Metamorphic constraints on the character and displacement of the South Tibetan fault system, central Bhutanese Himalaya

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ABSTRACT

The South Tibetan fault system (STFS), a family of primarily extensional faults that separates the metamorphic core of the Himalaya (expressed as the Greater Himalayan sequence (GHS)) from overlying, predominately unmetamorphosed Tibetan sedimentary sequence (TSS) units, has been mapped for over 2,000 km coincident with the Himalayan range crest. In most areas, the immediate hanging wall of the STFS sole detachment consists of predominately carbonate rocks of lower Paleozoic age. However, in the Bhutan sector of the eastern Himalaya (ca. 89–92°E), the hanging wall of the sole structure is instead frequently mapped at the base of a metamorphosed, predominately siliciclastic succession (the Chekha Formation), and the base of the overlying predominately carbonate rocks (Pele La and Tang Chu Groups) is mapped as a less significant splay of the STFS. Unfortunately, poor exposures throughout central Bhutan make mapping and structural interpretation of these important contacts difficult, resulting in many disparities among geologic maps made by different research groups. The STFS in other parts of the Himalaya accommodates a significant metamorphic discontinuity that should also be apparent in Bhutan. Therefore, as an alternative approach, we have used the Raman spectroscopy on carbonaceous material (RSCM) thermometer to evaluate the evidence for a metamorphic discontinuity across both putative STFS structures.

RSCM thermometric data from 17 samples across three purported STFS klippen in central Bhutan (the Dang Chu, Ura, and Zhemgang klippen) suggest that the contact between the Chekha Formation and the underlying GHS is not a fault with large, postmetamorphic displacement. We find no resolvable change in peak metamorphic temperature across the contact, with a consistent temperature of ca. 560°C, but we see a 130–140°C drop in paleotemperature across the higher contact between the Chekha Formation and overlying Pele La and Tang Chu groups. This change coincides with a major change in structural style, from high-strain, leucogranite-bearing rocks below to large-scale recumbently folded marbles above. Together, the change in deformational character and metamorphic grade suggest that the principal STFS detachment in Bhutan is the structural boundary of the Chekha Formation and the predominantly carbonate rocks above. The presence of an STFS detachment approximately 80 km south of the main STFS fault trace at the crest of the Himalaya, with no match between correlative footwall and hanging wall units along the direction of fault motion implies large displacements on the STFS in the eastern Himalaya.

Keywords: Himalaya; extension; Raman spectroscopy of carbonaceous material; geothermobarometry

INTRODUCTION

Over the past few decades the eastern Himalayan Kingdom of Bhutan has become increasingly accessible to foreign visitors, resulting in a flurry of geologic research that has added critical new information to our understanding of the Himalayan-Tibetan orogenic system (Carosi et al., 2006; Chakungal et al., 2010; Chambers et al., 2011; Cooper et al., in press; Corrie et al., 2012; Daniel et al., 2003; Davidson et al., 1997; Edwards et al., 1999; Edwards and Harrison, 1997; Gansser, 1983; Grujic et al., 2006; Grujic et al., 2002; Grujic et al., 2011; Hughes et al., 2011; Kellett et al., 2009; Kellett et al., 2010; Kellett and Grujic, 2012; Long and McQuarrie, 2010; Long et al., 2011a; Long et al., 2011b; Long et al., 2011c; Stüwe and Foster, 2001; Swapp and Hollister, 1991; Tobgay et al., 2012). However, research progress has been hindered by the dense vegetation and shortage of roads (and, in turn, road-cut outcrops) throughout most of the country. Only in the areas near the Tibetan border are outcrops sufficient to tightly constrain geologic mapping. As a result, there are still many disparities among geologic maps of Bhutan made by different research groups. One outstanding issue regards the position, character, and displacement of the principal basal (or "sole") detachment of the South Tibetan fault system (STFS), a family of primarily extensional faults that crops out for over 2,000 km along the length of the Himalayan range crest (Burchfiel et al., 1992; Burg and Chen, 1984; Hodges et al., 1992; Pognante and Benna, 1993; Searle et al., 1997; Searle, 1999).

Basal low-angle detachments of this system typically mark a metamorphic discontinuity between high-grade metamorphic gneisses and anatexites of the Himalayan core below and lower-grade or unmetamorphosed strata above (Burchfiel et al., 1992). Recent mapping in the central Bhutan Himalaya (Figures 1 and 2) suggests that there may be multiple detachments of the South Tibetan fault system there (e.g. Carosi et al., 2006; Edwards and Harrison, 1997;

Grujic et al., 2006; Grujic et al., 2002; Grujic et al., 2011; Kellett et al., 2009; Kellett et al., 2010; Kellett and Grujic, 2012; Long and McQuarrie, 2010; Long et al., 2011a; Long et al., 2011c), an observation similar to that made in several other parts of the orogen where structurally higher detachments are typically marked by tectonite fabrics but not by significant metamorphic discontinuities (Burchfiel et al., 1992; Hodges et al., 1994; Hodges et al., 1996; Searle and Godin, 2003; Searle, 1999).

The role of the extensional STFS in the development of the Himalayan orogen is a matter of active debate, largely because constraining the magnitude of its displacement has proved difficult. Generally exposed along the Himalayan range crest, down-dip exposures of STFS detachments that allow direct measurements of minimum displacement are rare. In a recent study in NW Bhutan, Cooper et al. (in press) traced the STFS from the range crest south for ca. 65 km, suggesting large displacements on the system. The presence of STFS detachments even farther south in central Bhutan suggests that minimum displacements on the STFS could be even larger. Grujic et al. (2011), for example, map the STFS ca. 100 km south of the range crest (Figure 2b). Alternatively, mapping by Long and McQuarrie (2010) implies that the breakaway zone for the STFS is present in southern Bhutan. The structural offset between this breakaway and hanging wall units to the north is at most 20 km suggesting limited slip on the STFS.

The differences in mapping and interpretation of the STFS in central Bhutan suggests that further work is needed in order constrain the position and thus the significance of the system there. Due to the poor exposures in Bhutan, which have hindered mapping of STFS structures thus far, we have used the widely-applicable Raman spectroscopy on carbonaceous material (RSCM) thermometer to evaluate the evidence for metamorphic discontinuities across the putative STFS structures mapped by previous workers.

STRUCTURAL SETTING

The Himalayan-Tibetan orogenic system

The Himalayan-Tibetan orogenic system is one of our planet's most spectacular signatures of continent-continent collision. Thought to have initiated in the Early Eocene with the closure of the neo-Tethys Ocean (de Sigoyer et al., 2000; Guillot et al., 2008; Leech et al., 2005; Rowley, 1996), collision of the Indian and Eurasian plates created both the highest mountain range and the most expansive area of regional uplift on Earth: the Tibetan Plateau. The Himalayan sector of the orogenic system comprises four broad lithotectonic belts of contrasting metamorphic grade separated by a series of north-dipping faults (Gansser, 1964; Heim and Gansser, 1939; Hodges, 2000; Le Fort, 1975). From south to north, these are the Subhimalayan zone, Lesser Himalayan zone, Greater Himalayan zone, and Tibetan zone. Each of these zones comprises a distinctive package of rocks known as the Eocene to Lower Miocene Rawalpindi and Lower Miocene to Pleistocene Siwalik Groups of the Subhimalayan zone, the Proterozoic to Middle(?) Miocene Lesser Himalayan sequence (LHS), the Neoproterozoic to Ordovician Greater Himalayan sequence (GHS), and the Paleozoic to Eocene Tibetan sedimentary sequence (TSS) (Acharyya and Sastry, 1979; Brasier and Singh, 1987; Brookfield, 1993; Burbank et al., 1997; Critelli and Garzanti, 1994; DeCelles et al., 1998; Gaetani and Garzanti, 1991; Gansser, 1983; Hodges, 2000; Najman et al., 1993; Najman et al., 1997; Parrish and Hodges, 1996; Singh et al., 1999; Stöcklin, 1980; Valdiya, 1980). Rocks of the Subhimalaya, LHS, and GHS are separated by orogen-parallel contractional structures of the Main Boundary thrust system (MBTS) and the Main Central thrust system (MCTS). In the Bhutanese Himalaya, an out-of-sequence thrust fault (the Kakhtang thrust) mapped by Gansser (1983) has been interpreted to have roughly doubled the thickness of the GHS (Davidson et al., 1997; Grujic et al., 2002) (Figure 1), although the location, age and displacement across this structure are poorly constrained. In contrast to its southern and lower boundary, the top of the GHS is bounded by extensional faults and shear zones of the STFS. The opposing-sense STFS and MCTS are both thought to have been active during the Miocene (Hodges et al., 1992; Hodges et al., 1996; Hubbard and Harrison, 1989; Searle and Rex, 1989), implying that the STFS played an important role in exhuming the GHS metamorphic core.

The structurally highest and northernmost zone is represented by the Tibetan sedimentary sequence (TSS), which generally crops out north of the Himalayan range crest. The TSS comprises low-grade to unmetamorphosed sediments deposited on the northern passive continental margin of India (Gaetani and Garzanti, 1991). Although it is generally accepted that the GHS and the TSS are separated by the STFS throughout most of the Himalaya, the relationships are more controversial in regions south of the range crest where the TSS occurs in a series of low-elevation outliers above GHS lithologies. In some cases, these contacts – typically poorly exposed – have been interpreted as detachments (presumably strands of the STFS), whereas they have been interpreted as depositional in others (Gehrels et al., 2003; Grujic et al., 2002; Robinson et al., 2006; Stöcklin, 1980). In Bhutan, both depositional and tectonic relationships have been reported for these outliers (e.g. Long and McQuarrie, 2010).

The South Tibetan fault system

The South Tibetan Fault system was first recognized in central Nepal (Caby et al., 1983) and later described in southern Tibet (Burchfiel et al., 1992; Burg and Chen, 1984) and northwest India (Herren, 1987; Searle, 1986; Valdiya, 1989). Although it comprises a variety of fault types including steeply dipping transfer faults (Wu et al., 1998) and low-angle, oblique faults with a significant component of strike slip motion (Pêcher, 1991), most descriptions focus on the basal structure of the system, a low-angle, north-dipping fault and associated ductile shear zone commonly referred to as the South Tibetan detachment.

The presence of the STFS within a zone of continental collision has led to considerable debate regarding its initiation and role in the construction of the orogen (e.g. Hodges, 2000; Law et al., 2006 and references therein). Two principal models have been put forward to explain its existence. In the first, the STFS forms a collection of passive roof faults over an evolving contractional orogenic wedge (e.g. Robinson et al., 2006; Yin, 2006; Yin et al., 1994). In this case, the STFS has only a minor role in extrusion with minimal displacement across the structure and little excision of material in the footwall. In the second, the MCTS and STFS are kinematically linked structures that collectively sustained Miocene southward extrusion of the metamorphic core of the Himalaya (Beaumont et al., 2001; Godin et al., 2006 and references therein; Grujic et al., 2002; Hodges et al., 2001; Nelson et al., 1996). This concept, often referred to as the 'channel flow' model, implies that the STFS would have accommodated many kilometers of displacement and is responsible for excision of several kilometers of structural section within the GHS (Searle et al., 2006).

However, because of the geographic coincidence of many of the basal detachments with the Himalayan range crest and the relatively subdued relief north of the crest, most of these structures cannot be traced far down dip, and their net displacements are derived from indirect geothermobarometric measurements (15–200 km: Cottle et al., 2011; Cottle et al., 2007; Dèzes et al., 1999; Searle et al., 2003; Searle et al., 2002; Walker et al., 1999) and studies of fault-related telescoped isograds (25–170 km: Herren, 1987; Law et al., 2011). Exceptions occur in the Mount

Everest region of Nepal and the Mount Jomolhari region of NW Bhutan, where components of the STFS can be traced parallel to their slip vectors, with no match between correlative footwall and hanging wall units for ≥ 34 km in Nepal (Carosi et al., 1998; Hodges et al., 1992) and ≥ 65 km in Bhutan (Cooper et al., in press), implying minimum displacements comparable to ca. 75–140 km minimum estimates for broadly contemporaneous S-directed slip on the Main Central Thrust system (MCTS) in the eastern Himalaya (Yin, 2006; Yin et al., 2010).

The STFS footwall comprises high-grade (upper amphibolite facies) paragneisses and orthogneisses of the GHS with abundant leucogranite sills, dikes, and plutons. Near the top of the footwall, these rocks are strongly deformed and most exposures contain well-developed S-C mylonites (Lister and Snoke, 1984) indicative of hanging wall down-to-the north (normal-sense) shearing with varying degrees of oblique slip. In most mapped transects, the basal detachment carries ummetamorphosed lower Paleozoic sedimentary rocks of the TSS in its immediate hanging wall (e.g. Herren, 1987 (India); Hodges et al., 1993 (southern Tibet)). In two areas – the Annapurna Range of central Nepal (e.g., Brown and Nazarchuk (1993)) and the Everest region of eastern Nepal (e.g., Searle, 1999) – hanging wall TSS units also experienced greenschist to lower or middle amphibolite facies metamorphism, but the STFS still marks a significant discontinuity in metamorphic pressures and temperatures.

Studies of the STFS in Tibet (Burchfiel et al., 1992; Hodges et al., 1994) and Nepal (Hodges et al., 1996; Searle and Godin, 2003; Searle, 1999) show that wherever the basal detachment carries metamorphosed TSS rocks in its hanging wall, there is at least one major detachment of the STFS at a structurally higher level. These structures typically place stratigraphically younger TSS lithologies on older lithologies, or lower grade (or unmetamorphosed) rocks on higher grade rocks. The character of deformation along and above the STFS detachments depends on the hanging wall lithology. Observations of the STFS in various localities in Nepal suggest that, when the basal detachment carries lower amphibolite or greenschist facies rocks in its hanging wall, there is typically a relatively wide shear zone above and below the detachment but often also a relatively sharp brittle-ductile shear zone at the contact itself (e.g. Deorali detachment: Hodges et al., 1996; Lhotse detachment: Searle, 1999; Annapurna detachment: Vannay and Hodges, 1996). Both ductile and brittle fabrics are transposed into parallelism with the detachment, indicating syn-detachment development. When the hanging wall is unmetamorphosed or weakly metamorphosed, there is a well-developed, relatively wide shear zone beneath the detachment and a usually pronounced (but sometimes thin) breccia zone at the contact. The breccia zone is oriented subparallel to the shear fabric in the footwall but the hanging wall-footwall contact is marked by an obvious cut-off of hanging wall strata, sometimes at a very high angle. Leucogranites cut the basal STFS detachment in several well-studied areas (e.g. Hodges et al., 1996), but examples of them cutting the upper detachment (e.g. Guillot et al., 1994; Hodges et al., 1998) are extremely rare.

The South Tibetan fault system in Bhutan and adjacent areas of Tibet

In the first regional study of the STFS, Burchfiel et al. (1992) mapped two transects across the GHS–TSS boundary just north of Bhutan at Wagye La and Lhozag-La Kang (Figure 1). In the Wagye La area, the contact is not exposed, but the topography and outcrop pattern indicate that it must dip shallowly northward, subparallel to well-developed S-C mylonitic planar fabrics in the footwall. The contact was interpreted by Burchfiel et al. (1992) as a segment of the basal detachment of the STFS, with classic GHS footwall units including amphibolite facies orthogneisses and psammitic and pelitic schists, all intruded by leucogranite sills and dikes. The hanging wall units (low-grade Ordovician marbles and phyllites) are themselves cut by a well-exposed upper detachment that carries unmetamorphosed Carboniferous-Permian limestones in its hanging wall.

At Lhozag La Kang, the principal STFS detachment has been deformed into ca. 10 km-wavelength, upright folds and subsequently cut by steeply N-dipping, E-striking normal faults with relatively minor displacement (Burchfiel et al., 1992; Edwards et al., 1999). This detachment cuts and thus postdates the ca. 12.5 Ma Khula Kangri leucogranite pluton (Edwards and Harrison, 1997) (Figure 1). At Gonto La (Edwards et al., 1996) (Figure 1), the detachment also cuts an older, structurally lower STFS detachment that is intruded by the Khula Kangri pluton.

In the central latitudes of Bhutan, Gansser (1983) mapped synformal erosional remnants of TSS lithologies above GHS units far south of the main outcrop trace of the STFS along the Bhutan-Tibet border (Figure 1). The structurally and stratigraphically highest units in the erosional remnants are Precambrian-Devonian(?), locally fossiliferous, low-grade calc-schists, calcarenites, and limestones of the Pele La Group and the Tang Chu Group (Hughes et al., 2011; Long and McQuarrie, 2010; Tangri and Pande, 1995), similar to basal TSS lithologies widespread in the Himalaya and southern Tibet (Dèzes et al., 1999; Gansser, 1964; Hodges et al., 1996; Le Fort, 1975; Searle and Godin, 2003; Searle et al., 2003). The rocks mapped as GHS throughout Bhutan comprise Proterozoic-Ordovician(?) granitic and migmatitic orthogneiss, migmatitic metasedimentary rocks, schist, paragneiss, quartzite, and discrete marble bands, pervasively intruded by Miocene leucogranites (Bhargava, 1995; Davidson et al., 1997; Gansser, 1983; Grujic et al., 2002; Hollister and Grujic, 2006; Long and McQuarrie, 2010; Long et al., 2011c; Swapp and Hollister, 1991). There is little controversy regarding correlations of these rocks with GHS units elsewhere in the Himalaya. Of less certain affinity is a unit interposed between classically GHS and TSS units referred to as the Chekha Formation (Gansser, 1983; Jangpangi, 1974; Nautiyal et al., 1964; Tangri and Pande, 1995).

The Chekha Formation in Bhutan comprises non-fossiliferous greenschist to amphibolite facies metapelite, paragneiss, augen gneiss, quartzite and calc-silicate intruded by leucogranite sills and dikes (Cooper et al., in press; Gansser, 1983; Grujic et al., 2002; Kellett et al., 2009; Long and McQuarrie, 2010; McQuarrie et al., 2008). Kellett et al. (2009); Kellett et al. (2010); and Kellett and Grujic (2012) correlated the Chekha regionally with TSS units in other parts of the Himalaya, notably the Everest Series and North Col Formation of eastern Nepal (Searle et al., 2003), the Annapurna Yellow Formation of central Nepal (Gleeson and Godin, 2006), and the Haimanta Group of NW India (Chambers et al., 2009). If this is the case, then age constraints for these other units suggest a probable Cambrian age for the Chekha (Burchfiel et al., 1992; Carosi et al., 1999; Colchen et al., 1986; Frank et al., 1973; Lombardo et al., 1993; Mu et al., 1973; Myrow et al., 2009; Wang and Zhen, 1975). Other workers have used the position of the Chekha at the base of the TSS and its lack of fossils to infer a Precambrian age (Gansser, 1983; Tangri and Pande, 1995) for the unit. Detrital zircon U-Pb age spectra from some Chekha samples are similar to those obtained for TSS samples, whereas others are more like those obtained for GHS samples collected in Bhutan (Gehrels et al., 2011; Hughes et al., 2011; Long and McQuarrie, 2010; McQuarrie et al., 2008). As Hughes et al. (2011) note, additional stratigraphic constraints on the depositional age of the Chekha Formation are needed.

The contacts between the Chekha Formation and units above and below have been variably interpreted. Gansser (1983) described the GHS–Chekha contact as conformable and noted that both the uppermost GHS pelitic units and the lowermost Chekha Formation schists contain distinct biotite porphyroblasts (cross-biotites) lying perpendicular to foliation but parallel to lineation. Grujic et al. (2002), on the other hand, found evidence for a diffuse top-to-the-north shear zone (width unconstrained) at the base of the Chekha Formation across Bhutan, and re-interpreted the Dang Chu (or Tang Chu), Ura, Zhemgang (or Black Mountain), and Sakteng (or Radi) exposures as klippen soled by the STFS basal detachment. Their main lines of evidence were: (1) Top-to-the-north shear sense indicators at the top of the GHS and the base of the Chekha Formation; (2) The presence of migmatite and sillimanite in the GHS that are absent from the Chekha Formation above; and (3) An upsection decrease in metamorphic grade within the Chekha Formation. However, despite these first-order observations across Bhutan, no discrete (meter-scale) brittle-ductile shear zone at the contact, upward increase in strain towards the contact, or definitive structural discordance between footwall and hanging wall units has yet been described at this structural level (e.g. Carosi et al., 2006; Grujic et al., 2002; Kellett et al., 2009), contrary to observations of classic STFS detachments in other parts of the Himalaya (e.g. Burchfiel et al., 1992; Hodges et al., 1992; Hodges et al., 1996; Pognante and Benna, 1993; Searle et al., 1997; Searle, 1999; Vannay and Hodges, 1996).

The ambiguity in the GHS–Chekha contact is exemplified by the contrasting mapping of two different groups working in Bhutan, which shows little agreement on either the position or the nature of the contact. Long and McQuarrie (2010), for example, largely followed the original mapping by Gansser (1983), and agreed with Grujic et al. (2002) that the base of the Chekha Formation in the Dang Chu, Ura, and Sakteng klippen was a top-to-the-north shear zone of the STFS. However, in contrast to Grujic et al. (2002), they suggested that interfingering of GHS and Chekha units at the base of the Zhemgang klippe in southern Bhutan indicated a depositional contact there (Figures 2a and 5). Grujic et al. (2011), on the other hand, map the Chekha to a far greater extent throughout central Bhutan, combining the Dang Chu and Zhemgang klippe into a single entity, and extending the Ura klippe northward, where it is cut by the KT (Figure 2b). A direct comparison between the maps of the two groups (Figure 2) suggests that the large areal extent of the Chekha mapped by Grujic et al. (2012) corresponds closely to the extent of the GHS metasedimentary unit mapped by Long and McQuarrie (Figure 5). This again reinforces the ambiguity between the two lithologic units and suggests that new data is needed to understand the structural relationship between them.

The difference in mapping of the STFS in central Bhutan has implications for the magnitude of displacement on the STFS. The interpretation by Long and McQuarrie (2010) that the base of the Zhemgang klippe is a conformable contact between GHS and TSS units but the base of the Ura klippe is a strand of the STFS led them to argue that the breakaway zone for the STFS must lie in between the two (Figures 2a and 3a). If this is the case then it limits slip on the STFS to a maximum of only 20 km, and reduces the significance of extensional faulting as a major orogen-building process. In contrast, mapping of STFS detachments (including at the base of the Zhemgang klippe) by Grujic et al. (2012) as far as 100 km south of the main STFS trace along the Himalayan range crest, with no observed breakaway zone, means that STFS hanging-wall-on-footwall relationships can be traced in the direction of slip for ca. 100 km, implying large displacements on this system.

Thermobarometric studies across the GHS–Chekha contact in Bhutan are limited. Studies by Davidson et al. (1997) and Daniel et al. (2003) found the GHS to have reached peak metamorphic temperatures of 600–750°C and pressures of 8–10 kbar. In a detailed thermobarometric study across the Ura klippe based on silicate mineral compositions, Kellett et al. (2010) infer a change in temperature across the GHS–Chekha contact, but see no discernable change in pressure. On closer inspection, their data show a similarly large spread in pressure-temperature (*P-T*) conditions for both the Chekha Formation (576–730°C and 6.9–8.7 kbar) and the GHS (560–789°C and 8.0–9.1 kbar), indicating no metamorphic discontinuity across this contact. Their results are similar in the Jomolhari region of NW Bhutan (referred to by the authors as the Lingshi klippe), where one sample from the base of the Chekha Formation gives a *P-T* of 721°C and 8.7 kbar, while 6 samples from the GHS give a spread of 622–787°C and 6.2–10.9 kbar. Thermobarometric data from a recent study across the GHS-Chekha contact at the base of the Zhemgang klippe by Corrie et al. (2012) supports the interpretation of Long and McQuarrie (2010) that it is a conformable contact, noting a gradual change in peak temperature and pressure across the contact from ca. 540–620°C and 9 kbar in the GHS approximately 2 km from the contact to 550°C and 7.5 kbar throughout the Chekha Formation. In the only other RSCM study in Bhutan to date, Kellett and Grujic (2012) obtained peak RSCM temperatures from Chekha and TSS rocks of the Linghsi klippe that show little variation, with a consistently low peak temperature of ca. 300°C. By combining these RSCM data with the *P-T* data of Kellett et al. (2010), Kellett and Grujic (2012)inferred a gradual change in temperature across the GHS–Chekha contact, which they ascribed to a diffuse shear zone at this structural level. However, the substantial drop in temperature to ca. 300°C is approximately 600 m above this contact, suggesting a more significant offset at a structurally higher position.

The nature of the contact between the Chekha Formation and the overlying indisputable TSS (Pele La Group and Tang Chu Group) is also unclear. Exposed in the Mount Jomolhari region in NW Bhutan and in the Dang Chu klippe (We refer to it as such because it is cut by the Dang Chu river. It is usually referred to as the Tang Chu klippe after Gansser (1983), but this is a potential source of confusion because the Tang Chu actually river lies to the east near the Ura klippe) in central Bhutan, Gansser (1983) and Carosi et al. (2006) mapped it as a conformable contact, but Edwards et al. (1996), Hollister and Grujic (2006), and Chambers et al. (2011) interpreted it as an STFS detachment. In NW Bhutan (Figure 1), Cooper et al. (in press) mapped recumbently folded fossiliferous marbles of the TSS above amphibolite facies metapelites, calc-silicates, and leucogranites of the Chekha Formation. The abrupt change in structural style across the contact between these two units together with the stark change in lithology and metamorphic grade led the authors to interpret this contact as a detachment of the STFS.

In the Dang Chu klippe, Gansser (1983) mapped two isolated exposures of the TSS lying above the Chekha Formation. In the more accessible northern exposure, the transition from Chekha Formation to TSS units of the Pele La Group and Tang Chu Group is marked by a dramatic change in structural style from foliated metapelites and quartzites to recumbently folded calc-silicates and marbles (Figure 4a-c). Just to the east of the southern TSS exposure mapped by Gansser (1983), Hughes et al. (2011) identified Cambrian brachiopod and trilobite fossils in siliciclastic and carbonate units of the Pele La Group. Although this location has been mapped by other researchers as part of the Chekha Formation (Grujic et al., 2002; Grujic et al., 2011; Kellett et al., 2009; Kellett et al., 2010; Long and McQuarrie, 2010; Long et al., 2011c), we join Hughes et al. (2011) as interpreting these fossiliferous outcrops as part of the TSS and have extended the southern exposure of this unit in the Dang Chu klippe eastward to include this locality (Figure 1).

Above the Chekha Formation in the center of the Zhemgang klippe (Figure 4e), Long and McQuarrie (2010) mapped the Maneting Formation, a biotite-garnet bearing phyllitic unit (Figure 4f) of the Pele La group (Tangri and Pande, 1995). Based on an observed upsection transition from Chekha quartzite to Maneting phyllite and interfingering of the two lithologies, they interpreted the contact between the Chekha and Maneting Formations to be conformable

(Figures 2a and 5). Thermobarometric data from Corrie et al. (2012) agree with this interpretation, suggesting a steady decrease in peak *P-T* conditions across the Chekha-Maneting contact, with no evidence for a structural break.

Because structural studies alone do not seem sufficient to determine the nature of the GHS–Chekha and Chekha–TSS contacts in the central latitudes of Bhutan, we applied thermometric techniques to evaluate the evidence for a metamorphic discontinuity across them. Although conventional pelitic thermobarometers are easily applied to many GHS rocks, Chekha Formation and TSS rocks typically contain less suitable high-variance mineral assemblages. As a consequence, we focused our studies on the establishment of peak metamorphic temperatures through the more widely-applicable Raman spectroscopy on carbonaceous material (RSCM) method. This relatively new technique (Aoya et al., 2010; Beyssac et al., 2002a; Beyssac et al., 2002b; Rahl et al., 2005) has become very popular in recent years and has been applied to rocks from several sectors of the Himalayan orogen (Beyssac et al., 2004; Bollinger et al., 2004; Célérier et al., 2009; Cottle et al., 2011; Kellett and Grujic, 2012). The popularity of the RSCM thermometer stems from its applicability to rocks of many bulk compositions, the fact that it is apparently independent of metamorphic pressure (unlike most of the commonly used metamorphic thermometers for amphibolite facies metamorphic rocks), and its resistance to retrograde resetting during protracted or polyphase metamorphism.

RSCM THERMOMETRY

Carbonaceous material (CM) is a common constituent of metasedimentary rocks, deriving from the solid-state metamorphic transformation of original organic material (Buseck and Huang, 1985). During diagenesis and metamorphism this CM experiences progressive structural organization until it transforms into graphite. The degree of organization is independent of pressure but strongly dependent on temperature such that the CM can be used as an indicator of metamorphic grade (Beyssac et al., 2002a; Beyssac et al., 2002b; Rietmeijer and Mackinnon, 1985; Wopenka and Pasteris, 1993). Beyssac et al. (2002a) demonstrated that peak metamorphic temperature (*T*) can be estimated in the range 330–650°C with a nominal uncertainty of ± 50°C (1σ) by measuring the peak area ratio (R2) of characteristic CM bands (D1, D2, G: Figure 6) in the Raman spectrum and inputting this parameter into the equation: $T(°C) = –445\ R2 + 641$.

Rahl et al. (2005) devised an alternative calibration of the RSCM thermometer that extends its range to 100–700°C. In this calibration, peak metamorphic temperature is calculated from both the peak area ratio (R2) of Beyssac et al. (2002a) and the peak height ratio (R1) of CM bands D1 and G. Temperature is calculated using the equation: $T(°C) = 737.3 + 320.9\ R1 – 1067\ R2 – 80.638\ R1^2$. However, both of these calibrations were made using a micro-Raman system with a 514 nm wavelength laser. At Arizona State University we use a 532 nm laser, which results in a slightly, but systematically larger R2 ratio than that of a 514.5 nm laser (Aoya et al., 2010). To account for this difference, Aoya et al. (2010) derived a new 532 nm laser calibration in which the temperature is calculated using the equation: $T(°C) = 221.0\ R2^2 – 637.1\ R2 + 672.3$, where the R2 ratio derives from the original Beyssac et al. (2002a) calibration. The Aoya et al. (2010) calibration is valid for samples in the range 340–655°C and we use this for all of our RSCM calculations.

Sampling and analysis

We collected 17 samples for RSCM analysis across the Dang Chu klippe, the Ura klippe, and the Zhemgang klippe, encompassing rocks of the GHS, Chekha Formation, and TSS (Figure 2).

Lithologies include paragneiss, pelitic schist, calc-silicate, slate, phyllite, and marble (Table 1). Laser Raman analyses of CM were made on microprobe-quality polished petrographic thin sections. In order to avoid variations in mineral orientation and anisotropy on the Raman spectra (Beyssac et al., 2002a; Katagiri et al., 1988), thin sections were cut normal to foliation and parallel to stretching lineation (when present).

Measurements were made using a custom-built Raman spectrometer in the LeRoy Eyring Center for Solid State Science at Arizona State University. The sample was excited using a Coherent *Compass* laser, with power controlled using neutral density filters. The laser was focused onto the sample using a ×50 Mitutoyo objective, and the signal was discriminated from the laser excitation with a Kaiser laser band pass filter followed by a Semrock edge filter. The system has a spectral resolution of 3.5 cm^{-1} using a 1200 g/mm grating and a spatial resolution of <1 μm with the ×50 objective lens. In order to avoid any mechanical disruption of the CM from the thin section making and polishing process (Beyssac et al., 2003), the laser was typically focused on CM situated beneath the surface of a transparent grain of quartz or calcite (Data Repository Item A). The data were collected using an Acton 300i spectrograph and a back thinned Princeton Instruments liquid nitrogen cooled CCD detector. Grains of CM were analyzed with a 3 mW beam for 120 seconds over a spectral window of 1100 to 2000 cm^{-1}. Depending on the abundance of CM, between 15 and 25 grains were analyzed in each sample in order to evaluate the degree of in-sample heterogeneity. Peak positions, band areas and band widths of the resulting Raman spectra were determined with the computer program PeakFit 4.12 (Systat Software Inc.).

Results

All temperatures were calculated using the 532 nm laser calibration of Aoya et al. (2010) and are given in Table 1. For comparison, we also calculated temperatures with the Beyssac et al. (2002b) and Rahl et al. (2005) 514 nm laser calibrations, which gave results in close agreement (Data Repository Item B). Examples of Raman spectra for each sample are shown in Figure 6 together with R2 values and calculated temperatures. Photographs of representative CM grains from selected samples can be found in Data Repository Item A.

In Table 1, the variation in R2 within each sample is indicated by the standard deviation (1σ). CM heterogeneity can result from differences in the original organic material, variations in the structure of the CM, the influence of the mineral matrix (e.g. shielding of CM within porphyroclasts), or the composition of metamorphic fluids (Beyssac et al., 2002a; Beyssac et al., 2002b; Large et al., 1994). The average variation in R2 for the 17 samples is 0.095, which corresponds to a temperature difference of ± 50°C. Sample FB132 has the highest variation in R2 at ± 0.122, which corresponds to a temperature difference of ± 75°C.

Temperatures calculated using the calibration of Aoya et al. (2010) are reported as standard means of multiple measurements from each sample. The internal uncertainty on our analytical procedures is reflected by the variation in temperature within each sample, and is reported as 1 standard deviation on the mean. However, for each individual value of R2, there is also an associated external uncertainty on the calculated temperature of ± 50°C stemming from the original calibration of CM organization against independent *P-T* data (Beyssac et al., 2002a). Therefore, in order to report a complete and more accurate uncertainty, we added our internal and external uncertainties in quadrature before dividing by the square root of the number of analyses per sample. Final temperatures are thus reported at 2 standard errors of the mean (Table 1 and Data Repository Item B).

Thirteen samples from Chekha and GHS units give very consistent temperatures, with an error-weighted mean average of 560 ± 2°C (2SE) (Figures 2, 7, and 9). The only change in peak temperature is seen in four samples across the Dang Chu klippe. Two foliated calc-silicates on the NW edge of the klippe, samples FB64, and FB85, give slightly lower peak temperatures of 508 ± 33°C and 489 ± 26°C, respectively. The lowest temperatures are seen in samples FB28, a folded marble collected at Pele La within the northern TSS exposure (Figure 4b), and FB77, a black slate located on the W side of the klippe in the Chekha Formation. These give temperatures 130–140°C lower than the majority of the samples at 430 ±30°C and 420 ± 21°C, respectively.

Comparison with GARB-GMBP thermometry

In order to verify the temperatures calculated with the RSCM method, we conducted independent *P-T* calculations on three of the 17 samples. Samples FB07, FB125, and FB132 have a mineral assemblage of garnet + biotite + muscovite + plagioclase, permitting the application of the well-established GARB (garnet-biotite) exchange thermometer (Ferry and Spear, 1978) and GMBP (garnet-muscovite-biotite-plagioclase) net-transfer barometer (Ghent and Stout, 1981). In order to minimize sources of uncertainty in the thermobarometric calculations, we followed the approach of Cooper et al. (2010) by characterizing textural and geochemical relationships in detail and conducting multiple independent calculations on each sample. For more details, see Data Repository Item C.

Mineral composition data were obtained with a JEOL JXA-8200 electron microprobe at the University of California, Los Angeles and a Cameca SX50 electron microprobe at the University of Massachusetts. Thermobarometric calculations were made using THERMOCALC v. 3.33 software (Powell and Holland, 1988), and the latest version of the Holland and Powell data set

(Holland and Powell, 1998). Activity-composition relationships were calculated using the AX program (Tim Holland: http://www.esc.cam.ac.uk/research/research-groups/holland/ax). Individual *P-T* calculations and representative mineral analyses can be found in Data Repository Items D and E.

RSCM temperatures and GARB-GMBP temperatures and pressures for each sample are given in Table 2 for comparison. The results show that there is good agreement between the three independent temperature measurements within the limits of the uncertainties on both methods and the pressure estimates on the three samples are also consistent, with an error-weighted mean pressure of 5.2 ± 0.5 kbar (2SE).

IMPLICATIONS FOR THE STFS IN CENTRAL BHUTAN

The lack of either a distinct discontinuity or a progressive change in temperature across the base of both the Dang Chu and Ura klippen, and similar temperatures in the center of the Zhemgang klippe raises questions about the interpretation of the GHS–Chekha contact being a strand of the STFS. In contrast, the lower peak temperatures reached by four samples in the Dang Chu klippe point to a likely detachment between the Chekha Formation and overlying TSS sediments, an interpretation supported by the change in structural style observed in rocks above and below the contact (Figure 4).

The interpretation that there is no structural discontinuity between the GHS and the Chekha Formation is consistent with the conclusion reached by Long and McQuarrie (2010) that the Chekha Formation of the Zhemgang klippe (which they interpret as part of the TSS) is in depositional contact with the GHS (Figures 1 and 2a). However, we disagree with Long and McQuarrie (2010) regarding the broader tectonic significance of that observation. We suggest that the Chekha Formation and overlying Maneting Formation are in the STFS footwall, and that the absence of evidence for fault slip at the GHS–Chekha contact in the Zhemgang klippe is not surprising as a consequence. On the other hand, the TSS units that give low peak temperatures of 420–430°C coincide with recumbently folded marbles that exhibit a wholly different structural style to both the Chekha and GHS units below (Figure 4). Although we have not found fossiliferous marbles in the northern TSS Dang Chu exposure, the fossils found to the south by Hughes et al. (2011) are from the TSS. If similar fossiliferous beds are present in the northern part of the klippe, they must lie at structurally higher elevations that have so far proved inaccessible. The strongly foliated, high-strain calc-silicate samples FB64 and FB85, which give intermediate peak temperatures of ca. 490–510°C, are interpreted as basal units of the TSS that have been heated and transposed by shearing along the STFS detachment. They therefore roughly define the position of the STFS shear zone.

Figure 8a shows our interpretation for the distribution of RSCM temperatures in central Bhutan. The Chekha Formation and GHS are combined as one sequence in the figure, although our data and observations do not speak to whether or not the two are separated by a major unconformity. We propose a different map pattern for the TSS in the Dang Chu area that includes the four lower-temperature samples FB28, FB64, FB77 and FB85, and we interpret the contact between the TSS and structurally lower units to be the sole STFS detachment. The high-strain calc-silicate samples FB64 and FB85 are mapped at the base of the TSS, and we suggest that their slightly higher peak temperatures result from shear heating along the STFS shear zone. This interpretation is consistent with all outcrops we have seen in the area, but the quality of outcrop is so poor that detailed field confirmation of this map pattern is difficult.

If our interpretation is correct, it suggests that to truly understand the kinematics and displacement history of the STFS, we need to focus on this upper contact in the Dang Chu area, not on the previously mapped GHS–Chekha contacts. Our interpretation is inconsistent with the contention by Long and McQuarrie (2010) that the stratigraphic contact between TSS and GHS units in the Zhemgang klippe can be used to place a limit of ca. 20 km on STFS displacement and thus the magnitude of putative channel flow. The presence of TSS units ca. 80 km south of the Himalayan range crest suggests that displacement on the STFS may in fact be even greater than previously thought (Figure 8b).

An alternative interpretation of the geology that fits with our data is that of Grujic et al. (2011), who map the Chekha Formation more extensively across Bhutan (Figure 2b). According to their mapping, the majority of RSCM samples that give a consistent temperature of ca. 560°C are situated within the Chekha Formation. The exceptions are samples FB125 and FB132, which lie within the GHS on the edge of the Dang Chu klippe and samples BT1134, BT1136, and BT1138, which lie within the Maneting Formation in the Zhemgang klippe. However, we do not favor their interpretation as we see no evidence for a discrete shear zone at any of the GHS–Chekha contacts mapped and we have found paragneisses reasonably attributed to the GHS within areas mapped as Chekha Formation by Grujic et al. (2011) in both the Dang Chu and Ura klippen. Grujic et al. (2011) also map the TSS very differently in the Dang Chu klippe, with no clear explanation as to why. The folded marbles at Baylangdra (Figure 4a) are mapped as part of the TSS but at Pele La (Figure 4b) they are mapped as Chekha. This is inconsistent with both our temperature and structural data.

CONCLUSIONS

RSCM thermometry data from 17 samples combined with structural observations across three purported STFS klippen in central Bhutan suggest that current maps of this structure require revision. We find no change in peak metamorphic temperature across the contact between Chekha Formation rocks and underlying indisputable GHS units. Instead, we see a 130–140°C drop in temperature across an upper contact between the Chekha Formation and Precambrian-Devonian(?) TSS sediments of the Pele La and Tang Chu Groups. We therefore see no reason to infer that the Chekha Formation and the GHS are separated by the basal strand of the STFS. We regard the upper contact between the Chekha Formation and indisputable TSS units as the sole STFS detachment, and suggest that future studies of the kinematics and displacement on this system should be focused on this upper contact. The lack of matching hanging wall and footwall lithologic units or metamorphic grade in the direction of STFS motion suggests that displacement on the STFS may be as much as ca. 80 km, not less than ca. 20 km as suggested by Long and McQuarrie (2010). In light of the new data presented here, there is no clear evidence for a breakaway zone for the STFS in southern Bhutan.

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FIGURE CAPTIONS

Figure 1. Simplified geologic map of Bhutan and surrounding regions. Compiled from Gansser (1983), Bhargava (1995), Grujic et al. (2002), Long and McQuarrie (2010), Long et al. (2011c), Hughes et al. (2011), and Cooper et al. (in press). Box indicates the location of the study area shown in Figure 3. Inset map: A simplified tectonic map of the Himalayan orogen (modified from Hodges (2000) and Long et al. (2011c)). Abbreviations: STFS = South Tibetan fault system; KT = Kakhtang thrust; MCTS = Main Central thrust system; MBTS = Main Boundary thrust system; MFTS = Main Frontal thrust system; PW = Paro window; YCS = Yadong cross structure; Jo = Mount Jomolhari; KK = Khula Kangri pluton; WL = Wagye La; GL = Gonto La; LLK = Lhozhag La Kang; DCK = Dang Chu (Tang Chu) klippe; UK = Ura klippe; ZK = Zhemgang (Black Mountain) klippe; SK = Sakteng (Radi) klippe. Interpreted contacts at the base of the Dang Chu, Ura, and Zhemgang klippen follow Long and McQuarrie (2010). Cross-section line A–A’ refers to Figures 3 and 9.

Figure 2. Alternative geologic interpretations of central Bhutan. (a) Long and McQuarrie (2010) interpret the Dang Chu and Ura klippen as being soled by the STFS but map the GHS-Chekha contact at the base of the Zhemgang klippe as a conformable contact. The breakaway zone for the STFS is inferred to lie between the two klippen. (b) Grujic et al. (2011) map the Chekha Formation more extensively across central Bhutan, joining the Dang Chu and Zhemgang klippen and extending the Ura klippe northward, where it is cut by the Kakhtang Thrust. RSCM sampling locations for this study and the location of Cambrian fossils found by Hughes et al. (2011) are shown. The RSCM results are split into three groups according to peak metamorphic temperature. Abbreviations follow Figure 1. Stars refer to outcrop photographs in Figure 4.

Figure 3. Schematic cross-sections for the contrasting geological interpretations of (a) Long and McQuarrie (2010) and (b) Grujic et al. (2011). In (a), the distance between the STFS breakaway zone and the Ura klippe to the north implies a maximum displacement on the STFS of ca. 20 km. In (b), the distance from the STFS exposed at the crest of the range to the southernmost extent of the Zhemgang klippe implies a minimum displacement of 100 km on the STFS.

Figure 4. Outcrops of Tibetan Sedimentary sequence, Chekha Formation, and Greater Himalayan sequence units illustrating differences in structural style. Locations are shown in Figure 2. (a) and (b) Large-scale recumbent folding in TSS marbles of the Dang Chu klippe, (a) next to the Baylangdra monastery, and (b) at Pele La. (c) A cliff of Chekha Formation quartzite in the Dang Chu klippe dips consistently to the north and shows no evidence for large scale folding. This fundamental change in structural style is the same as the change across the STFS mapped by Cooper et al. (in press) in the Jomolhari area of NW Bhutan. (d) GHS pelitic schists

north of the Ura klippe show a similar consistently north-dipping fabric, with no large-scale folding. (e) Chekha Formation quartzites and (f) interbedded quartzite and phyllite of the TSS Maneting formation (as mapped by Long et al. (2011c) in the Zhemgang klippe dips gently to the south and also shows no evidence for large-scale folding.

Figure 5. Simplified stratigraphic columns for central Bhutan showing how different research groups have interpreted the stratigraphy and positions of the major fault systems. For abbreviations, see Figure 1. Age ranges follow Hughes et al. (2011); Long and McQuarrie (2010); and Tangri and Pande (1995). Unit thicknesses (shown in kilometers on the right hand side of each column) are from Long and McQuarrie (2010); Long et al. (2011a); and Tangri and Pande (1995).

Figure 6. Examples of Raman spectra for each sample. The positions of the graphite band, G, and defect bands D1 and D2 are indicated. R2 values and temperatures calculated using the Beyssac et al. (2002a) calibration are given. Full details of peak positions for individual analyses are given in Data Repository Item B.

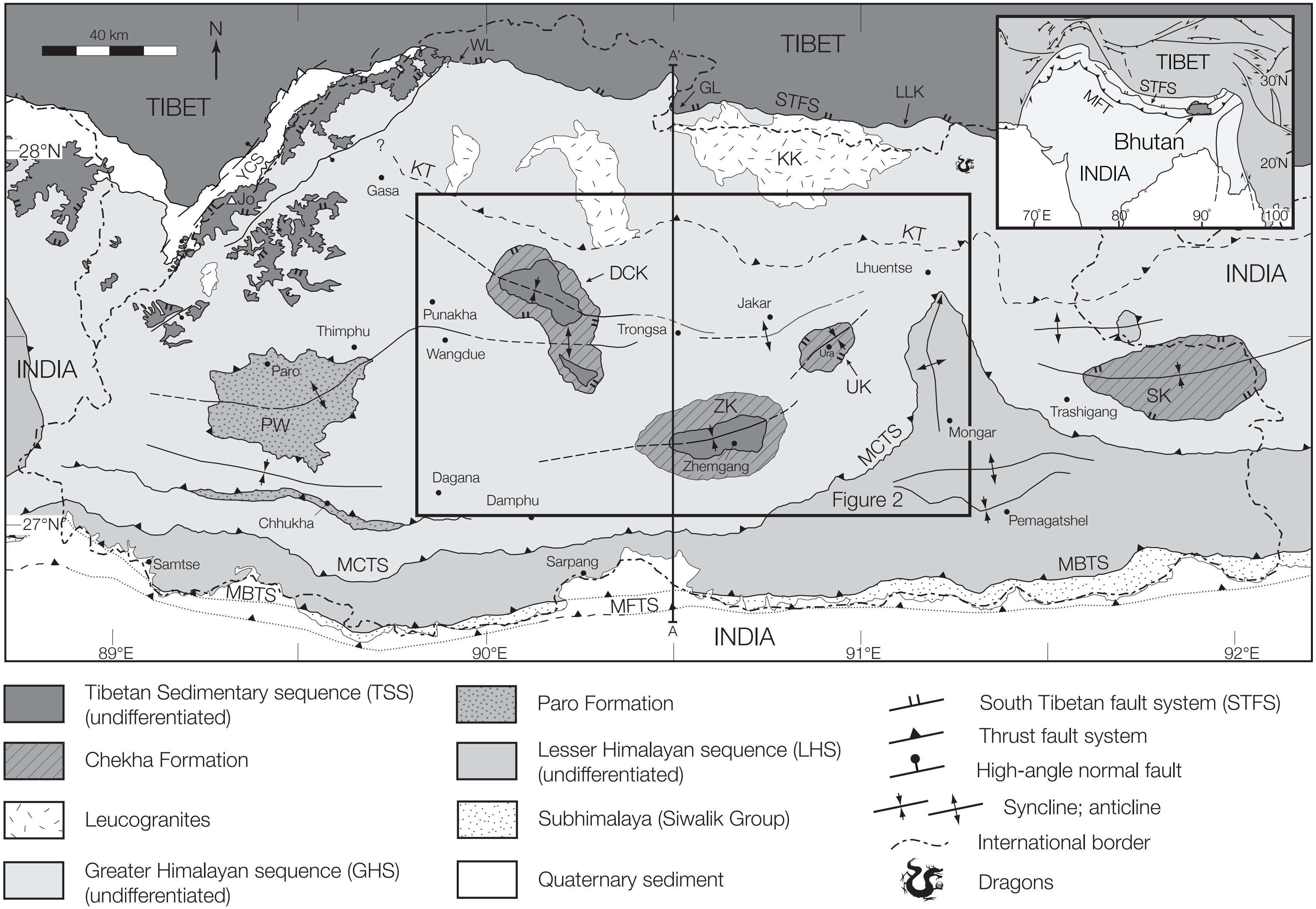
Figure 7. All 17 samples plotted in order of peak metamorphic temperature. 13 samples (FB52 to FB102) show very consistent temperatures, with an error-weighted mean average of 560 ± 2°C (2SE). These samples include TSS marbles and phyllites (Maneting Formation), Chekha Formation schists, quartzites, and calc-silicates as well as GHS paragneisses and schists across all three klippen (Figure 2). The lack of any temperature difference between the Chekha, GHS, and TSS Maneting Formation samples suggests that there is no metamorphic discontinuity across

between them. Four samples give distinctly lower temperatures: Samples FB64 and FB85, both foliated calc-silicates, give temperatures of 508 ± 33°C and 489 ± 26°C (2SE), respectively, while samples FB28, a marble and FB77, a black shale give 430 ± 30°C and 420 ± 21°C, respectively.

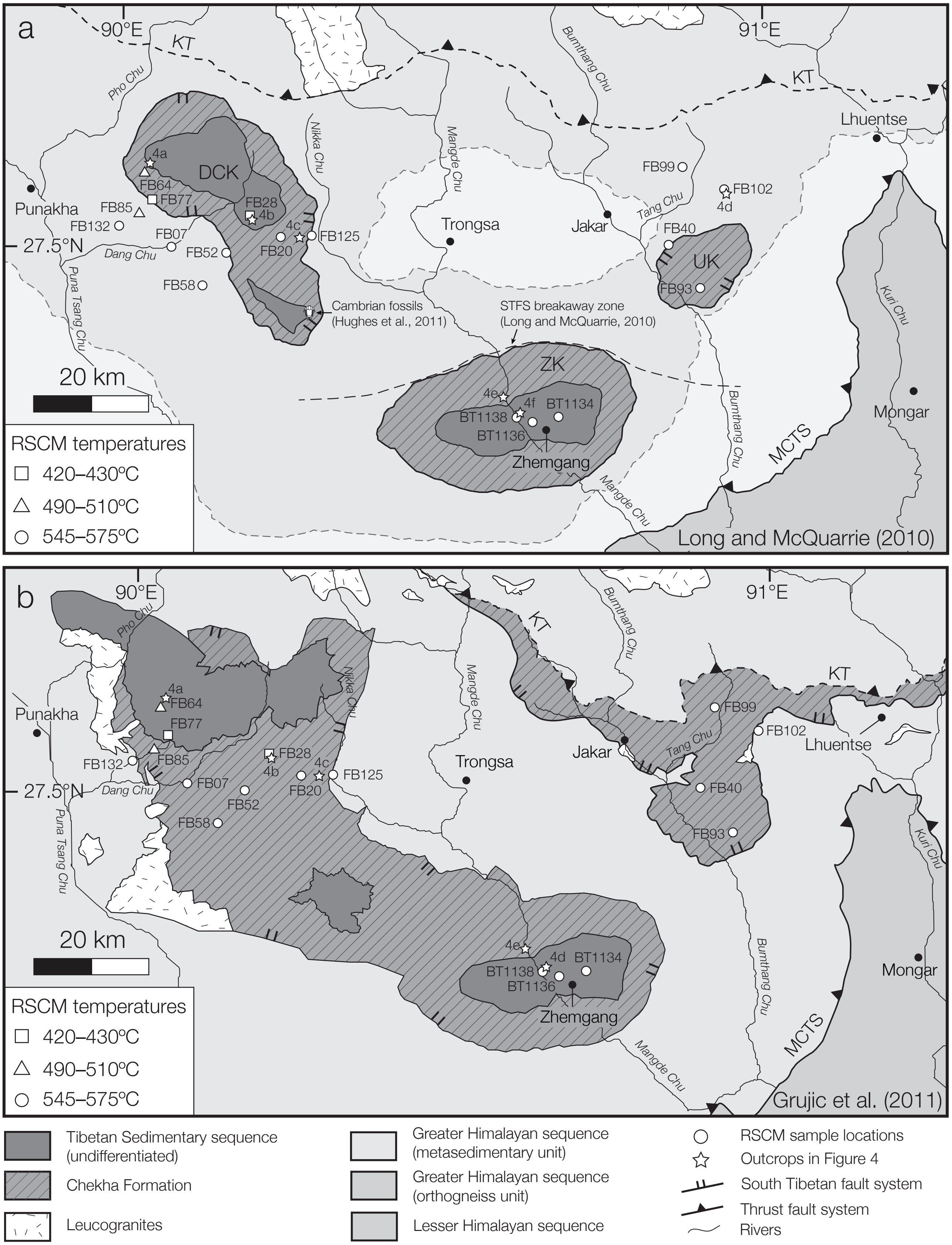
Figure 8. Our interpretation for the distribution of RSCM temperatures in central Bhutan. Abbreviations: DCKn = Dang Chu klippe, north; DCKs = Dang Chu klippe, south; STFS = South Tibetan fault system; KT = Kakhtang thrust; MCTS = Main Central thrust system; MBTS = Main Boundary thrust system. (a) The Chekha Formation and GHS are combined as one sequence due to their similar lithology, structural style and peak metamorphic temperature. The TSS in the Dang Chu klippe is mapped on the basis of the four lower-temperature samples, FB28, FB64, FB77 and FB85 as well as our structural observations of recumbently folded units and the location of fossils found by Hughes et al. (2011). We interpret the contact between the TSS and structurally lower units to be the sole STFS detachment. (b) Schematic cross-section through the north and south components of the Dang Chu klippe. The distance from the STFS exposed at the crest of the range to the southernmost extent of the Dang Chu klippe implies a minimum displacement of 80 km on the STFS.

[1]GSA Data Repository item 2012xxx, Examples of analyzed carbonaceous material, complete RSCM spectra data, and thermobarometric methods and data tables, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

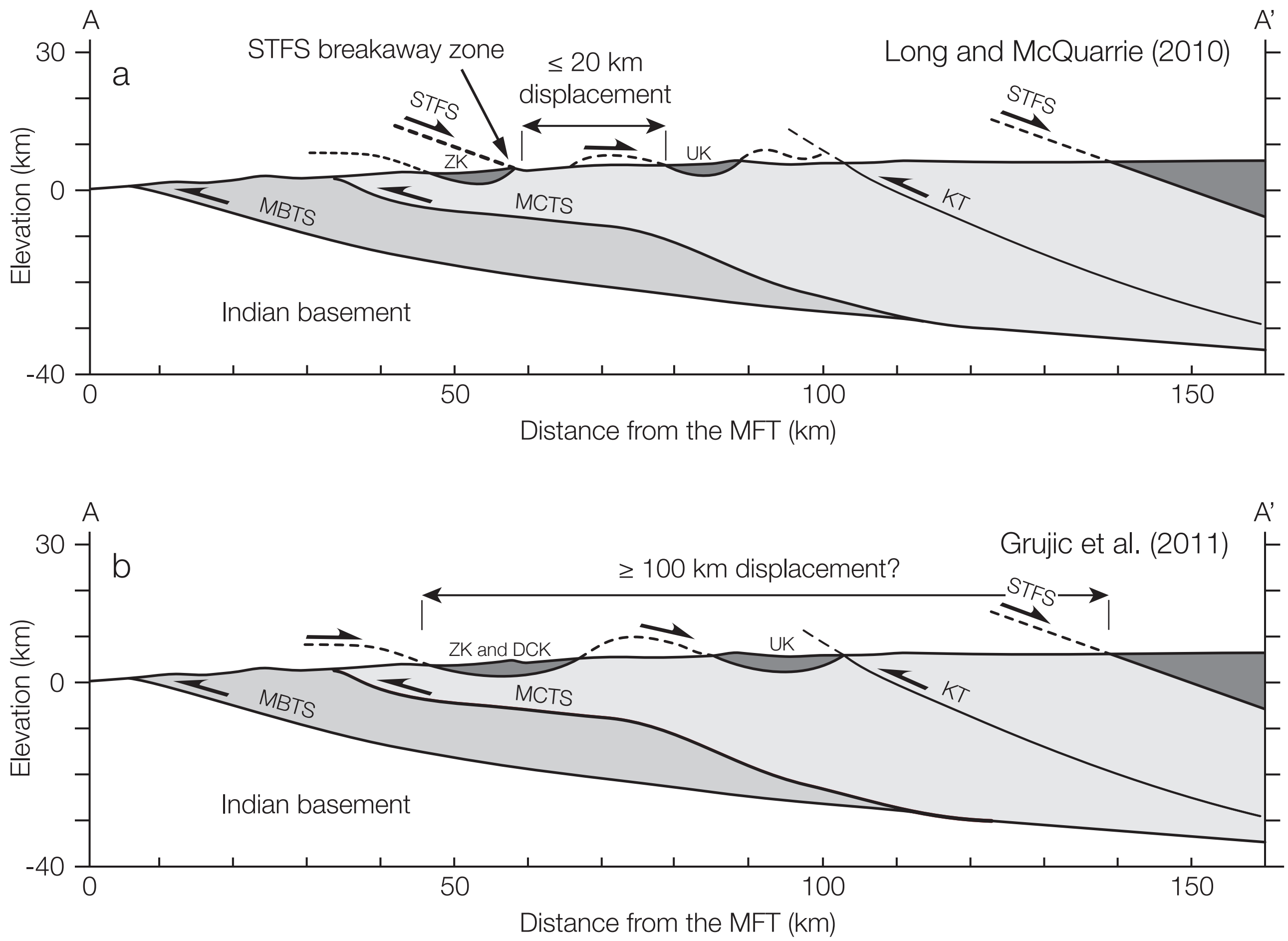
Cooper et al. Figure 1



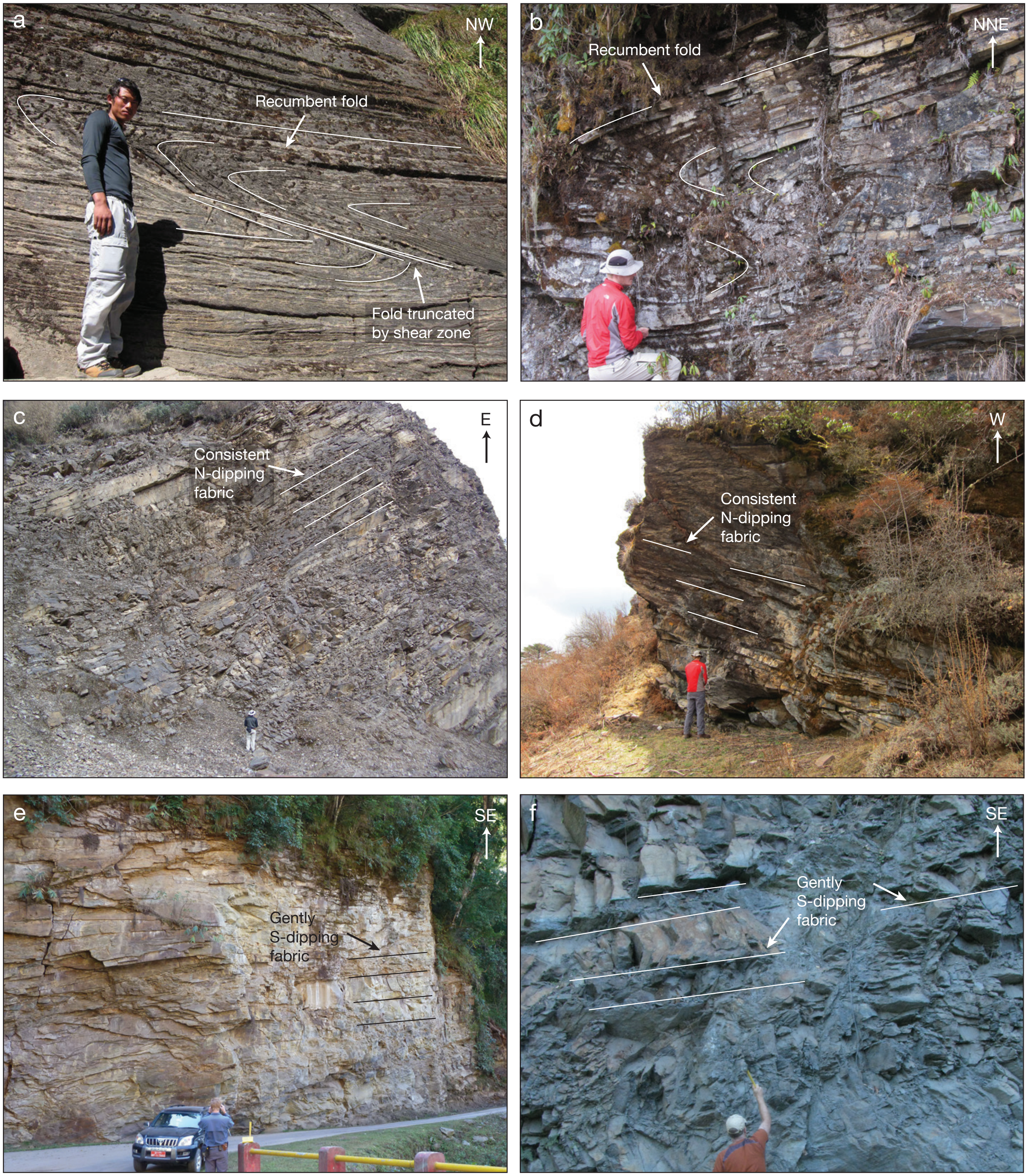
Cooper et al. Figure 2



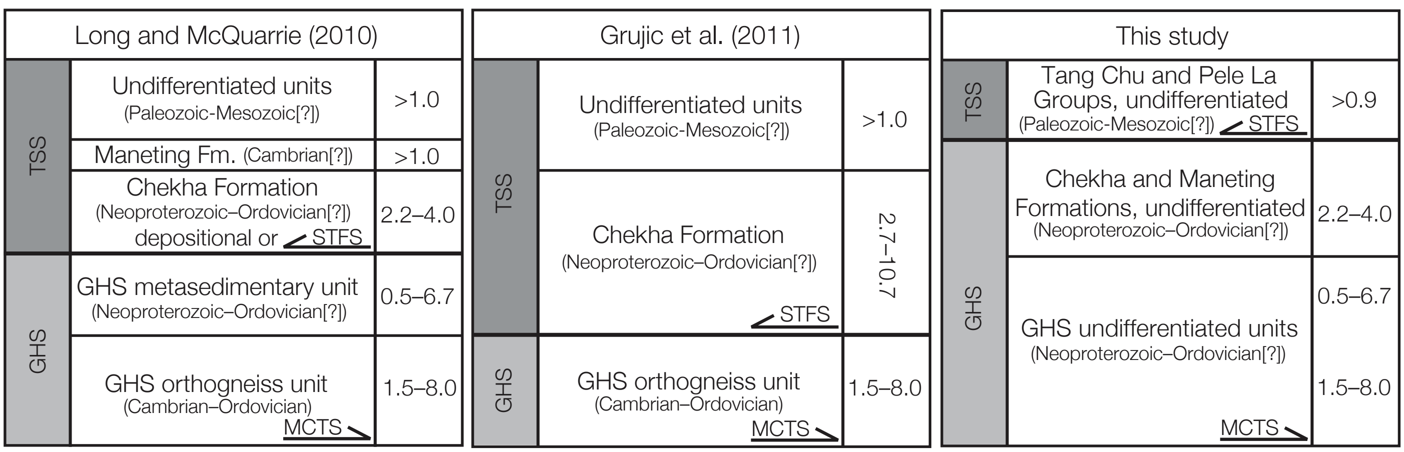
Cooper et al.   Figure 3



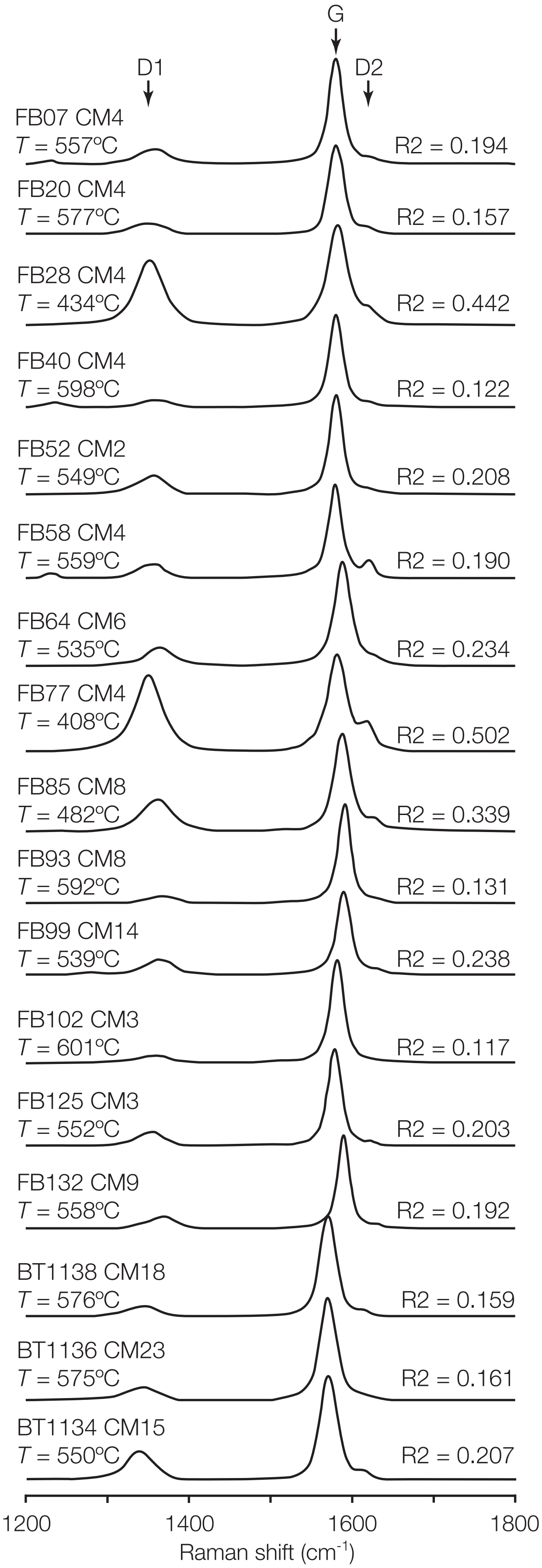
Cooper et al. Figure 4



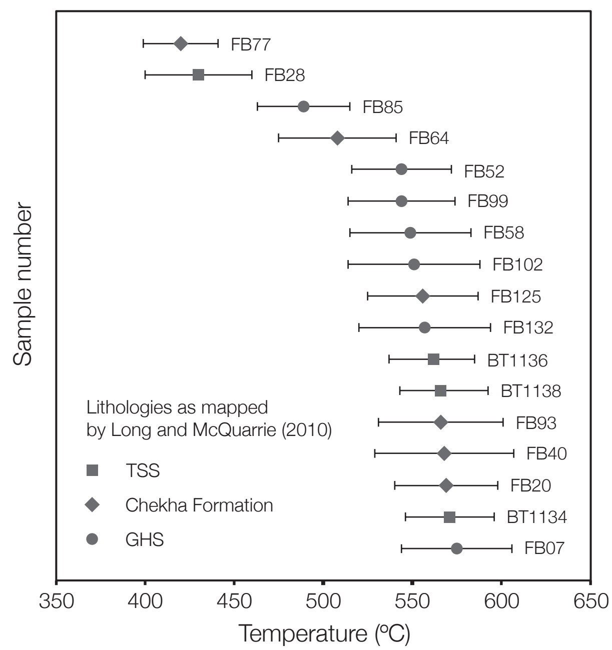
Cooper et al.   Figure 5



Cooper et al.   Figure 6



Cooper et al.   Figure 7



Cooper et al.   Figure 8

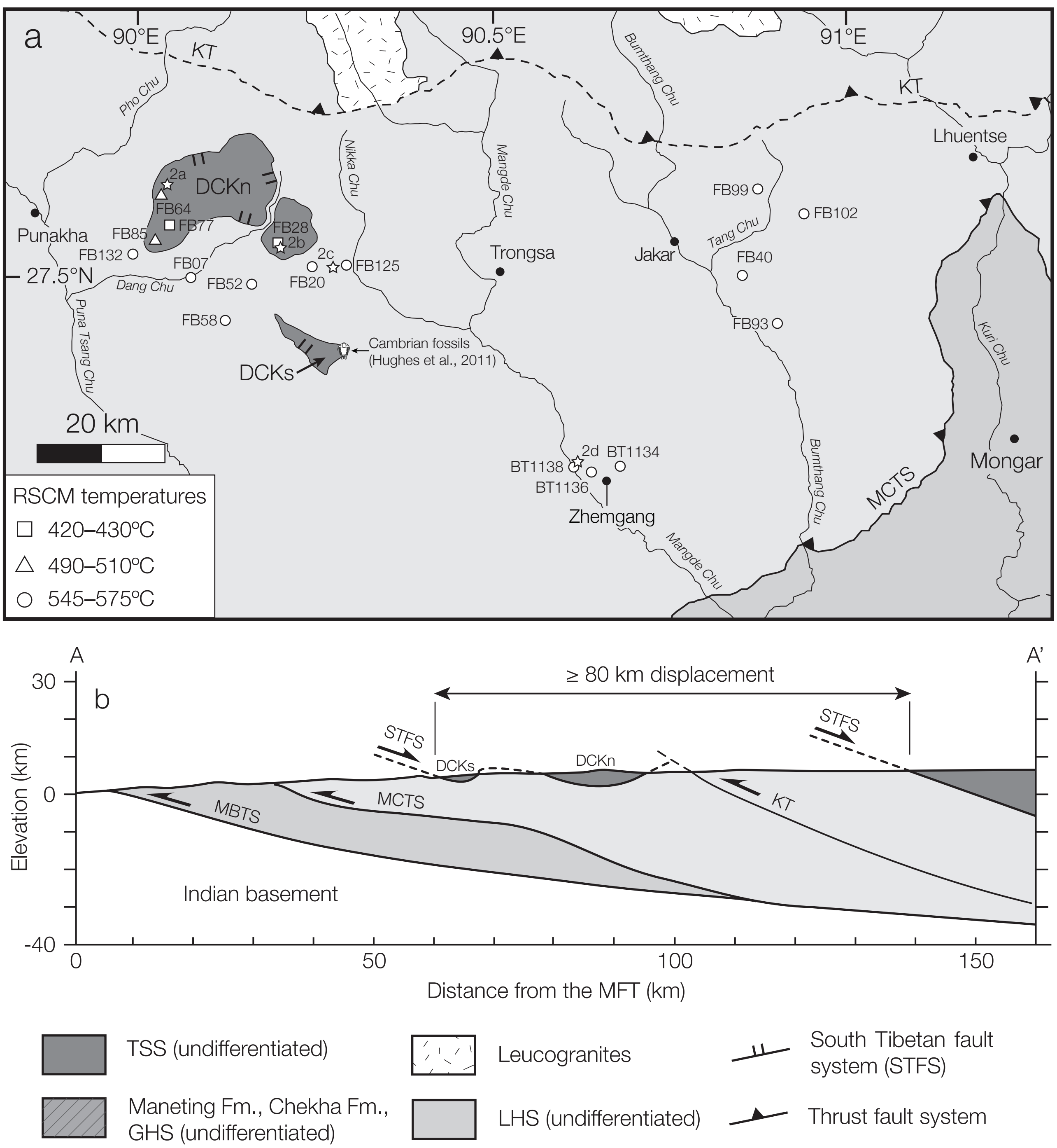


Table 1. RSCM temperatures

Sample	Lithology	Location		R2		Temp (°C)			n
		Latitude (°)	Longitude (°)	Mean	1σ	Mean	1σ	2SE	
FB07	Paragneiss	27.505	90.078	0.165	0.090	575	49	31	20
FB20	Quartzite	27.518	90.250	0.175	0.071	569	40	29	20
FB28	Marble	27.551	90.202	0.454	0.073	430	31	30	15
FB40	Paragneiss	27.504	90.854	0.178	0.104	568	57	39	15
FB52	Pelitic schist	27.496	90.165	0.220	0.073	544	39	28	20
FB58	Quartzite	27.445	90.127	0.212	0.080	549	43	34	15
FB64	Calc-silicate	27.617	90.036	0.288	0.082	508	40	33	15
FB77	Graphitic slate	27.577	90.048	0.474	0.038	420	16	21	25
FB85	Calc-silicate	27.556	90.028	0.326	0.061	489	31	26	20
FB93	Pelitic schist	27.436	90.905	0.169	0.105	566	47	35	15
FB99	Marble	27.625	90.876	0.220	0.083	544	46	30	20
FB102	Paragneiss	27.591	90.941	0.209	0.098	551	52	37	15
FB125	Paragneiss	27.520	90.299	0.200	0.098	556	53	31	22
FB132	Paragneiss	27.537	89.997	0.200	0.122	557	66	37	20
BT1134	Phyllite	27.236	90.681	0.171	0.070	571	39	25	25
BT1136	Phyllite	27.228	90.638	0.189	0.060	561	33	24	25
BT1138	Phyllite	27.234	90.615	0.179	0.055	566	31	23	25

R2 values calculated using the calibration of Beyssac et al. (2002a) and temperatures calculated using Aoya (2010). Variability of the R2 value within each sample is indicated by its 1σ uncertainty.

Temperatures are reported as standard means at the 1σ and 2 standard errors (2SE) confidence levels, accounting for both internal and external uncertainties (see also Data Repository Item B).

Table 2. RSCM vs GARB-GMBP results

Sample	RSCM[a] Temp (°C)			GARB[b] Temp (°C)		GMBP[b] Pressure (kbar)		
	Mean	2SE	n	Mean	2SE	Mean	2SE	n
FB07	575	31	20	579	48	5.0	0.6	3
FB125	556	31	22	532	56	6.2	0.8	4
FB132	557	37	20	536	75	4.5	0.8	3

[a]RSCM temperatures were calculated using the Aoya (2010) calibration. [b]GARB temperatures and GMBP pressures were calculated using THERMOCALC v. 3.33. All data are reported as means at the 2 standard errors confidence level.