

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/153391/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Ma, Lin, Wang, Qiang, Kerr, Andrew , Li, Zheng-Xiang, Dan, Wei, Yang, Ya-Nan, Zhou, Jin-Sheng and Li, Cheng 2023. Eocene magmatism in the Himalaya: response to lithospheric flexure during early Indian collision? *Geology* 51 (1) , pp. 96-100. 10.1130/G50438.1

Publishers page: <https://doi.org/10.1130/G50438.1>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



1 **Eocene magmatism in the Himalaya: A response to**  
2 **lithospheric flexure during early Indian collision?**

3

4 Lin Ma<sup>1, 2, 3, 4\*</sup>, Qiang Wang<sup>1, 3, 4\*</sup>, Andrew C. Kerr<sup>2</sup>, Zheng-Xiang Li<sup>5</sup>, Wei Dan<sup>1, 3, 4</sup>, Ya-Nan  
5 Yang<sup>1, 3</sup>, Jin-Sheng Zhou<sup>1</sup>, Jun Wang<sup>1</sup>, Cheng Li<sup>1, 4</sup>

6

7

8 <sup>1</sup> State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry,  
9 Chinese Academy of Sciences, Guangzhou 510640, China

10 <sup>2</sup> School of Earth and Environmental Sciences, Cardiff University, Cardiff, Wales CF10 3AT,  
11 United Kingdom

12 <sup>3</sup> Excellent Centre for Deep Earth Sciences, Chinese Academy of Sciences, Guangzhou  
13 510640, China

14 <sup>4</sup> College of Earth and Planetary Sciences, University of Chinese Academy of Sciences,  
15 Beijing 100049, China

16 <sup>5</sup> Earth Dynamics Research Group, TIGeR, School of Earth and Planetary Sciences, Curtin  
17 University, Perth, Western Australia, Australia

18

19 \*Corresponding author. E-mail: malin@gig.ac.cn (L. Ma), wqiang@gig.ac.cn (Q. Wang)

20 Eocene mafic magmatism in the Himalaya provides a crucial window for probing the  
21 evolution of crustal anatexis processes within the lower-plate in a collisional orogen. Here we  
22 report geochemical data from the earliest post-collision ocean island basalt-like mafic dikes  
23 intruding the Tethyan Himalaya near the northern edge of the colliding Indian plate. These  
24 dikes occurred coevally, and spatially overlap with, Eocene granitoids in the cores of gneiss  
25 domes and are likely derived from interaction of melts from the lithosphere-asthenosphere  
26 boundary with the Indian continental lithosphere. We propose that these mafic magmas were  
27 emplaced along lithospheric fractures in response to lithospheric flexure during initial  
28 subduction of the Indian continent and that the underplating of such mafic magmas resulted in  
29 orogen-parallel crustal anatexis within the Indian continent. This mechanism can explain the  
30 formation of coeval magmatism and the geological evolution of collisional orogen on both  
31 sides of the suture zone.

32

## 33 INTRODUCTION

34 The Himalaya belt is the most active collisional orogen in the world. It exposes the former  
35 passive margins of the Indian continent, and it is characterized by widespread Cenozoic  
36 crustal anatexis, high-grade metamorphism and some orogen-scale normal and strike-slip  
37 faulting ([Harrison et al., 1997](#); [Yin, 2006](#)) ([Fig. 1a](#)). These magmatic and metamorphic units  
38 distributed parallel to the suture within the lower plate/previously passive side of the  
39 collisional orogen, can yield significant information on the collision and related crustal  
40 reworking processes ([Hou et al., 2012](#); [Vanderhaeghe and Teyssier, 2001](#); [Wang et al., 2021](#);  
41 [Weller et al., 2021](#); [Zeng et al., 2011](#)).

42 Two critical episodes of Cenozoic metamorphism and magmatism have been identified  
43 from the Himalaya: 1) 48–35 Ma Barrovian-type prograde metamorphism with Eocene mafic  
44 and Na-rich adakitic melts (e.g., [Hou et al., 2012](#); [Ji et al., 2016](#)), and 2) Late Oligocene–  
45 Early Miocene retrograde metamorphism associated with leucogranite formation ([Harrison et](#)  
46 [al., 1997](#); [Vanderhaeghe and Teyssier, 2001](#); [Weller et al., 2021](#)) (Fig. 1).

47 Himalayan uplift and associated crustal anatexis ([Hou et al., 2012](#)) has been linked to a  
48 range of possible processes including thin-skinned thrusting ([DeCelles et al., 2002](#); [Yin, 2006](#)),  
49 middle-crustal melting and ductile flow ([Nelson et al., 1996](#); [Vanderhaeghe and Teyssier,](#)  
50 [2001](#)), or extrusion of an Indian crustal wedge ([Chemenda et al., 2000](#)). A variety of anatexis  
51 mechanisms beneath the Himalayas have been proposed, including: shear heating ([Harrison et](#)  
52 [al., 1998](#)), decompression melting ([Davidson et al., 2008](#)), radiogenic heating ([Searle et al.,](#)  
53 [2003](#)) and heat transferred from mantle-derived melts ([Zheng et al., 2016](#)). However, the links  
54 between the crustal anatexis event(s) and coeval tectonic developments remain unclear ([Guo](#)  
55 [and Wilson, 2012](#); [Hou et al., 2012](#) and references therein).

56 In this paper we report geochemical data from Eocene mafic dikes found in the Tethyan  
57 Himalaya that have ocean island basalt (OIB)-like compositions. This mafic magmatism  
58 occurred coevally, and spatially overlaps with, the well-developed Tethyan Himalayan  
59 granitoids and associated metamorphic event ([Hou et al., 2012](#)) (Fig. 1a-b). These dikes  
60 provide a rare opportunity to examine the origin of such enigmatic intraplate magmatism and  
61 related geodynamic evolution along the margin of the lower plate in a continental collision  
62 zone. Similar magmatism is also reported in other collisional orogens ([Vanderhaeghe et al.,](#)  
63 [2020](#); [Weller et al., 2021](#)) and in this study we present a new geodynamic model for such

64 orogen-parallel lower-plate magmatic and metamorphic belts.

65

## 66 **BACKGROUND AND SAMPLES**

67 The Himalaya-Tibet orogen was formed by the collision of the Indian continent with  
68 Eurasia that started along the Yarlung Zangbo Suture (YZS) (Fig. 1). The Lhasa block,  
69 immediately north of the YZS, represents the southern edge of the Asian upper plate, and  
70 experienced long-lived subduction of Neo-Tethyan ocean crust with extensive late Triassic to  
71 Eocene calc-alkaline plutonism and volcanism before the terminal collision (Zhu et al., 2013,  
72 2019). Following the collision and a magmatic flare-up with a peak of  $51 \pm 3$  Ma, arc  
73 magmatism in southern Tibet waned, as cold Indian lithosphere underthrust Tibet (Chung et  
74 al., 2005; Zhu et al., 2019).

75 On the opposite side of the suture is the lower Indian plate representing a pre-collisional  
76 stable craton, with slightly younger (ca. 48–35 Ma) high Sr/Y granitoids and limited OIB-type  
77 gabbros and medium-temperature eclogite–high pressure (EHP) granulite metamorphism (Fig.  
78 1; Hou et al., 2012; Ji et al., 2016; Weller et al., 2021; Zeng et al., 2011). The high Sr/Y  
79 granitoids are believed to have derived from partial melting of amphibolite at  $\sim 880^\circ\text{C}$  and  $\sim 10$   
80 kbar (Hou et al., 2012; Zeng et al., 2011). The 45 Ma Langshan gabbro, on the other hand, has  
81 HIMU (high  $\mu$ ,  $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$ )-type OIB signatures with depleted Sr-Nd isotopes. These  
82 gabbros are thought to have been generated by partial melting of the asthenosphere during  
83 detachment of the subducted Neo-Tethyan slab (Ji et al., 2016). Subsequent to this magmatic  
84 episode, kilometer-scale Himalayan leucogranite bodies ( $\sim 25$ – $15$  Ma and  $\sim 8$  Ma) were  
85 emplaced in the northern Himalaya (Fig. 1; Vanderhaeghe and Teyssier, 2001; Weller et al.,

2021). These leucogranites were produced by muscovite-dehydration melting of meta-sediments (Weinberg, 2016) at ultrahigh temperature (UHT) conditions (900–970°C and 6–11 kbar [ $\sim 40^\circ\text{C}/\text{km}$ ]), mostly between 25 and 15 Ma (Wang et al., 2021).

Several ENE-trending, broadly orogen-parallel, 5–8 m wide diabase dikes that intrude the Early Jurassic Ridang Formation limestone, marl limestone and shale, have recently been discovered near Gyangze (Figs. 1 and DR2). These dikes are coarse-grained and consist of clinopyroxene, plagioclase and amphibolite with secondary chlorite and sericite.

## GEOCHRONOLOGY AND GEOCHEMISTRY

Zircon grains from the Gyantse diabase sample JZ18-2-1 yielded a U-Pb age of  $48.6 \pm 0.5$  Ma (Fig. 2d, methodology and detailed analytical results in the Data Repository), that is slightly older than the Langshan OIB-type gabbro ( $45 \pm 1.4$  Ma, Ji et al., 2016) but overlaps with the earliest Cenozoic high Sr/Y granitoids (ca. 48–45 Ma; e.g., Hou et al., 2012). Zircon  $\delta^{18}\text{O}$  values ranging from 5.1‰ to 6.4‰ with a mean of  $5.9 \pm 0.6\text{‰}$ , are consistent (within error) with mantle zircon values ( $5.3 \pm 0.6\text{‰}$ ).

The Gyantse diabase dikes have relatively broad ranges of  $\text{SiO}_2$  (46.0 to 54.5 wt.%) and MgO (5.0 to 12.4 wt.%) contents, and plot in the field of alkali basaltic rocks (Fig. 2a). They have OIB-like element patterns with enriched Nb (11.4–21.5 ppm) and  $\text{TiO}_2$  (1.9–2.9 wt.%) and a slight Eu anomaly (chondrite normalized  $\text{Eu}/\sqrt{\text{Sm} \times \text{Gd}} = 0.85 - 1.10$ ). Initial Sr-isotope ratios (0.7076–0.7115) and  $\epsilon_{\text{Nd}}(t)$  (–2.7 to –2.0), are more enriched than the Langshan gabbro but less so than the coeval granitoids (Fig. 2c).

## 108    **PETROGENESIS AND GEOTECTONIC IMPLICATIONS**

109        The Gyantse mafic dikes have relatively low Nb (11.7–21.5 ppm) and more enriched Sr-Nd  
110    isotope compositions than the Langshan gabbro which was likely formed by partial melting of  
111    asthenosphere (Ji et al., 2016), that contained more-enriched components. Given the  
112    insignificant crustal contamination of the Gyantse mafic magmas (see details in Data  
113    Repository), the Indian lithospheric mantle (Shellnutt et al., 2014) is the most likely source of  
114    this enriched component. Our modeling indicates that the Gyantse mafic dikes were most  
115    likely derived from the lithosphere-asthenosphere boundary (LAB) melts at the top of the  
116    asthenosphere with a contribution from the Indian lithospheric mantle (Figs. 2c and DR3).  
117    Seismic profiles show that the present depth of the LAB below eastern Himalaya ranges from  
118    140 km to 100 km (Zhao et al. 2010), which is likely to be similar to, or greater than, the  
119    lithosphere thickness at the early stage of the collision (~50 Ma). Peridotite with 1.0–2.5 wt.%  
120    CO<sub>2</sub> or 200–300 ppm H<sub>2</sub>O can produce stable partial melts at 3 Gpa (Hirschmann et al., 2009).  
121    The LAB has recently been documented to be volatile enriched (Blatter et al. 2022), and thus  
122    provides the most likely source for mafic magmas in Tethyan Himalaya during early collision.

123        The Early Eocene (51–45 Ma) magmatism, dominated by crustal anatexis, occurred on  
124    both sides of the YZS during early collision. The southern margin of Asian plate is  
125    characterized by thickened juvenile crust and a relatively high crustal thermal state (Ma et al.,  
126    2017). In contrast, the northern edge of the Indian plate is marked by a thickened ancient crust  
127    with a moderate geothermal gradient during the early stage of collision (Hou et al., 2012;  
128    Weller et al., 2021 and references therein). The 48–35 Ma Tethyan Himalaya magmatism,  
129    consisting of high Sr/Y granitoids within gneiss dome and coeval gabbros and dikes, is slightly

130 younger than the magmatic peak in the Lhasa block ( $51\pm 3$  Ma) (Fig. 1). After that, another  
131 episode (25–8 Ma) of crustal anatexis of accreted sediments dominated the melting in the  
132 Himalaya (Guo and Wilson, 2012; Weller et al., 2021).

133 The sources of the two episodes of crustal anatexis along the northern Indian continental  
134 margin (one at around 48–35 Ma, and the other around 25–8 Ma) may be very different. The  
135 Miocene crustal anatexis accompanied by ultrahigh temperature (900–970 °C) metamorphism  
136 indicates a hotter crustal thermal state than the Eocene crustal anatexis events with moderate  
137 temperature (~600–750 °C) metamorphism (e.g., Wang et al., 2021; Weller et al., 2021).  
138 Numerous studies over the past few decades have been carried out on the Miocene crustal  
139 anatexis and related process, which led to the Cenozoic rise of the Himalaya orogen  
140 (Chemenda et al., 2000; DeCelles et al., 2002; Harrison et al., 1998; Nelson et al., 1996; Yin,  
141 2006; Wang et al., 2021). However, the Eocene crustal anatexis event is poorly understood  
142 due to the lack of critical evidence. A previous model for the generation of mafic magmas in  
143 Tethyan Himalaya involves decompression melting of the asthenosphere triggered by the  
144 break-off of the Neo-Tethyan lithosphere (e.g., Ji et al., 2016). However, such a model has  
145 difficulties in accounting for the following geological observations. 1) Similar OIB-like  
146 magma has not been found in the Lhasa terrane below which the break-off of the  
147 Neo-Tethyan lithosphere is proposed to have occurred. 2) It would have been extremely  
148 difficult for OIB-like magma to migrate southwards from beneath the Lhasa terrane and  
149 emplace as the Indian plate continued to push northward against Eurasia. An alternative  
150 model is therefore required to reconcile coeval metamorphic and magmatic records and  
151 geological observations along both sides of the suture zone in this collisional orogen.



152 It has been noted that a sudden increase in the convergence rate of the Indian continent  
153 toward Eurasia occurred prior to its initial collision with Eurasia was likely a response to  
154 enhanced pull caused by the steepening subduction of the Neo-Tethyan plate (Fig. 3; Chung et  
155 al., 2005). Such a steepening of subduction may also have resulted in the likely steep  
156 geometry of the early subduction of the Indian continental margin (Qi et al., 2020). This  
157 steepening Neo-Tethyan and Indian lithospheric subduction may also have triggered  
158 subduction channel widening and asthenospheric upwelling under the southern Lhasa terrane  
159 (Kelly et al., 2019). This would have eventually resulted in break-off of the Neo-Tethyan  
160 oceanic slab (Hou et al., 2012), and/or lithospheric delamination of southern Lhasa terrane  
161 (Qi et al., 2020), causing melting to produce the ca. 51 Ma magmatism in southern Lhasa  
162 block along the suture zone (Fig. 3).

163 We propose here that after the 51 Ma magmatic event, a lithospheric flexure formed along the  
164 northern Indian continent parallel to the suture, causing brittle cracking (i.e., bending-induced  
165 faults; Romeo and Álvarez-Gómez, 2018) and the 48–45 Ma melting in northern Himalaya  
166 (Fig. 3a). The lithospheric flexure could have resulted from either: 1) the break-off of the  
167 subducted Neo-Tethyan lithosphere at ca. 50 Ma (Fig. 3a), and the resultant  
168 buoyancy-induced upward bending of the leading edge of the Indian continental lithosphere;  
169 or 2) the slowdown of subduction along the leading-edge of the subducting Indian lithosphere  
170 at ca. 50 Ma due to the buoyancy of the Indian continental crust while the Indian plate was  
171 still continuously pushing northward. This is consistent with the rapid slowdown of the Indian  
172 continent's northward movement since 50 Ma (Fig. 1c, Cande et al., 2010). In addition, the  
173 loading caused by crustal thickening after the collision may also have contributed to

174 lithospheric bending (Fig. 3a).

175 In our model, the melts derived by decompression melting of the LAB intruded to the  
176 shallow levels of the lithosphere along extensional fractures below neutral plane of the  
177 downwarped lithosphere (Fig. 3). Given the rapid thickening of the Indian continental crust  
178 during the early collision, the neutral plane of the bended lithosphere could have been close to  
179 or above the Moho, with shortening above the neutral plane mostly absorbed by the series of  
180 crust thrusting (Fig. 3a). The high buoyancy of volatile-rich LAB melts and potential  
181 thermal–mechanical–chemical erosion could have driven the migration of the LAB melts  
182 through the lithosphere (Spence and Turcotte, 1985). Emplacement of such mafic magmas  
183 may not only form the reported gabbros and mafic dikes which are now exhumed to the  
184 surface by kilometers of erosion, associated mafic underplating in the crust likely also  
185 provided the heat source for the formation of coeval (51–40 Ma) orogen-parallel crustal  
186 anatexis, and thus the orogen-parallel gneiss domes (Hou et al., 2012; Weller et al., 2021).  
187 After this 48–35 Ma magmatic event, the ongoing over-thrusting and crustal compression  
188 enabled the accumulation of radiogenic heat in the lower crust. This radiogenic decay resulted  
189 in an elevated geotherm and causing the subsequent larger-scale crustal anatexis during the  
190 Miocene (Fig. 1). However, discussion and modelling of this process is beyond the scope of  
191 the present paper.

192 Overall, our model provides new insights into the mechanisms of magma generation and  
193 orogenic evolution within the lower plate (a previous passive margin)-side of convergent  
194 orogens. Such mechanisms may also be applicable to converging oceanic lower plates, where  
195 explanations for the mechanism of orogen-parallel magmatism range from a mantle transition

zone origin (Yang and Faccenda, 2020) to melts formed at the LAB due to either lithospheric flexure-related extension (e.g., Hirano et al., 2006; Pilet et al., 2016) or enhanced pull of the subducting plate (Dan et al., 2021). Elements of our model also share similarities to that of Yuan et al. (2010) proposed for the formation of Triassic granitoids in the eastern Songpan-Ganzi Fold Belt. Our model may also be applicable to magmatism along the passive side of other collisional orogens.

## ACKNOWLEDGMENTS

We appreciate valuable suggestions of Prof. U. Schaltegger, Prof. D. Brown, Prof. B. White, Prof. A. Yin, Prof. O. Vanderhaeghe and an anonymous reviewer. We also thank Prof. Yin-De Jiang and Dr. Xiu-Zheng Zhang for beneficial discussions. Financial support was provided by the Second Tibetan Plateau Scientific Expedition and Research (2019QZKK0702), the National Natural Science Foundation of China (Nos. 42122022, 41872062 and 42021002). ZXL acknowledge support from the Australian Research Council (Laureate Fellowship grant FL150100133). This is contribution XXXXXX from GIGCAS.

## Reference

- Blatter, D., Naif, S., Key, K., and Ray, A., 2022, A plume origin for hydrous melt at the lithosphere–asthenosphere boundary: *Nature*, v. 604, no. 7906, p. 491-494.
- Cande, S. C., Patriat, P., and Dymant, J., 2010, Motion between the Indian, Antarctic and African plates in the early Cenozoic: *Geophysical Journal International*, v. 183, no. 1, p. 127-149.
- Chapman, J. B., and Kapp, P., 2017, Tibetan Magmatism Database: *Geochemistry, Geophysics, Geosystems*, v. 18, no. 11, p. 4229-4234.

218 Chemenda, A., and Burg, J.-P., 2000, Evolutionary model of the Himalaya-Tibet system: Geopolem  
 219 based on new modelling, geological and geophysical data: *Earth and Planetary Science*  
 220 *Letters*, v. 174, p. 397-409.

221 Chung, S. L., Chu, M. F., Zhang, Y., Xie, Y., Lo, C. H., Lee, T. Y., Lan, C. Y., Li, X., Zhang, Q.,  
 222 and Wang, Y., 2005, Tibetan tectonic evolution inferred from spatial and temporal variations  
 223 in post-collisional magmatism: *Earth-Science Reviews*, v. 68, no. 3-4, p. 173-196.

224 Dan, W., Wang, Q., White, W. M., Li, X.-H., Zhang, X.-Z., Tang, G.-J., Ou, Q., Hao, L.-L., and Qi,  
 225 Y., 2021, Passive-margin magmatism caused by enhanced slab-pull forces in central Tibet  
 226 *Geology*, v. 49, p. 130–134.

227 Davidson, C., Grujic, D., Hollister, L., and Schmid, S., 2008, Metamorphic reactions related to  
 228 decompression and synkinematic intrusion of leucogranite, High Himalayan Crystallines,  
 229 Bhutan: *Journal of Metamorphic Geology*, v. 15, p. 593-612.

230 DeCelles, P. G., Robinson, D. M., and Zandt, G., 2002, Implications of shortening in the  
 231 Himalayan fold - thrust belt for uplift of the Tibetan Plateau: *Tectonics*, v. 21, no. 6, p.  
 232 12-11-12-25.

233 Harrison, T. M., Lovera, O. M., and Grove, M., 1997, New insights into the origin of two  
 234 contrasting Himalayan granite belts: *Geology*, v. 25, no. 10, p. 899-902.

235 Hirano, N., Takahashi, E., Yamamoto, J., Abe, N., Ingle, S. P., Kaneoka, I., Hirata, T., Kimura, J.-I.,  
 236 Ishii, T., and Ogawa, Y., 2006, Volcanism in response to plate flexure: *Science*, v. 313, no.  
 237 5792, p. 1426-1428.

238 Hirschmann, M. M., Tenner, T., Aubaud, C., and Withers, A., 2009, Dehydration melting of  
 239 nominally anhydrous mantle: The primacy of partitioning: *Physics of the Earth and Planetary*

240 Interiors, v. 176, no. 1-2, p. 54-68.

241 Hou, Z.-Q., Zheng, Y.-C., Zeng, L.-S., Gao, L.-E., Huang, K.-X., Li, W., Li, Q.-Y., Fu, Q., Liang,  
242 W., and Sun, Q.-Z., 2012, Eocene–Oligocene granitoids in southern Tibet: constraints on  
243 crustal anatexis and tectonic evolution of the Himalayan orogen: *Earth and Planetary Science*  
244 *Letters*, v. 349, p. 38-52.

245 Ji, W. Q., Wu, F. Y., Chung, S. L., Wang, X. C., Liu, C. Z., Li, Q. L., Liu, Z. C., Liu, X. C., and  
246 Wang, J. G., 2016, Eocene Neo-Tethyan slab breakoff constrained by 45 Ma oceanic island  
247 basalt-type magmatism in southern Tibet: *Geology*, v. 44, no. 4, p. 283-286.

248 Kelly, S., Beaumont, C., and Butler, J. P., 2019, Inherited terrane properties explain enigmatic  
249 post-collisional Himalayan-Tibetan evolution: *Geology*, v. 48, no. 1, p. 8-14.

250 Ma, L., Wang, Q., Kerr, A. C., Yang, J.-H., Xia, X.-P., Ou, Q., Yang, Z.-Y., and Sun, P., 2017,  
251 Paleocene (c. 62 Ma) Leucogranites in Southern Lhasa, Tibet: Products of Syn-collisional  
252 Crustal Anatexis during Slab Roll-back?: *Journal of Petrology*, v. 58, no. 11, p. 2089-2114.

253 Nelson, K. D., Zhao, W., Brown, L. D., Kuo, J., Che, J., Liu, X., Klemperer, S. L., Makovsky, Y.,  
254 Meissner, R., Mechie, J., Kind, R., Wenzel, F., Ni, J., Nabelek, J., Leshou, C., Tan, H., Wei,  
255 W., Jones, A. G., Booker, J., Unsworth, M., Kidd, W. S. F., Hauck, M., Alsdorf, D., Ross, A.,  
256 Cogan, M., Wu, C., Sandvol, E., and Edwards, M., 1996, Partially Molten Middle Crust  
257 Beneath Southern Tibet: Synthesis of Project INDEPTH Results: *Science*, v. 274, no. 5293, p.  
258 1684-1688.

259 Pilet, S., Abe, N., Rochat, L., Kaczmarek, M. A., Hirano, N., Machida, S., Buchs, D. M.,  
260 Baumgartner, P. O., and Müntener, O., 2016, Pre-subduction metasomatic enrichment of the  
261 oceanic lithosphere induced by plate flexure: *Nature Geoscience*, v. 9, no. 12, p. 898-903.

262 Qi, Y., Hawkesworth, C. J., Wang, Q., Wyman, D. A., Li, Z.-X., Dong, H., Ma, T., Chen, F., Hu,  
 263 W.-L., and Zhang, X.-Z., 2020, Syn-collisional magmatic record of Indian steep subduction  
 264 by 50 Ma: *GSA Bulletin*, v. 133, no. 5-6, p. 949-962.

265 Romeo, I., and Álvarez-Gómez, J. A., 2018, Lithospheric folding by flexural slip in subduction  
 266 zones as source for reverse fault intraslab earthquakes: *Scientific Reports*, v. 8, no. 1, p. 1367.

267 Searle, M., Simpson, R., Law, R., Parrish, R., and Waters, D., 2003, The structural geometry,  
 268 metamorphic and magmatic evolution of the Everest massif, High Himalaya of Nepal–South  
 269 Tibet: *Journal of the Geological Society*, v. 160, no. 3, p. 345-366.

270 Shellnutt, J. G., Bhat, G. M., Wang, K.-L., Brookfield, M. E., Jahn, B.-M., and Dostal, J., 2014,  
 271 Petrogenesis of the flood basalts from the Early Permian Panjal Traps, Kashmir, India:  
 272 Geochemical evidence for shallow melting of the mantle: *Lithos*, v. 204, p. 159-171.

273 Spence, D., and Turcotte, D., 1985, Magma - driven propagation of cracks: *Journal of*  
 274 *Geophysical Research: Solid Earth*, v. 90, no. B1, p. 575-580.

275 Vanderhaeghe, O., Laurent, O., Gardien, V., Moyon, J.-F., Gébelin, A., Chelle-Michou, C.,  
 276 Couzinié, S., Villaros, A., and Bellanger, M., 2020, Flow of partially molten crust controlling  
 277 construction, growth and collapse of the Variscan orogenic belt: the geologic record of the  
 278 French Massif Central: *Bulletin de la Société Géologique de France*, v. 191, no. 1, p. 25.

279 Vanderhaeghe, O., and Teyssier, C., 2001, Partial melting and flow of orogens: *Tectonophysics*, v.  
 280 342, no. 3, p. 451-472.

281 Wang, J.-M., Lanari, P., Wu, F.-Y., Zhang, J.-J., Khanal, G. P., and Yang, L., 2021, First evidence  
 282 of eclogites overprinted by ultrahigh temperature metamorphism in Everest East, Himalaya:  
 283 Implications for collisional tectonics on early Earth: *Earth and Planetary Science Letters*, v.

284 558, p. 116760.

285 Weinberg, R. F., 2016, Himalayan leucogranites and migmatites: nature, timing and duration of  
 286 anatexis: *Journal of Metamorphic Geology*, v. 34, no. 8, p. 821-843.

287 Weller, O. M., Mottram, C. M., St-Onge, M. R., Möller, C., Strachan, R., Rivers, T., and Copley,  
 288 A., 2021, The metamorphic and magmatic record of collisional orogens: *Nature Reviews*  
 289 *Earth & Environment*, v. 2, no. 11, p. 781-799.

290 Yang, J., and Faccenda, M., 2020, Intraplate volcanism originating from upwelling hydrous mantle  
 291 transition zone: *Nature*, v. 579, no. 7797, p. 88-91.

292 Yin, A., 2006, Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike  
 293 variation of structural geometry, exhumation history, and foreland sedimentation:  
 294 *Earth-Science Reviews*, v. 76, no. 1, p. 1-131.

295 Yuan, C., Zhou, M.-F., Sun, M., Zhao, Y., Wilde, S., Long, X., and Yan, D., 2010, Triassic  
 296 granitoids in the eastern Songpan Ganzi Fold Belt, SW China: magmatic response to  
 297 geodynamics of the deep lithosphere: *Earth and Planetary Science Letters*, v. 290, no. 3-4, p.  
 298 481-492.

299 Zeng, L., Gao, L.-E., Xie, K., and Liu-Zeng, J., 2011, Mid-Eocene high Sr/Y granites in the  
 300 Northern Himalayan Gneiss Domes: melting thickened lower continental crust: *Earth and*  
 301 *Planetary Science Letters*, v. 303, no. 3, p. 251-266.

302 Zhao, J., Yuan, X., Liu, H., Kumar, P., Pei, S., Kind, R., Zhang, Z., Teng, J., Ding, L., and Gao, X.,  
 303 2010, The boundary between the Indian and Asian tectonic plates below Tibet: *Proceedings*  
 304 *of the National Academy of Sciences*, v. 107, no. 25, p. 11229-11233.

305 Zheng, Y.-c., Hou, Z.-q., Fu, Q., Zhu, D.-C., Liang, W., and Xu, P., 2016, Mantle inputs to

306 Himalayan anatexis: Insights from petrogenesis of the Miocene Langkazi leucogranite and its  
307 dioritic enclaves: *Lithos*, v. 264, p. 125-140.

308 Zhu, D.-C., Wang, Q., Chung, S.-L., Cawood, P. A., and Zhao, Z.-D., 2019, Gangdese magmatism  
309 in southern Tibet and India–Asia convergence since 120 Ma: Geological Society, London,  
310 Special Publications, v. 483, no. 1, p. 583-604.

311 Zhu, D.-C., Zhao, Z.-D., Niu, Y., Dilek, Y., Hou, Z.-Q., and Mo, X.-X., 2013, The origin and  
312 pre-Cenozoic evolution of the Tibetan Plateau: *Gondwana Research*, v. 23, no. 4, p.  
313 1429-1454.



314 Figure 1. (a) Simplified geologic map of the Himalayan orogenic belt, southern Tibet  
315 (after [Zeng et al., 2011](#)) showing locations of the magmatism and metamorphism in  
316 the northern Himalaya, as well as the location of the study area. Locations and ages of  
317 Eocene magmatism in Tethyan Himalaya are listed in [Table DR1](#). YZS: Yarlung  
318 Zangbo suture; STDS: Southern Tibet Detachment System; MCT: Main Central  
319 Thrust; MBT: Main Boundary Thrust; LH: Lower Himalaya. (b) Geological map of  
320 the study area. (c) Histogram of ages for Eocene magmatic rocks in the Tethyan  
321 Himalaya. The convergence rate of Indian continent is shown as green dotted line.  
322 The dark blue line shows the kernel density estimate ([Chapman and Kapp, 2017](#)) for  
323 the age of the southern Lhasa magmatism. (d) Plots of representative  
324 pressure-temperature (P-T) and thermal gradients for Cenozoic metamorphism in the  
325 Himalaya. The data and references are listed in [Table DR5](#).

326

327 Figure 2. Geochemistry and Tera-Wasserburg diagram of the Gyantse dikes. The  
328 Langshan gabbro data are from [Ji et al. \(2016\)](#). The data for Tethyan MORB, Panjal  
329 basalt, Eocene granite and Oligo-Miocene leucogranite shown in [Table DR6](#).  
330 Langshan gabbro (12FW63,  $[\text{}^{87}\text{Sr}/\text{}^{86}\text{Sr}]_i = 0.706571$ ,  $\epsilon_{\text{Nd}}(t) = 5.8$ ) and Panjal low-Ti  
331 basalt (PJ2-014,  $[\text{}^{87}\text{Sr}/\text{}^{86}\text{Sr}]_i = 0.712667$ ,  $\epsilon_{\text{Nd}}(t) = -6.4$ ) represent the asthenospheric  
332 and lithospheric mantle end-members for modeling, respectively. The numbers along  
333 the blue tick-line indicate percentage contribution of asthenosphere material. MSWD  
334 = mean square of weighted deviation.

335

336 Figure 3. Schematic diagram illustrating the formation of the Eocene (ca. 50-35 Ma)  
337 orogen-parallel magmatic and metamorphic zone in the Tethyan Himalaya due to  
338 lithospheric flexure. Mafic melts from the lithosphere-asthenosphere boundary  
339 percolate into the Indian continental lithosphere and underplate the continental crust  
340 along fractures, causing coeval orogen-parallel thickened crustal anatexis. The  
341 steepening subduction of Neo-Tethyan and Indian lithosphere resulted in the  
342 subduction channel widening and asthenospheric upwelling and/or a slab break-off,  
343 causing melting to produce coeval magmatism in the Lhasa block. (b) Elevation and  
344 S-wave receiver function profiles along the dark blue dotted line in [Fig.1a](#), are  
345 adapted from [Zhao et al. \(2010\)](#). The blue low velocity zone indicates a possible  
346 partial melting zone.





