

1 Evolution of the melt source during protracted crustal anatexis;
2 an example from the Bhutan Himalaya

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20 **ABSTRACT**

21 The chemical compositions of growth zones of magmatic zircon provide
22 powerful insight into evolving magma compositions due to their ability to record
23 both time and the local chemical environment. *In situ* U-Pb and Hf isotope
24 analyses of zircon rims from Tertiary leucogranites of the Bhutan Himalaya
25 reveal, for the first time, an evolution in melt composition between 32-12 Ma.
26 The data indicate a broadly stable melt source from 32 Ma to 17 Ma, and the
27 progressive addition of an older source component to the melt from at least ~17
28 Ma, and possibly from as early as 21 Ma. Age-corrected ϵ_{Hf} ratios decrease from
29 between -10 to -15 down to values as low as -23 by 12 Ma. Complementary
30 whole-rock Nd isotope data corroborate the Hf data, with a progressive decrease
31 in $\epsilon_{\text{Nd}(T)}$ from ~18 to 12 Ma. Published zircon and whole-rock Nd data from
32 different lithotectonic units in the Himalaya suggest a chemical distinction
33 between the younger Greater Himalayan Series (GHS) and the older Lesser
34 Himalaya Series (LHS). The time-dependent isotopic evolution shown in the
35 leucogranites demonstrates a progressive increase in melt contribution from
36 older lithologies, indicative of increasing LHS involvement in Himalayan melting
37 over time. The time-resolved data therefore are consistent with a model
38 wherein LHS material was incorporated into the base of the hanging wall of the
39 Main Central thrust from ~17 Ma. Exhumation of this hanging wall material
40 along the thrust triggered decompression melting under fluid-absent conditions
41 during the later stages of orogenesis.

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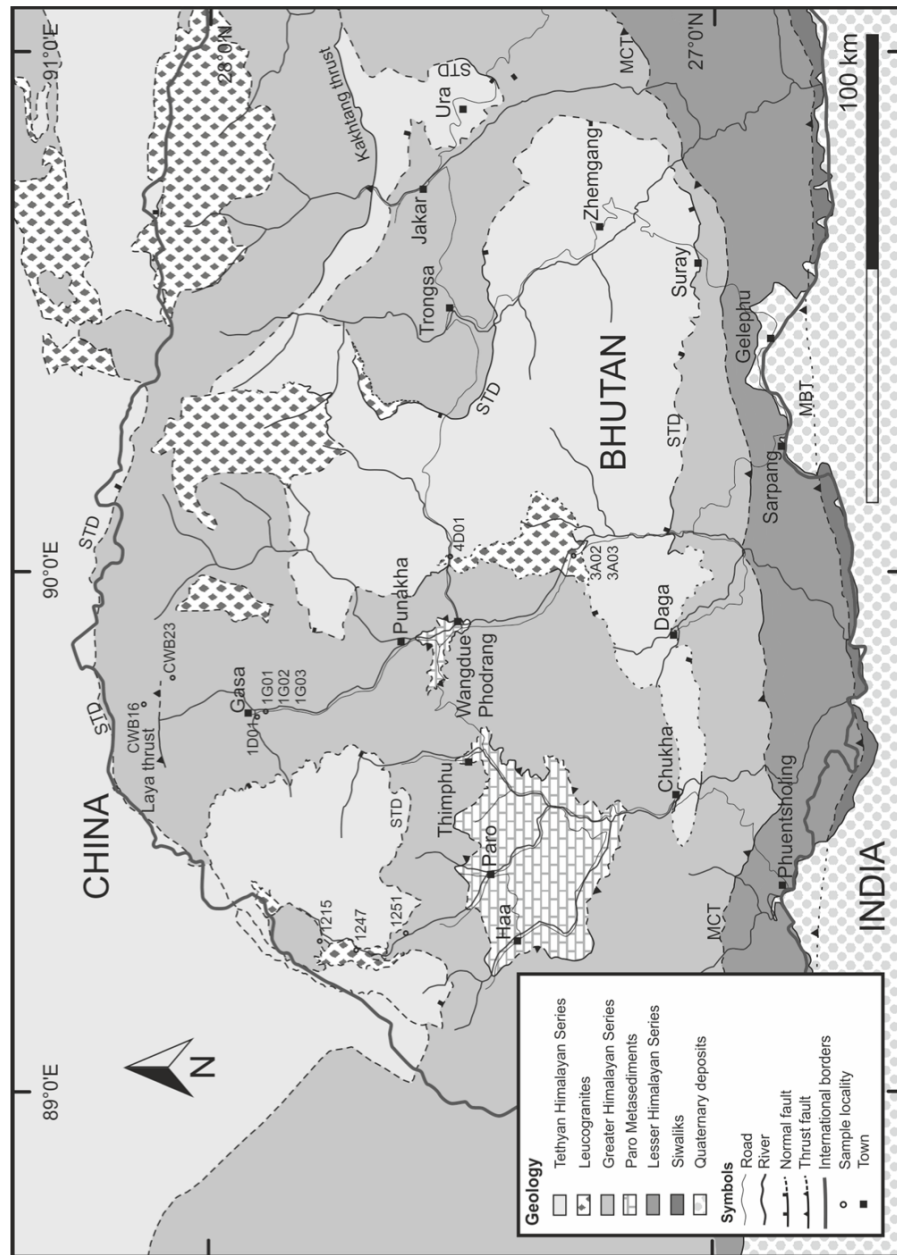
44 **INTRODUCTION**

45 Crustal melting is a fundamental process both for chemical differentiation
46 and for facilitating ductile deformation of the Earth's continental crust. In the
47 Himalaya, Late Oligocene-Miocene leucogranites provide a well-documented
48 example of crustal melting induced by continental collision. Oxygen and hafnium
49 isotope data from Himalayan leucogranite zircon rims demonstrate that these
50 granites are examples of pure crustal melting with no detectable mantle input
51 (Hopkinson et al., 2017). The timeframe across which melting has occurred along
52 the Himalaya orogen ranges from at least 25 Ma to 9 Ma (Guo and Wilson, 2012),
53 although granites as old as 39 Ma has been identified in the western Himalaya
54 (Prince et al., 2001). Despite this extensive period of regional anatexis, no time-
55 dependant change in the magmatic source has been recognised thus far. The
56 evolving thermal regime during collisional orogenesis should lead to migration
57 of melt source regions, and involvement of sources from different crustal levels.
58 In the case of the Himalayan leucogranites it is possible that the apparent
59 absence of time-dependent trends results from the lack of chronological
60 resolution using traditional whole-rock isotopic data. The importance of
61 recognising the temporal evolution of melt zones lies in better constraining
62 models of thermal and structural evolution of the continental crust during
63 orogenesis. Here we evaluate the Hf isotope composition of zircon sampled from
64 leucogranites in Bhutan (Eastern Himalaya), along with new whole-rock Nd
65 isotope data. The temporal changes observed in isotopic composition provides,
66 for the first time, direct evidence for a time-dependant change in the mid-crustal
67 material undergoing melting during Himalayan crustal thickening.

68

69 **REGIONAL SETTING**

70 We have analysed the isotopic composition of zircon from peraluminous
71 Oligocene to Miocene leucogranites exposed in the eastern Himalayan orogen in
72 Bhutan (Fig.1). The granites represent a range of mineralogical types, including
73 seven two-mica (1G03, 3A03, 4D01, 1247, 1251, CWB16 and CWB23), two
74 tourmaline-bearing (1G02, 1215), two garnet-bearing (1D01, 3A02) and one
75 pegmatitic two-mica (1G01) leucogranite. Across the orogen, such granites
76 intrude upper amphibolite-facies metasediments of primarily Neoproterozoic
77 source age, the Greater Himalayan Sequence (GHS; Ahmad et al., 2000; Gehrels et
78 al., 2011). In Bhutan, the leucogranites are emplaced in the uppermost
79 lithologies of the GHS, close to or crossing the tectonic boundary with the
80 Tethyan sediments (Greenwood et al., 2016) as is evident from Fig. 1.
81 Structurally below the GHS, and underthrust along the Main Central thrust
82 (MCT), is the Lesser Himalayan Sequence (LHS), a primarily Paleoproterozoic-
83 sourced stack of metasediments (Ahmad et al., 2000; Gehrels et al., 2011). Both
84 the GHS and LHS comprise a mix of pelitic, orthogneiss, carbonate and quartzite
85 compositions. The pelitic assemblages are significantly the most melt-fertile, and
86 therefore provide appropriate source materials for anatexic melts at
87 temperatures below $\sim 760^{\circ}\text{C}$ (at pressures equivalent to melting in the mid to
88 lower crust; Patiño Douce and Johnston, 1991).



89

90 *Figure 1. Geological map of western and central Bhutan, adapted from Greenwood et*

91 *al. (2016), showing sample localities. STD = South Tibetan Detachment, MCT =*

92 *Main Central Thrust, MBT = Main Boundary Thrust, MFT = Main Frontal Thrust.*

93

94 Whole-rock isotope geochemical data from equivalent High Himalayan
95 leucogranites exposed across the Himalayan orogen suggest that they formed
96 largely by partial melting of the pelitic lithologies of the GHS into which the
97 granites intrude (Le Fort et al., 1987; Harris and Massey, 1994; Hopkinson et al.,
98 2017). However, a whole-rock Sr–Nd isotope study has suggested that a small
99 contribution from LHS-derived fluids has also contributed to some leucogranite
100 melts (Guo and Wilson, 2012). Critically, there is no observed temporal control
101 on the proposed inputs from the LHS. Our new zircon rim U-Pb and age-
102 corrected ϵ_{Hf} isotope analyses coupled with whole-rock Nd isotope data show
103 that, at least in Bhutan, there is progressive increase in melt contribution from
104 the LHS after ~17 Ma.

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106 **METHODS**

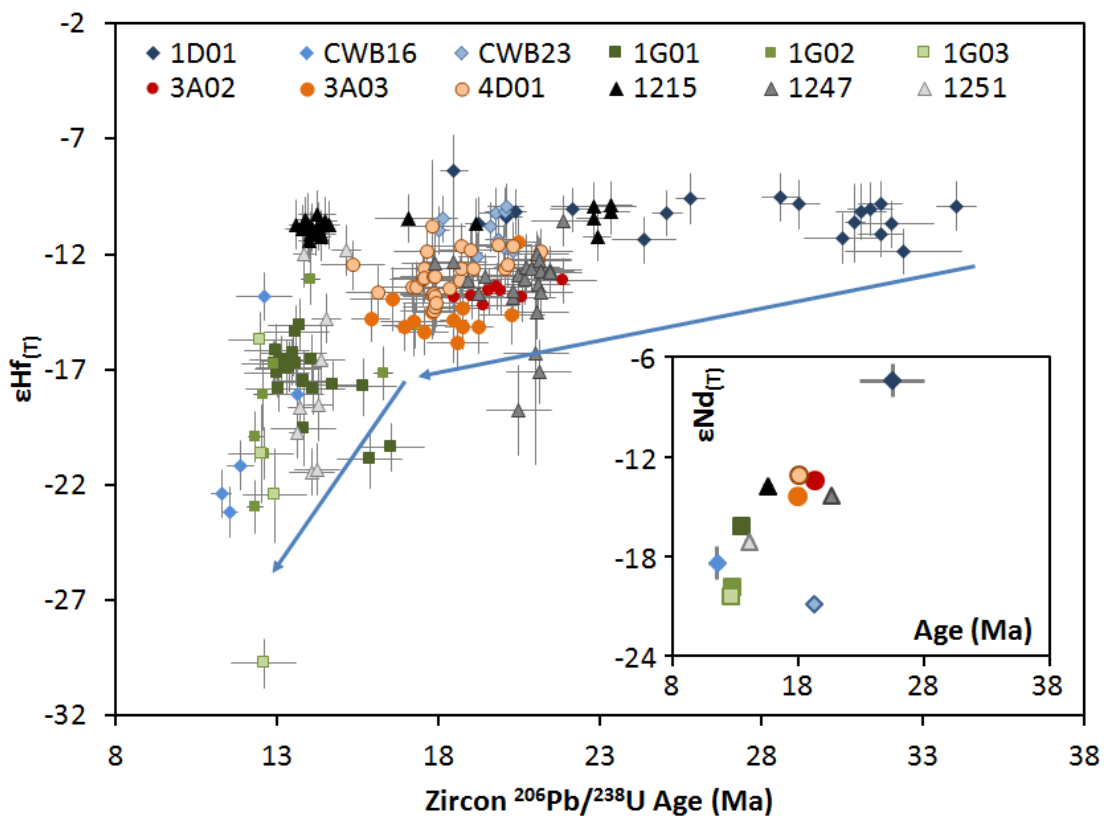
107 Zircon U-Pb and Lu-Hf isotope methods and data were previously reported
108 in Hopkinson et al. (2017). Whole-rock Sm-Nd isotope analyses were obtained at
109 the Open University (UK) by thermal ionization mass spectrometry. Further
110 methodological details and the full dataset is provided in the supplementary
111 information.

112

113 **RESULTS**

114 Zircon from all twelve samples provided rims of Tertiary age ranging from
115 34 to 11 Ma (Fig. 2, Table DR1), and the majority have inherited cores of Early
116 Paleozoic or Proterozoic age. The complete dataset is presented in Hopkinson et
117 al. (2017). Zircon from individual samples record growth over protracted

118 periods, with spans in individual zircon ages ranging from 0.9 to 15.5 Ma (Fig. 2).
119 This spread of ages from individual hand-samples is typical of Himalayan and
120 other S-type granites (Lederer et al., 2013), and the apparent longevity of melt
121 formation has been ascribed to protracted timescales of zircon crystallisation
122 and long magma residence times (Farina et al., 2018) and more specifically in the
123 Himalaya to episodic pulse melting of 1-2 Ma duration (Lederer et al., 2013).



124
125 *Figure 2. Zircon rim U–Pb age versus $\epsilon\text{Hf}_{(T)}$. Data from Hopkinson et al. (2017) and*
126 *Table DR1. Error bars are 2σ . Inset shows U–Pb age versus $\epsilon\text{Nd}_{(T)}$. Data from Table*
127 *DR2.*

128
129 Hafnium isotopic compositions are plotted against their corresponding
130 zircon age in Fig. 2. Age corrected isotope ratios ($\epsilon\text{Hf}_{(T)}$) range from -8.4 to -29.8.
131 Some granite samples preserve large differences in the Hf isotopic composition

132 of the zircon rims (e.g. samples 1G03 and 1247). This is likely a result of the lack
133 of homogenisation in the evolving magma, a characteristic that has been
134 documented in whole-rock studies of Himalayan leucogranites (Deniel et al.,
135 1987) and may be attributed to high melt viscosities of low-temperature, H₂O-
136 undersaturated siliceous magmas (Harris et al., 2000). Variability in Hf isotope
137 compositions at the hand-sample scale can also be linked to disequilibrium
138 melting and different mineral phases hosting different reservoirs of radiogenic
139 Hf (Farina et al., 2014; Tang et al., 2014).

140 Our data show a distinct secular change in $\epsilon\text{Hf}_{(T)}$ values, with increasingly
141 lower values in younger samples. Specifically, the zircon compositions show a
142 change in source, or in the balance between contributing sources, that is initiated
143 between 21 and 17 Ma. We note that the marked change occurs after 17 Ma, but
144 outlying data (sample 1247) suggest hints of earlier change at 21 Ma. After 17
145 Ma, the population of all but one sample (1215) decreases to $\epsilon\text{Hf}_{(T)} < -16$. In
146 terms of two-stage model ages for these zircons, zircon rims older than 17 Ma
147 have model ages of 1520 to 2000 Ma, whereas those after 17 Ma range from
148 2000 to 2620 Ma.

149 Whole-rock $\epsilon\text{Nd}_{(T)}$ ratios range from -7.4 to -20.9 (Fig. 2 inset). There is a
150 general decreasing trend through time across eleven of the twelve samples. This
151 trend broadly correlates with the *in-situ* zircon ϵHf data, except for sample
152 CWB23 that has a low ϵNd ratio. Assuming that the whole-rock data comprises a
153 complete dissolution of all minerals, and because the ϵHf data fit the broad array
154 exhibited by all samples, this sample points to a sample-specific disequilibrium
155 behaviour in the Sm-Nd system.

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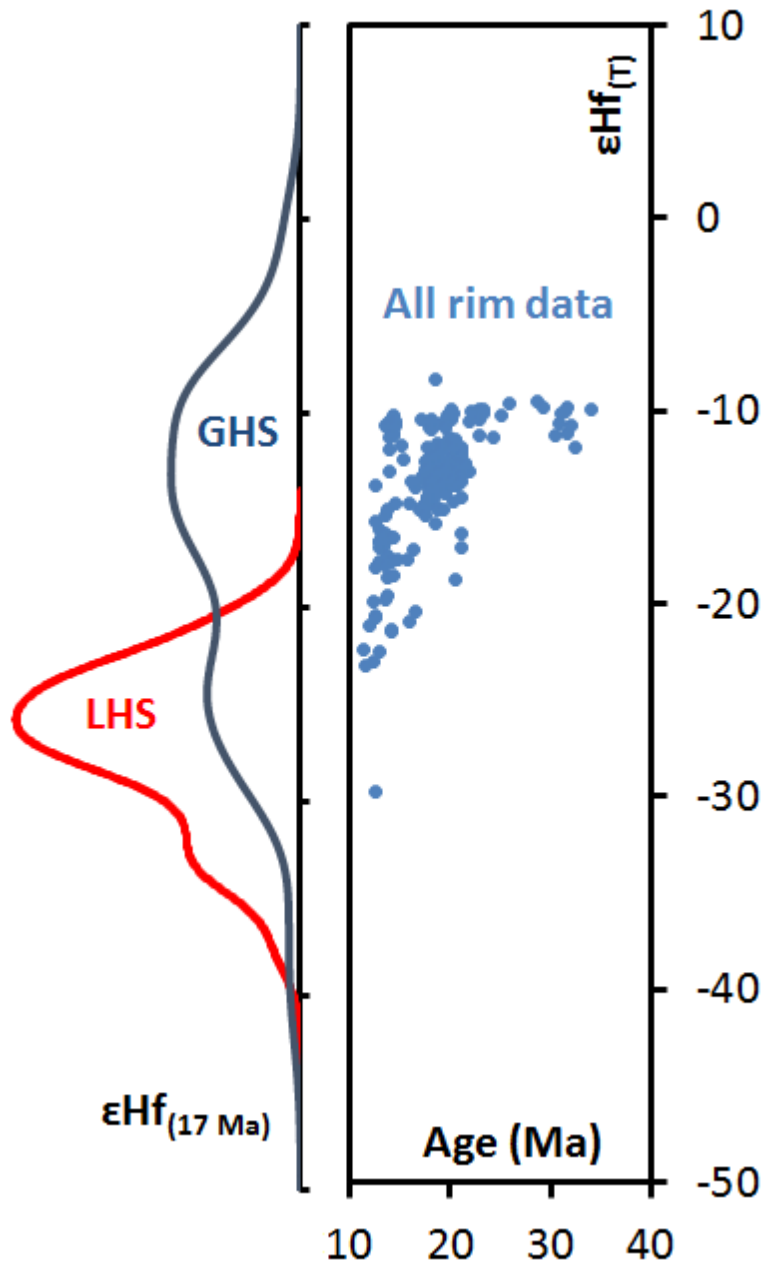
157 **DISCUSSION**

158 **An Evolving Magma Source**

159 Previous studies implicate the GHS as the dominant source for Himalayan
160 leucogranite melts (Harris and Massey, 1994; Guo and Wilson, 2017; Hopkinson
161 et al., 2017). To address the possible cause of the evolving isotopic signature of
162 the Bhutanese leucogranites in terms of source rocks, we compare our new
163 zircon-derived data with existing whole-rock Nd and Hf isotope data from the
164 Himalayan metasedimentary formations. Previous studies have described a clear
165 distinction between GHS and LHS units in terms of their isotopic signature, for
166 example, whole-rock Nd data taken from across the MCT in Sikkim (Mottram et
167 al., 2014), indicates ϵNd values of -12.1 to -18.3 in the GHS (hanging wall), and -
168 23.4 to -27.7 in the LHS (footwall). These overlap directly with the ranges
169 obtained from metasedimentary formations in Bhutan of ϵNd -12.1 to -17.6 for
170 the GHS and -25.9 to -32.3 for the LHS (Richards et al., 2006). Whole-rock Nd
171 isotope data for the samples in this study (Fig. 2, inset) have values of $\epsilon\text{Nd}_{(T)}$
172 ranging from -7.4 to -20.9, thus, the entire data array can broadly be generated
173 from GHS source rocks, but the lower values are compatible with an increasing
174 LHS component. The recognition of multiple sources for long-duration anatexic
175 melts is well established in previous zircon studies (Farina et al., 2018).

176 A plot of our *in-situ* zircon Hf isotope data vs. age is shown in Fig. 3 against
177 data compiled from across the GHS and LHS (Spencer et al., 2018). The compiled
178 data show that the GHS yields a broad range in $\epsilon\text{Hf}_{(17)}$ values, from -8 to -30, with
179 a dominant population between -8 to -18. The LHS mainly falls between $\epsilon\text{Hf}_{(17)}$ -
180 21 and -35. A boundary between GHS and LHS could be inferred around $\epsilon\text{Hf}_{(17)}$ -
181 22. As with the Nd isotope data, the leucogranite data can be generated by

182 derivation from a GHS source, but also indicate an increasing LHS (or at least
183 older) source through time.



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185

186 *Figure 3. Zircon rim U-Pb-Hf data from Figure 2 shown with Kernel Density*

187 *Estimates of GHS and LHS detrital zircon data, recalculated at 17 Ma, based on the*

188 *compilation of Spencer et al. (2018).*

189

190 In addition, the dataset of Hopkinson et al. (2017) shows that samples with
191 1800–1900 Ma zircon cores are only found in samples with younger zircon rims
192 (Table DR2; Fig. DR2). This Paleoproterozoic orogenic event uniquely affected
193 the LHS (Ahmad et al., 2000; Kohn et al., 2010), given that the GHS was not
194 deposited until the Neoproterozoic (Richards et al., 2006; Spencer et al., 2012).
195 Taken together, the isotopic evidence from zircon rims and whole-rock data, and
196 the age of zircon cores, strongly suggest that an increasing component of older
197 and more radiogenic material was being melted during the period of anatexis
198 from 17 Ma and possibly from as early as 21 Ma.

199 Given that the available melt-fertile (i.e. pelitic) source material is restricted to
200 two Himalayan formations (LHS and GHS) and that the GHS into which the granites
201 are emplaced is underthrust by the LHS (Heim and Gansser, 1939), then the results
202 from this study provide clear evidence for a GHS-sourced melt zone in the Oligocene,
203 and subsequent tectonic or thermal evolution to allow some melting of the LHS
204 during the early Miocene (since 17 Ma, and possibly 21 Ma). Direct evidence of
205 melting in the LHS is yet to be recognised from exposed lithologies in the MCT zone,
206 but kyanite-grade LHS schists have been identified that have reached temperatures of
207 ~640°C, sufficient for melting to occur in fertile lithologies (Caddick et al., 2007).

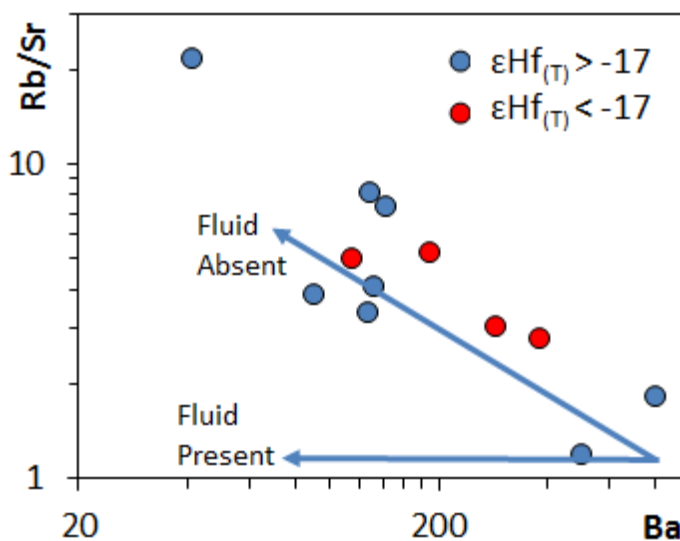
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209 **Tectonic Implications**

210 The key finding of this study is that increasing components of older material
211 are incorporated into the anatectic melt from at least 17 Ma. Whilst the data
212 presented here do not define a unique tectonic model for the evolution of the
213 Himalaya, they do require that the pelitic sediments of the LHS are subjected to
214 melting from the early Miocene during a period of rapid exhumation. For

215 exhumation to cause melting, the melt reaction must be characterised by a
216 positive gradient of the granite solidus, which in turn requires fluid-absent
217 melting (Harris and Massey, 1994). The Himalayan leucogranites provide a
218 classic example of fluid-absent muscovite melting, as indicated by their trace-
219 element geochemistry (Inger and Harris, 1993); more recently, some examples
220 of fluid-present melting have also been documented in the Himalaya (Gao et al.,
221 2017; Huang et al., 2017). The trace-element characteristics of the granites in
222 this study are indicative of fluid-absent melting (Fig. 4). There is no perceptible
223 systematic difference in either element chemistry (Table DR3) or mineralogy
224 between granites with older or younger source regions; each group includes
225 both peraluminous two-mica and tourmaline-bearing assemblages. These
226 observations, coupled with empirical thermobarometric evidence for
227 exhumation of the GHS in the eastern Himalaya at the time of melt formation
228 (~ 16 Ma) at a rate of 2 ± 1 mm yr⁻¹ (Harris et al., 2004), suggest that melting in
229 Bhutan was induced by decompression during exhumation.

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234 *Figure 4. Leucogranite Rb/Sr versus Ba plot. Samples are split by their weighted*
235 *mean $\epsilon Hf(T)$ values. Modelled trends are shown for fluid-absent and fluid-present*
236 *melting (Inger and Harris, 1993).*

237

238 A recent geochemical study of the ~5 km thick MCT zone in Sikkim argued
239 for progressive tectonic accretion of Lesser Himalayan material from the
240 footwall to the hanging wall of the MCT as it progressively cut structurally
241 downwards from ~17 Ma (Mottram et al., 2015; their Fig. 12), a scenario based
242 on the kinematic model of Bollinger et al. (2006). Metamorphism in the MCT
243 zone developed as heat advected downward from the overriding GHS
244 material. Following such accretion, exhumation along the hanging wall of the
245 thrust could have led to decompression melting of both GHS and accreted LHS
246 material. The introduction of LHS-sourced material into the melt zone may
247 therefore mark the initiation of accretion of the LHS into the hanging wall of the
248 thrust. It is probable that, irrespective of the precise cause of a changing melt
249 source around the MCT, melting will have enabled continued movement along
250 this key Himalayan structure through reducing the mechanical strength of
251 anatectic rocks around the thrust zone.

252

253 **CONCLUSIONS**

254 *In-situ* LA-ICP-MS analyses of zircon rims from Himalayan leucogranites
255 provide the first evidence for secular compositional change of melts generated
256 by protracted anatexis during the late Oligocene to mid Miocene. Increasing
257 components from older source regions from 21-17 Ma to 12 Ma requires

258 increased melting of LHS material during this period. Rapid exhumation of the
259 hanging wall of the MCT is well documented through the Miocene, and the
260 granites from the eastern Himalaya provide trace-element characteristics
261 indicative of fluid-absent melting. A tectonic model that is consistent with all
262 observations is one in which older LHS material was accreted to the hanging wall
263 of the MCT, and thus the base of the GHS, during the progressive evolution of the
264 structure.

265

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273 **REFERENCES CITED**

- 274 Ahmad, T., Harris, N., Bickle, M., Chapman, H., Bunbury, J., and Prince, C., 2000,
275 Isotopic constraints on the structural relationships between the lesser
276 Himalayan series and the high Himalayan crystalline series, Garhwal
277 Himalaya: Geological Society of America Bulletin, v. 112, p. 467–477.
- 278 Bollinger, L., Henry, P., and Avouac, J., 2006, Mountain building in the Nepal
279 Himalaya: Thermal and kinematic model: Earth and Planetary Science
280 Letters, v. 244, p. 58–71, <https://doi.org/10.1016/j.epsl.2006.01.045>.
- 281 Caddick, M.J., Bickle, M.J., Harris, N.B.W., Holland, T.J.B., Horstwood, M.S.A.,
282 Parrish, R.R., and Ahmad, T., 2007, Burial and exhumation history of a Lesser
283 Himalayan schist: Recording the formation of an inverted metamorphic
284 sequence in NW India: Earth and Planetary Science Letters, v. 264, p. 375–
285 390, <https://doi.org/10.1016/j.epsl.2007.09.011>
- 286 Deniel, C., Vidal, P., Fernandez, A., Le Fort, P., and Peucat, J.J., 1987, Isotopic study
287 of the Manaslu granite (Himalaya, Nepal): inferences on the age and source of
288 Himalayan leucogranites: Contributions to Mineralogy and Petrology, v. 96,
289 p.78–92.
- 290 Farina, F., Stevens, G., Gerdes, A., and Frei, D., 2014. Small-scale Hf isotopic
291 variability in the Peninsula pluton (South Africa): the processes that
292 control inheritance of source $^{176}\text{Hf}/^{177}\text{Hf}$ diversity in S-type granites:
293 Contributions to Mineralogy and Petrology, v. 168, p.1065,
294 <https://doi.org/10.1007/s00410-014-1065-8>.
- 295 Farina, F., Dina, A., Ovtcharova, M., Davies, J.H.F.L., Greber, N.D., Bouvier, A.S.,
296 Baumgartner, L., Ulianov, A., and Schaltegger, U., 2018. Zircon
297 petrochronology reveals the timescale and mechanism of anatectic magma

- 298 formation: *Earth and Planetary Science Letters*, v. 495, p. 213–223,
299 <https://doi.org/10.1016/j.epsl.2018.05.021>.
- 300 Gao, L.E., Zeng, L., and Asimow, P.D., 2017. Contrasting geochemical signatures of
301 fluid-absent versus fluid-fluxed melting of muscovite in metasedimentary
302 sources: *The Himalayan leucogranites: Geology*, v. 45, p.39-42,
303 <https://doi.org/10.1130/G38336.1>.
- 304 Gehrels, G.P., Kapp, P., DeCelles, A., Pullen, R., Blakey, A., Weislogel, A., Ding, L.,
305 Duynn, J., Martin, A., McQuarrie, N., and Yin, A. 2011, Detrital zircon
306 geochronology of pre-Tertiary strata in the Tibetan-Himalayan orogen:
307 *Tectonics*, v. 30, no. 5,. doi:10.1029/2011TC002868.
- 308 Greenwood, L.V., Argles, T.W., Parrish, R.R., Harris, N.B.W., and Warren, C., 2016,
309 The geology and tectonics of central Bhutan: *Journal of the Geological*
310 *Society*, v. 173, p. 215–238, <https://doi.org/10.1144/jgs2015-031>.
- 311 Guo, Z., and Wilson, M., 2012, The Himalayan leucogranites: constraints on the
312 nature of their crustal source region and geodynamic setting: *Gondwana*
313 *Research*, v. 22, p. 360–376, <https://doi.org/10.1016/j.gr.2011.07.027>.
- 314 Harris, N., and Massey, J., 1994, Decompression and anatexis of Himalayan
315 metapelites: *Tectonics*, v. 13, p. 1537–1546,
316 <https://doi.org/10.1029/94TC01611>.
- 317 Harris, N., Vance, D., and Ayres, M., 2000, From sediment to granite: timescales of
318 anatexis in the upper crust: *Chemical Geology*, v. 162, p.155–167,
319 [https://doi.org/10.1016/S0009-2541\(99\)00121-7](https://doi.org/10.1016/S0009-2541(99)00121-7).
- 320 Harris, N.B.W., Caddick, M., Kosler, J., Goswami, S., Vance, D., and Tindle, A.G.,
321 2004, The pressure-temperature-time path of migmatites from the Sikkim

- 322 Himalaya: *Journal of Metamorphic Geology*, v. 22, p. 249–264,
323 <https://doi.org/10.1111/j.1525-1314.2004.00511.x>.
- 324 Heim, A., and Gansser, A., 1939, Central Himalaya: Geological Observations of the
325 Swiss Expedition, 1936: *Memoires de la Société Helvetique des Sciences*
326 *Naturelles*, v. 73.
- 327 Hopkinson, T.N., Harris, N.B.W., Warren, C.J., Spencer, C.J., Roberts, N.M.W.,
328 Horstwood, M.S.A., Parrish, R.R., and EIMF, 2017, The identification and
329 significance of pure sediment-derived granites: *Earth and Planetary Science*
330 *Letters*, v. 467, p. 57–63, <https://doi.org/10.1016/j.epsl.2017.03.018>.
- 331 Huang, C., Zhao, Z., Li, G. and Zhu, D.C., Liu, D., and Shi, Q., 2017, Leucogranites
332 in Lhozag, southern Tibet: Implications for the tectonic evolution of the
333 eastern Himalaya: *Lithos*, v. 294–295, p. 246–262,
334 <https://doi.org/10.1016/j.lithos.2017.09.014>.
- 335 Inger, S., and Harris, N., 1993, Geochemical constraints on leucogranite magmatism
336 in the Langtang Valley, Nepal Himalaya: *Journal of Petrology*, v. 34, p. 345–
337 368, <https://doi.org/10.1093/petrology/34.2.345>.
- 338 Kohn, M.J., Paul, S.K., and Corrie, S.L., 2010, The lower Lesser Himalayan
339 sequence: A Paleoproterozoic arc on the northern margin of the Indian plate:
340 *Geological Society of America Bulletin*, v. 122, no. 3–4, p. 323–335,
341 <https://doi.org/10.1130/B26587.1>.
- 342 Le Fort, P., Cuney, M., Deniel, C., France-Lanord, C., Sheppard, S.M.F., Upreti,
343 B.N., and Vidal, P., 1987, Crustal generation of the Himalayan
344 leucogranites: *Tectonophysics*, v. 134, p. 39–57.
- 345 Lederer, G.W., Cottle, J.M., Jessup, M.J., Langille, J.M., and Ahmad, T., 2013,
346 Timescales of partial melting in the Himalayan middle crust: insight from the

- 347 Leo Pargil dome, northwest India: Contributions to Mineralogy and
348 Petrology, v. 166, p. 1415–1441, <https://doi.org/10.1007/s00410-013-0935-9>.
- 349 Mottram, C.M., Argles, T.W., Harris, N.B.W., Parrish, R.R., Horstwood, M.S. A.,
350 Warren, C.J., and Gupta, S., 2014, Tectonic interleaving along the Main
351 Central Thrust, Sikkim Himalaya: Journal of the Geological Society, v. 171, p.
352 255–268, <https://doi.org/10.1144/jgs2013-064>.
- 353 Mottram, C.M., Parrish, R.R., Regis, D., Warren, C.J., Argles, T.W., Harris, N.B.W.,
354 and Roberts, N.M.W., 2015, Using U-Th-Pb petrochronology to determine
355 rates of ductile thrusting: time windows into the Main Central Thrust, Sikkim
356 Himalaya: Tectonics, v. 34, p. 1355–1374,
357 <https://doi.org/10.1002/2014TC003743>.
- 358 Patiño Douce, A.E., and Johnston, A.D., 1991, Phase equilibria and melt productivity
359 in the pelitic system: implications for the origin of peraluminous granitoids
360 and aluminous granulites: Contributions to Mineralogy and Petrology, v. 107,
361 p. 202–218.
- 362 Prince, C., Harris, N., and Vance, D., 2001, Fluid-enhanced melting during prograde
363 metamorphism: Journal of the Geological Society, v. 158, p. 233–241,
364 <https://doi.org/10.1144/jgs.158.2.233>.
- 365 Richards, A., Parrish, R., Harris, N., Argles, T., and Zhang, L., 2006, Correlation of
366 lithotectonic units across the eastern Himalaya, Bhutan: Geology, v. 34, 341–
367 344, <https://doi.org/10.1130/G22169.1>.
- 368 Spencer, C.J., Dyck, B., Mottram, C.M., Roberts, N.M., Yao, W.H., and Martin, E.L.,
369 2018. Deconvolving the pre-Himalayan Indian margin–tales of crustal growth
370 and destruction: Geoscience Frontiers,
371 <https://doi.org/10.1016/j.gsf.2018.02.007>.

- 372 Spencer, C.J., Harris, R.A., and Dorais, M.J., 2012, Depositional provenance of the
373 Himalayan metamorphic core of Garhwal region, India: Constrained by U-Pb
374 and Hf isotopes in zircons: *Gondwana Research*, v. 22, p, 26–35,
375 <https://doi.org/10.1016/j.gr.2011.10.004>.
- 376 Tang, M., Wang, X.L., Shu, X.J., Wang, D., Yang, T., and Gopon, P., 2014. Hafnium
377 isotopic heterogeneity in zircons from granitic rocks: geochemical evaluation
378 and modeling of “zircon effect” in crustal anatexis: *Earth and Planetary
379 Science Letters*, v. 389, p.188-199, <https://doi.org/10.1016/j.epsl.2013.12.036>.
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384