Supplementary Information

Deep Mantle Anomalies Block Early Earth Melting, Challenging a Primordial Origin

Arnab Roy[1], Eric Mittelstaedt[1], C.M. Cooper[2]

1: Department of Earth and Spatial Sciences, University of Idaho, Moscow, ID 83844, USA

2: School of the Environment, Washington State University, Pullman, WA 99164, USA

Contents

Supplementary Information

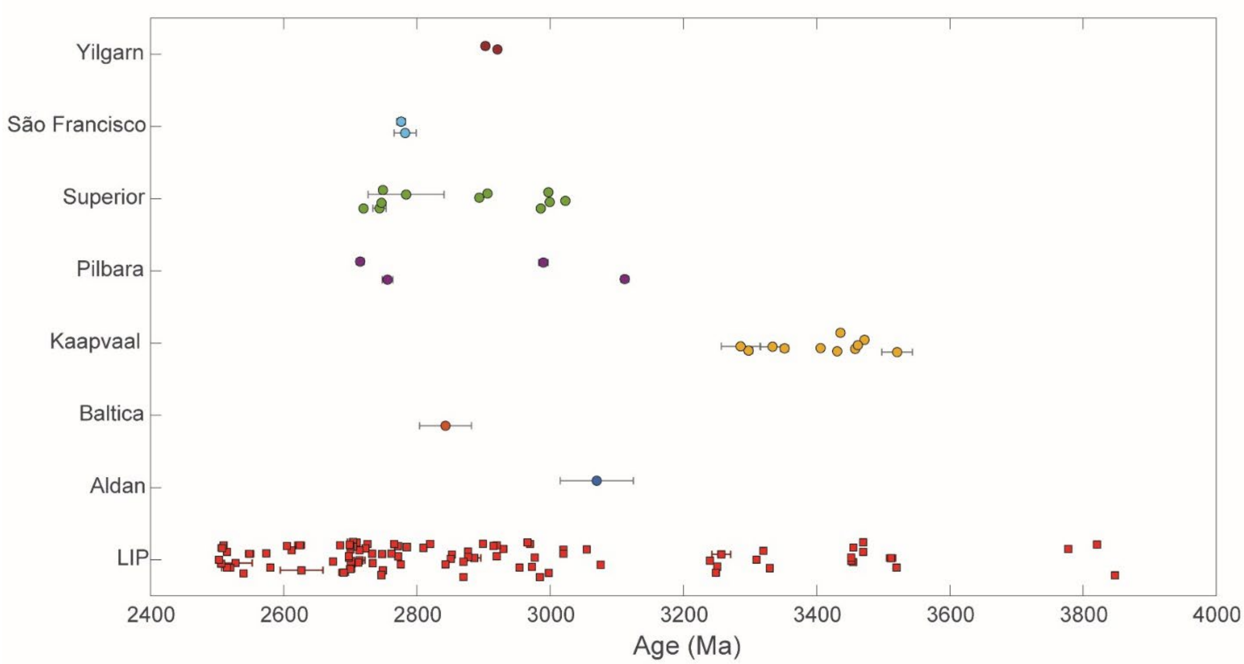

***Figure S1**: Compilation of komatiite and LIP emplacement ages (with 2σ uncertainties) across major Archean cratons. Each point represents an individual age measurement, color-coded by craton, with red squares marking LIP ages. Data span from the late Hadean to late Archaean, showing clustering of komatiite ages and multiple pulses of LIP magmatism through the Archaean. The data used to compile this figure are available in table S1 and S2 below.*

S1. Isotope record of the Early Earth

The ϵHf values derived from detrital zircons consistently fall below the depleted mantle (DM) evolution line, with many also plotting below the chondritic uniform reservoir (CHUR), indicating that these zircons crystallised from melts derived from enriched, reworked sources rather than primordial mantle. Similarly, the whole-rock ϵNd data from the same mafic units predominantly lie below the DM curve, with numerous samples exhibiting negative ϵNd values—signatures characteristic of crustal sources that evolved with low Sm/Nd ratios over extended timescales (indicating a reworked crustal source rather than primordial mantle).

Supplementary Information

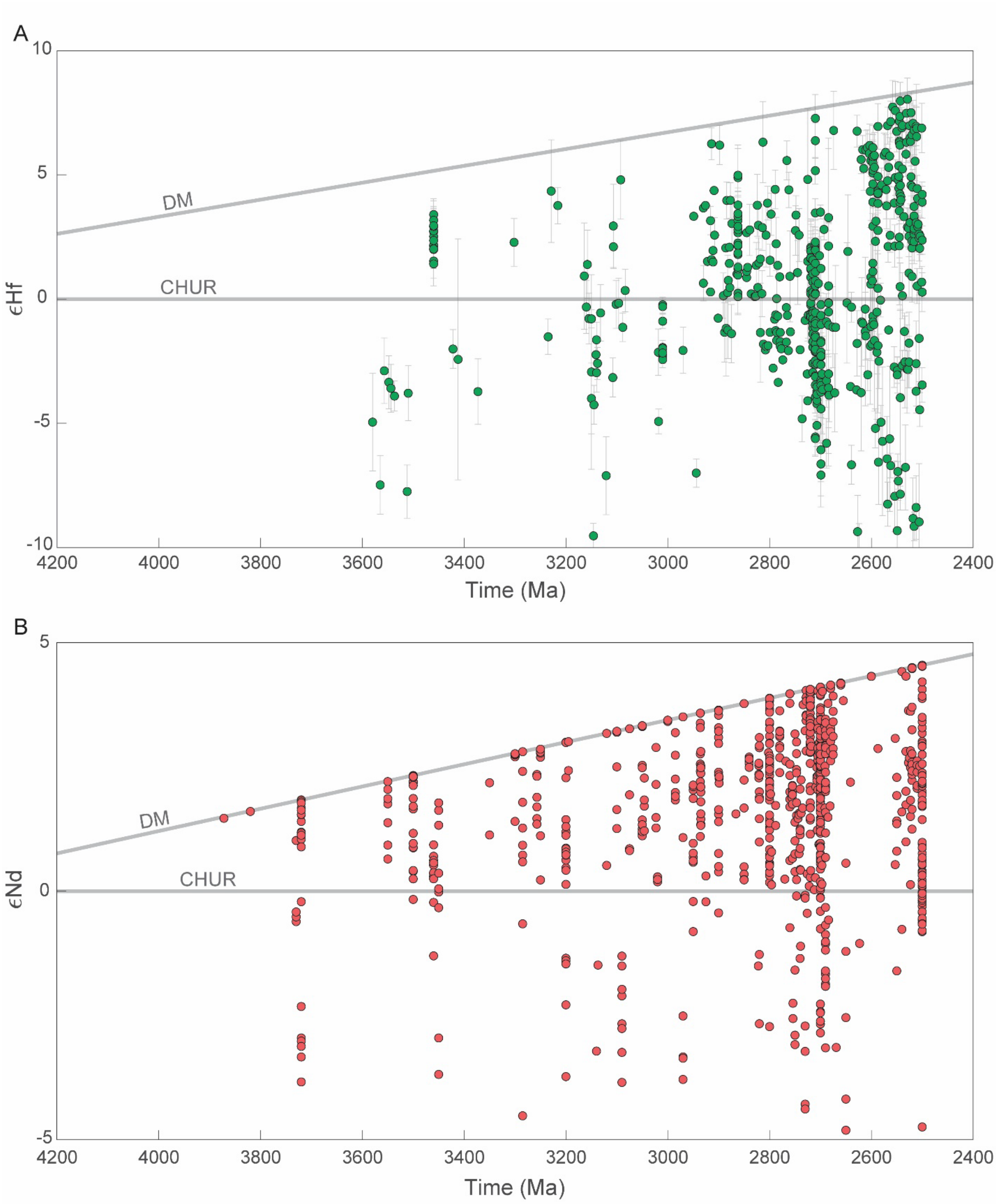

Figure S2: *Isotopic data compiled from Archaean terrains. (A) Zircon Hf isotope data for magmatic rocks, where each point represents the mean zircon ϵHf value for a single metaigneous rock calculated at the magmatic crystallization age, itself derived from pooled zircon U-Pb data and (B) the whole-rock isotope record for Nd expressed in the epsilon format, calculated for mafic rocks at the time of assumed magmatic crystallization. Abbreviations: CHUR, chondritic uniform reservoir; DM, depleted mantle. All data are sourced from the global database compiled by Puetz et al. (2024).*

Supplementary Information

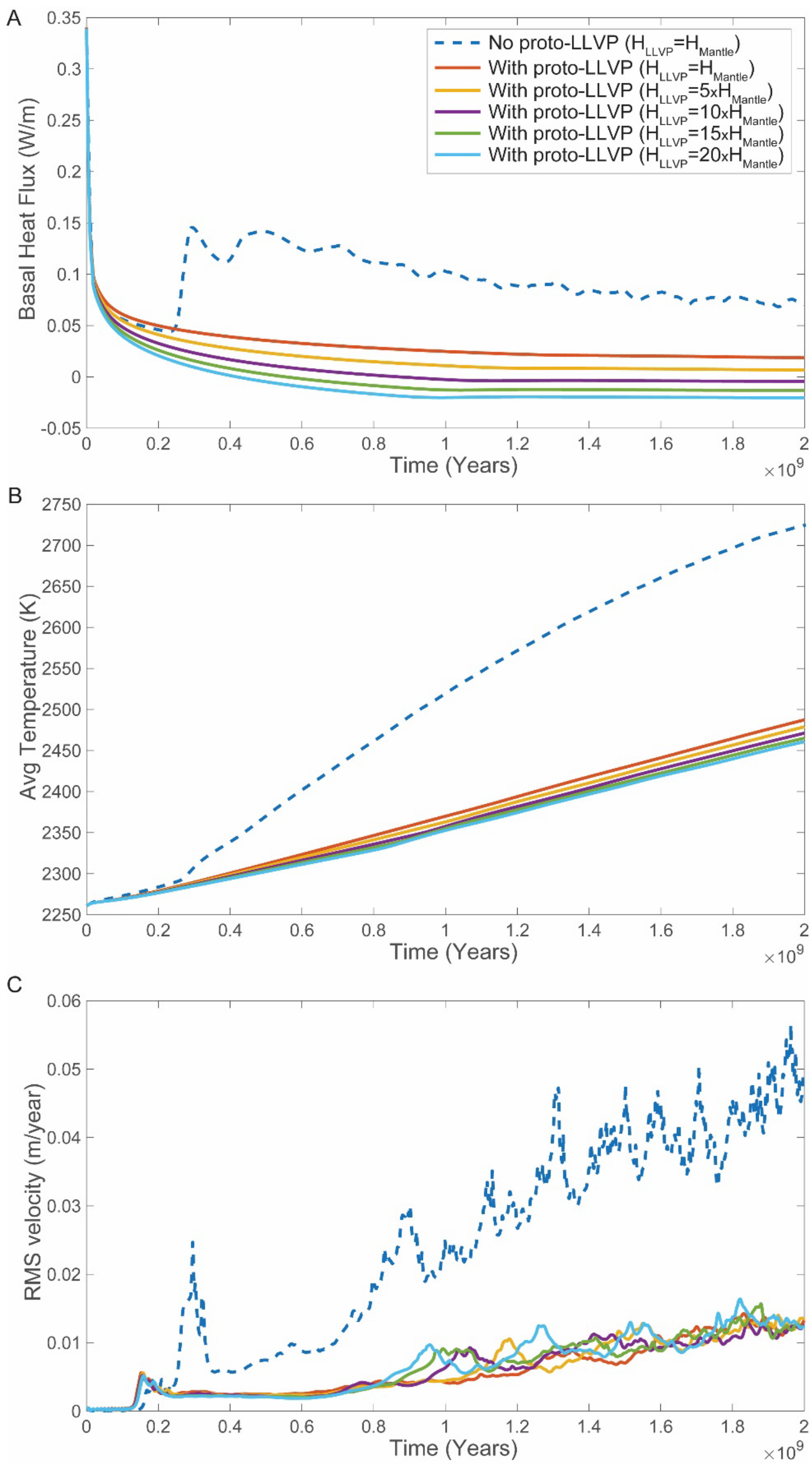

Figure S3: *Effect of increasing radiogenic heat in the proto-LLVP layer on mantle parameters (A) Basal heat flux, (B) spatially averaged mantle temperature, and (C) root mean square (RMS) velocity.*

Supplementary Information

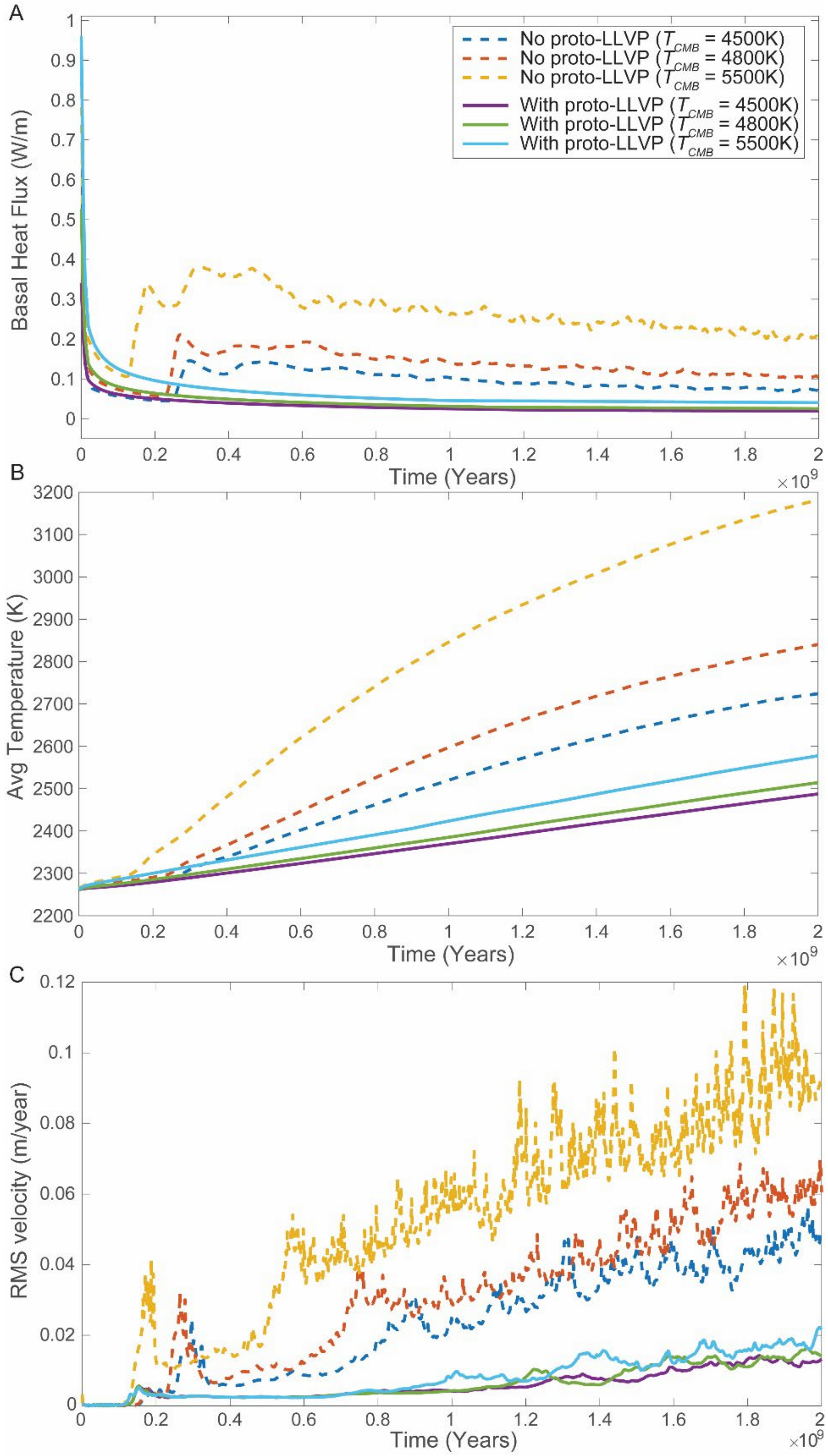

Figure S4*: Effect of increasing core-mantle boundary temperature (T_{CMB}) in experiments with and without proto-LLVP on mantle parameters (A) Basal heat flux, (B) spatially averaged mantle temperature, and (C) root mean square (RMS) velocity.*

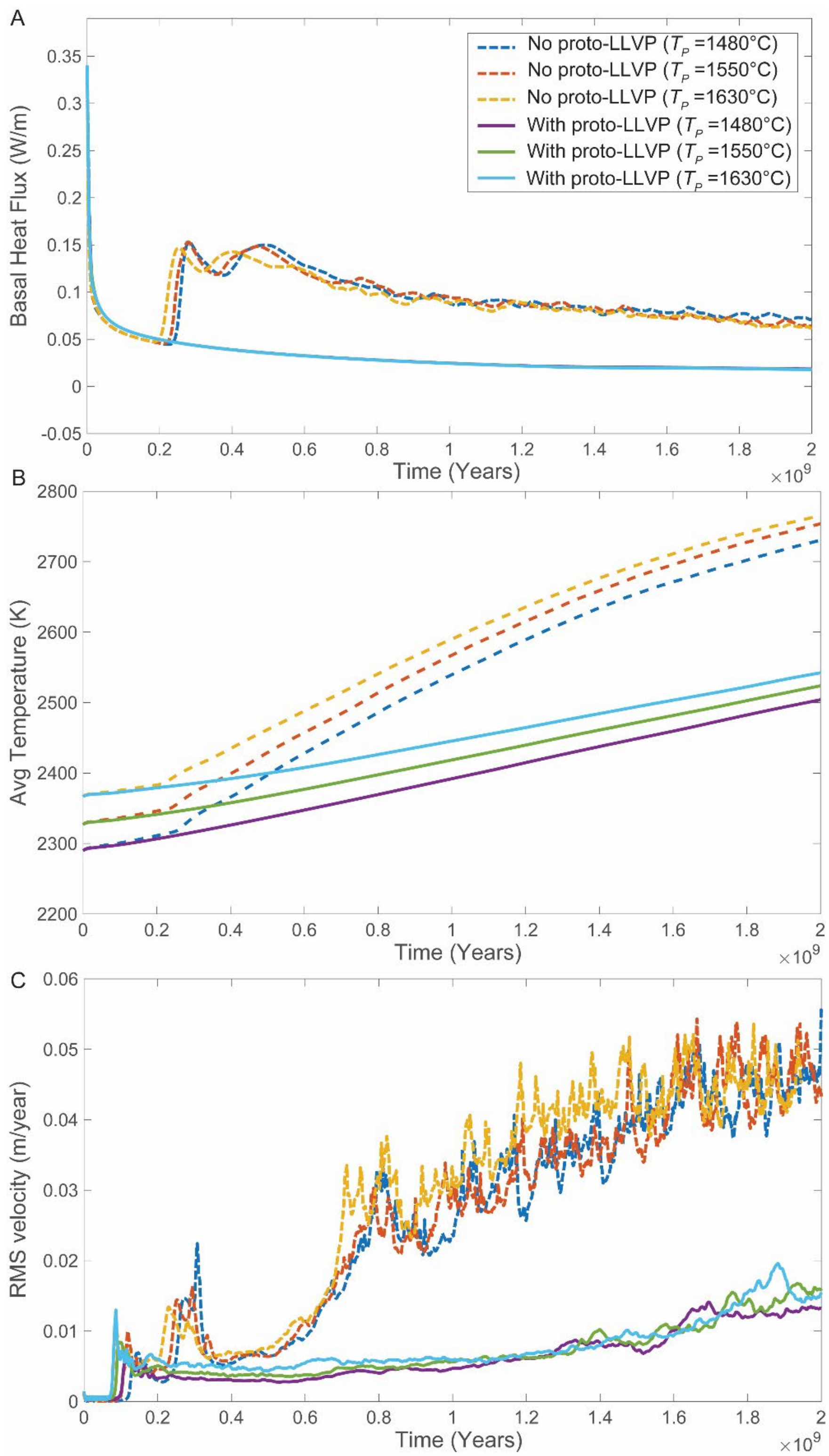

Figure S5: *Effect of increasing mantle potential temperature (T_P) in experiments with and without proto-LLVP on mantle parameters (A) Basal heat flux, (B) spatially averaged mantle temperature, and (C) root mean square (RMS) velocity.*

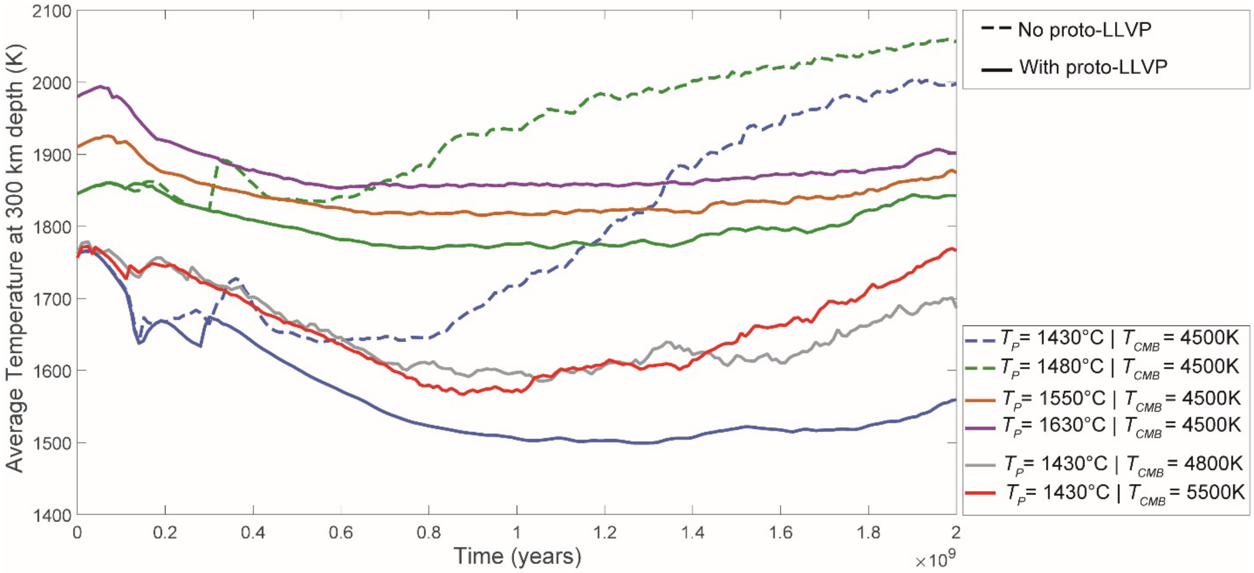

Figure S6*: Temporal evolution of the average mantle temperature at 300 km depth for models with and without a proto-LLVP. Solid lines indicate simulations including a proto-LLVP, while dashed lines show cases without it. Different colors correspond to varying initial mantle potential temperatures (T_P) and core–mantle boundary temperatures (T_{CMB}).*

Supplementary Information

Supplementary Tables

Table S1: Komatiite emplacement ages in Archean Cratons

Craton	Location of Komatiite Units	Age or Age Constraint (Ma)	Method	References
Kaapvaal	Dwalile Greenstone Belt	3521 ± 23 and 3436 ± 5	U-Pb	Kröner and Tegtmeyer [1994]
Kaapvaal	Barberton Mountain Land: Songimvelo and Steynsdorp Blocks, Lower Onverwacht	3472 ± 5 and 3458 ± 2	U-Pb	Armstrong et al. [1990]
Kaapvaal	Warrawoona Group, Salgash Subgroup	3462 ± 2 and 3431 ± 4	U-Pb	McNaughton et al. [1993]
Kaapvaal	Nondweni Greenstone Belt	3406 ± 3	U-Pb	Wilson and Versfeld [1994]
Kaapvaal	Barberton Mountain Land: Songimvelo and Steynsdorp Blocks, Upper Komatii and Hooggenoeg Formations	3352 ± 6	U-Pb	Kamo and Davis [1994]
Kaapvaal	Commondale Greenstone Belt	3334 ± 18	Sm-Nd	Wilson and Carlson [1989]
Kaapvaal	Barberton Mountain Land: Ulundiha Block, Upper Onverwacht, Mendon Formation	3298 ± 6	U-Pb	Byerly et al. [1996]
Kaapvaal	Barberton Mountain Land: Kaap Valley Block, Upper Onverwacht, Weltevreden Formation	3286 ± 29	Sm-Nd	Lahaye et al. [1995]
Pilbara	Regal Supersequence, Roeburn Belt	3112 ± 6 and 2990 ± 7	U-Pb	Krapež [1993]
Aldan	Olondo Greenstone Belt	3070 ± 55	Sm-Nd	Velikoslavinsky et al. [1993]
Superior	North Spirit Lake Greenstone Belt, Sachigo Subprovince (lower supracrustal sequence)	3023 ± 2 and 2986 ± 3	U-Pb	Corfu and Wood [1986]
Superior	Lumby Lake Greenstone Belt	2999.4 ± 2.9 and 2906 ± 3	U-Pb	Davis and Jackson [1988]
Superior	Red Lake Greenstone Belt, Uchi Subprovince	2997.5 ± 1.45 and 2893.7 ± 1.2	U-Pb	Corfu and Wallace [1986]
Yilgarn	Lake Johnston Greenstone Belt	2921 ± 4 and 2903 ± 5	U-Pb	Wang et al. [1996]
Baltica	Kostomuksha Greenstone Belt	2843 ± 39	Sm-Nd	Puchtel et al. [1997b]
Superior	Vizen Greenstone Belt, Minto Block	2784 ± 57	Sm-Nd	Shukol and Percival [1996]
São Francisco	Rio das Velhas Greenstone Belt, Nova Lima	2782.5 ± 16.5 and 2776.5 ± 6.5	U-Pb	Machado et al. [1992]
Pilbara	Fortescue Group, Pyradie Formation	2756 ± 8 and 2715 ± 6	U-Pb	Arndt et al. [1991]

Supplementary Information

Superior	Michipicoten Greenstone Belt, Wawa Subprovince (lower supracrustal sequence)	2749 ± 2 and 2744 ± 10	U-Pb	Turek et al. [1982]
Superior	Abitibi Greenstone Belt, Wabewawa Group	2747 ± 2 and 2720 ± 2	U-Pb	Mortensen [1993] and Corfu and Noble [1992]
Kaapvaal	Barberton Mountain Land: Songimvelo and Steynsdorp Blocks, Upper Komatii and Hooggenoeg Formations	3778 ± 2 and 3777 ± 2	Ar-Ar	Lopez Martinez et al 1984

Table S2: Large Igneous Provinces (LIP) emplacement ages in Archean Cratons

Large Igneous Province, Location	**Age (Ma)**	**Uncertainty**	**Reference**
Innersuartuut greenstone, SW Greenland	3848.0	5.0	Jenner et al., 2013 Geology 41: 327-330
Nuvvuagittuq greenstone belt, Quebec	3821.0	5.0	O'Neil et al., 2012 Precambrian Research doi:10.1016/j.precamres.2012.07.009
Isua greenstone, SW Greenland	3778.0	4.0	Furnes et al., 2009 Lithos 113: 115-132
Coonterunah Group, Pilbara, Western Australia	3520.0	4.0	Smithies, 2005 Earth Planetary Science Letters 238: 284-297; Smithies et al., 2007 Geological Survey Western Australia Report 104
Tarssartoq-Ameralik dykes 1, SW Greenland	3512.0	7.0	Nutman et al., 2004 Journal of the Geological Society of London 161: 421-430
Hooggenoeg complex, Barberton greenstone, South Africa	3470.0	3.0	Furnes et al., 2012 Gondwana Research doi:10.1016/j.gr.2012.05.007; Furnes et al., 2012 South African Journal of Geology 115: 225-264
Mt Ada basalts Low-Ti group, Pilbara, Western Australia	3470.0	3.0	Smithies, 2005 Earth Planetary Science Letters 238: 284-297; Smithies et al., 2007 Geological Survey Western Australia Report 104
Kromberg complex, Barberton greenstone, South Africa	3455.0	2.0	Furnes et al., 2012 Gondwana Research doi:10.1016/j.gr.2012.05.007; Furnes et al., 2012 South African Journal of Geology 115: 225-264
Pietersburg greenstone, South Africa	3455.0	5.0	Brandl and de Wit, 1997, in de Wit and Ashwal (editors), Greenstone Belts, Clarendon Press, Oxford, Chapt 5.8
Warrawoona Group, Pilbara, Western Australia	3452.0	2.0	Green et al., 2000 Tectonophysics 322: 69-88
Onverwacht Group, Barberton greenstone, South Africa	3452.0	3.0	Campbell, 2003 American Journal of Science 303: 319-351
Mendon Formation, Ncakini section,	3330.0	4.0	Furnes et al., 2012 Gondwana Research doi:10.1016/j.gr.2012.05.007; Furnes et al., 2012 South African Journal of Geology 115: 225-264

Barberton greenstone, South Africa			
Nondweni greenstone, South Africa	3320.0	3.0	Hofmann and Wilson, 2007, Earths Oldest Rocks, Elsevier, p. 571-605
Verkhovtsevo greenstone, Ukrainian shield	3310.0	3.0	Kushev and Kornilov, 1997, in de Wit and Ashwal (editors), Greenstone Belts, Clarendon Press, Oxford, Chapt 5.17
Tarssartoq-Ameralik dykes 2, SW Greenland	3257.0	14.0	Nutman et al., 2004 Journal of the Geological Society of London 161: 421-430
Tungurcha greenstone, Aldan shield	3251.0	4.0	Dobretsov et al., 1997, in de Wit and Ashwal (editors), Greenstone Belts, Clarendon Press, Oxford, Chapt 5.16
Regal Formation (Cleaverville), Pilbara, Western Australia	3249.0	3.0	Ohata et al., 1996 Lithos 37: 199-221; Hickman, 2004 Precambrian Research 131: 153-172
Sulfur Springs succession, Pilbara, Western Australia	3240.0	2.0	Smithies, 2005 Earth Planetary Science Letters 238: 284-297; Smithies et al., 2007 Geological Survey Western Australia Report 104
Ivisaartoq greenstone, SW Greenland	3076.0	3.0	Ordonez-Calderon et al., 2009 Lithos 113: 133-157; Polat et al., 2008 Lithos 100: 293-321
Subgan greenstone, Aldan shield	3055.0	3.0	Dobretsov et al., 1997, in de Wit and Ashwal (editors), Greenstone Belts, Clarendon Press, Oxford, Chapt 5.16, p. 716
Southern Cross greenstone, Yilgarn, Western Australia	3020.0	3.0	Angerer et al., 2013 Precambrian Research 224: 110-128
Koolyanobbing greenstone, Yilgarn, W Australia	3020.0	2.0	Angerer et al., 2013 Precambrian Research 224: 110-128
Olondo greenstone, Aldan shield	2998.0	4.0	Puchtel, 2004 Developments in Precambrian Geology, Vol. 13, Elsevier, p. 405-423; Dobretsov et al., 1992 Precambrian Research 58: 427-446
Kaapvaal GDS, South Africa	2985.0	4.0	Gumsley et al., 2014 Geological Society of America, Abstract 291-7, Vancouver meeting
North Caribou greenstone, Canada	2977.0	3.0	Hollings and Kerrich, 1999 Precambrian Research 93: 257-279; Biczok et al., 2012 Precambrian Research 192-195:209-230
Balmer Assemblage, Red Lake, Canada	2973.0	2.0	Hollings et al., 1999 Lithos 46: 137-161
Lumby Lake greenstone, Canada	2970.0	3.0	Hollings et al., 1999 Lithos 46: 137-161; Tomlinson et al., 1999 Lithos 46: 103-136
Badplaas dyke swarm, South Africa	2966.0	2.0	Olsson et al., 2010 Precambrian Research 183: 490-500
Heaven Lake greenstone, Wabigoon belt, Canada	2954.0	4.0	Tomlinson and Condie, 2001 Geological Society America Special Paper 352: 341-357
Steep Rock Lake greenstone, Ontario	2930.0	2.0	Tomlinson et al., 1999 Lithos 146: 103-136
D'Alton Lake-Toronto Lake belt, Canada	2920.0	3.0	Tomlinson et al., 1999 Lithos 146: 103-136

Vedlozero-Segozero Karelia	2920.0	2.0	Svetov et al., 2001 Geochemistry International 39 (Suppl. 1): s24-s38
Yuzhno-Vygozero-Shilos basalts/komatiites, Karelia	2915.0	3.0	Bozhko, 2010 Moscow University Geology Bulletin 65(3): 161-176
Urik greenstone, Siberia	2899.0	3.0	Turkina and Nozhkin, 2008, Petrology 16: 468-491
Rice Lake greenstone (Garner assemblage), SE Manitoba	2886.0	10.0	Anderson, 2006 Manitoba Geological Survey, Report of Activities 2006, p. 155-169
Vodla greenstone, Karelia, Russia	2877.0	2.0	Puchtel et al., 2007 Precambrian Research 158: 119-137
Sumozero-Kenozero greenstone, Baltica	2877.0	3.0	Puchtel et al., 1999 Geochimica et Cosmochimica Acta 63: 3579-3595
Hlagothi complex and dyke swarm, Kaapvaal craton	2870.0	4.0	Gumsley et al., 2012 Lithos doi: 10.1016/j.lithos.2012.06.007
Pickle-Crow assemblage, Superior Province	2870.0	2.0	Hollings and Kerrich, 2004 Precambrian Research 134: 1-20
Northern Superior province greenstones, Quebec	2853.0	4.0	Maurice et al., 2003 Canadian Journal of Earth Sciences 40: 431-445
Belingwe lower greenstones, Zimbabwe	2851.0	3.0	Bolhar et al., 2003 Geology 31: 295-298; Kusky and Kidd, 1992 Geology 20: 43-46
Kostomuksha greenstone, Russia	2843.0	4.0	Puchtel et al., 1998 Earth & Planetary Science Letters 155: 57-74
Tipasjärvi greenstone, Finland	2820.0	3.0	Huhma et al., 2012 Geological Survey of Finland, Special Paper 54: 74-175
Kuhmo greenstone, Finland	2810.0	3.0	Huhma et al., 2012 Geological Survey of Finland, Special Paper 54: 74-175; Maier et al., 2013 Precambrian Research 228: 63-84
Tikshozero greenstone, Karelia	2785.0	3.0	Mil'kevich et al., 2007 Geochemistry International 45 (5): 428-450
Derdepoort Flood Basalts, South Africa	2776.0	4.0	de Kock et al., 2009 Precambrian Research 174: 145-154
Black Range dykes, Pilbara craton	2772.0	2.0	Evans et al. 2017 Australian Journal of Earth Sciences 2017 doi.org/10.1080/08120099.2017.1289981
Fortescue-Kylena dyke swarm, Pilbara craton	2772.0	5.0	Wingate, 1999 Australian Journal of Earth Sciences 46: 493-500
Fortescue dykes Package 2, Pilbara craton	2766.0	2.0	Evans et al. 2017 Australian Journal of Earth Sciences 2017 doi.org/10.1080/08120099.2017.1289981
Singhbhum dyke swarm, India	2762.0	2.0	Kumar et al 2017 Precambrian Research 292: 163-174
Wawa-White River greenstone, Canada	2749.0	3.0	Polat et al., 1999 Precambrian Research 94: 139-173; Polat and Kerrich, 2000 Earth & Planetary Science Letters 175: 41-54

Vermillion Lake greenstone, Superior province	2748.0	4.0	Lodge et al., 2013 Precambrian Reserarch 235: 264-277
Sylvania Inlier dykes, N Pilbara	2747.0	4.0	Wingate, 1999 Australian Journal of Earth Sciences 46: 493-500
Slave Province-Swarm 1, NW Canada	2734.0	2.0	Ketchum et al., 2004 Precambrian Research 135: 149-176
Ahmeyim Great Dyke, Mauritania	2733.0	2.0	Tait et al., 2012 Lithos doi: 10.1016/j.lithos.2012.09.014
Uaua swarm 2, Sao Francisco craton	2726.0	3.0	Oliveira et al., 2013 Lithos 174: 308-322
Stoughton-Roquemaure, Abitibi	2723.0	2.0	Dostal and Mueller, 2012 Gondwana Research 23: 493-505
Ventersdorp flood basalts, South Africa	2714.0	8.0	Tinker et al., 2002 South African Journal of Geology 105: 107-134; Schmitz and Bowring 2003 Geological Society of America Bulletin 115: 533-548
Abitibi greenstone 2, Quebec	2714.0	1.0	Wyman, 1999 Precambrian Research 97: 27-42
Kilimafedha greenstone, NE Tanzania	2712.0	2.0	Messo et al., 2012 Journal of Geological Research ID 603971, doi.org/10.1155/2012/603971
Stillwater Complex and dykes, Montana	2710.0	2.0	Wall et al., 2010 American Geophysical Union, Fall Meeting 2010, Abstract #V31A-2309
Mashaba-Chibi dykes, Zimbabwe	2704.0	8.0	Soderlund et al., 2010 Precambrian Research 183: 388-398; Prendergast, 2004 Journal of the Geological Society of London 161: 431-445
Taishan greenstone belt, NE China	2704.0	5.0	Peng et al., 2012 Precambrian Research doi:10.1016/j.precamres.2013.01.017; Polat et al., 2006 Chemical Geology 230: 60-87
Lower basalts, Kalgoorlie, Yilgarn, Western Australia	2702.0	3.0	Said et al., 2012 Australian Journal of Earth Sciences 59: 737-763
Norseman 1, Western Australia	2701.0	3.0	Xie et al., 1995 Chemical Geology 126: 29-42
Forrestania greenstone, Western Australia	2700.6	6.0	Collins et al., 2012 Economic Geology 107: 1433-1455
Cowarna rocks dyke swarm, Western Australia	2700.5	3.0	Lambert et al., 1998 Australian Journal of Earth Sciences 45(2): 265-284
Abitibi greenstone 1, Quebec	2700.4	2.0	Wyman, 1999 Precambrian Research 97: 27-42
Morro de Ferro greenstone belt, Brazil	2699.0	2.0	Brenner et al., 2006 Economic Geology 85: 904-920
Wawa greenstone, THB basalts, Canada	2698.0	2.0	Polat, 2009 Precambrian Research 168: 83-105
Central Hearne province, Canada	2698.0	4.0	Sandeman et al., 2004 Precambrian Research 134: 113-141
Belingwe upper greenstones, Zimbabwe	2690.0	7.0	Bolhar et al., 2003 Geology 31: 295-298; Kusky and Kidd, 1992 Geology 20: 43-46

Slave Province dyke swarm, NW Canada	2684.8	3.3	Bleeker et al., 1999 Canadian Journal of Earth Sciences 36: 1083-1109
Sultanpura greenstone, India	2674.0	3.0	Manikyamba and Naqvi 1997 Gondwana Research 1: 69-89
Yellowknife mafic dykes, Canada	2627.0	32.0	Yoshihara and Hamano, 2000 Physics of Earth & Planetary Interiors, 117: 295-307
Uaua swarm 1, Sao Francisco craton	2624.0	7.0	Oliveira et al., 2013 Lithos 174: 308-322
Yandinilling dyke swarm, Yilgarn craton	2612.0	3.0	Stark et al 2017 Precambrian Research 317: 1-13
Stockford dykes, Limpopo orogen	2605.0	2.0	Xie et al., 2017 Precambrian Research 289: 129-141
Caraiba GDS, San Fancisco craton	2580.0	3.0	Oliveira et al., 2004 Precambrian Research 128: 143-165
Great Dyke Zimbabwe	2574.0	3.0	Oberthur et al., Precambrian Research 113: 293-305
Qingyuan Greenstone Belt, North China craton	2549.0	6.0	XuDong et al., 2010 Chinese Science Bulletin 55(27): 3197-3204
Kanjamalai mafic complex, Dharwar craton	2540.0	4.0	Noack et al., 2013 Precambrian Research .doi.org/doi:10.1016/j.precamres.2013.04.018
Kangamuit older dykes, W Greenland	2528.0	25.0	Willigers et al., 1999 Geology 27: 775-778
Harris greenstone, Gawler craton, Australia	2520.0	4.0	Swain et al., 2005 Precambrian Research 141: 106-136
Mistassini dyke swarm, SE Quebec	2515.0	3.0	Sandeman et al., 2012 Precambrian Research doi:10.1016/j.precamres.2012.06.002
Shandong GDS, N China craton	2515.0	8.0	Liu et al., 2015 Lithos 216-217: 148-157
Crystal Springs event, Zimbabwe	2510.0	4.0	Soderlund et al., 2010 Precambrian Research 183: 388-398
Irsuaq swarm, N Quebec	2508.0	6.0	Sandeman et al., 2012 Precambrian Research doi:10.1016/j.precamres.2012.06.002
Ptarmigan mafic dykes, Canada	2506.0	2.0	Buchan et al., 1998 Canadian Journal of Earth Sciences 35: 1054-1069
Kilarsaarfik vent, N Atlantic craton	2503.0	4.0	Nilsson et al., 2013 Lithos 174: 255-270