RECONCILING HIMALAYAN MIDCRUSTAL DISCONTINUITIES: THE MAIN CENTRAL THRUST SYSTEM

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Abstract

The occurrence of thrust-sense tectonometamorphic discontinuities within the exhumed Himalayan metamorphic core can be explained as part of the Main Central thrust system. This imbricate thrust structure, which significantly thickened the orogenic midcrustal core, comprises a series of thrust-sense faults that all merge into a single detachment. The existence of these various structures, and their potential for complex overprinting along the main detachment, may help explain the contention surrounding the definition, mapping, and interpretation of the Main Central thrust. The unique evolution of specific segments of the Main Central thrust system along the orogen is interpreted to be a reflection of the inherent basement structure and ramp position, and structural level of exposure of the mid-crust. This helps explain the variation in the timing and structural position of tectonometamorphic discontinuities along the length of the mountain belt.

1. Introduction

Investigation of the role the middle and lower crust plays during the development of orogenic belts has led to a better understanding of internal convergence accommodation processes. In the Himalaya, this type of investigation has recently demonstrated that the exhumed mid-crust, or Greater Himalayan sequence (GHS), which was previously thought to be relatively homogeneous and characterized by diffuse pervasive strain (e.g. Grujic et al., 1996; Jamieson et al., 1996; Searle et al., 2006; Larson et al., 2010), is actually cut internally by a number of cryptic, thrust-sense shear zones commonly referred to in the literature as tectonometamorphic discontinuities (e.g. Montomoli et al., 2014; Cottle et al. 2015). The GHS is characterized by amphibolite to granulite, and locally eclogite, facies metamorphism (Kohn, 2014), often with an inverted metamorphic sequence at its base (e.g. Mallett, 1875; Bordet, 1961; Gansser, 1964; Hashimoto et al., 1973; Arita, 1983). These rocks are thought to represent the metamorphosed and deformed equivalents of the former sedimentary wedge that was built upon the northern passive margin of India prior to collision with Asia and the closure of the Tethys ocean (Parrish and Hodges, 1996; Searle et al., 1997; Myrow et al., 2003; Murphy, 2007). Discontinuities within the GHS have been identified in various locations along the length of the orogen (Figure 1; Table 1), recognized mainly through abrupt breaks in pressure and temperature estimates and/or pressure-temperature-time $\pm$ deformation (P-T-t(-D)) paths (e.g. Carosi et al., 2010; Corrie and Kohn, 2011; Larson et al., 2013; Montomoli et al., 2013; Rubatto et al., 2013; Warren et al., 2014; Ambrose et al., 2015).

The discovery of these cryptic structures within the Himalaya has led to a transition away from geologic models that have either not accounted for deformation

50 within the high-grade core (e.g. DeCelles et al., 2001; Robinson et al., 2006; Webb et al.,
51 2007; Robinson, 2008), or implicitly assumed that deformation was diffuse and pervasive
52 throughout its history (e.g. Searle and Szulc, 2005; Larson and Godin, 2009; Larson et
53 al., 2010). The widespread recognition of thrust-sense faults within the GHS implies that
54 deformation was localized on discrete structures for at least the later part of the finite
55 strain history recorded by these rocks (Cottle et al., 2015). Moreover, it also indicates that
56 the GHS has been significantly thickened (Montomoli et al., 2013; Larson and Cottle,
57 2014; Ambrose et al. 2015) and that shortening estimates made based on structural
58 restorations (e.g. DeCelles et al., 2001; McQuarrie et al., 2008; 2014; Long et al., 2011a;
59 Khanal and Robinson, 2013; Webb, 2013), which are acknowledged as minimums, may
60 actually severely underestimate real shortening values.

61 As interpreted, these discontinuities have typically been classified into one of two
62 end-member types: early (late Oligocene to earliest Miocene) in-sequence thrust
63 structures (e.g. Carosi et al., 2010; Corrie and Kohn, 2011; Kohn et al., 2005; Larson et
64 al., 2013; Montomoli et al., 2014; 2013) or late (middle Miocene) out-of-sequence thrust
65 structures (e.g. Grujic et al., 2011; Warren et al., 2011a; 2014; Kellett and Grujic, 2012;
66 Larson and Cottle, 2014). Attempts to reconcile the data characterizing the various
67 tectonometamorphic discontinuities mapped along the Himalaya into a coherent
68 kinematic model have been focused on, and informed primarily by, data from the early
69 in-sequence structures (e.g. Montomoli et al., 2014). The majority of these types of
70 structures have been identified near the middle of the exhumed midcrustal core in west-
71 central Nepal (Carosi et al., 2010; Corrie and Kohn, 2011; Kohn et al., 2005; Montomoli
72 et al., 2013), whereas discontinuities farther east are typically younger in age and occur

as out-of-sequence thrusts structurally higher in the exhumed metamorphic core (Daniel et al., 2003; Grujic et al., 2011; Warren et al., 2011a; 2014). The existing kinematic models for the evolution of these structures are not compatible with the variability in the type of structure that occurs along the orogen (i.e. in or out-of-sequence), the differences in timing, or why the structures occur at different structural levels in different locations. This study attempts to elucidate the development of these discontinuities and their variability along and across the orogen as part of an integrated imbricate thrust system model.

2. Previous Interpretations

The current model proposed to explain the development of major thrust-sense tectonometamorphic discontinuities within the migmatitic rocks of the GHS suggest all such structures along the orogen are part of one feature, ‘the High Himalayan Discontinuity’ (Montomoli et al., 2014). In this model, the rocks in the hanging wall of the structure were initially metamorphosed deep in the hinterland and then thrust towards the foreland (Carosi et al., 2010; Corrie and Kohn, 2011; Montomoli et al., 2013). As hanging wall rocks were translated southward, metamorphism occurred in the overridden footwall (e.g. Pêcher, 1989; Harrison et al., 1997; Hubbard, 1996; Long et al., 2011b). Therefore, metamorphism in the footwall and hanging wall is expected to be diachronous with earlier, typically higher temperature metamorphism in the hanging wall and later, higher pressure metamorphism in the footwall (Figure 2; Montomoli et al., 2014). As interpreted, the development of the High Himalayan Discontinuity is thought to have occurred in the late Oligocene or earliest Miocene (Montomoli et al., 2014), at least

96 partially coeval with motion along the South Tibetan detachment system, a top-to-the-
97 north-sense structure marking the top of the GHS (Figure 2). After movement along the
98 High Himalayan Discontinuity ceased, deformation migrated towards the foreland and
99 down structural section initiating activation of the Main Central thrust (Figure 2;
100 Montomoli et al., 2013).

101 This High Himalayan Discontinuity model was largely developed for structures
102 observed in west-central Nepal. There, along the Himalayan front, the GHS can be very
103 thin - only a few kilometers in structural thickness (e.g. locations 3 and 4 in Figure 1).
104 This contrasts sharply with the GHS exposed in eastern Nepal and neighbouring regions
105 where it is in excess of 30 km thick (e.g. locations 12-16 in Figure 1). In the High
106 Himalayan Discontinuity model of Montomoli et al. (2014), a single structural break is
107 interpreted to occur along the length of the orogen that connects recognized
108 discontinuities. There are, however, incompatibilities between the various recognized
109 structures in their timing of displacement and the structural level at which they occur. In
110 Bhutan and adjacent NE India, for example, the Kahktang thrust and equivalents (Laya
111 and Zimithang thrusts) were active near the top of the GHS in the mid-Miocene (Daniel
112 et al., 2003; Grujic et al., 2011; Warren et al., 2011a; 2014), not near the middle of the
113 GHS during the late Oligocene as the High Himalayan Discontinuity is interpreted to be
114 in areas farther west (Carosi et al., 2010; Montomoli et al., 2013). Moreover, in contrast
115 to the High Himalayan Discontinuity in the model of Montomoli et al. (2014), structures
116 in the eastern Himalaya are interpreted as out-of-sequence thrust faults that post-date
117 metamorphism in the footwall (e.g. Grujic et al. 2011; Warren et al. 2014). Similar
118 interpretations have been made for an unnamed and undated structure in northern Sikkim,

which has been tentatively correlated to the Laya thrust in nearby Bhutan (Rubatto et al., 2013). The only structure identified in the eastern Himalaya with apparently similar characteristics as the High Himalayan Discontinuity is the High Himal thrust (Goscombe et al., 2006; Imayama et al., 2012). The data used to infer timing of displacement on that structure, however, are entirely from the footwall of the fault and as such do not constrain metamorphism in the hanging wall or movement across it. Based on monazite petrochronology from both sides of the High Himal thrust in the Kanchenjunga region, Ambrose et al. (2015) reinterpreted the structure as an out-of-sequence thrust that was active between ca. 20 and 18 Ma and that the data Imayama et al. (2012) used to infer movement on the High Himal thrust actually mark a distinct, structurally lower, discontinuity. The Ambrose et al. (2015) study actually outline no less than five tectonometamorphic discontinuities in the Kanchenjunga region, which demonstrates the potential complexity of deformation within the GHS and calls further into question the interpretation of recognized discontinuities across the orogen as a single structure.

3. Development of the Main Central thrust system

The variability in timing, structural position, and number of discontinuities observed along the orogen requires the development of a new kinematic model. Recent studies have interpreted the development of thrust-sense structures in the GHS as part of a larger system (Larson and Cottle, 2014; He et al. 2015; Ambrose et al. 2015). The interpreted processes are similar to underplating thermal-kinematic models (e.g. Avouac, 2003; Bollinger et al. 2006; Herman et al. 2010) and inferred crustal thickening via duplexing (Murphy, 2007; Grandin et al. 2012; Cannon and Murphy, 2014) for material structurally below the GHS in the footwall of the Main Central thrust. In an imbricate

thrust system model, differences in the kinematic evolution between spatially distinct areas may reflect changes in regional geology such as crustal ramp geometries and/or the initial thickness of the GHS protoliths. It also has important implications for the evolution of the Main Central thrust.

The definition, position, and kinematic significance of the Main Central thrust, a crustal scale, orogen-wide fault/shear zone, have been the subject of much debate (e.g. Upreti, 1999; Yin, 2006; Searle et al., 2008; Mottram et al., 2014) leading to various studies re-interpreting and potentially misinterpreting previously published data based on different definitions of the structure. A wireframe construction of the kinematic model presented herein (Figure 3) potentially sheds some light on why interpretations of the Main Central thrust have been so varied in its definition and mapped location (e.g. Upreti, 1999; Searle et al. 2008).

In the proposed kinematic model, the thickening and southward translation of the GHS is accomplished through the development of an imbricate thrust system with the sequential addition of material to the hanging wall (Figure 3A, B). The active fault in the area of subcretion, effectively the Main Central thrust, changes with each slice of material that is added. Once the former sole thrust is no longer active it becomes part of the over-riding plate, whereas the newly active structure becomes the sole thrust. The thrusts merge both up-dip and down-dip from the ramp. This results in the progressive overprinting of the various deformation histories along a single structure (the Main Central thrust) both towards the foreland and the hinterland (Figure 3C, D). This type of evolution for the Main Central thrust could result in significantly different geologic histories recorded in a region, depending on the structural level of exposure and other

factors (see below) that may control kinematic history and potential thrust system development in that area.

The South Tibetan detachment system may allow early lateral ductile flow of the mid-crust (e.g. Jamieson et al. 2006) or wedging (e.g. Webb et al. 2007) of the mid-crust southward (Figure 3A). In the first case, the South Tibetan detachment system would accommodate channel flow before or during imbricate thrust stacking (Larson and Cottle, 2014); in the second possibility the South Tibetan detachment system would develop as a roof back-thrust of the imbricate system (He et al., 2015). In either case, movement along the structure ceases as the thrust system evolves.

4. Integrated Kinematic Model

Initial development of tectonometamorphic discontinuities within the GHS occurred at similar times across (at least) Nepal with the High Himalayan Discontinuity (Montomoli et al., 2014) initiating in the Dolpo region of west –central Nepal at ca. 26-27 Ma (Carosi et al., 2010; Montomoli et al., 2013) and the earliest structure initiating in the Kanchenjunga region between 31 and 26 Ma (Ambrose et al., 2015). In both areas, geochronology and P-T data indicate that over-thrusting of the hanging wall resulted in prograde metamorphism in the footwall (Montomoli et al., 2014; Ambrose et al., 2015). Following this early, shared history, the spatially distinct differential development of the Himalayan mid-crust may be related to regional geologic changes such as crustal ramp geometries, structural level of exposure, or the location of the brittle-ductile transition (e.g. Bollinger et al., 2006; Cannon and Murphy, 2014).

In west-central Nepal, where the exposed GHS along the Himalayan front is as thin as 3 km (Le Fort et al., 1987; Carosi et al., 2007; 2010), deformation migrated structurally lower from the High Himalayan Discontinuity with the addition of the metamorphosed and deformed High Himalayan Discontinuity footwall (Figure 4; Carosi et al., 2010; Montomoli et al., 2013). Movement along the base of that imbricate, mapped as the Main Central thrust, occurred between ~19 and 13 Ma (Montomoli et al., 2013), post-dating local movement on the South Tibetan detachment system (Carosi et al., 2013). In eastern Nepal, where the exposed GHS is typically >30 km thick (e.g. Schelling, 1992), the development of the GHS was significantly different. Multiple imbricates were added to the Main Central thrust system between 24 and 20 Ma (Figure 4; Ambrose et al., 2015). The difference observed between the regions may reflect: 1) progressively deeper erosion levels (with respect to the crystalline core) from west to east across the orogeny (Webb et al. 2011), or 2) a more pronounced ramp structure in eastern Nepal that increased the volume of material accreted from the footwall. In the Kanchenjunga region, movement of the thrust sheets toward the foreland appears to have slowed by ~ 20 Ma. This may reflect encroachment of a significant change in footwall lithology leading to a change in fault geometry. Deformation then stepped out-of-sequence, towards the hinterland, cutting the previously imbricated GHS and driving deformation back towards the foreland (20 – 18 Ma). The location of the out-of-sequence thrust may be related to the position of the GHS above the main crustal ramp (e.g. Kellett et al., 2009; Warren et al., 2011a).

A similar history, with distinct timing, is postulated for the GHS of Bhutan and NE India. There, out-of-sequence thrusting occurs both significantly later (14-11 Ma) and

211 farther toward the hinterland (Grujic et al., 2011; Warren et al., 2011a; 2014). This may
212 reflect a similar lithologic change in the footwall encountered farther towards the
213 foreland (Figure 4); the GHS moving along the basal detachment would take longer to
214 encounter the effects of the forced change in fault geometry, thereby impeding its
215 movement later than that in the Kanchenjunga region. Moreover, the GHS would have
216 translated farther south by the time deformation slowed and out-of-sequence thrusting
217 began. The resulting out-of-sequence thrust, located above the dominant crustal ramp
218 (e.g. Kellett et al., 2009; Warren et al., 2011a), would have cut through the GHS later and
219 higher up in the structural section (Figure 4).

220 Subsequent to the development of the Main Central thrust system in west-central
221 Nepal, and the out-of-sequence thrust faults that cut the imbricate stack farther east, the
222 GHS in all areas appear to have been largely exhumed through the development of the
223 Lesser Himalayan duplex and concomitant erosion (e.g. DeCelles et al., 1998; McQuarrie
224 et al., 2014; 2008; Robinson et al., 2001). The development of that duplex structure
225 occurred at different times along the orogen corresponding to the time at which
226 deformation was focused on different units in the down-going plate. In west-central
227 Nepal, cooling of the GHS occurred between ca. 15 and 8 Ma; dominated by the earlier
228 ages (Martin et al., 2014; Vannay and Hodges, 1996). Whereas exhumation and
229 associated development of the Lesser Himalayan duplex in western Bhutan is much
230 younger, with exhumation interpreted to have occurred between 9 Ma and the present day
231 (McQuarrie et al., 2014).

232 A thrust imbricate model for the kinematic evolution of the GHS does not
233 invalidate models of lateral midcrustal flow. 'Channel'-type flow could occur during

coeval movement along the Main Central thrust and South Tibetan detachment system, however, it would be relatively short-lived phenomena, with thrust imbrication being the dominant convergence accommodation process. Some published thermo-mechanical models (e.g. HT111; Jamieson et al. 2006) actually demonstrate vertical juxtaposition of formerly laterally adjacent rock units within the mid-crust during lateral transport, resulting in a similar final geometry to that presented herein. As modeled, however, the timing of juxtaposition and exhumation are not compatible with existing data.

5. Summary

The variation in the timing and structural position of tectonometamorphic discontinuities identified along the Himalaya is interpreted to reflect fundamental differences in the development of the Main Central thrust system. As described herein, these differences are interpreted reflect variations in the underlying basement/ramp structure of the basal detachment and perhaps structural level of exposure with respect to the mid-crust. This model is consistent with available along and across-strike geologic controls in the Himalaya and provides an integrated solution to help explain the occurrence and development of cryptic structures within an evolving orogenic midcrustal core.

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7. Figure Captions:

Figure 1 – Simplified geologic map (after He et al., 2015) showing the spatial distributions of mapped tectonometamorphic discontinuities within the exhumed Himalayan mid-crust. See Table 1 for references corresponding to locations.

Figure 2 – Summary diagram of activity on the High Himalaya Discontinuity (HHD) and subsequently the Main Central Thrust (MCT) based on Montomoli et al. (2014). Movement of different particles demonstrates relative movement across the structures. Timing constraints are from western Nepal (Montomoli et al. 2013). STDS – South Tibetan detachment system.

Figure 3 – Evolution of the Main Central Thrust (MCT) system. The structure evolves such that the current floor thrust at any given time later becomes inactive as new material is incorporated into the thrust system. Motion along active structures is accommodated away from the site of addition along pre-existing faults potentially resulting in complex over-printing and/or protracted motion. Final exposure of the exhumed Himalayan metamorphic core above the Lesser Himalayan (LH) Duplex results in the surface exposure of a number the faults that comprise the Main Central Thrust system. Colors identify different discontinuities that in (D) merge up and down-dip into a single structure

(black) in present-day geometry. Throughout Himalayan development each would have been the Himalayan sole thrust. STDS – South Tibetan Detachment System.

Figure 4 – Conceptual development of the Main Central Thrust system at different points along the length of the orogen. See text for detailed discussion.

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554

Figure 1

Larson et al., Fig. 1

Figure 2

Larson et al., Fig. 2

Figure 3

Larson et al., Fig. 3

Figure 4

Larson et al., Fig. 4

Table 1

Table 1: Metamorphic and Geochronologic Contstraints Defining Interpreted Tectonometamorphic Discontinuities

Location (Figure 1)	(Name), Location	Footwall			Hanging Wall			PT Method	Shear Zone Age (Ma)	References
		P (GPa)	T (°C)	Age (Ma)	P (GPa)	T (°C)	Age (Ma)			
1	¹ Garhwal, NW India	0.7-1.2↑	~550	-	1.4-0.8↓	~750	-	ER+TE	-	Spencer et al., 2012
2	Karnali, NW Nepal	0.8-1.1↑	600-630	-	1.0-0.5↓	650-720	-	AvPT	-	Yakymchuk and Godin, 2012
3	<i>Mangri Shear Zone</i> , Mugu Karnali, W Nepal	0.9-1.1	665-700	<i>21-17</i>	0.7-0.8	690-700	<i>25-18</i>	ER	(<i>21-17</i>)	Montomoli et al., 2013
4	<i>Toijem Shear Zone</i> , Lower Dolpo, W Nepal	0.7-0.9↑	640-675	<i>43-33</i>	0.63	620-640	<i>29-17</i>	ER	(<i>26-17</i>)	Carosi et al., 2010
5	<i>Kalopani Shear Zone</i> , Annapurna, central Nepal	0.7	450-650	<i>35</i>	1.0	650-750	<u><i>34-35</i></u>	ER	(<u><i>23-15</i></u>)	Vannay and Hodges, 1996; Godin et al., 2001
6	<i>Bhanuwa Thrust</i> , Modi Khola, central Nepal	1.0-1.2	550-700	<i>33-24, 22-17</i>	1.1-1.4↓	700-775	<i>26-24, 23-21</i>	ER+TE	(<i>23-19</i>) or (<i>16-11</i>)	Martin et al., 2010; Corrie and Kohn, 2011; Martin et al., 2014
	<i>Sinuwa Thrust</i> , Modi Khola, central Nepal	1.1-1.4↓	700-775	<i>26-24, 23-21</i>	1.1-1.4↑	730-800	<i>32-27, 22-19</i>	ER+TE	(<i>27-19</i>)	Martin et al., 2010; Corrie and Kohn, 2011; Martin et al., 2014
7	¹ Manaslu-Himal Chuli, central Nepal	0.6-1.3↑	525-650↑	<i>21.5, 15-12</i>	1.1-0.30↓	640-675	<i>26-15</i>	ER	~ <i>21</i>	Larson et al., 2010, 2011; Kohn et al., 2001
8	<i>Langtang Thrust</i> , Langtang, Nepal	0.75-1.0	680-800	<i>36-16, 15-13</i>	0.6-0.95	750-850	<i>31-21, 19-16</i>	ER	(<i>20-16</i>)	Reddy et al., 1993; Fraser et al., 2000; Kohn et al., 2005; Kohn, 2008
9	<i>Nylam Thrust</i> , Bhote Kosi, Nepal	0.3-1.3↓	600-700	-	0.3-0.9↓	700-800	<u><i>48-30, 19-14</i></u>	ER	(<i>30-19</i>)	Wang et al., 2013
	¹ <i>Main Central Thrust</i> , Bhote Kosi, Nepal	0.8-1.0	620-650	-	0.9-1.5	660-720	-	PE	-	Wang et al., 2015
10	¹ " <i>Lower Discontinuity</i> ", Tama Kosi Region, Nepal	0.64-0.7	610-640	<i>10-8</i>	1.0-0.7↓	700-750	<i>23-19, 19-14</i>	PE	(<i>14-8</i>)	Larson et al., 2013; Larson and Cottle, 2014
	<i>"Upper Discontinuity"</i> , Tama Kosi Region, Nepal	1.0-0.7↓	700-750	<i>23-19, 19-14</i>	-	-	<i>24-21, 19-16</i>	PE	(<i>22-19</i>)	Larson and Cottle, 2014
11	Likhu Khola, Nepal	0.9-1.3↑	725-900	-	0.3-1.0↓	750-900	<i>27-23, 22-15</i>	AvPT	(<i>22-15</i>)	From et al., 2014
12	<i>Khumbu Thrust</i> , Everest Region, Nepal	0.4-0.6	600-700	<i>32-21</i>	-	-	<i>24</i>	AvPT, ER	-	Searle et al., 1999, 2003; Simpson et al. 2000; Jessup et al., 2008
13	<i>"Lower Discontinuity"</i> , Arun Region, Nepal	0.6-07	550	-	0.8-1.0↑	600-650↑	-	PE	-	Groppo et al., 2009
	<i>"Upper Discontinuity"</i> , Arun Region, Nepal	0.8-1.0↑	600-650↑	-	0.7-1.0↑	650-800↑	-	PE	-	Groppo et al., 2009
14	<i>High Himalayan Thrust</i> , Tamor/Ghunsa, Kanchenjunga, Nepal	0.5-1.2↓	700-800	<u><i>30-28, 27-18</i></u>	0.6-0.4	700-850	-	AvPT, PE	~ 20	Goscombe et al., 2006; Imayama et al., 2010, 2012; Ambrose et al., 2015
	Kanchenjunga Duplex, Nepal			<i>multiple discontinuities/structures</i>						Ambrose et al., 2015
15	<i>"Age Discontinuity"</i> , Northern Sikkim	0.8	750-850	<i>31-28, 28-25, <25</i>	0.9	750-850	<i>26-23, 23-20, 20-17</i>	PE	-	Rubatto et al., 2013
16	<i>Laya-Kakhtang Thrust</i> , Bhutan	0.3-0.6	~650	<i>22-17</i>	0.8-1.0↑	750-800	<i>15-13</i>	ER	(<i>13-10</i>)	Swapp & Hollister 1991; Davidson et al., 1997; Grujic et al., 1996, 2002, 2011; Daniel et al., 2003; Warren et al., 2011a, b
17	<i>Zimithang Thrust</i> , NE India	0.8-09	535-715↓	<i>27-16</i>	-	535-630↑	<i>17-12</i>	ER, TB	(<i>12-7</i>)	Warren et al., 2014

¹Indicates interpreted structure is equivalent to the 'MCT' of Jamieson et al. (2004). ↑ indicates an increase up structural section, ↓ indicates decreasing values up structural section. Where multiple age ranges are present, the first indicates prograde-path metamorphism, the second indicates retrograde-path/decompression metamorphism. In the one case were three ranges are given, the third range indicates late stage isobaric cooling. Parentheses indicate the ages are interpreted to bracket movement. Ages in italics are from monazite; underlined ages are from zircon, grey ages are from thermochronologic constraints. ER = 'traditional' exchange reaction and net transfer reaction thermobarometry; TE = thermodynamic equilibrium - based thermobarometry; AvPT = THERMOCALC-based thermobarometry; PE = Phase equilibria modelling-based thermobarometry; TB - titanium in biotite thermometry.