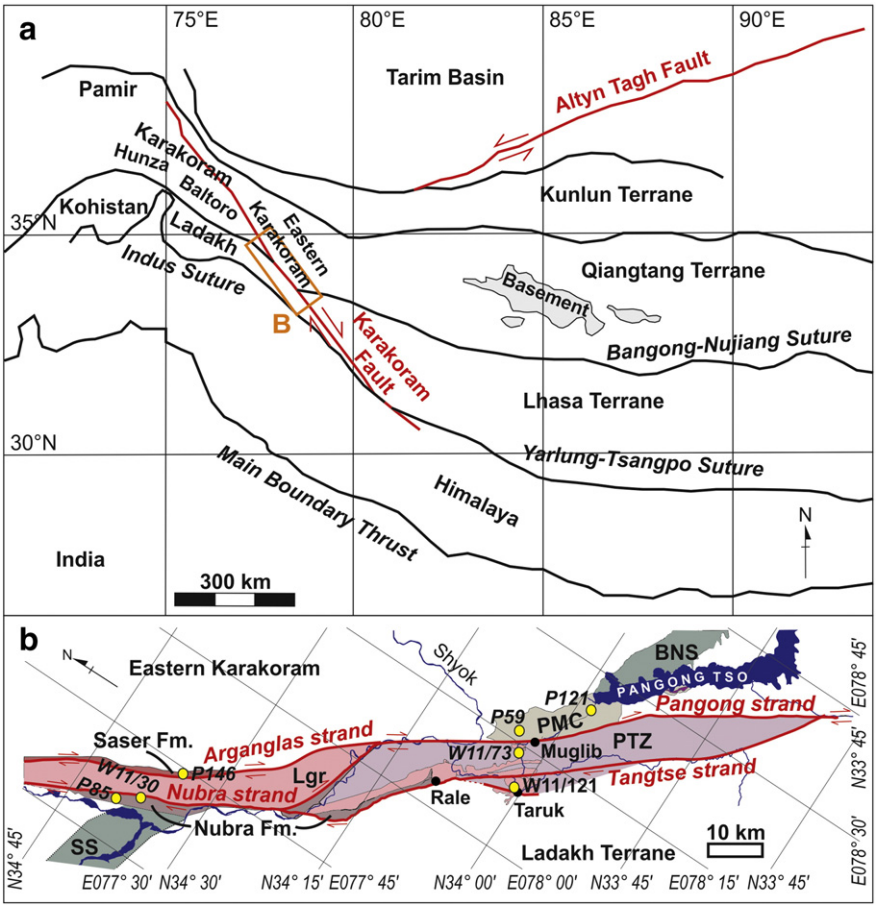

Fig. 1. Location maps. (a) Simplified terrane map of the Himalaya and Tibet showing the location of the Hunza, Baltoro and eastern Karakoram (modified from Searle et al., 2011). Also shown is the extent of basement exposure within the Qiangtang terrane in Tibet (from Pullen et al., 2011). The study area is marked by the orange box and expanded in part (b). (b) The central portion of the Karakoram fault zone in Ladakh, NW India showing the four subunits of the Eastern Karakoram Metamorphic Complex; the Pangong Transpressional Zone (PTZ), Pangong Metamorphic Complex (PMC), Nubra Formation and Saser Formation. Also shown are the major bodies of Miocene leucogranites (Lgr), Bangong–Nujiang sutre (BNS) and Shyok suture (SS). Sample localities are marked in yellow.
Modified from Phillips (2008).

2001; Rolland et al., 2009; Valli et al., 2008), or alternatively was the result of widespread crustal thickening (Searle et al., 1998, 2011; Streule et al., 2009). Rolland and Pêcher (2001) and Rolland et al. (2009) propose that high geothermal gradients within the KFZ demonstrate that it is a lithospheric-scale fault that has generated shear heating and channelled magmas during plate-like extrusion of the Tibetan Plateau. Elevated $^{3}He/^{4}He$ ratios from geothermal springs on the fault have also been put forward as evidence that the KFZ accesses the mantle (Klemperer et al., 2013). However, cross-sections based on shortening estimates across the Himalaya require that the KFZ is confined within the Tibetan crust as it must by underlain by subducted Indian lithosphere for much of its length (Searle et al., 2010). Also, peak metamorphism adjacent to the KFZ predates strike-slip deformation on the fault (Streule et al., 2009) and can be correlated with metamorphic events away from the KFZ in the Hunza region of the Karakoram (Fraser et al., 2001; Palin et al., 2012). Thus, prograde metamorphism throughout the Karakoram may be the result of regionally extensive crustal thickening and magmatism, rather than localised deformation. Wallis et al. (2013) reported that deformation within the KFZ is associated with retrograde metamorphism during exhumation and fluid flux, rather than prograde metamorphism.

The age of the KFZ has also been contested and depends primarily upon the relative ages of the fault and Miocene granitoid intrusions along its length. Interpretations that the intrusions are synkinematic with respect to the KFZ have led some authors to suggest that the KFZ initiated as early as 22–34 Ma (Boutonnet et al., 2012; Lacassin et al., 2004a,b; Leloup et al., 2011, 2013; Valli et al., 2008; Weinberg et al., 2009). These suggestions are based on synkinematic interpretations of outcrop-scale structures or microstructures. However, such interpretations are made more difficult and potentially less reliable by overprinting of high temperature microstructures by later lower temperature deformation fabrics and by the potential for older pre-KFZ outcrop- to micro-scale structures to rotate into alignment with the fault during later deformation. Alternative prekinematic interpretations of the intrusions, based on regional mapping, thermochronology and field and microstructural criteria, have also been put forward as evidence that the KFZ initiated after c. 15.7 Ma and is therefore a significantly more recent structure (Phillips and Searle, 2007; Phillips et al., 2004; Searle, 1996; Wang et al., 2011, 2013a,b). If this is the case then the KFZ cannot have been the cause of anatexis and leucogranite generation between c. 22 and 16 Ma (Phillips et al., 2013). In this contribution we investigate metamorphism throughout the Eastern Karakoram Metamorphic Complex (EKMC) and its relationship to regional and local (i.e. KFZ) tectonic events.

2. The Eastern Karakoram Metamorphic Complex

The EKMC in Ladakh, NW India, makes up the metamorphic country rock of the Karakoram terrane in this region and has been correlated with the Karakoram Metamorphic Complex in the Baltoro and Hunza regions (Fig. 1a) of Pakistan (Searle and Phillips, 2007; Searle et al., 2010; Streule et al., 2009). The EKMC is composed of four sub-units: the Pangong Transpressional Zone (PTZ) and Pangong Metamorphic