Mid-crustal detachment beneath western Tibet exhumed where conjugate Karakoram and Longmu–Gozha Co faults intersect

Nicholas J. Van Buer a,⁎, Oliver Jagoutz a, Rajeev Upadhyay b, Marcel Guillong c

a Department of Earth, Atmospheric, and Planetary Sciences, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, United States
b Center of Advanced Study in Geology, Kumaun University, Nainital-263002, Uttarakhand, India
c Institute of Geochemistry and Petrology, ETH Zürich, Clausiusstrasse 25, NW CH 8092 Zürich, Switzerland

A R T I C L E   I N F O

Article history:
Received 1 July 2014
Received in revised form 30 December 2014
Accepted 31 December 2014
Available online xxxx
Editor: TM. Harrison

Keywords:
metamorphic petrology
mechanical decoupling
geochronology
defor-mation
geologic map

A B S T R A C T

Models for how shortening is accommodated in the India–Asia collision vary between an end member in which largely rigid blocks are extruded eastwards between lithospheric-scale strike-slip faults and an end member in which a hot, weak mid-crustal layer aids distributed deformation. Here the mode of crustal deformation is evaluated by studying the intersection of two main conjugate strike-slip faults at the west end of the Tibetan plateau. Our field mapping suggests that these faults, the right-lateral Karakoram fault and the left-lateral Longmu–Gozha Co fault, an eastward continuation of the Altn Tagh fault, may be connected by a large-scale, east-dipping listric normal fault, exposing a wedge of mid-crustal rocks in its footwall. Pseudosection modeling of matrix and porphyroclast rim compositions from footwall metamorphic rocks yield late- syntectonic pressures of 640 ± 100 MPa and temperatures around 600 ± 50 °C. Extensive networks of narrow granitic dikes give U–Pb zircon ages as young as 13.7 ± 0.2 Ma, suggesting that footwall rocks remained hot until the late Miocene and were not exhumed until after this time. We infer > 40 km heave across the Angnom fault, and suggest that it absorbs effectively all of the slip across the Longmu–Gozha Co fault (which it appears to truncate), so the Longmu–Gozha Co fault is seemingly confined to the upper crust. Similar mechanical decoupling likely occurs throughout the plateau, with strike-slip faulting in western Tibet limited to the upper, brittle part of the crust.

1. Introduction

Whether continent–continent collision zones are marked by plate-like tectonics or more pervasive strain largely depends on the properties of the middle and lower crust (Royden et al., 1997; Copley et al., 2011). In the archetypal India–Eurasia collision, one model emphasizes the importance of continuous deformation (England and Houseman, 1988), possibly aided by a weak, ductile mid-crustal layer beneath Tibet that allows decoupling between the upper crust and deeper parts of the lithosphere (Fig. 1B; Royden et al., 1997). This end-member model is supported by heat flow and geophysical data thought to indicate the presence of a hot (>600 °C), low-viscosity, mid-crustal layer (Alsdorf and Nelson, 1999; Wang, 2001; Mechie et al., 2004). Rare crustal xenoliths from Cenozoic alkaline volcanics also record high temperatures in the mid to lower Tibetan crust (Hacker et al., 2000).

Alternatively, it has been proposed that the Tibetan plateau behaves as a strong, rigid plate (Tapponnier et al., 1982), with an upper and lower crust that are mechanically coupled (Copley et al., 2011). In this model, substantial deformation is accommodated by lateral extrusion along lithospheric-scale conjugate strike-slip faults bounding the Tibetan plateau (Fig. 1A, Tapponnier et al., 2001). These two end-member crustal deformation models make specific predictions for the intersections of large-scale strike-slip faults (Fig. 1), which we evaluate in this paper using new field, petologic, and geochronologic data.

The different rheological models for the deformation of the Tibetan crust can be tested, as they make detailed predictions for what happens at the intersections of large-scale, plateau-bounding strike-slip faults. For example, in the North American Basin and Range province, where the presence of a weak lower crust is well established, strike-slip faults of the Death Valley fault system, the Panamint Valley fault, and the conjugate Garlock fault are connected by large-scale normal fault systems (Burchfiel et al., 1989; Serpa and Pavlis, 1996). The presence of a weak mid-crustal layer below the upper crust deflects the normal and strike-slip faults into a subhorizontal detachment system, allowing for large-scale displacement of the upper crust with respect to the lower crust.

http://dx.doi.org/10.1016/j.epsl.2014.12.053
0012-821X/© 2015 Elsevier B.V. All rights reserved.
Fig. 1. A. In one end-member model for the India–Asia collision, the whole Tibetan crust behaves as a relatively coherent unit, causing deformation to be concentrated on lithospheric-scale faults, mostly concentrated around the edges of the plateau. Central inset shows mapped faults near western Tibet. B. In the other end-member, a weak middle crust facilitates distributed deformation throughout the plateau as it flows eastwards. Minor faulting related to that deformation is distributed throughout the plateau. C. D. These panels compare the predicted outcomes of the two end-member models on a conjugate fault junction. The block diagrams are oriented to mimic the approximate orientation of the junction between the right-lateral Karakoram fault (parallel to the left edge of the block diagrams) and the left-lateral Longmu–Go'za Co fault (cutting across the center of the blocks). C is based on the analog model PA1 of Peltzer and Tapponnier (1988). Stress is distributed throughout the vertically integrated crust, allowing the extruded block to remain largely intact while strain in concentrated along its margins by shear weakening. Significant deformation is limited to the area where the two blocks straddling the extruded block are zipped together. D is based on the model of Burchfiel et al. (1989), for the Death Valley/Garlock conjugate fault system. In this case, extrusion between the right-lateral/normal oblique faults in the foreground and the left-lateral fault cutting across the center is accommodated by large-offset, low-angle normal faults that root into the middle crust.

(Fig. 1D; Wernicke et al., 1988; Burchfiel et al., 1989; Lister and Davis, 1989). In the case of a more rigid crust, analog models indicate that lithospheric strike-slip faults might intersect without loss of vertical integrity of the crust, with most of the deformation accommodated by horizontal shortening where the two strike-slip faults zipper together behind the extruding block (Fig. 1C; Peltzer and Tapponnier, 1988). In this case, significant normal faulting would not be expected, and listric faulting within the crust would be precluded by the presence of a strong middle crust (Fig. 1C).

Even though it has been documented that normal faults play an important kinematic role in minor conjugate strike-slip zones within the Tibetan plateau (Taylor et al., 2003), the intersections of major plateau-bounding strike-slip faults have not been studied. To constrain how the evolution of the Tibetan crust and plateau fits between the two end-member rheological models, we present a detailed study of the intersection of two of the most important plateau-bounding strike-slip faults in western Tibet. We mapped in detail the intersection between the right-lateral Karakoram fault (KKF) and the left-lateral Longmu–Go'za Co fault (LGF), an eastward continuation of the Altyn Tagh fault (Figs. 1, 2).

2. Field relationships

2.1. West end of the Longmu–Go'za Co fault

Geologic mapping, via fieldwork where accessible, and also using ASTER and Landsat imagery processed via principal component analysis, suggests that the KKF and LGF are linked by a set of north–south-striking, east-dipping faults in the Chang Chenmo Range, which we refer to as the Angmong fault system (Fig. 2). In the next section, we argue that these faults represent a major normal fault system. Between the Angmong fault system and the Altyn Tagh fault, the LGF strikes about N 80° E. Along the transect of Matte et al. (1996), the LGF separates Mesozoic slate,
sandstone and limestone to the north (Tianshuihai terrane) from Perm-Carboniferous sediments of Gondwanan/Phanerian affinity, intruded by Cretaceous granites, to the south (Qiangtang terrane). Based on remote sensing data and reports from early expeditions (Hedin, 1916; Norin, 1946), similar low-grade Mesozoic sediments probably continue along the north side of the LGF into our study area ("undifferentiated metasediments", purple, in Fig. 2). South of the LGF and east of the Angmong fault (in its hanging wall), in the Chang Chenmo Range, we observed low-grade metasediments including low-grade phyllites, calcareous sandstones, conglomerates, diamictites, limestones, and occasional vesicular basalt ("low-grade metasediments", tan, in Fig. 2). These lithologies are similar to those found further east in the Qiangtang terrane and Lhasa block, and the presence of dropstones in some of the fine-grained units suggests specific correlation to Gondwanan glacio-marine sediments deposited in the Late Carboniferous (cf. Tapponnier et al., 1991; Matte et al., 1996). In our study area, these units overlie felsic to intermediate plutonic rocks that form a sizeable and locally homogeneous batholith ("Chang Chenmo batholith", yellow in Fig. 2). Observed intrusive rocks were mostly two-mica granite, with local co-magmatic (as demonstrated by magma mingling relationships) quartz monzonite and gabbro bodies. We were not able to access the south-dipping metasediment/granite contact, but it may match the intrusive relations between Cretaceous granitoids and Paleozoic strata observed further to the east (cf. Matte et al., 1996). Further northeast in the Chang Chenmo Range, an orthogneiss ("Chang Chenmo basement gneiss", orange-tan in Fig. 2) is present (Hedin, 1916). On the south side of the low-grade Chang Chenmo metasediments, along the inaccessible north shore of Pangong Tso, the metasediments are inferred to be overthrust by ophiolitic melange and associated rocks of the Bangong suture zone (green in Fig. 2; e.g., Jain and Singh, 2008). All of these units south of the LGF appear to be truncated abruptly to the west by the Angmong fault. The LGF itself also appears to die out west of the Angmong fault; the ENE linear trends of the strands of the strike-slip LGF are replaced by north-dipping structures that curve...
off to the WNW (Fig. 2), showing no evidence of active strike slip displacement in satellite imagery (cf. Bohon, 2014). Although the LGF cannot be traced through to the KKF, the KKF takes a broad ~27 km left step in this region (Fig. 2), consistent with offset related to the LGF (Raterman et al., 2007).

2.2. Angmong fault system

The Angmong fault system curves in a broad, concave to the east arc that trends on average NNE between the KKF and the apparent west end of the LGF, and consists of two major strands, each marked by kilometer-high east-facing topographic escarpments (Figs. 2, 3A). These faults juxtapose faceted mountain fronts against shallow basins and low-relief hanging walls (Fig. 3A), in a geomorphic expression consistent with normal faulting. Smaller, west-facing scarp suggest the presence of anthetic faults in the hanging wall. The surface of the main fault itself was not exposed in the outcrops studied: however, a subsidiary fault surface was measured dipping 55° east, with top to the east striations. Poorly consolidated fluvial/alluvial sediments between two strands of the fault system are backtilted about 5° (dipping west: upstream), providing further evidence for fairly recent normal fault activity (Fig. 3B). A swarm of three earthquakes with magnitudes between 4.8–5.2 and upper-crustal depths were recorded February 1968 in the vicinity of this fault, documenting recent seismic activity (ANSS Catalog); unfortunately moment tensors are not available.

The east strand of the Angmong fault also coincides with an abrupt break in metamorphic grade and structural style (Fig. 2). Unlike the low-grade metasediments in the hanging wall (described in Section 2.1), footwall rocks are uniformly high-grade, consisting of upper-amphibolite-facies garnet–staurolite schists, quartzfeldspathic biotite schists (Fig. 3C), marble, tremolite- or diopside-bearing calc-silicates, and occasional hornblende amphibolite (collectively, “high-grade metasediments,” red in Fig. 2). These rocks could conceivably be the high-grade equivalent of the hanging-wall metasediments, but they are too high grade to make the correlation obvious. Further north, plutonic rocks occur on both sides of the Angmong fault system, but, similarly, the character of the rocks is very different on opposite sides of the fault (Fig. 2).

Whereas the Chang Chenmo batholith in the hanging wall consists of large, generally monotonous, felsic plutons preserving a mild magmatic foliation, the footwall plutonic rocks are a complex assemblage of 10 cm to 10 m wide tonalite and diorite dikes with a strong solid-state foliation/lineation (“sheared plutonic injection complex,” orange in Fig. 2; Fig. 3D). These locally intrude older gneisses, including augen gneisses. This diverse complex of small intrusions within the footwall is itself intruded by peraluminous leucogranite dikes that form a pervasive network (Fig. 3D). These leucogranite dikes intrude footwall high-grade metasedimentary rocks as well. These dikes vary in width from ~1 cm to 10 m. They tend to be equigranular and medium-grained, lack any sort of chilled margins, and only a minority contain pegmatitic or aplitic textures indicative of particularly high fluid content (Fig. 3E). As some dikes are strongly folded or boudined, whereas others appear relatively undeformed in the field, it is likely that there are multiple generations of syn-deformational dikes (Fig. 3D).

Structurally, the Angmong fault separates rocks with open, upright folds in the hanging wall from rocks with tight to isoclinal, upright or overturned folds in the footwall (Fig. 2). Fold hinge lines are subhorizontal and follow similar NW–SE trends in the footwall as in the hanging wall. Hanging wall strata range exhibit sub-vertical dips, and mineral lineations are typically weak or absent; whereas in the footwall, folds are much tighter, with limbs that are often near-vertical or overturned to the SW, and are accompanied by parallel, horizontal mineral lineations trending N 50° W (Fig. 2). Folds in the footwall are found at scales ranging from outcrop-scale to km-scale. Although footwall fabrics are superficially similar to steep shear fabrics along the KKF, S–C fabrics or other indicators of a consistent direction of simple shear were not observed more than ~1 km NE of the main KKF trace. If the footwall fabrics were primarily a product of strike-slip shearing, it is difficult to understand why rocks SE along strike of the KKF, but across the Angmong fault, would not be affected by compatible shear fabrics. Instead, we suggest the combination of tight to isoclinal subvertical folding and horizontal mineral lineation is consistent with NE–SW pure-shear shortening and NW–SE extension. In the footwall, rocks of the same structural style and metamorphic grade (henceforth referred to as the “footwall suite”) continue for at least 40 km to the NW, forming a triangular wedge that trails behind the Angmong fault, parallel to the direction of stretching lineations (Fig. 2).

High-grade metamorphic rocks and plutonic injection complex also occur in the Pangong massif between the strands of the KKF (Fig. 2; hereafter referred to as the “Pangong Complex”), but these rocks are different in a few important ways: Rocks in the core of the Pangong Complex are of higher grade and include granulites and migmatites; they often have strong dextral C–S fabrics with lineations that dip quite consistently to the NW; and they continue well to the SE of the Angmong fault (Fig. 2; e.g., Searle et al., 1998; Phillips et al., 2004; Rolland et al., 2009). Therefore, we do not interpret that the Angmong footwall suite and the Pangong Complex share a common tectonic history.

Major changes in structure and metamorphic grade are almost exclusively associated with the East Angmong fault, suggesting that this strand absorbed most of the system’s displacement; however, the sharp topographic expression of the West Angmong fault suggests normal slip may have recently been migrating westward onto younger and steeper fault surfaces that have cut across older, lower angle shear fabrics (Figs. 2, 3A). This could also explain why subhorizontal stretching lineations in the footwall rarely roll over into the relatively steep (~35°) brittle fabrics observed.

Geographically, the Angmong fault system marks the boundary between the jagged, high relief peaks typical of the Karakoram Range and the more subdued, hilly terrain characteristic of the Tibetan Plateau (Figs. 2, 3A). The Angmong fault system also coincides with a bedrock step in the channel of a now-abandoned river, the previous outflow to Pangong Lake (cf. Huntington, 1906; Dorch et al., 2011a), and is apparently responsible for tectonically damming its 28,000 km² basin (Fig. 2).

We develop our interpretations based on field and map data as follows: Two east-dipping normal faults occur along the east end of an exposure of high-grade metasediments and sheared plutonic injection complex (Fig. 2). We infer that the close juxtaposition of these “footwall suite” rocks to much lower grade metasediments, more homogeneous plutons of the Chang Chenmo batholith, and Chang Chenmo gneisses east of these faults (henceforth collectively described as the “hanging-wall suite”) is caused by substantial normal separation across this fault system (Fig. 2). Furthermore, the presence of anthetic normal faulting in the hanging wall (Fig. 2) suggests a listric geometry at depth. Because similar high-grade rocks containing stretching lineations parallel to the inferred displacement across the Angmong fault continue for ~40 km to the NW of this fault, we hypothesize that all of these footwall-suite rocks may have been exposed by large horizontal displacement from beneath a detachment-style Angmong fault. Because our field mapping shows that the Angmong fault system terminates southwest against the KKF and, based on remote sensing data, terminates northwards against the LGF at the probable eastern end of that fault’s strike-slip activity, we interpret that the Angmong fault has enabled the eastward escape of Tibetan upper crust between the conjugate KKF and LGF, while the middle crust upwells in the Angmong footwall (similar to Fig. 1D). In the remainder of this
paper, we examine these field-based hypotheses using metamorphic petrology and geochronology.

2.3. Relationship between metamorphism, granite emplacement, and deformation

Multiple lines of evidence indicate that the metamorphism recorded in the footwall suite and the intrusion of the leucocratic dikes are syn-deformational with respect to the observed main foliation and folding event. The presence of multiple generations of variably deformed leucogranite dikes throughout the Angmong footwall suite attest to a protracted history of syn-magmatic deformation at high temperature. This pervasive network of medium-grained leucogranite dikes, down to the centimeter scale, do not have chilled margins or other textures indicative of rapid cooling, and sometimes have diffuse or interfingered contacts with the host rock (Fig. 3C). Although some granitic veins and dikes in the area have pegmatitic textures indicative of very high fluid contents and lower viscosities, most granitic magmas are quite viscous, and cannot flow into long, narrow dikes faster than they solidify against the dike walls unless the wallrock temperatures are close to the magma’s solidus, especially since cooling time varies as the inverse square of dike thickness (e.g. Rubin, 1995; Baker, 1998). This suggests that high metamorphic temperatures were maintained (or regained) in the host rocks during the intrusion and deformation of the narrow leucogranite dikes.

The microstructures preserved in the metamorphic rocks similarly point to an extended history of metamorphism that was syn-deformational. Garnet and staurolite porphyroclasts frequently preserve older foliations in their cores, marked by the alignment of opaque minerals (Fig. 4A, C, D). However, garnet rims sometimes record a younger relict foliation, which often changes continuously from the inner part of the rim to the outer part, suggesting rotation (deformation) during garnet growth (Fig. 4A), clearly indi-
Fig. 4. Plane-polarized light photomicrographs of metamorphic rocks from the Angmong footwall suite. Matrix minerals and porphyroclast rims generally appear to be late syntectonic. Scale at lower right; all images at same scale. Abbreviations: Amph – amphibole, Bt – biotite, Cpx – clinopyroxene, Cz – clinozoisite, Gt – garnet, Ms – muscovite, Pl – plagioclase, q – quartz, Sill – sillimanite, St – staurolite. A. Garnet porphyroclasts in sample LB12-21 preserve an older foliation marked by aligned opaque minerals; however, the rims often record syntectonic garnet growth during porphyroclast rotation. For example, although the center of the garnet preserves an older parallel foliation, near the rim an inclined foliation is preserved, and the current foliation orientation can again be seen in the very youngest part of the rim, just to the right of the large ilmenite grain at left. B. The foliation defined by the opaque minerals (mostly ilmenite) wraps around the porphyroclasts in LB12-27, but sillimanite is more weakly aligned, suggesting late syntectonic growth. Staurolite and the outer garnet rim overgrow this late sillimanite in places. Staurolite and sillimanite often seem to form pseudomorphs after an earlier porphyroblastic phase. C. Staurolite porphyroclasts in LB12-28 are generally euhedral but preserve an older foliation that is often slightly rotated with respect to the current foliation. Biotite occasionally forms post-tectonic growths over staurolite, but is also present as foliation-parallel crystals in the matrix. D. Matrix phases in sample LB12-68 are only weakly aligned with the tectonic foliation, indicating recrystallization late into the syntectonic period. Although wraps of opaque minerals in the garnet cores often follow an earlier, rotated foliation, a narrow, clear rim contains larger inclusions in an orientation pattern similar to the current matrix (e.g., at very bottom edge of the porphyroclast).

cating contemporaneous deformation and metamorphism. Matrix phases are typically well aligned with the final tectonic foliation, which wraps around the porphyroclasts (Fig. 4A, C), but in some cases crystals (particularly sillimanite and biotite) have begun to grow with a static, post-tectonic texture (Fig. 4B, D). Often the outermost part of the rims around the porphyroclasts overlap the latest tectonic foliation (Fig. 4A, D), or the very outermost rim may actually overlap static-textured sillimanite (Fig. 4B), indicating that rims continued at least minor growth until after most deformation was complete. Therefore, although porphyroclast cores may record a prolonged history of metamorphism, possibly dating back to the original burial of the metasediments, microstructural observations clearly indicate that high-grade metamorphic conditions prevailed while the rocks deformed. As intrusions of the leucogranite are also syn-deformational (Fig. 3B), they must have been intruded during metamorphism. We do not exclude the possibility that metamorphism in the area significantly preceded the emplacement of the leucocratic dikes, but we conclude that it continued at least until the emplacement of the dikes.

3. Methods

3.1. P–T pseudosections

In order to quantify the change in metamorphic grade across the Angmong fault, we constrained the metamorphic pressure and temperature (P–T) conditions of a sample transect across the normal faults and into the footwall suite (Figs. 2, 5, 6; Table 1; Table S1). Polished thin sections were analyzed via optical microscope and electron microprobe to determine the composition of the minerals present, their progress of growth, and relationship to metamorphic fabrics (Fig. 4; Table 1). Mineral modes were visually estimated using optical microscopy.
Figure 5. A. Metamorphic pressure vs. distance from East Angmong Fault. B. At same horizontal scale, interpretive cross section showing Angmong fault system (dashed where inferred in eroded part) and schematic isobars, labeled in MPa. The plateau of high pressures in the footwall region where constrained by our petrology samples (black squares) suggests that a broad swath of mid-crustal material has been emplaced from beneath a listric detachment. Where unconstrained, isobars are drawn speculatively, based on the minimum-displacement version of our detachment model. Geologic units shown using same patterns as Fig. 2, also based on the minimum-displacement model where under-constrained (effects of thrusting perpendicular to section at NW end not shown).

Mineral compositions were determined on carbon-coated thin sections using a JEOL JXA-733 electron microprobe at MIT in wavelength-dispersive mode using an accelerating voltage of 15 kV, a beam current of ~10 nA, and a focused spot of 2 μm (spot size was increased to 10 μm for plagioclase and hydrous minerals). The machine was calibrated using natural and synthetic mineral standards. Major elements were counted for 40 s and wt.% oxides (Table S1) were calculated from the raw X-ray counts using the CITZAF correction procedure.

Metamorphic temperatures and pressures were estimated via phase diagram modeling of P–T pseudosections (Powell et al., 1998), using bulk compositions calculated from mineral modes and rim-weighted mineral compositions; H2O and CO2 were calculated from the mineral formulas (Table S1). The direct comparison of mineral modes and compositions with calculated phase relationships in the corresponding modeled pseudosections permits deduction of pressure and temperature from the phases considered to be in chemical equilibrium. In the footwall-suite samples successfully used to generate P–T constraints, all matrix minerals and porphyroclast rims showed equilibrium textures (Fig. 4), with the exception of very local alteration to chlorite, zeolite or clay minerals – these minerals were excluded from calculations. Although footwall-suite rocks are extensively recrystallized, hanging-wall rocks frequently preserve sedimentary textures such as rip-up clasts and graded bedding, and grains larger than 50 μm do not appear to be in metamorphic equilibrium (Fig. 3f). Consequently, only matrix phases were considered in our analysis of these rocks. The P–T pseudosections were calculated using PerpleX software (Connolly, 2005) including the thermodynamic database of Holland and Powell (1998, with updates). Pseudosections were calculated in PerpleX treating H2O and CO2 as thermodynamic components, rather than assuming fluid saturation. The following set of PerpleX mineral solution models were implemented in all calculations (except calcite and dolomite were omitted from carbonate-free samples): F, Gt(HP), GrTrFsPsPg, hCrD, Pl(h), Mica(CHA), Chl(HP), Kf, melk(HP), ILGKy, San, St(HP), Cpx(HP), Bio(TCC), Do(HP), Cc(AE).

Example pseudosections are shown in Fig. 6; pseudosections for other samples are available in Fig. S1. Pressure and temperature were estimated based on the regions in P–T space where calculated phase assemblages and solution phase compositions matched those observed (Fig. 6). To test the effect of errors in bulk composition on model results, hanging wall sample LB12-04 was run repeatedly, using bulk compositions generated by varying the mineral modes by a random factor between 0.5 and 1.5 and renormalizing – actual errors in the mineral modes are expected to be much less than this. In runs where the observed assemblage was stable under any conditions, the calculated maximum pressure only varied within ±50 MPa (Fig. 6c). In addition to metamorphic constraints, the magmatic emplacement pressure of one quartz diorite (containing plagioclase, quartz, hornblende, biotite, K-feldspar, magmatic epidote and titanite) was estimated using the aluminum in hornblende geobarometer (Anderson and Smith, 1995) in combination with hornblende–plagioclase thermometry (Holland and Blundy, 1994).

3.2. Zircon U–Pb geochronology

Zircon U–Pb LA-ICPMS geochronology on granitic dikes was used to constrain the time of crystallization and, based on the above described field relationships, provide a maximum age for deformation and metamorphism (Fig. 7 and Table S2). Zircons were separated using standard methods, mounted in epoxy, ground and polished about halfway through, and imaged via cathodoluminescence to reveal spot context (Fig. 8). U–Pb analyses of zircons were conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at ETH Zürich (Fig. 7, Table S2). Zircons were ablated with a Resonetic Resolution 155 193 nm excimer laser using a spot diameter of 30 μm, a repetition rate of 5 Hz and an energy density of 2 J/cm². The ablated material is carried in a mixture of helium and argon gas into the plasma source of a Thermo Element XR high sensitivity sector field ICP-MS equipped with a single triple mode detector (pulse counting, analog, and Faraday cup) and a fast scanning magnet. 235U, 238U, 204Hg, 204Pb, 206Pb, 207Pb, and 208Pb were measured for each sample with a settling time of 1 ms between masses and a dwell time of 10 ms (204Pb), 20 ms (205Pb and 207Pb, 232Th, 235U) and 40 ms (206Pb, 207Pb, 208Pb). Each analysis consisted of a 5 pulse pre-ablation to remove surface contamination, a 10 s measurement of the background (laser off) and 30 s integrations with the laser firing. Ablation pits are ~12 microns in depth. Sample analyses were calibrated by bracketing with 1 primary (GI-1) and 2–3 secondary reference materials (Plesovice, Mudtank, Temora) every 30 sample analyses. Data were reduced using the Iolite (Patton et al., 2011) and VizualAge (Petrus and Kamber, 2012) programs on the IgorPro platform following the methods described in Patton et al. (2010, 2011), and Petrus and Kamber (2012). Ages reported are 206Pb/204Pb ages; analyses with statistically significant (nonzero at 2σ) amounts of 204Pb were not used. Discordant analyses (outside a 95% confidence error ellipse) were also not used. Reported errors for single grains are 2σ analytical errors, and for populations, the standard deviation (groups were in general too small or broadly distributed for standard errors of the mean to be robust).

4. Results

4.1. Metamorphic conditions

Our P–T results indicate hanging-wall metamorphic pressures <100 MPa, in accordance with the preservation of nearly unmetamorphosed sediments (Figs. 5, 6, Table 1). The relatively high ~350°C temperature estimated for our hanging wall sample (LB12–04; Table 1) likely reflects regional contact metamorphism related to the Chang Chenmo batholith, which appears to underlie the area along a shallowly south-dipping contact from satellite imagery, as well as a sampling bias towards the highest grade parts of this regional aureole, which show the coars-
est and presumably most thoroughly equilibrated matrix metamorphic mineral textures.) On the contrary, metamorphic conditions for four samples within 15 km distance from the Angmong fault on the footwall side yield rather constant temperatures of 550–650 °C and pressures of 640 ± 100 MPa (Table 1). These metamorphic conditions were determined using porphyroclast rims and matrix minerals that appear to have reached equilibrium late in their history of tectonic deformation (Fig. 4), so we infer that these approximate P–T conditions were present until the final stages of ductile deformation of the Angmong footwall suite.

These metamorphic conditions are also in agreement with the independent estimate of 610 ± 100 MPa based on hornblende barometry from a nearby tonalite (sample LB12-18; Table 1). High emplacement pressures are also suggested by the presence of magmatic epidote in the same granitoid, which only crystallizes above ~500 MPa in felsic to intermediate compositions (Schmidt and Thompson, 1996).
### Table 1

Mineral modes and sample locations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>lb12-04</th>
<th>lb12-21</th>
<th>lb12-27</th>
<th>lb12-28</th>
<th>lb12-68</th>
<th>lb12-18</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum pressure (Mpa)</td>
<td>phyllite</td>
<td>schist</td>
<td>schist</td>
<td>schist</td>
<td>schist</td>
<td>quartz diorite</td>
</tr>
<tr>
<td>maximum pressure (Mpa)</td>
<td>0</td>
<td>620</td>
<td>530</td>
<td>340</td>
<td>540</td>
<td>510</td>
</tr>
<tr>
<td>minimum temperature (°C)</td>
<td>90</td>
<td>650</td>
<td>680</td>
<td>740</td>
<td>760</td>
<td>710</td>
</tr>
<tr>
<td>maximum temperature (°C)</td>
<td>340</td>
<td>580</td>
<td>580</td>
<td>540</td>
<td>570</td>
<td>680</td>
</tr>
<tr>
<td>N latitude</td>
<td>350</td>
<td>600</td>
<td>650</td>
<td>640</td>
<td>660</td>
<td>760</td>
</tr>
<tr>
<td>E longitude</td>
<td>33.91692</td>
<td>33.97636</td>
<td>34.0535</td>
<td>34.0535</td>
<td>34.04299</td>
<td>34.15019</td>
</tr>
<tr>
<td>NW distance from E Angmong Fault (km)</td>
<td>78.28206</td>
<td>78.41028</td>
<td>78.40696</td>
<td>78.40696</td>
<td>78.31749</td>
<td>78.22399</td>
</tr>
<tr>
<td>quartz</td>
<td>20</td>
<td>43</td>
<td>29</td>
<td>45</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>Modal%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>biotite</td>
<td>17</td>
<td>25</td>
<td>1</td>
<td>10</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>muscovite</td>
<td>40</td>
<td>15</td>
<td>20</td>
<td>29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ilmenite</td>
<td>1</td>
<td>0.4</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calcite</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>garnet</td>
<td></td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plagioclase</td>
<td>15.5</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>staurolite</td>
<td>12</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>apatite</td>
<td>tr</td>
<td>tr</td>
<td>tr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rutile</td>
<td>tr</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>titanite</td>
<td>tr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tourmaline</td>
<td>tr</td>
<td>tr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>zircon</td>
<td>20 (chl)</td>
<td>8 (sill)</td>
<td>tr (mon)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.2. Ages of magmatism

We dated four granitoid samples from the Angmong footwall suite: three leucogranite dikes (LB11-O-67, LB12-48, and LB12-65), and one sheared tonalite (LB12-18; Fig. 7). The tonalite (LB12-18, Fig. 7) was one of the larger coherent intrusions in the injection complex, with similar-looking tonalities, heavily intruded by younger dikes, extending over a distance of at least several kilometers. This tonalite exhibited a solid-state foliation with extensive post-magmatic recrystallization. Therefore we interpret that this tonalite predated most of the deformation and metamorphism in the area. Most zircons from this sample clustered in an incoherent group around 150 ± 5 Ma, suggesting probable crystallization around this time. However, three younger ages from oscillatory zoned zircons are difficult to conclusively discount, and could represent periods of later magma rejuvenation within the hot middle crust.

Three equigranular, medium-grained leucogranite dikes less than one meter in width intruding the footwall suite were sampled for U–Pb dating. The leucogranite samples generally displayed more complex U–Pb zircon age spectra, as is typical for peraluminous magmas, probably due to repeated crystallization and scavenging of zircon crystals during successive partial melting episodes in the source region (e.g., Howard et al., 2011; Bouilhol et al., 2013). Here we followed the accepted practice of interpreting the youngest concordant U–Pb zircon age as the time of final emplacement of these intrusions. Although the youngest sampled spots include cores and rims (Table S2), all analysis spots come from areas of oscillatory zoning in euhedral zircons, pointing to a magmatic origin for the dated zircons (Fig. 8). These samples yield ages of 18.8 ± 0.4 Ma (LB11-O-67), 18.8 ± 0.5 Ma (LB12-65), and 13.7 ± 0.2 Ma (LB12-48). These samples also contain significant populations of inherited grains from the Mesozoic (approx. 160–90 Ma) and the Late Oligocene to Early Miocene (post-26 Ma), suggesting there may have been intermittent periods of magmatic activity in the hot middle crust around these times as well (Fig. 7).

Samples LB11-O-67 and LB12-65 were from relatively undeformed dikes, but sample LB12-48 (the youngest sample) was from a boudinaged and folded dike that clearly predated the end of deformation. All of these dikes have intrusive relations suggesting that they were intruded while the wall rocks were still quite hot, as discussed earlier. Therefore we interpret these dikes to approximately constrain a maximum age for the late syn-kinematic/post-kinematic high-grade metamorphic conditions and deformation in the footwall suite.

### 5. Discussion

#### 5.1. Comparison to previous results

Most previous detailed petrological work near the present study area has been conducted within the Pangong Complex, opposite the east strand of the KKF, but a couple of studies have included high-grade metamorphic rocks from within the Karakoram shear zone, but on the NE side, which are lithologically similar to rocks of the Angmong footwall suite (approximate location shown by a red triangle in Fig. 2; Streule et al., 2009; Thanh et al., 2011). These studies found similar metamorphic
Fig. 7. LA-ICP-MS zircon U–Pb ages from three leucogranite dikes and a tonalite, grouped by age. Grey bars show weighted averages for youngest accepted zircon populations. At bottom, inverse concordia plots are shown for Tertiary ages from three of the dikes. The scatter of ages seems to indicate a protracted history of magmatism, most active in the late Jurassic to mid Cretaceous and the late Oligocene to mid Miocene.

conditions to those measured here, with estimated pressures of 605–850 MPa and temperatures of 585–680 °C (Streule et al., 2009; Thanh et al., 2011). To the northwest of our immediate study area (red hexagon in Fig. 2) high-grade rocks are also found, with estimated pressure and temperature around 550 MPa and 660 °C (Rolland et al., 2009). The age of metamorphism is not constrained at this location.

Additional age constraints exist from igneous rocks of the footwall suite (red star in Fig. 2). One apparently undeformed leucogranite dated via a combination of SHRIMP and LA-ICP-MS U–Pb zircon geochronology yielded age of 157 ± 3 Ma for zircon cores and one 18.9 ± 0.3 Ma rim age (Horton and Leech, 2013). However, as only one spot of the zircon rim was analyzed, the significance of this age remains uncertain.
Our results show a range of zircon U–Pb spot ages from our samples, which are generally consistent with magmatic activity elsewhere in the region. Inherited Mesozoic zircon ages from our samples at ~150 Ma are similar to ages from the Hushe orthogneiss (Searle, 1991) and various intrusions in the Qiangtang terrane (Zhang et al., 2012); and ages around 100 Ma are similar to those measured in the Hunza granodiorite (Fraser et al., 2001) and in the eastern Karakoram batholith near Saser La/Skyangpoche (Ravikant et al., 2009). The Miocene intrusion ages of the leucogranites in this study are also similar to ages of regional magmatism around 21–18 Ma from among the Baltoro granites and the Pangong Complex, and 13.7 Ma leucogranites from the Pangong Complex and the Nubra Valley (Searle et al., 1998; Phillips et al., 2004).

5.2. Age of metamorphism

Based on our field and textural observations, we consider the emplacement of leucocratic dikes to be contemporaneous with both the recorded high-grade metamorphic conditions and also the deformation that formed the pervasive fabric observed in the footwall suite, which may have accompanied the early, ductile stages of its exhumation. Our results indicate that deformation and high-grade metamorphic conditions occurred at ~19–14 Ma. These ages are synchronous with the age constraints for the activity on the KKF by Searle (1996) or Phillips et al. (2004) but postdate the inferred initiation age of the KKF by Lacassin et al. (2004) by ~10–20 Ma. Our interpretation is in accordance with existing thermochronology data in the region. K/Ar ages on muscovite indicate that the sampled rocks remained at temperatures above 500–430 °C until about 10 Ma (Thanh et al., 2011; from two locations: red star and red triangle on Fig. 2). These data are in line with our field observations that indicate emplacement of leucocratic dikes and veins into relatively hot country rocks. Additional thermochronology data from igneous rocks near the bend of the Shyok River (near red star in Fig. 2), include biotite Ar/Ar ages of 9.2–7.5 Ma, zircon U-Th/He ages of 4.4–3.4 Ma, and apatite U-Th/He ages of 3.3–2.7 Ma (Bohon, 2014). These data also strongly support recent exhumation of the Angmong footwall suite.

These results however contrast with U–Pb ages of monazite inclusions from the cores of garnet porphyroblasts that have been interpreted to date peak metamorphism at 108 ± 0.6 Ma (Streule et al., 2009; red triangle in Fig. 2). We do not dispute the interpretation that high grade metamorphic conditions also existed in the Cretaceous in the Pangong area, but because these samples are from within the Karakoram shear zone, it is not certain whether the results apply to parts of the footwall suite further from the KKF. Independently of their detailed structural position, the significance of U–Pb ages from monazite inclusions in garnet is highly debated (e.g., Montel et al., 2000; Appel et al., 2011). In any case, the monazite cores cannot be used to constrain the time of final rim-matrix equilibration at 585–605 °C and 605–725 MPa (Streule et al., 2009).

In summary, the existing data indicate that the Angmong footwall suite had not been substantially cooled and/or exhumed before the late Miocene. We interpret that initiation of extension and exhumation by the Angmong fault is linked to the onset of east-west extension around 16–12 Ma elsewhere in the Tibetan plateau (Styron et al., 2013; Sundell et al., 2013).

5.3. Geometry of the Angmong Fault

The constant exhumation level recorded in the footwall suite over at least 15 km distance orthogonal from the main fault trace is most consistent with a listric fault geometry, and relatively minor displacement across the West Angmong fault (Fig. 5). If the footwall of the fault system were simply tilted back via rigid block rotation, as is typical for high-angle normal faults, pressures should decrease rapidly away from the fault, where shallower parts of the tilted footwall would be exposed. This is not what is observed (Fig. 5). Rather, the constant pressures around 640 ± 100 MPa are more consistent with exhumation from beneath a rolling-hinge detachment bottoming out at ~22 km (assuming a crustal density of 2800 kg/m³; Fig. 5).

The major change in metamorphic grade across the Angmong normal fault implies that this fault has a substantial throw. Unfortunately, because pressure data are sparse more than 15 km from the Angmong fault, it is difficult to precisely determine the total horizontal displacement of the inferred detachment and the position of its breakaway zone. The minimum displacement is constrained by assuming that the rocks found within 15 km of the Angmong fault were exhumed from a depth over 20 km along a rolling-hinge fault dipping no steeper than 55°, which results in a total horizontal displacement across the fault of ~40 km (Fig. 5).

A maximum displacement can be approximated by assuming that the entire triangular wedge of footwall-suite rocks was exhumed from beneath the Angmong fault, indicating a maximum heave of ~50–70 km (Fig. 2). In this model, rocks that were at mid-crustal depths as late as 13.7 ± 0.2 Ma (based on the age of the youngest leucogranite dikes) have been displaced at least 44 ± 4 km NW from beneath the hanging wall of the Angmong fault (error due to displacement vector uncertainty; Fig. 2). This implies a horizontal displacement rate of at least 3.2 ± 0.3 mm/yr along the Angmong fault, consistent with the geodetic strike-slip displacement rate (3 ± 1 mm/yr) across the LGF (Raterman et al., 2007).

In this rolling-hinge model, as the Ladakh block, south of the KKF, and the Tianshuaihai block, north of the LGF, are brought together by the conjugate strike slip on the KKF and LGF faults, the Tibetan upper crust escapes eastward above the Angmong detachment (Fig. 9). The midcrustal footwall of the Angmong fault is exhumed vertically to fill the space left as the upper crust evacuates, and shortened in an NE–SW direction as it is caught between the converging Ladakh and Tianshuihai blocks (Fig. 9). This form of deformation would explain the subhorizontal stretching lineations and tight, relatively upright, NW trending folds in the footwall suite. The NW-tapering-wedge shape of the footwall suite may be caused by progressive shortening (and/or thrust burial) of footwall-suite rocks further NW into the compressive zone past the Angmong fault (Figs. 2, 9).

Fig. 8. Cathodoluminescence images of the youngest dated zircons, with LA-ICP-MS spots circled. Several of the younger ages are from zircon cores, not just rims, and the oscillatory zoning patterns indicate magmatic rather than metamorphic growth, supporting a Miocene intrusion age for the three dikes.
An alternative hypothesis might be that the Angmong fault is not a major detachment, but simply acts as a sort of accommodation fault, allowing rocks on its NW side to be exhumed by compressional uplift and erosion, while rocks to the SE are not shortened and uplifted, because they can escape to the east. This scenario would be similar to that pictured in Fig. 1c, but with erosion helping to remove material where the flanking blocks are zipperied together. But whereas detachment of the upper crust can expose deep rocks without extreme amounts of erosion, rapid exhumation of mid-crustal rock by erosion alone would require average erosion rates over 20 times higher than cosmogenically estimated for recent erosion in the nearby Ladakh Range (Dorch et al., 2011a, 2011b). This model also fails to explain why subhorizontal stretching lineations are ubiquitous even in areas unaffected by the dextral fabrics limited to areas near the KKF. It would also require the LGF to continue past the Angmong fault as a significant strike-slip fault, which our mapping does not seem to support (Fig. 2). For these reasons, this scenario is not preferred. However, existing data cannot prove or rule out either model.

### 5.4. Kinematics of Western Tibet

If our preferred model, in which essentially all of the slip across the LGF is absorbed by an east-dipping Angmong detachment system, proves to be correct, this has important implications for the kinematics of western Tibet. Although the LGF and Angmong fault, as well as the KKF southeast of its Angmong intersection, show evidence for fairly rapid Quaternary activity (Chevalier et al., 2005; Raterman et al., 2007), there is evidence for slower Quaternary strike-slip activity NW of the Angmong fault (Brown et al., 2002), decreasing to no recent activity 250 km to the NW (Robinson, 2009). A decrease in right-lateral slip on the KKF from SE to NW of the Angmong fault would be consistent with the Angmong normal fault transferring left-lateral motion from the LGF. Other westward decreases in displacement and/or slip rate across the KKF could possibly be related to similar kinematic transfers across additional undescribed normal faults north of the KKF, possibly explaining some of the discrepancies in published displacements and slip rates for the KKF (Brown et al., 2002; Chevalier et al., 2005; Searle et al., 2011).

If strike slip on the northwest KKF is negligible, the wedge of the Tibetan Plateau between the KKF and LGF is sliding out above the Angmong detachment, while the blocks astride the northwestern KKF are mostly being pushed together (Fig. 9; cf. Robinson, 2009), consistent with the presence of down-dip, top-to-the SW lineations along this part of the KKF and studies suggesting active thrusting (Fig. 2; Bohon, 2014). This model is, at the surface, consistent with the kinematic model of Raterman et al. (2007), in which displacement across the LGF leads to oroclinal bending of the KKF. However, the proposed role of the Angmong detachment in exposing middle crust from underneath the eastward-escaping Tibetan hanging wall suggests that mid-crustal material does not keep pace with the upper crust, and may follow a distinct set of trajectories relative to the upper crust.

Unlike the KKF, which continues NW past the Angmong Fault, the east–west trending LGF appears to end at its intersection with the Angmong fault (Fig. 2). If the Angmong fault truncates the LGF and bottoms out into a mid-crustal detachment as we hypothesize, then the LGF must also displace the upper crust relative to the middle crust, by the same amount as the Angmong detachment (Fig. 9). This is consistent with the observation that the total displacement across the LGF estimated from satellite imagery (25–32 km; Raterman et al., 2007) is no greater than the heave across the Angmong fault suggested by our model (>40 km). These relationships suggest that the LGF, and likely other strike-slip faults in the parts of Tibet underlain by hot, weak crust, might well translate the upper crust without extending below the middle crust.

### 6. Conclusion

Our geologic mapping demonstrates that two of the main conjugate strike-slip faults bounding the western Tibetan plateau are linked via a recently active normal fault. Our observations show that the rocks in the footwall of the Angmong normal fault are recently exhumed, hot, ductile middle crust. Similar mid-crustal conditions likely prevail throughout the Tibetan plateau (e.g., Nelson et al., 1996; Alsdorf and Nelson, 1999). These hot, ductile conditions contrast with those in the low-grade, brittle upper crust observed on the hanging-wall side of the Angmong fault, which is cut by localized normal and strike-slip faults. If horizontal displacements across the weak mid-crustal layer frequently prove to be as large as we hypothesize for the Angmong detachment, this would indicate that the plate-like kinematics of the upper crust of Tibet are largely decoupled from the kinematics of the middle and lower crust (Fig. 9). Although strike-slip faults in the Tibetan plateau are a surface manifestation of its deformation in the India–Asia collision (Fig. 1), our study suggests that this rigid translation of upper crustal blocks may actually be enabled by the hot, weak, viscously deforming middle crust (Fig. 9).

### Acknowledgements

This research was supported by OJ’s MIT start-up funds and NSF EAR 0910644. J. Pershken and Y. Adhikari provided field assistance. ASTER GDEM elevation data shown in Fig. 2 is a product of METI and NASA. Earthquake data for this study were accessed through the Northern California Earthquake Data Center (NCEDC). Helpful and constructive reviews were given by A. Robinson and an anonymous reviewer.

### Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.12.053. These data include the Google map of the most important areas described in this article.


extension and north–south shortening in the interior of the Tibetan Plateau. 


