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A review of definitions of the Himalayan Main Central Thrust

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0. ABSTRACT

Most workers regard the Main Central Thrust (MCT) as one of the key high strain zones in the Himalaya because it accommodated at least 90 km of shortening, because that shortening exhumed and buried hanging wall and footwall rocks, and due to geometric and kinematic connections between the Main Central Thrust and the structurally overlying South Tibet Detachment. Geologists currently employ three unrelated definitions of the MCT: metamorphic-rheological, age of motion-structural, or protolith boundary-structural. These disparate definitions generate map and cross-section MCT positions that vary by up to 5 km of structural distance. The lack of consensus and consequent shifting locations impede advances in our understanding of the tectonic development of the orogen. Here I review pros and cons of the three MCT definitions in current use. None of these definitions is flawless. The metamorphic-rheological and age of motion-structural definitions routinely fail throughout the orogen, whereas the protolith boundary-structural definition may fail only in rare cases, all limited to sectors of the eastern Himalaya. Accordingly, a definition based on high strain zone geometry and kinematics combined with identification of a protolith boundary is the best working definition of the MCT.

Keywords: Himalaya; MCT; thrusts; fold-thrust belts; orogens; definitions

1. INTRODUCTION

The identification of major high strain zones is a long-standing challenge in investigations of fold-thrust belt geology. By 1890, geologists had documented regional-scale thrusts in many orogens (Callaway, 1883; Lapworth, 1883; McConnell, 1887; Tornebohm, 1888; Hayes, 1891). Controversies about the existence, definition, location, and tectonic significance of some of these high strain zones erupted only a few years after they were first proposed (e.g., Murchison, 1860; Nicol, 1861). Decades of research resolved these first debates, but newer disputes persist (e.g., Mazur et al., 2015; 2016; Narkiewicz and Petecki, 2016). In the Himalaya, the definition and location of the Main Central Thrust (MCT) remain continuing sources of conflict.

The MCT accommodated more than 90 km of offset (e.g., Schelling and Arita, 1991; Long et al., 2012; 2016; Webb, 2013; Robinson and Martin, 2014) and has been mapped continuously along the entire Himalayan fold-thrust belt (Fig. 1; Martin, 2016). Most workers therefore consider it to be one of the major thrusts in the orogen (Fig. 2). The MCT figures prominently in models of the Cenozoic tectonic development of the Himalaya, both because of the large amount of Cenozoic shortening accommodated by the thrust and due to the implications for exhumation and burial, and resulting metamorphism, of hanging wall and footwall rocks (e.g., Le Fort, 1975; Searle et al., 1992; Harrison et al., 1998; Jamieson et al., 2004; Celerier et al., 2009a; Long et al., 2011a; Rubatto et al., 2013). Further, some articles interpret the structurally higher South Tibet Detachment (Figs. 1, 2), another tectonically important high strain zone in the orogen, to have branched from the MCT in the up-dip (south) direction (Caby et al., 1983; Yin, 2006; Webb et al., 2007; 2011a; He et al., 2015) or in the down-dip (north) direction (Burchfiel and Royden, 1985; Burchfiel et al., 1992; Grujic et al., 1996; Dubey and Bhakuni, 2007). Although most geologists agree on its importance, we face a challenge in identifying the MCT because it is just one of many thrusts in the Himalayan fold-thrust belt. How do we decide which thrust to designate as the MCT?

Opposing workers answer this question differently through the use of unrelated definitions of the MCT (Fig. 3; Table 1). The original definition of the MCT was structural and metamorphic: the MCT is the thrust that produced a marked break in metamorphic grade between higher-grade hanging wall and lower-grade footwall rocks (Heim and Gansser, 1939). Searle et al. (2008) reviewed the multiple definitions of the MCT employed by Himalayan geologists in the following 70 years, concluding that a metamorphic-rheological definition is the best choice. Subsequently, Webb et al. (2013) proposed a new definition based on the age of thrusting and Martin (2016) advanced a modified version of an older definition of the MCT as both a high strain zone and a protolith boundary. The merits and shortcomings of these three definitions have not been compared.

The competing definitions of the MCT place the high strain zone in locations that differ by up to 5 km of structural distance (Valdiya, 1980; Martin et al., 2005; Robinson et al., 2006; Yakymchuk and Godin, 2012; Parsons et al. 2016a; 2016b; 2016c). This lack of agreement on location hinders comparison of maps, cross-sections, and tectonic models. For example, proximal hanging wall rocks according to one definition become distal footwall rocks in a different study. Tectonic models that explain the metamorphism of these rocks as either in the footwall or hanging wall of the MCT consequently vary considerably (c.f. Robinson et al. 2006 versus Yakymchuk and Godin, 2012; or Martin et al., 2010 and Corrie and Kohn, 2011 versus Parsons et al. 2016b). The problem is so severe that some recent articles avoided the issue, refraining from using any definition of the MCT at all (e.g., Larson et al., 2013; From et al., 2014; Larson and Cottle, 2014; Cottle et al., 2015; He et al., 2015; Larson et al., 2015). Consensus on a definition would advance tectonic research in the Himalaya by enabling direct comparison of maps, cross-sections, and tectonic models.

In this article, I discuss pros and cons of the three recent MCT definitions and propose a working resolution to the definition conflict. The discussion focuses on the part of the Himalayan orogen between the western and eastern syntaxes, in Pakistan, India, Nepal, Bhutan, and Tibet (Fig. 1).

2. DEFINITION OF TERMS AND GEOLOGIC FRAMEWORK

Strain is a tensorial quantity that describes dilation and/or distortion of rocks (Passchier and Trouw, 2005; Davis et al., 2012). Strain can accrue via brittle, ductile, or a combination of both processes. Throughout the article, compass directions are given using modern orientations. Brittle faults and ductile shear zones share similar geometries in that both occupy a volume of deformed rock, and this volume typically is tabular – much smaller in one dimension than the other two (e.g., Childs et al., 2009; Rennie et al., 2013; Sullivan et al., 2013). Further, some aspects of the kinematics of brittle faults and ductile shear zones are alike: both types of high strain zone accommodate shear offset of one side of the high strain zone relative to the other side. Based on these similarities, and for simplicity and consistency, throughout the article I use the general term "high strain zone" to refer to a tabular structure that accommodated shear offset via brittle or ductile mechanisms, or both.

The Himalaya is the orogen that formed at the leading edge of the broad region of deformation that has resulted from continuing convergence between India and Asia (Jade et al., 2007; Yin, 2010). Initial collision between Indian continental crust and more northern terranes began in Middle or Late Paleocene time (DeCelles et al., 2014; Hu et al., 2015). The rear and frontal boundaries of the Himalayan orogen are the Indus-Yarlung Suture and the Main Frontal Thrust, respectively (Fig. 1; Martin, 2016). The western edge of the orogen is the left-slip Chaman Fault (located in Afghanistan and Pakistan) and the eastern limit is the right-slip Sagaing Fault (located in Myanmar).

The MCT stretches at least from the western to the eastern syntaxis, an along-strike distance of approximately 2500 km (Fig. 1). Estimates of the thickness of the MCT range from approximately 100 m to 10 km (Vannay et al., 2004; Yin et al., 2010; Law et al., 2013; Mukherjee, 2013; Gibson et al., 2016; He et al., 2016; Long et al., 2016). This large span stems both from along-strike differences in the geology and from the application of different definitions of the MCT. Regardless of which MCT definition they prefer, most geologists agree that the MCT accommodated offset of at least 90 km (Schelling and Arita, 1991; Long et al., 2012; 2016; Webb, 2013; Robinson and Martin, 2014) between ca. 23 and 10 Ma (Yin et al., 2010; Corrie and Kohn, 2011; Webb et al., 2011b; Tobgay et al., 2012; Mottram et al., 2015; see also Larson and Cottle, 2014). Most of this deformation occurred in the ductile regime (Martin et al., 2005; Larson and Godin, 2009; Mukherjee and Koyi, 2010; Law et al., 2013; Mukherjee, 2013; Gibson et al., 2016; He et al., 2016; Long et al., 2016; Parsons et al. 2016b). Some high strain zones near or overlapping the MCT were active after ca. 10 Ma; this late offset was brittle in some locations (Whipple et al., 2016; review in Mukherjee, 2015). In nearly all locations, the documented post-10 Ma offset was less than a few km (Mukherjee, 2015).

Most geologists utilize the name “Lesser Himalayan” for rocks in the footwall of the MCT and “Greater Himalayan” or “Higher Himalayan” for hanging wall rocks (e.g., see reviews by Hodges, 2000; Yin, 2006; Dhital, 2015). Unfortunately, different geologists use these terms to indicate disparate aspects of the fold-thrust belt: elevation, structural position, metamorphic grade, or stratigraphic and intrusive relationships. The resulting confusion is untenable for clear discussion of definitions of the MCT. The current article achieves the requisite disambiguation by following Martin (2016) in using the label "assemblage" to refer to a rock package with depositional or intrusive relationships between members of the assemblage. That is, the contact between adjacent members of an assemblage originally was either depositional or intrusive, not a high strain zone. In the Himalaya there are two such assemblages with members that most geologists agree shared depositional or intrusive relationships, Himalayan Assemblage A and Himalayan Assemblage B (Fig. 1). Martin (2016) additionally argued that Assemblage A never shared depositional relationships with Assemblage B, a more controversial interpretation (cf. DeCelles et al., 2000 and Myrow et al., 2003 versus Martin, 2016). The resolution of this controversy is irrelevant for the discussion of MCT definitions in the current article. This article does not employ the terms Lesser Himalayan, Greater Himalayan, or Higher Himalayan except in reference to historical usage of these expressions.

The following brief summary of Assemblage A and Assemblage B sedimentation, intrusion, and metamorphism was adapted from Martin (2016). Along the entire northern margin of India, Assemblage A strata were deposited during Paleoproterozoic to early Mesoproterozoic and latest Cretaceous to Quaternary time, and additionally during late Carboniferous to Permian time in the eastern half of the margin. Paleoproterozoic granite and gabbro intruded the basal Assemblage A deposits. Neoproterozoic to Ordovician strata are present in the eastern part of Assemblage A. Assemblage B is a Neoproterozoic through Quaternary supracrustal succession, intruded by granite in Neoproterozoic, late Cambrian to middle Ordovician, Permian, and Cenozoic time. In both assemblages, depositional environments for most units were continental or shallow marine, on the continental shelf or slope. Both successions therefore mostly consist of interlayered mudstone, sandstone, and limestone, plus much less voluminous felsic and mafic volcanic and intrusive rocks. Where exposed in medial positions of the fold-thrust belt, Assemblage A and Assemblage B rocks contain evidence for Cenozoic metamorphism.

3. METAMORPHIC-RHEOLOGICAL DEFINITION

The original method for identifying the MCT among the other high strain zones in the Himalayan orogen was recognition of the thrust that produced a marked contrast in metamorphic grade between high-grade hanging wall and lower-grade footwall rocks. Working with Auden (1937), Heim and Gansser (1939, p. 78) described a key geologic relationship in the region of the border between northwestern India and western Nepal:

> "With a sharp contact, called the Main Central Thrust, the crystalline Rocks at Darchula rest upon the metamorphic limestone series."

Heim and Gansser identified the hanging wall crystalline rocks as orthogneiss, augengneiss, and schist (p. 78) whereas the proximal footwall rocks are "slightly metamorphic" limestone and quartzite (p. 90). To facilitate application of the metamorphic-strucutral definition along the Himalaya, Sinha-Roy (1982) modified the original definition to place the MCT at the base of the package of rocks that exhibit inverted metamorphism.

Building on the work of Stephenson et al. (2000; 2001) in northwestern India, Searle et al. (2008) added rheology to the definition because Searle et al. (2008) viewed a wholly metamorphic definition as an inappropriate basis on which to define a structure such as a high strain zone (Fig. 3A). Note, however, that the Heim and Gansser (1939) definition was not completely metamorphic because Heim and Gansser (1939) called the contact a thrust, which is a structure that carries geometric and kinematic significance. Instead, Heim and Gansser (1939) utilized the metamorphic part of the definition to recognize and label a particular thrust among others in the orogen. Nevertheless, responding in part to the use of the metamorphic definition by more recent articles, Searle et al. (2008, p. 532) wrote that the definition of the MCT is:

> "The base of the large-scale zone of high strain and ductile deformation, commonly coinciding with the base of the zone of inverted metamorphic isograds, which places Tertiary metamorphic rocks of the Greater Himalayan Sequence over unmetamorphosed or low-grade rocks of the Lesser Himalaya".

In most sectors of the orogen, the position of the MCT indicated by the Heim and Gansser (1939) definition lies structurally higher than and hindward of the locations designated by the Sinha-Roy (1982) and Searle et al. (2008) definitions; the Sinha-Roy (1982) and Searle et al. (2008) locations are similar.

Many subsequent articles followed the Searle et al. (2008) definition nearly exactly (e.g., Larson et al., 2010; 2011; Searle, 2010; Streule et al., 2010; Yakymchuk and Godin, 2012; From and Larson, 2014). Others emphasized the rheological part of the definition (e.g., Larson and Godin, 2009; Parsons et al., 2016a; 2016b; 2016c). Gibson et al. (2016) removed most of the metamorphic aspects from the definition, adopting an almost purely rheological definition. A wholly rheological definition could be written: "The MCT is the fossil brittle-ductile transition in quartz that currently outcrops on the foreland side of exposed ductilely deformed rocks." This rheological definition essentially maintains the position of the MCT delineated by the Searle et al. (2008) definition. For the purpose of identifying the location of the MCT, the brittle-ductile transition is taken as the edge of the zone of dynamically recrystallized quartz, including by workers such as Parsons et al. (2016b) who also examined calcite, dolomite, plagioclase, and alkali feldspar. I treat the metamorphic and rheological definitions together in this section because they are formally linked in the Searle et al. (2008) definition, and even when not so formally linked (Gibson et al., 2016), the identified locations of the MCT are nearly identical.

3.1 Pros of the metamorphic-rheological definition

1. The metamorphic-rheological definition of the MCT is similar to common definitions of the structurally higher South Tibet Detachment, which include separation of higher-grade rocks in the footwall from lower-grade rocks in the hanging wall (e.g., Searle and Godin, 2003; Martin, 2016). This correspondence of definitions can simplify interpretations of the tectonic evolution of the two high strain zones and the rocks that contain them (e.g., Streule et al., 2010; Parsons et al., 2016b; 2016c; Soucy La Roche et al., 2016).
2. If multiple Himalayan thrusts moved at the same time, the definition would remain useful and valid.

3.2 Cons of the metamorphic-rheological definition

1. The Searle et al. (2008) definition of the MCT is inconsistent with these authors’ reason for rejecting older definitions that traced a metamorphic isograd. Searle et al. (2008, p. 523) argued that an isograd should not be used to define a structure such as a thrust because isograds provide information about metamorphic reactions, not structures. However, the part of the Searle et al. (2008) definition that specifies metamorphic rocks placed over unmetamorphosed or low-grade rocks in fact follows an isograd. The boundary between low-grade and higher-grade metamorphism is an isograd.

2. Law et al. (2013) attempted to apply the Searle et al. (2008) definition in northwestern India. Law et al. (2013) successfully applied this definition in frontal parts of the orogen, but found the definition inadequate in hinterland positions (p. 26). In the hinterland, Law et al. (2013) reverted to the MCT definition of Vannay et al. (2004), which labeled one thrust among many based on metamorphic grade, but used a higher metamorphic grade than the Searle et al. (2008) definition. Using the Vannay et al. (2004) definition situated the MCT structurally higher than called for by the Searle et al. (2008) definition, thereby placing ductilely deformed, amphibolite facies rocks in the footwall of the MCT (Caddick et al., 2007). The inability of experts such as Law et al. (2013) to apply the Searle et al. (2008) definition consistently in both frontal and hinterland positions within the same sector of the orogen indicates a deficiency in the definition.
3. All high strain zones, brittle and ductile, consist of a volume of strained rock (e.g., Childs et al., 2009; Rennie et al., 2013; Sullivan et al., 2013). Nevertheless, unless discussing high strain zone processes, most authors depict a high strain zone as a line on maps and cross-sections, even when the spatial scale would allow marking the volume of rocks deformed by motion on the high strain zone. Drawing the line that represents the MCT at the edge of the ductilely strained rocks places that line at a location that accommodated little displacement between proximal hanging wall and footwall rocks, even though the MCT as a whole accommodated offset of more than 90 km (e.g., Schelling and Arita, 1991; Long et al., 2012; 2016; Webb, 2013; Robinson and Martin, 2014).

4. The Searle et al. (2008) definition utilizes only one component of the total strain, the ductile strain, and geologists who apply this definition likewise measure only ductile strain, not both brittle and ductile strain (e.g., Larson and Godin, 2009; Larson et al., 2010; Yakymchuk and Godin, 2012; Law et al., 2013; From and Larson, 2014; Gibson et al., 2016; Parsons et al., 2016b). These authors place the MCT at an exposed steep gradient in recorded ductile strain in quartz: zero ductile, only brittle strain toward the foreland and some ductile strain in the hinterland (Figure 3A). This location is thus an exhumed fossil brittle-ductile transition in quartz. For any chosen mineral, by definition, there is a steep gradient in ductile strain at the brittle-ductile transition in an orogen, from no ductile strain above the transition to some ductile strain below (Fig. 4). However, the brittle-ductile transition is not necessarily a high strain zone; the steep gradient in ductile strain does not necessarily indicate offset across the brittle-ductile transition (Fig. 4). It is impossible to determine whether a high strain zone exists at the location of the exhumed fossil brittle-ductile transition if the definition of the high strain zone, and measurements to recognize it, include only ductile strain. One means of exposing a fossil brittle-ductile transition that is not itself a high strain zone is shown in Figure 5. In this scenario, the outcropping fossil brittle-ductile transition dips toward the foreland. Users of the Searle et al. (2008) definition of the MCT assume that the fossil brittle-ductile transition in quartz dips toward the hinterland, but there are no data that support this supposition. Note that brittle shear strain is present near the MCT in many sectors of the Himalaya (e.g., Mukherjee and Koyi, 2010; Mukherjee, 2013). Some of this brittle deformation overprints the ductile

deformation, but it is possible that some preserved footwall brittle shear strain also occurred at the same time as some of the ductile shear strain.

5. The choice of quartz rather than another mineral when applying the Searle et al. (2008) or Gibson et al. (2016) definition is arbitrary from a structural perspective. Instead, quartz is chosen for the following two practical reasons. (A) Except in carbonate units, quartz is present throughout the exposed Himalayan rocks. (B) Quartz deforms ductilely over much of the range of temperature conditions of interest in the evolution of orogenic crust (Stockhert et al., 1999). Choosing plagioclase, white mica, or another mineral instead of quartz would change the location of the MCT identified by the Searle et al. (2008) and Gibson et al. (2016) definition. None of the possible locations using different minerals inherently carries structural or tectonic significance.
6. The Searle et al. (2008) definition is difficult to use in carbonate units. Quartz rheology is minimally or not applicable because many carbonate units in the Himalaya contain very little quartz. Similarly, the metamorphic part of the definition is difficult to employ because carbonate units lack the mineral assemblages necessary for traditional thermobarometry. The peak or deformation temperature experienced by carbonate units can be estimated using nontraditional geothermometers (e.g., Parsons et al., 2016b). However, uncertainties on these temperature estimates make recognition of potential temperature discontinuities challenging. Accordingly, geologists essentially ignore carbonate units when applying the Searle et al. (2008) definition to locate the MCT (Larson and Godin, 2009; Larson et al., 2010; Yakymchuk and Godin, 2012; Law et al., 2013; Gibson et al., 2016; Parsons et al., 2016a; 2016b;

2016c). It is thus difficult, and in practice effectively impossible, to test whether the MCT is present within a carbonate unit using the Searle et al. (2008) definition. One consequence is shown in Figure 6. If the MCT passed in a lateral, oblique, or frontal ramp from a quartz-rich to a quartz-poor lithology, geologists would not be able to recognize the ramp or the high strain zone within the carbonate unit, instead drawing the MCT structurally too low or too high. This problem is relevant in the Himalaya because both Assemblage A and Assemblage B contain several thick carbonate successions along all of the orogen between the syntaxes (Martin, 2016). Some layers within these successions are nearly devoid of quartz. This drawback to the Searle et al. (2008) definition was described by Yin et al. (2010) and Webb et al. (2013).

7. The Searle et al. (2008) definition of the MCT does not work in down-dip locations where both hanging wall and footwall rocks deformed ductilely and were metamorphosed beyond “low-grade” (Fig. 7).
8. Likewise, if hanging wall rocks that did not deform ductilely are preserved at the frontal tip of the MCT, it is impossible to recognize the MCT there using the Searle et al. (2008) definition (Fig. 7).
9. Along much of the orogen between the syntaxes, exposed proximal footwall rocks to the MCT as defined by Searle et al. (2008) experienced greenschist facies metamorphism, so these footwall rocks are not unmetamorphosed (Kohn, 2014; note that Kohn did not use the Searle et al. definition of the MCT). “Low-grade” or “slightly metamorphosed” are left undefined.
10. This definition does not guarantee that different segments of the MCT along strike moved at the same time.

4. AGE OF MOTION-STRUCTURAL DEFINITION

Building on the conclusions of Yin (2006) and Webb et al. (2011a; 2011b), Webb et al. (2013) proposed to label as the MCT the Himalayan thrust that accommodated foreland-vergent motion in early to middle Miocene time (Fig. 3B).

4.1 Pros of the age of motion-structural definition

1. Applying this definition guarantees that all along-strike segments of the MCT experienced at least one episode of motion at approximately the same time, ca. 23-14 Ma.
2. Geologists can choose to draw a line that represents the high strain zone on a map or cross-section at the location of the most intense deformation within the volume of the high strain zone.

4.2 Cons of the age of motion-structural definition

1. In many parts of the Himalaya there are at least two separate early to middle Miocene thrusts that offset amphibolite facies metasedimentary rocks (Larson et al., 2015). Using a definition based on the age of motion, it is impossible to decide which of these high strain zones to label as the MCT.
2. Further, there are numerous foreland-vergent thrusts in the orogen (e.g., Webb, 2013; McQuarrie et al., 2014; Robinson and Martin, 2014). Picking one of these thrusts to call the MCT because that thrust moved in a selected time range is arbitrary; consequently, the choice does not necessarily carry tectonic significance.

5. PROTOLITH BOUNDARY-STRUCTURAL DEFINITION

France-Lanord et al. (1993), Parrish and Hodges (1996), and Whittington et al. (1999) utilized whole rock neodymium and strontium isotopic values along with detrital zircon uranium/lead ages to show that most parts of Assemblage A and Assemblage B were deposited at different times and received sediment from at least partially different sources. Note that these authors employed the term “Lesser Himalaya” instead of “Himalayan Assemblage A” as well as “Tethyan Himalaya” and “Greater Himalaya” in place of “Himalayan Assemblage B”. Building on the conclusions from these articles, Ahmad et al. (2000) identified the MCT among the other Himalayan thrusts as the foreland vergent thrust that juxtaposed these two rock packages that have different sedimentary provenance, depositional ages, or igneous crystallization ages. Using this definition, the MCT is a protolith boundary in addition to a thrust-sense high strain zone (see also Schmid et al., 1989). Many subsequent workers applied essentially this definition (e.g., DeCelles et al., 2000; Robinson et al., 2001; Kohn et al., 2004; Martin et al., 2005; Pearson and DeCelles, 2005; Richards et al., 2005; Imayama and Arita, 2008; Corrie and Kohn, 2011; Long et al., 2011b; Mottram et al., 2014; Robinson and Martin, 2014). Martin (2016) used the protolith boundary as a terrane boundary, proposing to label as the MCT the foreland-vergent thrust that accommodated Cenozoic motion and juxtaposed Himalayan Assemblage B against Himalayan Assemblage A or other units of the Indian Shield (Fig. 3C). Assemblage A constitutes the footwall between the syntaxes, the focus region for this article. The location of Assemblage B prior to the Cenozoic Era is controversial (Fuchs and Willems, 1990; DeCelles et al., 2000; Myrow et al., 2003; van Hinsbergen et al., 2012; Huang et al., 2015; Martin, 2016). The resolution of these controversies is irrelevant for this definition of the

MCT. If Assemblage B were not exotic and never separated from Assemblage A and northern India, the thrust at the non-exotic protolith boundary would remain the MCT using this definition. Mottram et al. (2014) argued for a 5 km-thick zone of structurally interleaved MCT hanging wall and footwall rocks near their contact in Sikkim. This proposed zone of protolith mixing lies within the volume of deformed rock that is the MCT. This result does not affect the protolith boundary-structural definition of the MCT: the MCT remains the high strain zone that separates Assemblage A from Assemblage B, regardless of the extent of mixing near their contact.

5.1 Pros of the protolith boundary-structural definition

1. The position of the MCT employing this definition is consistent along- and across-strike: it is always the thrust at the protolith contact. The location of the MCT does not change depending on lithology, metamorphic grade, deformation temperature, deformation mechanisms, up-dip or down-dip position of observation, or the age of high strain zone motion.
2. If multiple Himalayan thrusts moved at the same time, the definition would remain valid for identifying the MCT among other thrusts.
3. Geologists can choose to draw a line that represents the high strain zone on a map or cross-section at the location of the most intense deformation within the high strain zone volume that juxtaposes Himalayan Assemblage B against Assemblage A.

5.2 Cons of the protolith boundary-structural definition

1. In areas where there is no chemical, depositional age, or igneous crystallization age difference between Himalayan Assemblage B and Neoproterozoic or Paleozoic members of Assemblage A, and additionally the original contacts between members within each assemblage have been obscured, it would be difficult to distinguish the two rock packages.
2. This definition does not ensure that all along-strike segments of the MCT moved at the same time.

6. DISCUSSION

None of the three definitions of the MCT considered in this article is flawless; each can fail in some circumstances. Failures of the metamorphic-rheological definition are ubiquitous. In every sector of the Himalaya, there is no way to test whether the brittle-ductile transition is a high strain zone if geologists only account for ductile strain (Fig. 4). Both the metamorphic and the rheological aspects of the definition fail in the down-dip direction across the entire orogen (Fig. 7). Meta-limestone units are present in both Assemblage A and Assemblage B along nearly the entire fold-thrust belt, confounding both the metamorphic and rheological facets of the definition (Fig. 6). Likewise, the problems with the age of motion-structural definition occur commonly. In many sectors of the Himalaya, geologists have recognized at least two major thrusts that moved in early to middle Miocene time (Larson et al., 2015), and it is impossible to label just one of these thrusts the MCT using the age of motion-structural definition (Fig. 3B).

In contrast, the potential flaws in the protolith boundary-structural definition rarely materialize. West of central Nepal, Assemblage A does not contain Neoproterozoic or Paleozoic strata, and it is straightforward to distinguish the Paleoproterozoic-lower

Mesoproterozoic and uppermost Cretaceous-Cenozoic Assemblage A deposits from Assemblage B rocks based on depositional age, crystallization age, and/or geochemical characteristics (e.g., Whittington et al., 1999; Ahmad et al., 2000). In and east of central Nepal, Neoproterozoic-Ordovician and upper Carboniferous-Permian Assemblage A strata share depositional ages, and in many cases geochemical characteristics, with members of Assemblage B. Paleoproterozoic-lower Mesoproterozoic Assemblage A strata were juxtaposed directly against Assemblage B strata in some eastern areas of the orogen such as the Kathmandu area, Tamar Khola Window, and Sikkim, and differentiating the assemblages there is as straightforward as west of central Nepal (e.g., Parrish and Hodges, 1996; Imayama and Arita, 2008; Mottram et al., 2014; Khanal et al., 2015). In other eastern areas, Neoproterozoic or Paleozoic Assemblage A strata were juxtaposed against Assemblage B, and it is difficult to distinguish the assemblages near their contact based on geochemistry or detrital zircon age spectra alone. For example, in Bhutan the Paleozoic Jaishidanda Formation is exposed directly structurally below undisputed Assemblage B rocks, and depositional ages and geochemical characteristics do not permit discrimination of the Jaishidanda Formation from Assemblage B deposits (McQuarrie et al., 2013). These and other authors interpreted the basal boundary of the Jaishidanda Formation to be depositional on incontrovertible Assemblage A members, whereas the top contact of the Jaishidanda Formation is a high strain zone against Assemblage B strata. This depositional relationship establishes the Jaishidanda Formation as part of Assemblage A. If the depositional contact were not exposed, it would not be clear whether to place the MCT structurally above or below the Jaishidanda Formation. Although the protolith boundary-structural definition does not guarantee movement of different along-strike segments at the same time, in practice geologists have found that the thrust at the Assemblage A-

Assemblage B contact was active in early to middle Miocene time everywhere they have dated its motion (e.g., Kohn et al., 2005; Celerier et al., 2009b; Yin et al., 2010; Corrie and Kohn, 2011; Long et al., 2012; Tobgay et al. 2012; Mottram et al., 2015). Thus despite its possible failures, the protolith boundary-structural definition appears to be the best of the three choices because its potential drawbacks are not actual problems in nearly every sector of the Himalaya, whereas the fatal defects in the other two definitions exist throughout the orogen.

Searle et al. (2008) objected to the use of the protolith boundary-structural definition largely because all along- and across-strike segments of the MCT did not follow one particular stratigraphic horizon; the definition is untenable if some parts of the MCT cut, rather than paralleled, a stratigraphic horizon that originally was the protolith boundary. The proposition that Cenozoic motion on the MCT reactivated a pre-Cenozoic high strain zone offers a resolution to the potential problem identified by Searle et al. (2008). In this scenario, the MCT followed an ancient high strain zone that separated protoliths with different provenances; this protolith division then was maintained during Cenozoic offset on the MCT. Numerous authors proposed that the MCT reactivated a pre-Cenozoic high strain zone, though there is disagreement about the older sense of motion. Yin (2006), Dubey and Bhakuni (2007), and Mottram et al. (2014) postulated pre-Cenozoic normal-sense motion, DeCelles et al. (2000) suggested Late Cambrian to Early Ordovician thrusting, and Brookfield (1993) and Martin (2016) proposed Late Jurassic to Early Cretaceous strike-slip on a high strain zone that was reactivated as the MCT during the Cenozoic Era. Regardless of which sense of ancient motion is correct, Cenozoic reactivation of a pre-existing high strain zone could resolve the objection raised by Searle et al. (2008).

It is important to state explicitly that this article is not arguing that a south-vergent thrust does not exist at the position indicated by the Searle et al. (2008) definition. If there is a thrust at the Searle et al. (2008) location, the thrust should be labeled with a name other than the Main Central Thrust unless that position also corresponds to the contact between Himalayan Assemblage A and Assemblage B.

The observed dissimilarities in detrital zircon age spectra and geochemical characteristics between most members of Assemblage A and Assemblage B resulted from provenance differences. Whereas derivation of sediment from India alone can explain the ages of detrital zircon in Paleoproterozoic-lower Mesoproterozoic Assemblage A deposits (DeCelles et al., 2000; Gehrels et al., 2011; McKenzie et al., 2011), the sources of Neoproterozoic to Jurassic Assemblage B detritus comprised all major sectors of East Gondwana including Australia, East Antarctica, India, and East Africa or Arabia (DeCelles et al., 2000; Yoshida and Upreti, 2006; Cawood et al., 2007; Myrow et al., 2010; Gehrels et al., 2011; McKenzie et al., 2011; McQuarrie et al., 2013). The eastern Himalayan Neoproterozoic to Ordovician and upper Carboniferous to Permian Assemblage A deposits are the Assemblage A rocks most geochemically similar to broadly coeval Assemblage B strata (Gehrels et al., 2011; McQuarrie et al., 2013). This similarity can be explained by a combination of the following factors. (1) Eastern India, and thus eastern Assemblage A, was adjacent to western Australia and East Antarctica in Gondwana (Torsvik and Cocks, 2013). (2) Sediment sources at the times of deposition included nearly all of East Gondwana, and the resulting detritus was nearly homogeneous along the northern continental margin of East Gondwana (Myrow et al., 2010; Gehrels et al., 2011).

Some authors labeled multiple high strain zones in the same transect the MCT using variations such as MCT-I and MCT-II or Upper MCT and Lower MCT (e.g., Maruo et al., 1979; Arita, 1983; Harrison et al., 1998; Sachan et al., 2001; Searle and Godin, 2003; Catlos et al., 2004; Imayama and Arita, 2008; Bhattacharyya and Mitra, 2009; Mitra et al., 2010; Nandini and Thakur, 2011). It is confusing to assign essentially the same name to multiple different high strain zones. Accordingly, I recommend applying the MCT label to only one high strain zone, and employing dissimilar names for other high strain zones (e.g., Valdiya, 1980; Gururajan and Choudhuri, 2003; Pearson and DeCelles, 2005; Long et al., 2011b; McQuarrie et al., 2014; Khanal et al., 2015). The appellations do not change the geometric, kinematic, or mechanical properties of the high strain zones, but different labels do facilitate organization and discussion of different high strain zones as well as the rocks that contain them. Further, mapping one thrust within a high strain zone and also a second thrust at the edge of the same high strain zone is misleading because such a practice gives the appearance that there are two high strain zones when in fact there is only one.

Larson et al. (2015) elucidated the Cenozoic structural development of the MCT and nearby thrusts without defining or even identifying one particular thrust as the MCT. These authors implied that labeling one thrust as the MCT may no longer be constructive. If the name is not useful, perhaps it should be abandoned. Larson et al. (2015) and other authors such as Robinson et al. (2006), Webb (2013), McQuarrie et al. (2014), He et al. (2015), and Khanal et al. (2015) made compelling cases that there is nothing special about the Cenozoic geometry, kinematics, or mechanics of the MCT compared to other thrusts exposed in medial parts of the Himalayan orogen. However, from an organizational viewpoint, it is convenient to assign a name to the high strain zone that separates Himalayan Assemblage A from Assemblage B. In this article I retain the historical term "Main Central Thrust", although any appellation that designates the thrust contact between the two assemblages could be acceptable. I leave the ultimate decision about applying a new name to this assemblage-bounding thrust to future workers.

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FIGURE CAPTIONS

1. Geologic map of the Himalayan orogen and surrounding regions. Modified from Webb (2013).
2. Balanced cross-section through the frontal half of the Himalaya in western Bhutan. Gross structural architecture is similar along strike. Modified from McQuarrie et al. (2014).
3. Contrasting definitions of the MCT. (A) Metamorphic-rheological definition (Searle et al., 2008). (B) Definition based on age of thrust motion (Webb et al., 2013). The listed ages are typical for thrusts along the orogen in general, the listed ages do not indicate actual times of motion in any particular location. (C) Protolith boundary-structural definition (Martin, 2016). The South Tibet Detachment is not shown for clarity.
4. Diagram of the quartz brittle-ductile transition in a fold-thrust belt. By definition, the brittle-ductile transition is the location of a steep gradient in ductile strain, whether or not a high strain zone is present at the brittle-ductile transition. Measuring only ductile strain, not both brittle and ductile strain, it is not possible to determine whether a high strain zone is present at the brittle-ductile transition. In the case depicted here, the brittle-ductile transition is not the location of a high strain zone; the brittle and ductile strain depicted in the footwall of the thrust results only from motion on that thrust and structurally overlying high strain zones. In figures 4-7, the depicted thrusts represent structural architecture in general, they do not show structural geometry in any particular sector of the Himalayan fold-thrust belt. In these figures, the geometry of the brittle-ductile transition was inspired by, but does not replicate, the numerical modeling results of Bollinger et al. (2006). The figures do not depict the geometry of the brittle-ductile transition in any particular sector of the Himalayan fold-thrust belt.

5. One mechanism to expose a fossil brittle-ductile transition in quartz in which the fossil brittle-ductile transition is not a high strain zone. In panels A-C, exhumation is constant across the cross-section for simplicity. Spatially variable exhumation, though more geologically realistic, would not change the mechanism of exposure of the fossil brittle-ductile transition. In panel D, exhumation is greater above the duplex than elsewhere.
6. Illustration that the Searle et al. (2008) definition is blind to the presence of the MCT in quartz-poor rocks such as carbonate units. Offset on the high strain zones is not depicted.
7. Depiction of the MCT during motion. The Searle et al. (2008) definition is only applicable to one part of the high strain zone; the definition fails in up-dip and down-dip segments.

Figure 1

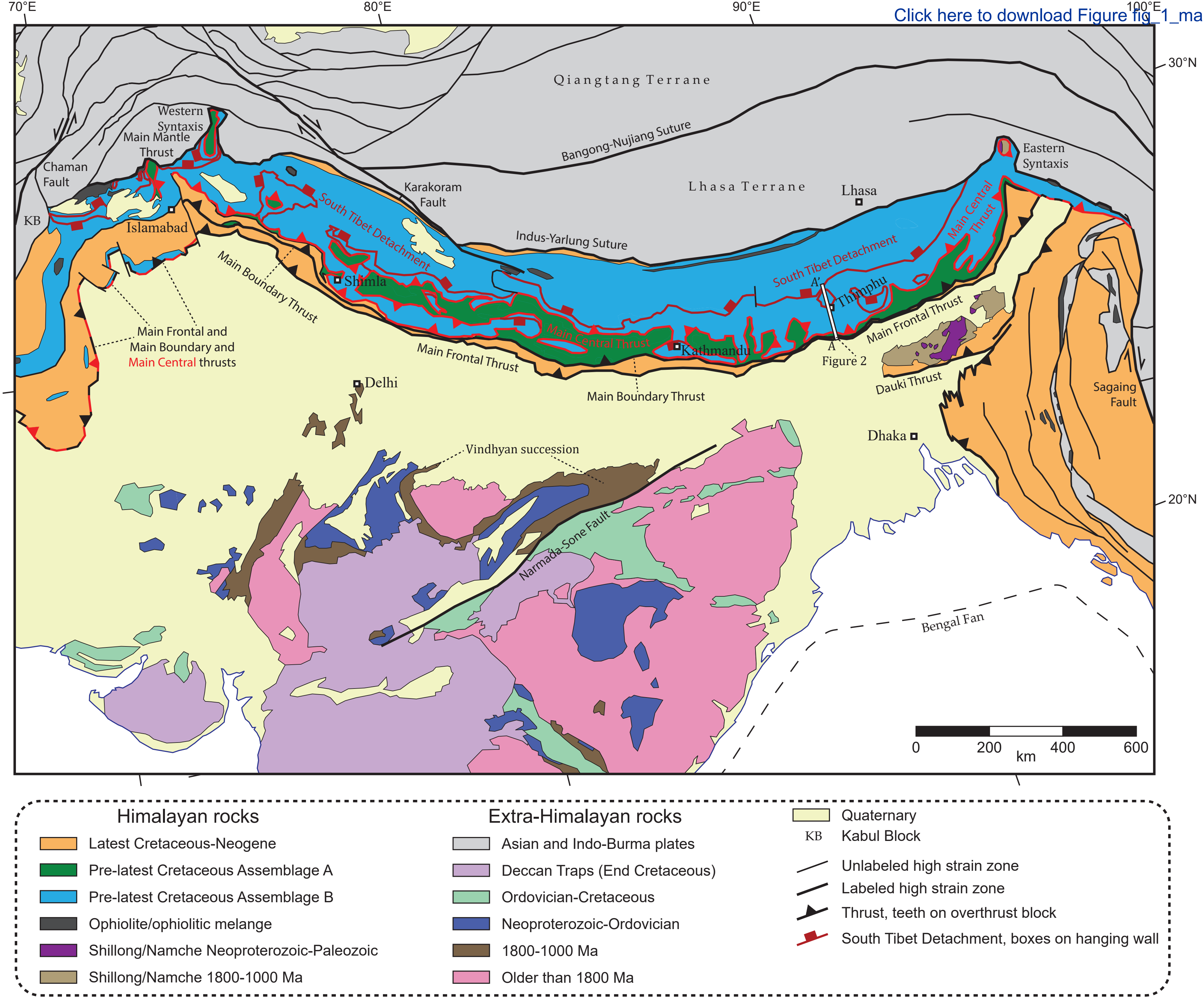
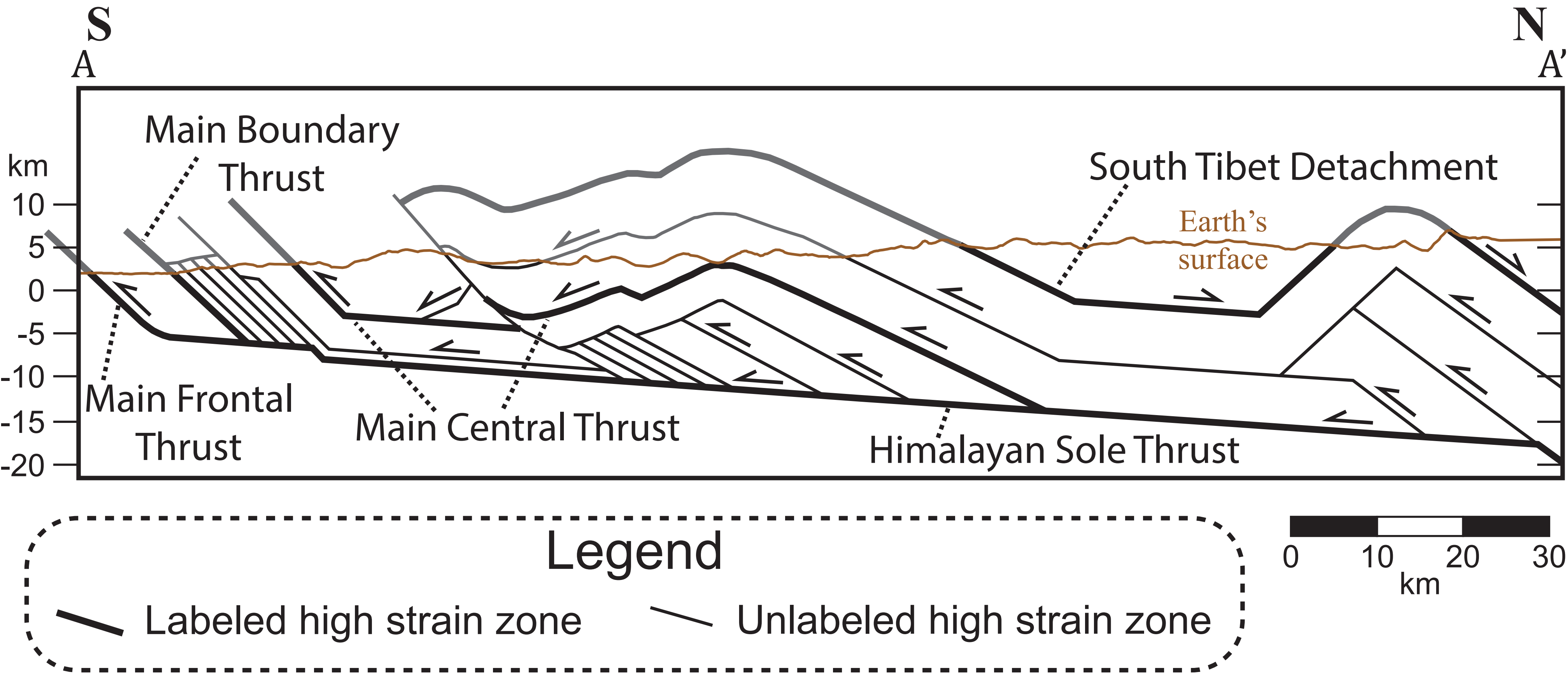


Fig. 1 (Martin)


S
N
A
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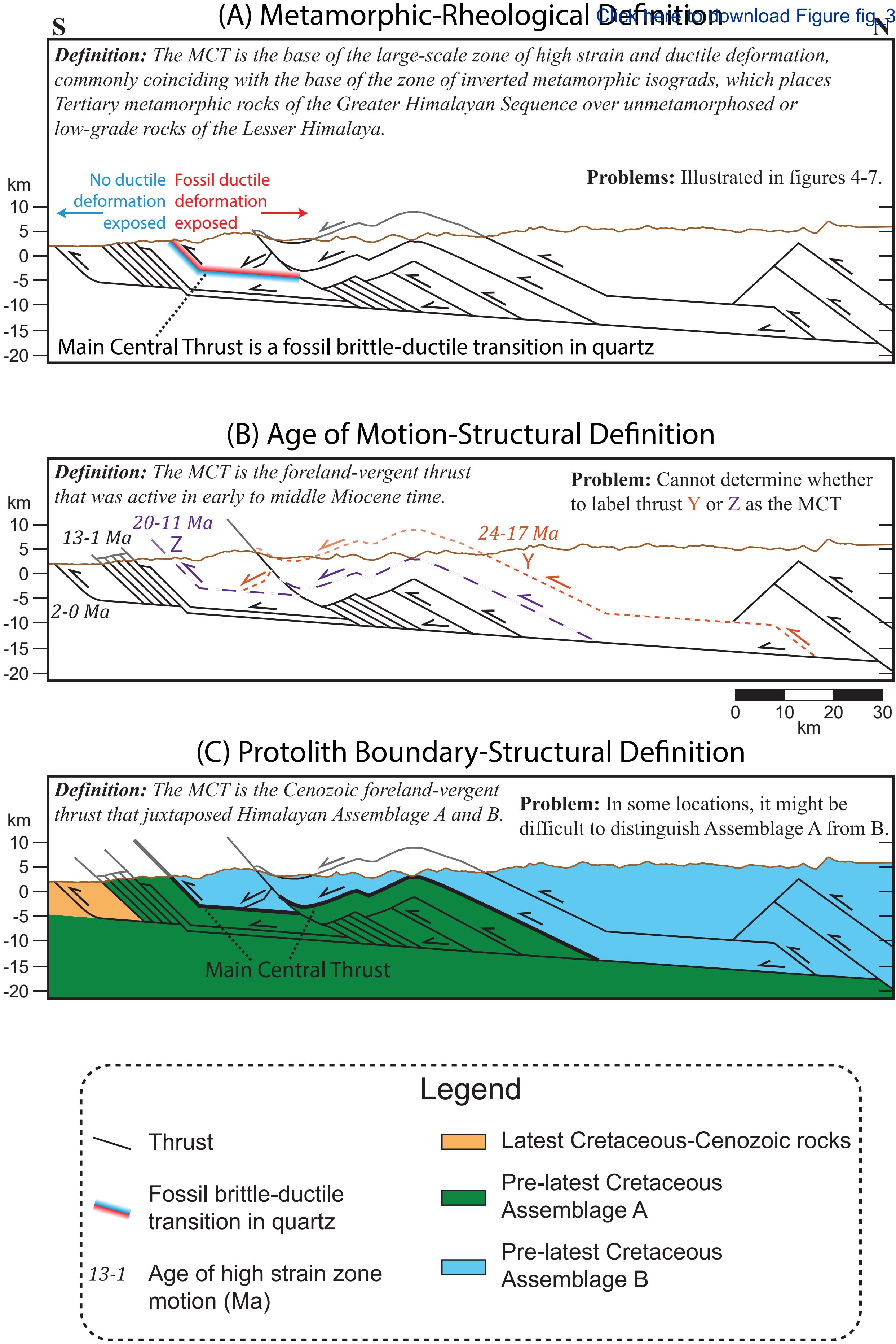
km
10
5
0
-5
-10
-15
-20
Main Boundary Thrust
South Tibet Detachment
Earth’s surface
Main Frontal Thrust
Main Central Thrust
Himalayan Sole Thrust
Legend
Labeled high strain zone
Unlabeled high strain zone
0
10
20
30
km

Fig. 2 (Martin)



(A) Metamorphic-Rheological Definition

Definition: *The MCT is the base of the large-scale zone of high strain and ductile deformation, commonly coinciding with the base of the zone of inverted metamorphic isograds, which places Tertiary metamorphic rocks of the Greater Himalayan Sequence over unmetamorphosed or low-grade rocks of the Lesser Himalaya.*

Problems: Illustrated in figures 4-7.

Main Central Thrust is a fossil brittle-ductile transition in quartz

(B) Age of Motion-Structural Definition

Definition: *The MCT is the foreland-vergent thrust that was active in early to middle Miocene time.*

Problem: Cannot determine whether to label thrust Y or Z as the MCT

(C) Protolith Boundary-Structural Definition

Definition: *The MCT is the Cenozoic foreland-vergent thrust that juxtaposed Himalayan Assemblage A and B.*

Problem: In some locations, it might be difficult to distinguish Assemblage A from B.

Fig. 3 (Martin)

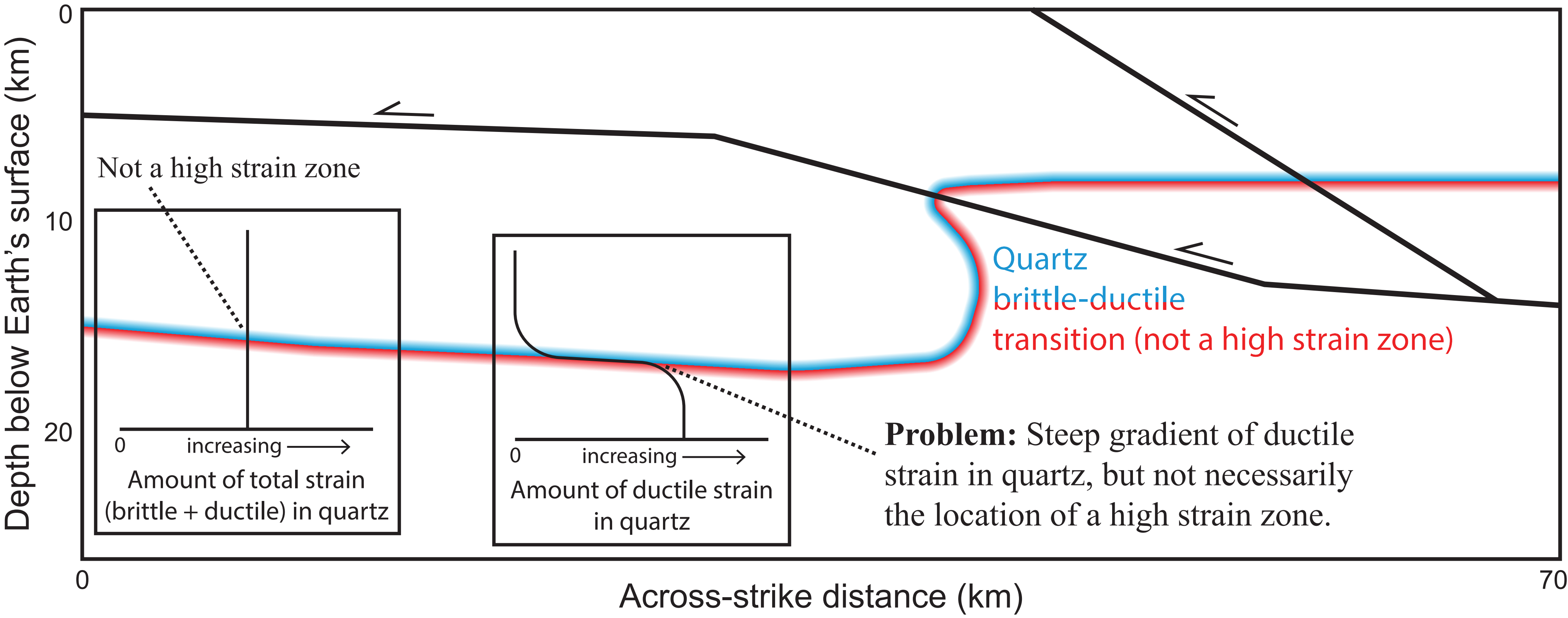

0
10
20
Depth below Earth's surface (km)
Not a high strain zone
0
increasing
Amount of total strain
(brittle + ductile) in quartz
0
increasing
Amount of ductile strain
in quartz
Quartz
brittle-ductile
transition (not a high strain zone)
Problem: Steep gradient of ductile
strain in quartz, but not necessarily
the location of a high strain zone.
0
70
Across-strike distance (km)

Fig. 4 (Martin)

Figure 5

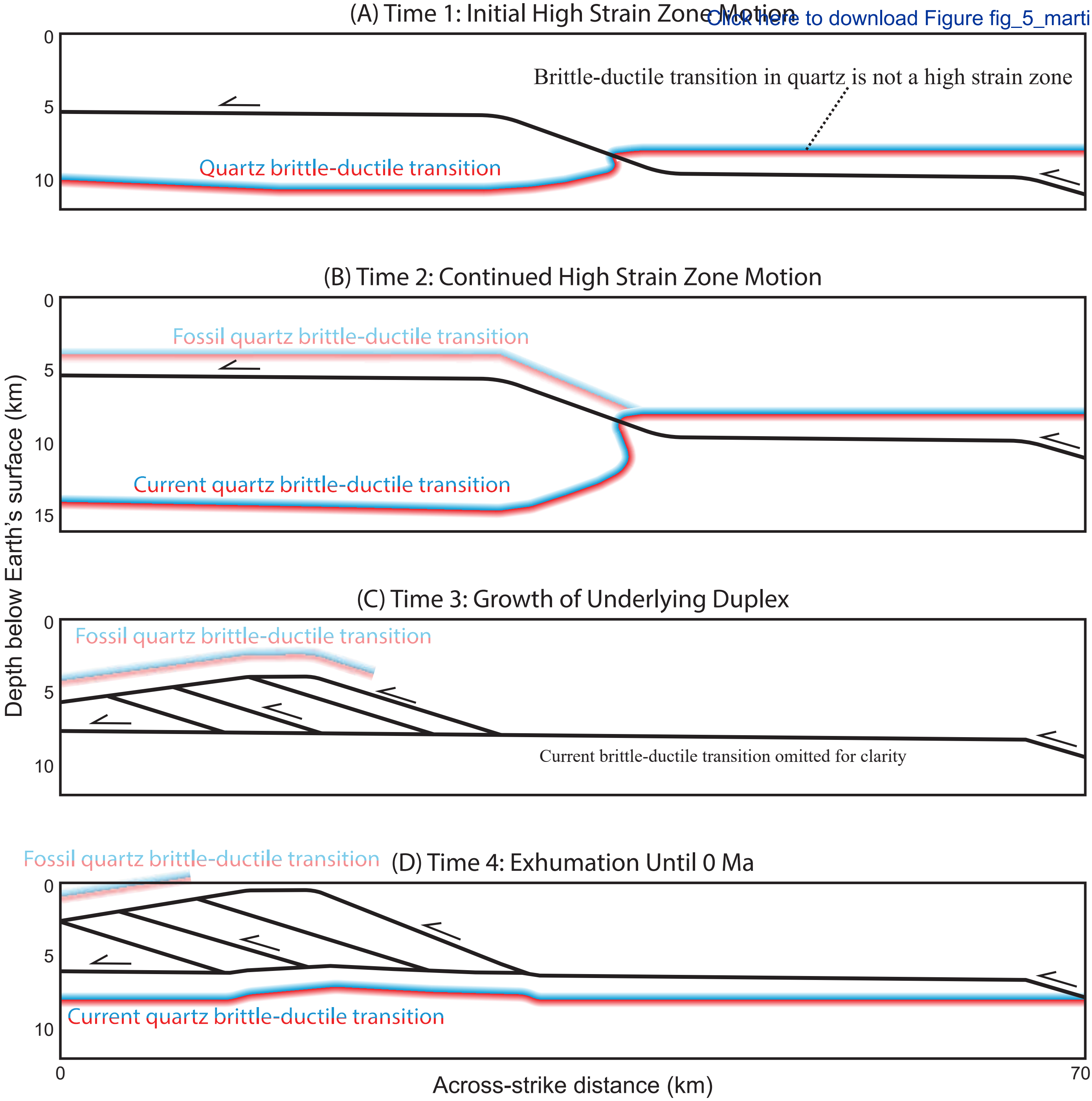


Fig. 5 (Martin)

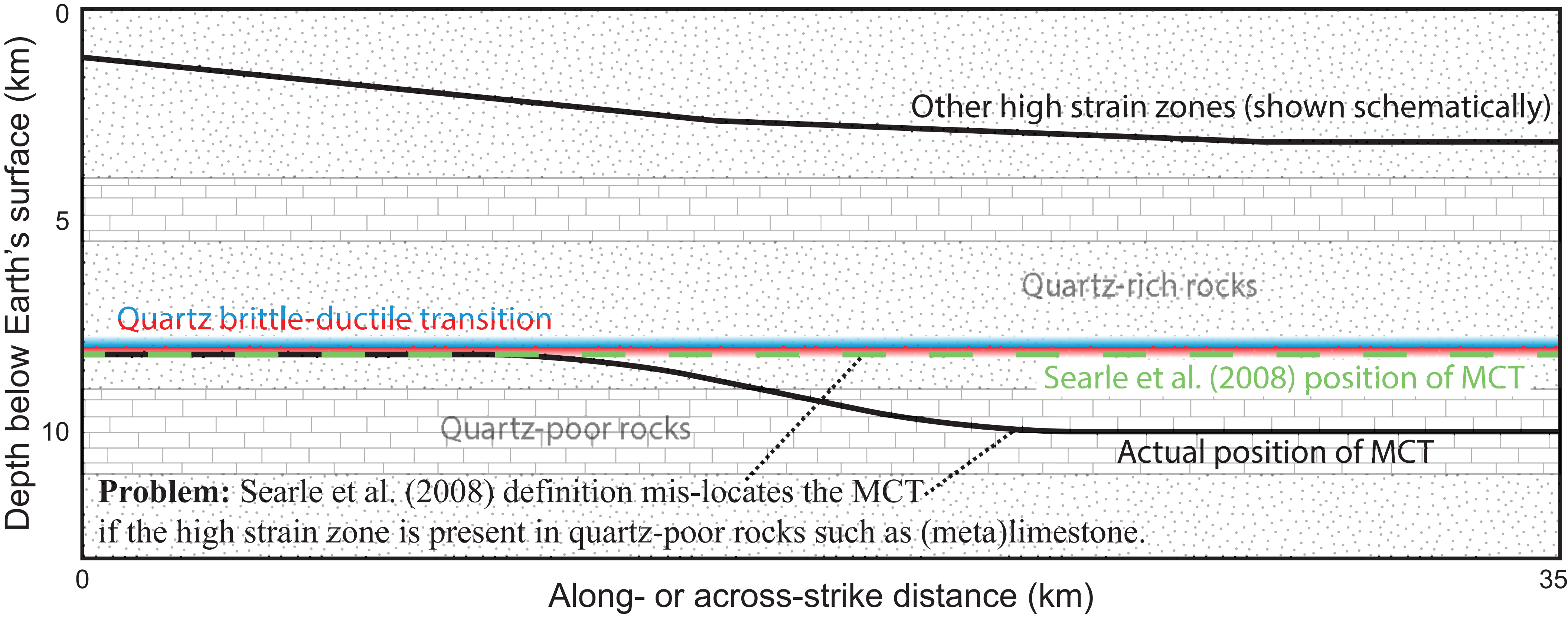

0
5
10
Depth below Earth's surface (km)
Other high strain zones (shown schematically)
Quartz-rich rocks
Quartz brittle-ductile transition
Searle et al. (2008) position of MCT
Quartz-poor rocks
Actual position of MCT
Problem: Searle et al. (2008) definition mis-locates the MCT if the high strain zone is present in quartz-poor rocks such as (meta)limestone.
0
35
Along- or across-strike distance (km)

Fig. 6 (Martin)

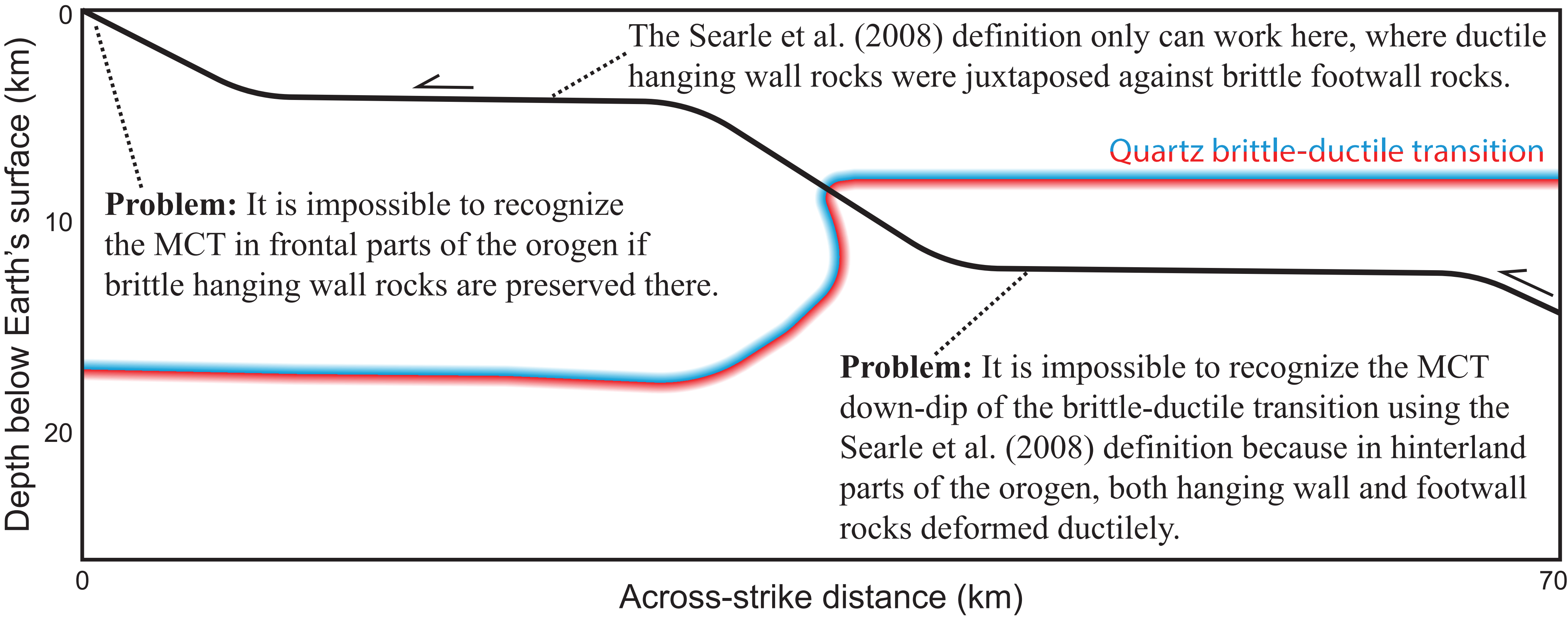

0
10
20
Depth below Earth's surface (km)
0
70
Across-strike distance (km)
The Searle et al. (2008) definition only can work here, where ductile hanging wall rocks were juxtaposed against brittle footwall rocks.
Quartz brittle-ductile transition
Problem: It is impossible to recognize the MCT in frontal parts of the orogen if brittle hanging wall rocks are preserved there.
Problem: It is impossible to recognize the MCT down-dip of the brittle-ductile transition using the Searle et al. (2008) definition because in hinterland parts of the orogen, both hanging wall and footwall rocks deformed ductilely.

Fig. 7 (Martin)

Table 1

Table 1: Key MCT definition articles discussed in text

Authors	Year
Metamorphic-rheological definition	
Heim and Gansser	1939
Sinha-Roy	1982
Searle et al.	2008
Gibson et al.	2016
Age of motion-structural definition	
Yin	2006
Webb et al.	2013
Protolith boundary-structural definition	
Ahmad et al.	2000
Martin	2016