# A matter of minutes: Breccia dike paleomagnetism provides evidence for rapid crater modification

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## 1 ABSTRACT

2 Following an impact event, a crater's transient structure adjusts gravitationally. Within complex
3 craters, a central uplift rises and collapses resulting in large-scale rotations of the target rock.
4 Estimated crater modification rates from numerical models indicate that complex impact craters
5 likely modify to a structurally stable state within tens of seconds to several minutes after initial
6 excavation. However, there is little direct geologic evidence constraining these rates. We show
7 how paleomagnetic measurements of clastic breccia dikes emplaced during crater excavation can
8 be used to constrain the rate of crater modification within the central uplift of the ~34 km
9 diameter Slate Islands impact structure, Ontario, Canada. The uniformity and linearity of
10 paleomagnetic directions among the clasts and matrix of breccia dikes throughout the impact
11 structure indicate that breccia dikes were frictionally heated above the magnetite Curie
12 temperature (580°C) during their emplacement and subsequently cooled *in situ* through magnetic
13 blocking temperatures. The tight grouping of these paleomagnetic directions implies that these
14 breccia dikes cooled and locked in magnetic remanence over a time interval in which the impact
15 structure was not experiencing structural rotations and had already reached a stable state.

16  Conductive cooling of the thinnest sampled breccia dike would have led to the recording of

17  magnetic remanence approximately six minutes after emplacement. This constraint necessitates a

18  stable crater structure only minutes after impact and presents a rare case in which a geological

19  process can be resolved on such a short timescale.

## INTRODUCTION

21  Breccia dikes are a ubiquitous feature of impact craters that can be broadly characterized as

22  injections of fragmented or molten target rock into the crater subsurface during an impact event.

23  These dikes can be categorized by their matrix composition as either: 1) impact melt glass

24  dominated (Type A of Lambert (1981)) or 2) clastic (Type B of Lambert (1981)). Type A breccia

25  dikes (also commonly referred to as pseudotachylites) are emplaced during shock compression,

26  whereas thicker, Type B clastic breccia dikes are emplaced immediately after the passage of the

27  shock wave, during dilatation of the target rock and excavation of the transient crater (Lambert,

28  1981; Masaitis, 2005).

29    The Slate Islands archipelago in northern Lake Superior exposes portions of the eroded central

30  uplift of an otherwise underwater crater approximately 34 km in diameter. Clastic breccia dikes

31  within the Slate Islands are abundant and well-exposed (Dressler and Sharpton, 1997). These

32  dikes have irregular branching geometries with individual branches ranging from cm-scale to

33  several meters in thickness (Fig. 1). The breccia clasts are generally polymictic and sourced from

34  the variety of target rocks through which the dike intruded, possibly at cumulative distances >2

35  km (Dressler and Sharpton, 1997). However, clast lithologies are dominated by that of the

36  immediately surrounding host rock. Clasts are angular to sub-angular and range from

37  sub-millimeter to more than 3 meters in diameter (Fig. 1). The matrix comprises target rock

38  detritus composed of monomineralic grains and lithic fragments and is either green or red in color

39  (Fig. 1).
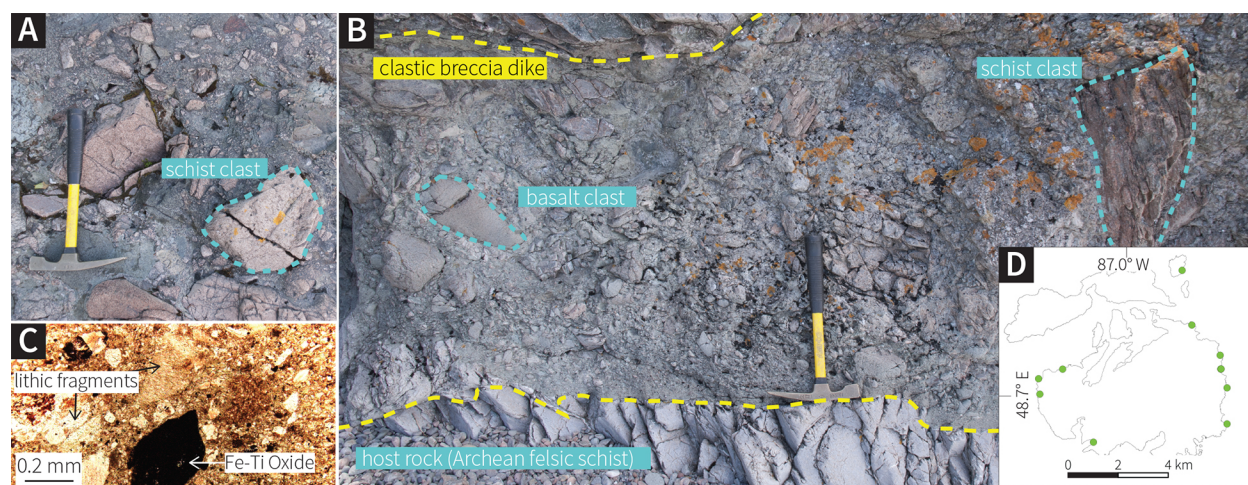
**Figure 1.** Outcrop photos of breccia dike PI24 (a, b) and photomicrograph (plane polarized light) of breccia dike PI15. The inset map of the Slate Islands (d) shows the location of studied breccia dikes.

Previous paleomagnetic analysis of clastic breccia dikes in the Slate Islands found that samples of the dike matrix record a unidirectional magnetization with the same direction as a partial overprint recorded by unbrecciated host rocks (Halls, 1979). Breccia dike clasts were not sampled in the Halls (1979) study. Two plausible origins of this matrix magnetization include: 1) thermoremanent magnetization (TRM) acquired by frictional heating during the breccia dike's emplacement (as interpreted by Halls (1979)) and 2) chemical magnetization (CRM) imparted by the precipitation of new ferromagnetic minerals during post-impact hydrothermal activity. The paleomagnetism of breccia dike clasts provides a way to discriminate between the thermal and chemical hypotheses. Due to their lower permeability than the matrix, breccia clasts are less susceptible to chemical remagnetization. If the remanence held by the matrix is a CRM, the interior of many clasts would be relatively unaffected and retain pre-impact remanence directions. However, if the dikes were heated above ferromagnetic Curie temperatures during emplacement, the clasts should be fully remagnetized in contrast to the partial overprints observed within unbrecciated host rock (Halls, 1979). If the breccia dike magnetizations were thermally acquired during their emplacement, the remanence directions would have been locked in quickly within thin dikes and could have subsequently rotated if crater modification was ongoing over a

56 prolonged period. In this way, the magnetization of breccia dikes could provide useful constraints

57 on the timeline of crater modification.

## 58 METHODS and RESULTS

59 To evaluate the consistency of breccia dike paleomagnetic directions, and to establish whether

60 breccia clasts were fully overprinted in addition to the matrix, we collected samples for

61 paleomagnetic analysis from 11 breccia dike sites throughout the impact structure, five of which

62 were amenable to the sampling of clasts. In the UC Berkeley Paleomagnetism Laboratory,

63 samples were thermally demagnetized at increments of 25°C or less up to a peak temperature of

64 580°C (the Curie temperature of magnetite). For two sites (DeI2 and PI2), heating to the 680°C

65 Néel temperature of hematite was required for complete demagnetization. Small present local

66 field overprints were removed by heating to ∼200°C (Fig. 2). Consistent with the work of Halls

67 (1979), matrix samples of dikes throughout the impact structure yield magnetization components

68 that persist to 580°C and conform to a single direction. Likewise, the remanence directions of

69 clasts from the dikes are unidirectional up to 580°C and yield the same direction as the matrix

70 (Fig. 2b). Paleomagnetic conglomerate tests (Watson, 1956) conducted on these clast

71 magnetization directions held by magnetite show that directional randomness can be rejected at

72 the 99% confidence level for all 5 breccia dikes in which clasts were sampled.[1] This behavior is

73 seen both for clasts of Mesoproterozoic diabase/basalt and Archean metamorphics and the

74 thermal unblocking spectra are consistent with (titano)magnetite. This result is a strong

75 indicator that the clasts were thermally remagnetized after their emplacement. In addition to the

76 remanence held by magnetite, 2 dikes with a red appearance (the majority of sampled dikes have

77 a green-colored matrix) in the field also have remanence in the matrix held by hematite that is

78 removed at higher unblocking temperatures following removal of a distinct magnetite component.

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[1]GSA Data Repository item 2016XXX, paleomagnetic data and statistical test results, and details of the conductive cooling model, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
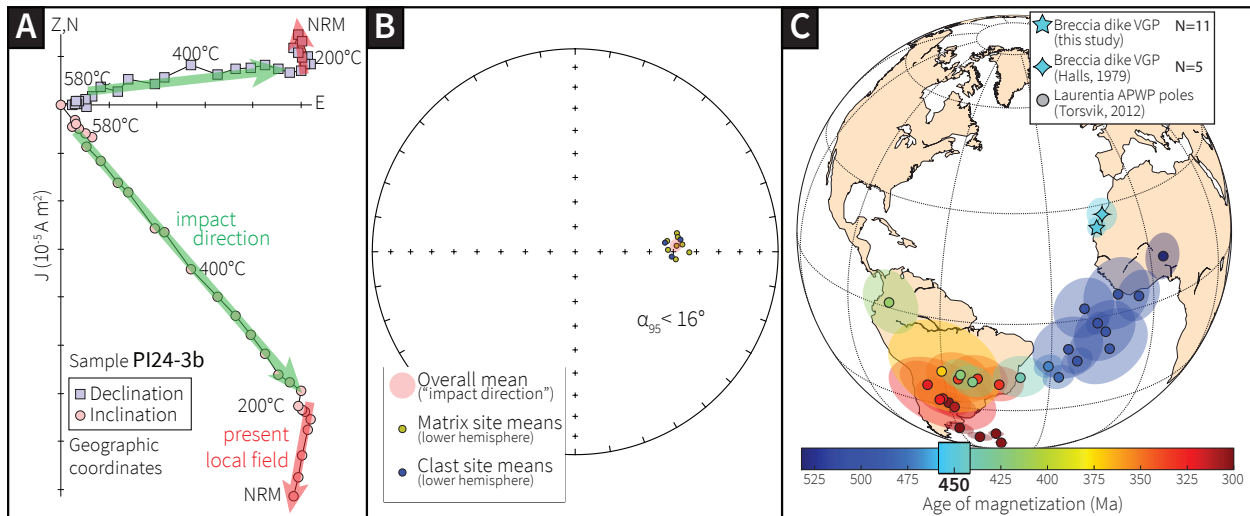
**Figure 2.** Paleomagnetic data of Slate Islands clastic breccia dikes. a) Example Zijderveld plot of paleomagnetic data from a breccia clast sample, with least squares fits indicated by labeled arrows. b) Equal area plot with site means from both matrix and clast samples and their overall mean with associated $\alpha_{95}$ confidence ellipse. c) Comparison of Slate Islands VGP (this study; Halls (1979)) with the Paleozoic APWP of Laurentia (Torsvik et al., 2012).

79  These magnetizations held by hematite generally correspond to the impact direction as well and

80  were likely acquired during either post-impact cooling or hydrothermal activity.

81   In contrast to the clasts within the breccia dikes, host rocks throughout the crater retain

82  pre-impact magnetizations with partial impact overprints (Halls, 1979). These pre-impact

83  directions are particularly coherent and well-resolved in Keweenawan lava flows exposed on the

84  west side of Patterson Island. In these flows, impact related overprints are typically removed by

85  ~275°C. However, a flow hosting an impact breccia dike reveals an overprint persisting to higher

86  temperatures. We interpret this result as a positive baked contact test consistent with local

87  heating associated with breccia dike emplacement (see *Breccia dike host rock* section of the Data

88  Repository). We observed similar behavior in Archean schist host rock. For example, at site PI16,

89  the same metamorphic lithology which is fully overprinted to unblocking temperatures >500°C

90  when encountered as breccia clasts has remanence unrelated to the impact direction removed at

91  high temperatures in samples collected multiple dike widths away. The partial overprinting of

92  host rock demonstrates that the full overprinting of breccia clasts is the result of localized heating

93  that reached significantly higher temperatures than the more widespread heating of central uplift

94  target rocks.

## DISCUSSION

### Direction of impact magnetization

97  The magnetization of breccia dikes and the overprint in Slate Islands host rocks record the local

98  geomagnetic field at the time of the Slate Islands impact. In contrast, similar lithologies as some

99  overprinted target rocks found outside the crater are minimally overprinted with stable primary

100  magnetizations that date to their formation in the 1.1 Ga Midcontinent Rift (Halls, 1975;

101  Swanson-Hysell et al., 2014), supporting the interpretation that the overprint is indeed associated

102  with the impact event rather than being associated with broader tectonic processes. As described

103  by Halls (1979), the virtual geomagnetic pole (VGP) calculated from breccia dike paleomagnetic

104  directions corresponds to Laurentia's apparent polar wander path (APWP) at ca. 1000 Ma (the

105  "Grenville Loop"). This age assignment is consistent with geological constraints that require that

106  the impact occurred after cessation of Midcontinent Rift magmatism (ca. 1085 Ma). Dressler

107  et al. (1999) interpreted a plateau in the $^{40}$Ar-$^{39}$Ar release spectrum of a single pseudotachylite

108  sample as implying a Silurian age for the impact crater. The integrated age derived from this

109  spectrum was $436 \pm 3$ Ma. Two Midcontinent Rift basalt samples from the Slate Islands crater

110  were dated by the same study and yielded integrated ages of ca. 1074 and ca. 990 Ma;

111  discordance in the low temperature portion of the $^{39}$Ar release spectra are consistent with a more

112  recent heating event.

113   The breccia dike VGP is ∼47° from the Silurian paleopoles of the Laurentia APWP and ∼35°

114  from the Ordovician paleopoles (Torsvik et al. (2012); Fig. 2c). Given that the magnetization of

115  the breccia dikes would have been quickly acquired during cooling, the calculated pole is not

116  time-averaged and should not be expected to fall directly on the APWP. However, even with this

117  lack of time-averaging, a 50° difference from the APWP is quite large and calls the Silurian age

118  into question. If the impact did occur in the Silurian, the crater likely formed during a period of

119  significant geomagnetic deviation from the geographic pole (i.e. an excursion). The geocentric

120  axial dipole (GAD) model TK03.GAD gives a ~6% probability for >30° divergence of a VGP

121  from geographic north and ~3% probability for >40° divergence (Tauxe and Kent, 2004) making

122  such a deviation a plausible, but low probability, event.

## Timescale of crater modification

124  Numerical models of large impacts have provided understanding of a process that is too rare to be

125  directly observed on human time scales (Pierazzo and Collins, 2004). These hydrocode models

126  indicate that the main stages of impact cratering (compression, excavation, and modification;

127  Gault et al. (1968)) are rapid and occur on second to minute timescales. For example, hydrocode

128  simulations of a ~40 km terrestrial impact crater (similar in size to the Slate Islands impact

129  structure) showed that crater modification was largely complete ~300 s (~5 minutes) after the

130  impact (Collins, 2014). However, Melosh and Ivanov (1999) noted that the material behaviors

131  assumed in hydrocode models are often insufficient descriptors of the dynamic rock failure that

132  occurs during crater modification. While it remains unclear how significantly the duration of

133  crater modification would deviate from the estimates of these models, it is apparent that

134  additional geophysical and observational constraints are valuable for understanding the timing of

135  this process.

136  One such constraint comes from the melt sheets of the Boltysh and Manicouagan impact

137  structures which have been observed to encircle the central uplifts, implying that the melt pool

138  solidified after central uplift formation (Melosh and Ivanov, 1999). From this observation, Melosh

139  and Ivanov (1999) estimated the duration of central uplift formation to be <100 seconds, the

140  calculated timeframe for viscosity increase of the melt associated with melt-clast heat exchange

141  (Onorato et al., 1978). However, given that complete solidification of the Manicouagan melt is
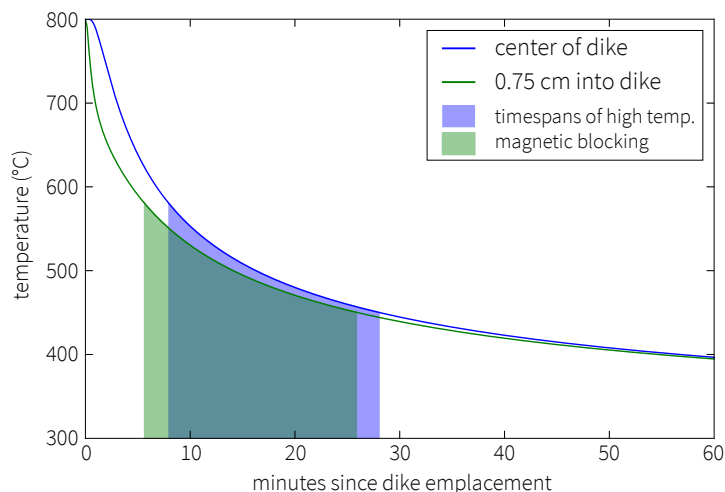
**Figure 3.** Conductive cooling model for a 4 cm-thick breccia dike emplaced at 800°C into host rock with a temperature of 275°C. The two curves represent the thermal history of the samples as the 2.5 cm diameter cores span from ∼0.75 cm to 2 cm from the dike edge. This model indicates that magnetic remanence began being blocked ∼6 minutes after dike emplacement–minimal rotation of the dike could have occurred from this time onwards given the unidirectional magnetization consistent with breccia directions across the crater.

estimated to have taken ca. 35 years at 10 meters from the edge and ca. 1600 years 100 meters

into the melt (Onorato et al., 1978), evidence of melt sheet deformation by the central uplift

might not be preserved due to prolonged convection within the melt pool.

  The complete overprinting of magnetite-held clast magnetizations, in contrast to the partial

overprints of the same lithologies in host rocks, strongly support the hypothesis that clastic

breccia dikes in the Slate Islands were frictionally heated above 580°C and acquired a full TRM.

Because of their thermal origin, the magnetic directions of clastic breccia dikes serve as effective

structural tracers for segmented blocks of the impact structure: as breccia bodies cool through

magnetic blocking temperatures, their paleomagnetic directions would record any relative

rotations of their host rock during crater modification. If their cooling rates can be constrained,

these impact features may thereby provide a relative timeline of crater modification in the Slate

Islands, with chaotic paleomagnetic directions among breccia dikes linked to structural rotations

and, conversely, the alignment of these directions signaling a stable crater structure.

155    The linearity and directional uniformity of paleomagnetic data from breccia dikes across the

156 impact structure suggest that the broader crater structure was stable throughout the timeline of

157 breccia dike cooling and TRM acquisition. To quantify this timeline, it is necessary to assign a

158 maximum emplacement temperature from which breccia dikes may have cooled. Petrographic

159 analysis reveals an absence of autochthonous melt within the matrix of clastic breccia dikes (Fig.

160 1). Given the preponderance of uplifted Archean basement rock in the Slate Islands (schistose

161 Archean metavolcanics and metaintrusives) and this lithology's dominant presence in clastic

162 breccia dikes, we take this petrographic observation as a strong indicator that breccia dike

163 emplacement temperatures did not exceed a schist solidus of ∼800°C (Douce and Harris, 1998;

164 Whittington et al., 2009). A frictionally heated breccia dike would have undergone conductive

165 cooling following emplacement. We take the simplest whole time solution of Delaney (1987)

166 utilizing transient heat conduction theory for a plane of motionless material undergoing heat

167 transfer to surrounding rock with no chemical reactions as a good representation of the problem.

168 Conductive cooling of the thinnest sampled breccia dike (4 cm) from 800°C to estimated ambient

169 temperatures of 275°C would have led to the recording of magnetic remanence (beginning upon

170 cooling to 580°C) approximately 6 minutes after its emplacement (Fig. 3; code in the Data

171 Repository). Since emplacement of these clastic breccia dikes are understood to occur during the

172 excavation stage of cratering prior to crater modification (Lambert, 1981; Masaitis, 2005), this 6

173 minute timespan represents the maximum duration of crater modification that brought the Slate

174 Islands central uplift to the gravitationally stable state recorded in breccia dike magnetizations.


## ACKNOWLEDGEMENTS

# References

Collins, G. S., 2014, Numerical simulations of impact crater formation with dilatancy: Journal of Geophysical Research: Planets, vol. 119, p. 2014JE004,708, doi:10.1002/2014JE004708.

Delaney, P. T., 1987, Heat transfer during emplacement and cooling of mafic dykes: *In* Halls, H. and Fahrig, W., eds., Mafic dyke swarms, Geological Association of Canada, vol. 34, pp. 123–135.

Douce, A. E. P. and Harris, N., 1998, Experimental constraints on Himalayan anatexis: Journal of Petrology, vol. 39, pp. 689–710, doi:10.1093/petroj/39.4.689.

Dressler, B. O. and Sharpton, V. L., 1997, Breccia formation at a complex impact crater: Slate Islands, Lake Superior, Ontario, Canada: Tectonophysics, vol. 275, pp. 285–311, doi:10.1016/S0040-1951(97)00003-6.

Dressler, B. O., Sharpton, V. L., and Copeland, P., 1999, Slate Islands, Lake Superior, Canada: A mid-size, complex impact structure: Geological Society of America Special Papers, vol. 339, pp. 109–124, doi:10.1130/0-8137-2339-6.109.

Gault, D. E., Oberbeck, V., and Quaide, W., 1968, Impact cratering mechanics and structures: *In* French, B. M. and Short, N. M., eds., Shock metamorphism of natural materials.

Halls, H. C., 1975, Shock-induced remanent magnetisation in late Precambrian rocks from Lake Superior: Nature, vol. 255, pp. 692–695, doi:10.1038/255692a0.

Halls, H. C., 1979, The Slate Islands meteorite impact site: a study of shock remanent magnetization: Geophysical Journal of the Royal Astronomical Society, vol. 59, pp. 553–591, doi:10.1111/j.1365-246X.1979.tb02573.x.

Lambert, P., 1981, Breccia dikes - Geological constraints on the formation of complex craters: *In* Merill, R. B. and Schultz, P. H., eds., Multi-ring basins: Formation and Evolution, pp. 59–78.

Masaitis, V. L., 2005, Redistribution of lithologies in impact-induced dikes of impact structures: pp. 111–129.

Melosh, H. J. and Ivanov, B. A., 1999, Impact crater collapse: Annual Review of Earth and Planetary Sciences, vol. 27, pp. 385–415, doi:10.1146/annurev.earth.27.1.385.

Onorato, P., Uhlmann, D., and Simonds, C., 1978, The thermal history of the Manicouagan impact melt sheet, Quebec: Journal of Geophysical Research: Solid Earth (1978–2012), vol. 83, pp. 2789–2798, doi:10.1029/JB083iB06p02789.

Pierazzo, E. and Collins, G., 2004, A brief introduction to hydrocode modeling of impact cratering: *In* Cratering in marine environments and on ice, Springer, pp. 323–340, doi:10.1007/978-3-662-06423-8_16.

Swanson-Hysell, N. L., Vaughan, A. A., Mustain, M. R., and Asp, K. E., 2014, Confirmation of progressive plate motion during the Midcontinent Rift's early magmatic stage from the Osler Volcanic Group, Ontario, Canada: Geochemistry Geophysics Geosystems, vol. 15, pp. 2039–2047, doi:10.1002/2013GC005180.

Tauxe, L. and Kent, D., 2004, A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: was the ancient magnetic field dipolar?: *In* Channell, J., Kent, D., Lowrie, W., and Meert, J., eds., Timescales of the paleomagnetic field, American Geophysical Union, vol. 145 of *Geophysical Monograph*, pp. 101–116, doi:10.1029/145GM08.

Torsvik, T. H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., van Hinsbergen, D. J. J., Domeier, M., Gaina, C., Tohver, E., Meert, J. G., McCausland, P. J. A., and Cocks, L. R. M., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, vol. 114, pp. 325–368, doi:10.1016/j.earscirev.2012.06.007.

Watson, G., 1956, A test for randomness of directions: Geophysical Journal International, vol. 7, pp. 160–161, doi:10.1111/j.1365-246X.1956.tb05561.x.

221  Whittington, A. G., Hofmeister, A. M., and Nabelek, P. I., 2009, Temperature-dependent thermal diffusivity of the
222     Earth's crust and implications for magmatism: Nature, vol. 458, pp. 319–321, doi:10.1038/nature07818.