The Clean Paper

WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

Crust jalqabaa thin, half-molten: model Hadean keessatti impacts, internal heat miti, ol-aantummaa qaban

Hadean rock record almost hin dhiifne. Modelling study kun impacts ignore gochuu dhiisanii crust akkam ta'uu akka qabu gaafata. Stochastic declining impact-flux model fi benchmarked crust/mantle heat-flow simulations fayyadamuun, impact heat Hadean yeroo baay'ee Earth internal heat hunda at least order of magnitude caalaa ta'uu, crust <~5 km thin fi few km down partially molten ta'uu argan — plate tectonics'f weak, mantletti recycle ta'uu danda'u, Hadean material maaliif dhabame explain. Impacts ~3.9 Ga booda waned yeroo lasting continental crust oldest felsic rocks waliin mul'achuu danda'e — authors careful language keessatti 'likely not a coincidence.' Lower-bound heating purposely fayyadamame, kanaaf qualitative result robust, exact numbers fixed miti. Strong coherent model dha, direct observation miti.

Written by Lucio Vaglio · Cross-checked by Laura Nesso · Edited by Michele Renda · Figures by Laura Nesso and Nova Vela · AI-assisted, human-reviewed

Paper: *Impact heating and the hidden Hadean*, Tim E. Johnson, Craig O'Neill, Simon Turner, Christopher L. Kirkland, Science (2026), 392:1408-1412 · DOI: 10.1126/science.aeb5402

Boqonnaa seenaa Lafaa fuulli isaa jechuun ni danda'ama hundi bade

Lafni pilaaneetii beeknu keessaa ardiiwwan — lafa silica-rich fi buoyant nuti irra jiraannu — qabu isa qofa. Garuu ardiiwwan jalqaba akkamitti uumaman ji'ooloojii keessatti gaaffii durii keessaa tokko; sababni isaa hamaa dha: ragaa jechuun ni danda'ama hundi badeera.

Iiyoonii jalqabaa Lafaa, Hadean, uumamuu pilaaneetii irraa hanga naannoo waggaa biliyoona 4.03 dura (4.03 Ga)tti. Half-billion waggoota jalqabaa sana irraa waan baay'ee xiqqaa qofa hafe. Felsic (continental-type) dhagaa intact durii naannoo 4.03 Ga; basaltic dhagaa muraasni ~4.2 Ga ga'u. Maa-teriyaalii hundumaa keessaa duriin zircon kiristaalota muraasa — Jack Hills, Western Australia irraa beekamoo — hanga 4.4 Ga. Kuusaa ragaa infancy Lafa guutuun kana qofa: localities muraasa fi albu-udota sand-grain hammamtaa.

Qorannoo kun kuusaa ragaa sana irratti dhagaa haaraa hin dabalu. Waan biraa godha: fiiziksii sana jalatti Hadean qola lafaa akkam fakkaachuu akka qabu fiizikaalaa moodeela ijaara, gaaffii early-Earth moodeelota hedduun dhiisan gaafata. Yeroo jalqabaa Lafa bombarded ta'aa ture fact ignore gochuu dhiifte maal ta'a?

Deebiin barreessitoonni striking dha. Hadean keessaa yeroo baay'ee ho'a rukuttaawwan irraa dhufu keessaa ho'a Lafa hunda caalee, qola lafaa haphii fi walakkaa baqee taasise — ammayyaa tektooniksii pleetii fakkaatuuf baay'ee dadhabaa, jechuun argue godhu. Moodeela dha, yaadannoo miti. Garuu moodeela yeroo kanaa violence isaa account gochuuf yaalu keessaa tokko.

A model of the Hadean, not a memory of it

The logic is thermal: impacts heat, crust melts, the archive erases itself.

Energy

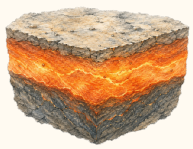
Impact heat dominates

At least an order of magnitude larger than internal heat for much of the Hadean.

Consequence

Thin, shallowly molten crust

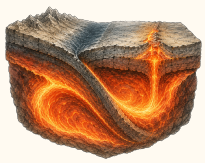
<5 km crust; >30% melt near 5 km in the model.



Record

Most crust recycles

Rare survivors: zircons and oldest rocks.



Around the 4.0-3.9 Ga transition, lasting crust appears.

Rukuttaa ho'a moodeela anniisaa budget keessatti ol-aana; qola lafaa haphii, shallowly molten of-recycle godha;

enduring continental qola lafaa 4.0–3.9 Ga transition naannoo qofa mul'ata. Kun Hadean moodeela dha, kallattii yaadannoo miti.

The Clean Paper CC BY 4.0

Barreessitoonni maal godhan

Wantoota bu'uuraa yeroo baay'ee addaan ilaalaman sadii walitti fidan.

Tokkoffaa, **tasaa moodeela rukuttaa yaa'a** — asteerooyidota fi bodies guddoo inner Solar Sirna Hadean/jalqabaa Archean keessatti rukutan. Kun duraa "Late Heavy Bombardment" spike tokko miti. Yaa'a jalqabaa cimaa, yeroo waliin **hir'ata** godha; guddaa rukuttaawwan tasaa/tasaa ta'een dhufu. Lunar/inner-Solar-System rukuttaa istaatistikii irraa rescale godhame, zircon age speektra fi jiru paleomagnetic ragaa waliin wal-simu ta'uuf filatame.

Lammaffaa, **ji'oodaynaamikii fakkeessuuwwan** ho'a qola lafaa fi gubbaa maantilii keessa akkamitti socho'u. Benchmarked lattice-Boltzmann koodii (Planet_LB) fayyadaman, salphaa 1D temperature-vs-depth shallaggiiwwan fi guutuu 2D maantilii convection snapshots 4.1 Ga irratti. Idilee keessaa ho'a maddoota — radioactive decay fi core ho'a — dabalata; importantly **magmatic advection**, ho'a rising melt'n ol geeffamu, kan thermal moodeelota hedduun omit godhan.

Sadaffaa, **phase-equilibrium modelling** realistic jalqabaa qola lafaa — hydrated Hadean metabasalt Nuvvuagittuq greenstone belt irraa — ho'a/depth kam irratti dhagaa akkasii melt jalqabu adda baasuuf.

Mala choice tokko barruu guutuu akkam dubbifamu irratti barbaachisaa: barreessitoonni deliberately xumura ofii isaanii *against* deck stack godhan. "Nonchondritic" maantilii — heat-producing radioactive maateriyaalii istaandaardii chondritic wabii caalaa xiqqaa — keessaa heating istaandaardii moodeela keessaa walakkaa gadi qabu assume godhan, conservative heating saffisoota fayyadaman, young close Moon tidal heating ignore godhan. Kanaaf calculated qola lafaa temperatures **minima/gadi-aanaa bounds** dha. Dhugaa Hadean isaan moodeela godhan caalaa hotter ta'uu mala.

Maal argatan

Rukuttaawwan, keessaa ho'a miti, Hadean anniisaa budget dominate godhan. Rukuttaa ho'a yeroo irratti integrate godhamu keessaa contribution caalaa — Hadean yeroo baay'ee yoo xiqqaate order of magnitude — guddaa. Picture kana keessatti rukuttaa heating jalqabaa tectonism engine ijoo, radioactive decay miti; gahee xiqqaa garaatti ~**3.9 Ga** booda qofa gadi bu'a.

Ho'a kun qola lafaa haphii fi shallowly molten godhe. Rukuttaawwan/melt advection malee moodeela Hadean qola lafaa gariin molten below ~10–15 km. Rukuttaa ho'a dabaluuun melt zone dramatic ol ba'a: qola lafaa qofa **kilometers muraasa gadi** (gara 2–5 km) gariin molten ta'a. 5 km depth naan-

noo moodeelota >30% melt tilmaamu — dhagaa rigid plate ta'ee of qabachuu hin dandeenye. 5–10 km keessatti ~1000–1100°C, composition kamuu keessatti qola lafaa extensively molten. Surviving jajjabaa qola lafaa **haphii, ~5 km gadi**.

walakkaa baqee qola lafaa ofii isaa haqaa ture. Extensive melting dense iron/magnesium-rich maateriyaalii akka gadi sink/adda ta'u, lighter silica-rich melts ol akka ba'an godha. Yeroo waliin giddugaleessa qola lafaa caalaa evolved, silica-rich compositions garaatti deema; felsic melt zircon crystallize godhu uuma. Haphii qola lafaa kana keessaa jechuun ni danda'ama hundi convecting maantilii keessatti gadi recycle ta'a, chemical/isotopic galmee waliin wal-simu. Moodeela kana keessatti Hadean dhagaa dhabamu "gap" miti — *tilmaama* dha. 4.2 Ga dhagaa fi 4.4 Ga zircons muraasa survivors qola lafaa yeroo uumamu jechuun ni danda'ama immediately destroyed ta'ee turan.

Bombardment xumuramuun jalqabaa lasting ardiiwwan waliin wal-sima. 4.0–3.9 Ga transition keessa bombardment waned yeroo ta'u qola lafaa finally thicken/endure danda'e. Oldest surviving continental dhagaa transition sana naannoo mul'atu. Barreessitoonni careful: enduring continental qola lafaa yeroo sana mul'achuun "carraan isaa guddaa miti a coincidence."

mata-duree inference: haalawwan kana jalatti — haphii qola lafaa, kilometers muraasa gadi molten — **Hadean tektooniksii pleetii implausible**.

Duraa hojii faallaa xumura maaliif argate illee agarsiisu. Tasaa rukuttaawwan qorannoowwan durii xiqqaa than 2.5% qola lafaa anytime molten jedhu; isaan wantoota lama omit godhan: guddaa rukuttaawwan waliigalaa dhiibbaa deep maantilii melting irratti fi ho'a sana rising magma'n ol transport. Lamaan deebisi, thermal picture baay'ee jijjiirama.

Moodeela yaadannoo miti

Wantoonni gubbaa fakkeessuuwwan bu'aa dha, Hadean dhagaa irraa dubbisuu miti — sababni dhagaa jechuun ni danda'ama hunda hin jirre. Kun bu'aa dadhabaa hin godhu; gosa bu'aa maal akka ta'e murteessa.

Chain: rukuttaa yaa'a *moodeela* → maantilii/qola lafaa ho'a flow *moodeela* → particular dhagaa akkam melt godhu *moodeela*. Link tokkoon tokkoon physically motivated, bakka danda'amaa benchmarked; garuu guutuu coherent argument "amansiisaa fiiziksii jalatti Hadean akkam *ta'uu qaba*" jedhu dha, "akkam *ture*" safartuu miti.

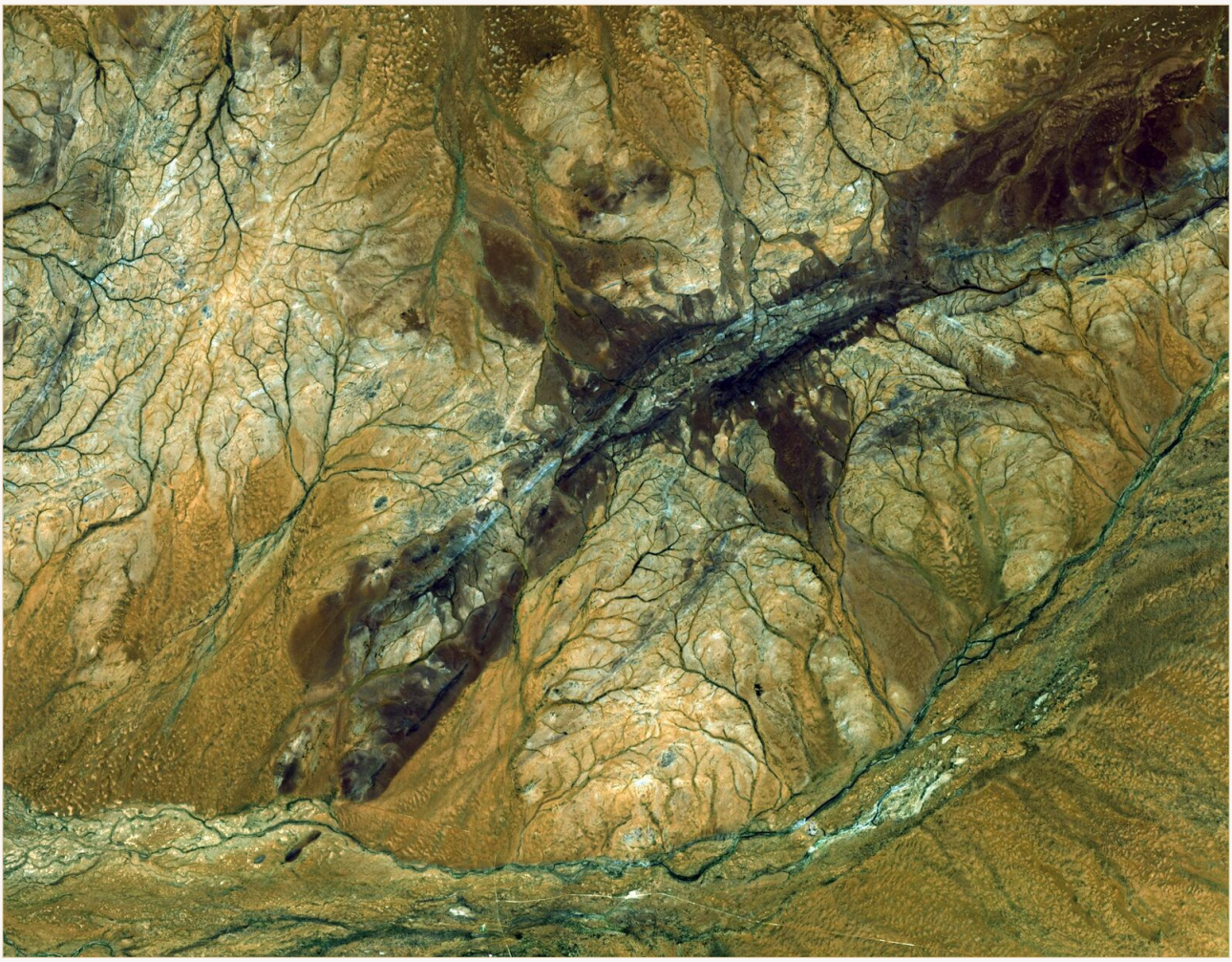
Kanaaf conservative yaadota bu'uuraa barreessitoonni barbaachisaa. Lower-bound heating filatanii ammallee pervasively molten shallow qola lafaa argan; qualitative xumura — Hadean qola lafaa hot fi dadhabaa — choices irratti jabaataa. Garuu sirrii geotherms, sirrii melt fractions, sirrii crustal thickness pin down hin ta'u. Direction cimaa ta'ee dubbisi, decimal places provisional.

Kun maal *hin* mirkaneessu

- Hadean qola lafaa kallattii hin observe. Dhagaa era kanaa jechuun ni danda'ama hin jiru; fiiziksii hiika modelling bu'aa dha, safartuu miti.
- "Late Heavy Bombardment" irratti hin hirkatu. Rukuttaa yaa'a declining tasaa dha, sudden spike hin barbaadu/hin invoke.
- Plate-tectonics debate hin settle. "Implausible" cimaa physically grounded inference hot stagnant/squishy-lid jalqabaa Lafa caalatti filatu, garuu Hadean tectonic mode contested dha.
- Rukuttaawwan ardiiwwan 4.0–3.9 Ga irratti *caused* appearance hin mirkaneessuu. Timing match cimaa association, barreessitoonni "carraan isaa guddaa miti a coincidence" jedhu — compelling walitti dhufeenya, demonstrated cause miti.
- Jack Hills zircons preserved ardiiwwan **miti**. Muraasa surviving grains felsic maateriyaalii fi water jalqabaa jiraachuu agarsiisu; moodeela qabxii qola lafaa isaan uume irra caalaa recycled.
- Guutuu early-Earth seenaa hin reconstruct. Fakkeessuuwwan idealized — 1D profiles fi 2D equatorial slices rukuttaawwan equator naannoo confined, snapshots — guutuu 4D pilaaneetii moodeela miti.

Ragaan hammam cimaa dha?

Central himannaa — rukuttaa heating Hadean qola lafaa first-order to'annoo, haphii/shallowly molten — coherent fi barbaachisaa sense keessatti conservative dha. Benchmarked geodynamics koodii, physically reasonable galteewwan, lower-bound yaadota bu'uuraa, ho'a madda duraa moodeelota hedduun ignore godhan integrate godha. Facts rakkisaa lama yeroo tokko ibsa: ~4 Ga dura dhagaa jechuun ni danda'ama hin survive (near-total recycling), lasting qola lafaa bombardment fade yeroo mul'atu.



Jack Hills, Western Australia, NASA ASTER'n ilaalame. Zircons naannoo kana irraa maateriyaalii jalqabaa qola lafaa Lafa surviving durii keessaa; iiyoonii dhagaa isaa irra caalaa erased irraa clues xixiqqoo.

NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team fair-use

Daangaalee deep-time moodeela hundaa: moodeelota irratti moodeelota, sparse dhagaa galmee irratti anchored; quotable "tektooniksii pleetii is implausible" inference dha, ilaalcha miti. Sirrii posture cimaa, well-reasoned hypothesis Hadean reframe godhu, yaadota bu'uuraa — keessumaa impact-flux choice — kanneen biroo qormaata akka godhan waamu, haala xumurame miti.

Faayidaa qabu cuunfaa "Hadean akkas ture" yookaan "fakkeessuu qofa" miti. Inni: amansiisaa conservative fiiziksii jalatti heavy bombardment jalqabaa Lafa haphii, walakkaa baqee, self-recycling qola lafaa qabaata — yaada tokko little ragaa argamu keessaa baay'ee ibsa.

Maaliif barbaachisaa dha

Popular jalqabaa Lafa image extremes lama gidduu: serene plate-tectonic water world har'a fakkaatu yookaan hellish lava pilaaneetii. Hojii kun middle addaa, physically motivated sketch godha: qola lafaa haphii, muraasa km down irraa repeatedly remelted, destroyed/remade; rukuttaawwan —

keessaa ho'a miti — terms set godhan.

Reframing kun hojii dhugaa godha. Facts infancy Lafa lama — dhagaa galmee jechuun ni danda'ama absent fi timing jalqabaa enduring ardiiwwan — adeemsa hojii tokkoon ibsa, rukuttaa heating neglected adeemsa seenaa giddugala kaa'a. Hold up yoo godhe, Lafa yeroo tasgabbaa'aa ardiiwwan pilaaneetii ta'e akkam sababa goonu jijjiira; biraa rocky worlds bombardments ofii isaanii jalatti formed irratti illee carry over.

Moodeela dhumaa jecha ta'uu hin qabu. Hypothesis qoruuf gahaa gaarii ta'uu qaba; surviving zircon/isotope galmee waliin tie godha. "Hidden Hadean" qabxii dha: era moodeela qofaan jechuun ni danda'ama reach goonu, sababni era ofii ragaa isaa erased.

Cuunfaa gabaabaa

Hadean, iiyoonii Lafa jalqabaa (~4.03 Ga dura), dhagaa galmee jechuun ni danda'ama hin dhiifne. Qorannoo modeling kun rukuttaawwan ho'a madda moodeelota yeroo baay'ee omit godhan dabaltee qola lafaa akkam ta'uu akka qabu gaafata. Tasaa declining impact-flux moodeela + benchmarked 1D/2D qola lafaa/maantilii heat-flow fakkeessuuwwan (rising melt ho'a transport dabalatee) fayyadamuun, time-integrated rukuttaa ho'a Hadean yeroo baay'ee Lafa keessaa ho'a hunda yoo xiqqaate order of magnitude caalaa ta'uu argan. Consequence: qola lafaa haphii (<~5 km), muraasa km down irraa gariin molten, ~5 km depth irratti >30% melted — rigid plate sustain gochuuf dadhabaa; Hadean tektooniksii pleetii barreessitoonni implausible jedhu. Qola lafaa akkanaa irra caalaa maantilii keessatti recycle, Hadean maateriyaalii maaliif dhabame explain; rukuttaawwan 4.0–3.9 Ga transition keessatti waned yeroo lasting continental qola lafaa boca gochuu danda'e, oldest felsic dhagaa survive yeroo sana — "carraan isaa guddaa miti a coincidence." Conservative lower-bound heating waan fayyadameef qualitative bu'aa jabaataa, sirrii lakkoofsota dhaabbataa miti. Cimaa coherent moodeela infancy Lafa dha — kallattii ilaalcha miti.

Sakatta'a ifaa

barruun maal agarsiisa: Physically grounded fakkeessuuwwan rukuttaa heating + magmatic ho'a transport dabalatan keessatti Hadean qola lafaa haphii, muraasa km down gariin molten, rukuttaa ho'a'n keessaa ho'a caalaa dominated, irra caalaa mantletti recycled, moodeela kana jalatti tektooniksii pleetii support hin dandeenye.

Waan amansiisaa ta'e garuu hin mirkanoofne: Rukuttaawwan sababa enduring ardiiwwan ~3.9 Ga irratti mul'atan; Hadean stagnant/squishy-lid mannaa jalqabaa plate tectonic; dhagaa jechuun ni danda'ama hin survive molten qola lafaa self-recycled waan ta'eef.

Waan hin agarsiifne: Hadean qola lafaa kallattii safartuu; plate-tectonics debate settled; fading bombardment fi jalqabaa ardiiwwan sababa-qabeessa link demonstrated; Jack Hills zircons preserved ardiiwwan; guutuu jalqabaa pilaaneetii moodeela.

Daangaawwan ijoo: Hadean dhagaa galmee jechuun ni danda'ama nonexistent; moodeela stacking rukuttaa yaa'a→geodynamics→sadarkaa equilibria; rukuttaa yaa'a representative garuu uncertain; fakkeessuuwwan idealized 1D/2D equatorial slices/snapshots. Conservative gadi-aanaa bounds qualitative xumura strengthen, sirrii geotherms sirrii hin taasisu.

Dubbisaan waliigalaa amanamummaa hammam qabaachuu qaba? amansiisaa fiiziksii jalatti heavily bombarded jalqabaa Lafa hot, haphii, shallowly molten qola lafaa qabaata irratti ol-aanaa. Kun Hadean tektooniksii pleetii carraan isaa xiqqaa fi missing dhagaa galmee explain gochuu irratti moderate. Ardiiwwan exactly akkam/when formed mirkaneessuu godha himannaa irratti gadi-aanaa. Stance sirrii: cimaa conservative moodeela Hadean reframe godhu, kallattii look miti.

Maddoota

Johnson, O'Neill, Turner & Kirkland, Science 392:1408-1412 (2026)
https://doi.org/10.1126/science.aeb5402