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Thin, half-molten first crust: model inda impacts, ba internal heat ba, suka tafiyar da Hadean

First eon na Earth, Hadean, ya bar almost no rock record. Wannan modelling study ya tambayi yadda crust zai kasance idan ka daina ignoring impacts. Ta stochastic declining impact-flux model da benchmarked simulations na crust da mantle heat flow, authors sun find impact heat would exceed entire internal heat na Earth by at least an order of magnitude ga most Hadean, yana bar thin crust (under ~5 km) partially molten few kilometres down — too weak, suna argue, for plate tectonics, kuma prone to recycling into mantle, wanda zai explain why so little Hadean material survives. As impacts waned after ~3.9 Ga, lasting continental crust could form around when oldest surviving felsic rocks appear — "likely not a coincidence." Saboda conservative lower-bound heating, qualitative result robust ne even though exact numbers not fixed. Strong coherent model ne na infancy na Earth — ba direct observation ba.

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

Babi na tarihin Duniya da kusan duk shafukansa suka ɓace

Duniya ce kaɗai duniyar da muka sani tana da nahiyoyi — manyan yankunan ƙasa masu yawan silica da suke shawagi a kan kayan da suka fi nauyi a ƙasa. Amma yadda nahiyoyin farko suka samu yana daga cikin tsoffin tambayoyin ilimin ƙasa da har yanzu ba a warware ba. Dalilin yana da tsauri: kusan duk shaidar da za ta ba mu amsa ta ɓace.

Zamanin farko na tarihin Duniya, **Hadean**, ya fara daga samuwar duniyar har zuwa kusan shekaru biliyan 4.03 da suka wuce (Ga). Daga rabin biliyan na farko, kusan babu wani dutse da ya tsira. Tsofaffin duwatsun felsic — irin na nahiyoyi — da suka tsira ba tare da rushewa ba suna da kusan 4.03 Ga. Wasu duwatsun basalt da ba kasafai ake samu ba sun kai kusan 4.2 Ga. Tsohon abu mafi dadewa da aka sani kuwa wasu ƙwayoyin zircon ne da suka bazu a wurare kaɗan, musamman a Jack Hills na Yammacin Ostiraliya, waɗanda shekarunsu suka kai 4.4 Ga. Wannan shi ne kusan duk kundin tarihin yarintar Duniya: wurare kaɗan da wasu ƙananan ma'adanai masu girman ƙwayar yashi.

Wannan binciken bai ƙara sabon dutse a wannan kundin tarihi ba. Ya yi wani abu dabam: ya gina samfurin zahiri na yadda ɓawon Duniya na Hadean zai kasance idan aka yi la'akari da yanayin zafi da ƙarfin da ake tsammani a wancan lokaci, sannan ya tambayi abin da yawancin samfuran farkon Duniya suke barin a gefe. Me zai faru idan ba a yi watsi da gaskiyar cewa ana ci gaba da yi wa Duniya ruwan duwatsun sararin samaniya ba?

Amsar da marubutan suka samu tana da ban sha'awa. A yawancin Hadean, zafin da tashe-tashen duwatsun sararin samaniya suka kawo zai fi duk zafin da ke fitowa daga cikin Duniya ƙarfi sosai. Wannan zai bar ɓawon Duniya siriri kuma wani ɓangarensa yana narkewa kusa da saman ƙasa — ya yi rauni, a cewar marubutan, har ba zai iya ɗaukar tsarin faranti irin na yau ba. Wannan **samfuri ne, ba tarihin da aka auna kai tsaye ba**. Amma aƙalla samfurin ya yi ƙoƙarin saka tashin hankalin wancan zamani cikin lissafi.

A model of the Hadean, not a memory of it

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

Energy

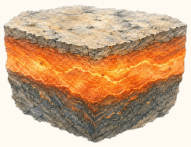
Impact heat dominates

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

Consequence

Thin, shallowly molten crust

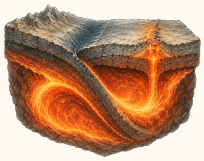
<5 km crust; >30% melt near 5 km in the model.



Record

Most crust recycles

Rare survivors: zircons and oldest rocks.



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

A cikin samfurin, zafin tashe-tashen duwatsun sararin samaniya ne ya mamaye ma'aunin makamashi. Ɓawon Duniya mai siriri, wanda yake narkewa kusa da saman ƙasa, yana sake zagayawa cikin mantle; ɓawon nahiyoyi mai ɗorewa ya fara bayyana ne kawai a kusan sauyin 4.0–3.9 Ga. Wannan samfurin Hadean ne, ba rikodin kai tsaye na abin da ya faru ba.

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Abin da marubutan suka yi

Tawagar ta haɗa abubuwa uku da galibi ake nazarinsu dabam-dabam.

Na farko, sun yi amfani da **samfurin yiwuwar yawan tashe-tashen duwatsun sararin samaniya** — wato yawan asteroids da manyan jiki da suka riƙa bugun cikin Tsarin Rana a Hadean da farkon Archean. Muhimmin abu shi ne wannan ba tsohon ra'ayin wani bugun gaggawa guda ɗaya na "Late Heavy Bombardment" ba ne. A maimakon haka, yawan bugun yana da ƙarfi sosai a farko sannan **yana raguwa a hankali da lokaci**, yayin da manyan bugun suke faruwa bazuwar lokaci ba tare da jadawali ba. An daidaita samfurin daga kididdigar bugun Wata da sauran sassan cikin Tsarin Rana, sannan aka zaɓi sigar da ta dace da rarrabuwar shekarun zircon da shaidar paleomagnetism da ake da ita.

Na biyu, sun yi **simulations na geodynamics** don duba yadda zafi ke motsawa a ɓawon Duniya da saman mantle. Sun yi amfani da lambar lattice-Boltzmann da aka gwada da ma'auni, Planet_LB, suna gudanar da lissafin 1D na zafin jiki bisa zurfi da kuma hotunan 2D na convection a mantle a 4.1 Ga. Lissafin ya haɗa hanyoyin zafin cikin Duniya da aka saba sani — lalacewar rediyoaktif da zafin da ke fitowa daga core — sannan, abin da ya fi muhimmanci, **ɗaukar zafi ta magma mai tashi**. Yawancin samfuran zafin ɓawon Duniya ba sa haɗa wannan hanyar.

Na uku, sun yi **lissafin daidaiton matakai na ma'adinai** a kan irin dutse da zai yi kama da ɓawon Duniya na farko: hydrated Hadean metabasalt daga Nuvvuagittuq greenstone belt. Hakan ya ba su damar ƙididdige zafin jiki da zurfin da irin wannan dutse zai fara narkewa.

Akwai zaɓin hanya guda da yake da muhimmanci wajen fassara dukan takardar: marubutan sun yi ƙoƙarin sanya sharuddan da za su **rage**, ba ƙara ba, sakamakon da suke samu. Sun ɗauka cewa mantle ɗin "nonchondritic" ne, wato yana ɗauke da ƙarancin sinadaran rediyoaktif masu samar da zafi fiye da ma'aunin chondritic, da ƙasa da rabin zafin cikin Duniya na samfurin da aka saba amfani da shi. Sun kuma yi amfani da ƙididdigar zafi masu taka-tsantsan, kuma ba su saka zafin tidal daga Wata, wanda a lokacin yana kusa da Duniya, ba. Saboda haka zafin ɓawon Duniya da suka lissafa **ƙananan iyaka ne**. Idan akwai karkata, a zahiri Hadean zai fi abin da suka ƙididdige zafi.

Abin da suka gano

Zafin bugun duwatsun sararin samaniya, ba zafin cikin Duniya ba, ne ya mamaye ma'aunin makamashi na Hadean. Idan aka tara zafin bugun a duk tsawon lokaci, ya zarce gudummawar zafin cikin Duniya da aƙalla kusan sau goma a yawancin Hadean. A wannan hoto, bugun duwatsun sararin samaniya — ba lalacewar rediyoaktif

ba — shi ne babban abin da ke motsa harkokin tectonics na farko, kuma tasirinsa bai zama ƙarami ba sai bayan kusan **3.9 Ga**.

Wannan zafin ya bar ɓawon Duniya siriri kuma yana narkewa kusa da saman ƙasa. Idan aka cire bugun duwatsun sararin samaniya da ɗaukar zafi ta magma, samfurin ya nuna cewa ɓawon Hadean zai fara narkewa ne kawai a ƙasa da kusan kilomita 10–15. Da zarar an ƙara zafin bugun, yankin narkewar ya hau sama sosai: dutse ya fara narkewa a zurfin **kilomita kaɗan kawai**, kusan 2–5 km. A kusan zurfin 5 km, samfurin ya nuna narkewar fiye da 30%; a irin wannan yanayi, dutse ya yi rauni sosai har ba zai iya zama faranti mai tauri ba. A 5–10 km, zafin kusan 1000–1100°C yana nufin ɓawon zai narke sosai ko da kuwa sinadaransa sun bambanta. Ɓangaren da zai kasance daskararre zai kasance **siriri, ƙasa da kusan 5 km**.

Ɓawon da rabinsa ke narkewa yana shafe tarihin kansa. Idan narkewa ta yi yawa, kayan da suka fi nauyi masu yawan ƙarfe da magnesium suna nutsewa su rabu, yayin da narkakkun kayan da suka fi sauƙi kuma suka fi silica ke tashi sama. A hankali wannan yana canza matsakaicin sinadaran ɓawon zuwa nau'ikan da suka fi silica, kuma yana samar da irin narkakken felsic da zai iya samar da zircon. Sannan kusan duk wannan siririn ɓawon zai sake nutsewa cikin mantle mai convection, abin da ya dace da bayanan sinadarai da isotopes. A wannan samfurin, kusan rashin duwatsun Hadean ba kawai gibi ba ne a tarihin duwatsu — **sakamako ne da samfurin ya hango**. Duwatsun 4.2 Ga da zircon na 4.4 Ga su ne kaɗan daga abubuwan da suka tsira daga ɓawon da yawancinsa yake lalacewa da sauri kamar yadda yake samuwa.

Raguwar bugun duwatsun sararin samaniya ta yi daidai da lokacin da nahiyoyin farko masu ɗorewa suka fara bayyana. Yayin da bugun ya ragu a tsakanin 4.0 da 3.9 Ga, ɓawon Duniya ya sami damar yin kauri da tsira na dogon lokaci. Tsofaffin duwatsun nahiyoyi da suka tsira sun bayyana kusan a wannan sauyi. Marubutan sun faɗa cikin taka-tsantsan cewa bayyanar ɓawon nahiyoyi mai ɗorewa a wannan lokaci "mai yiwuwa ba daidaituwa kawai ba ce."

Babban abin da suka ɗauka daga sakamakon shi ne: idan ɓawon yana da wannan siririn kuma yana narkewa a zurfin kilomita kaɗan, **samuwar plate tectonics a Hadean ba ta da sauƙin yarda**.

Sun kuma bayyana dalilin da ya sa wasu binciken baya suka sami akasin haka. Wasu samfuran bugun bazuwar lokaci sun nuna tasiri kaɗan ne kawai, inda ƙasa da 2.5% na ɓawon ke narkewa a kowane lokaci. Amma waɗannan binciken ba su haɗa abubuwa biyu da wannan binciken ya saka ba: tasirin manyan bugun a duniya baki ɗaya wajen narkar da sassan mantle masu zurfi, da kuma ɗaukar wannan zafin zuwa sama ta magma mai tashi. Idan aka saka waɗannan hanyoyi, hoton zafi ya canza sosai.

Me ya sa samfuri ba ya zama rikodin kai tsaye

Duk abin da aka bayyana a sama sakamakon simulations ne, ba ma'aunin da aka ɗauka daga duwatsun Hadean ba — domin kusan babu irin waɗannan duwatsu da suka tsira. Wannan ba ya sa sakamakon ya zama marar amfani, amma yana fayyace **irin shaidar** da muke da ita.

Tsarin hujjar yana tafiya ne haka: **samfurin** yawan bugun duwatsun sararin samaniya yana ba da shigarwa ga **samfurin** yadda zafi ke gudana a mantle da ɓawon Duniya; sannan ana kwatanta hakan da **samfurin** yadda wani irin dutse yake narkewa. Kowace mahaɗa tana da tushen kimiyyar zahiri kuma, inda zai yiwu, an gwada ta da ma'auni. Amma gaba ɗaya hujja ce game da yadda Hadean **ya kamata** ya kasance idan waɗannan ka'idojin zahiri

masu yiwuwa sun yi aiki — ba ma'aunin yadda **a zahiri** yake ba.

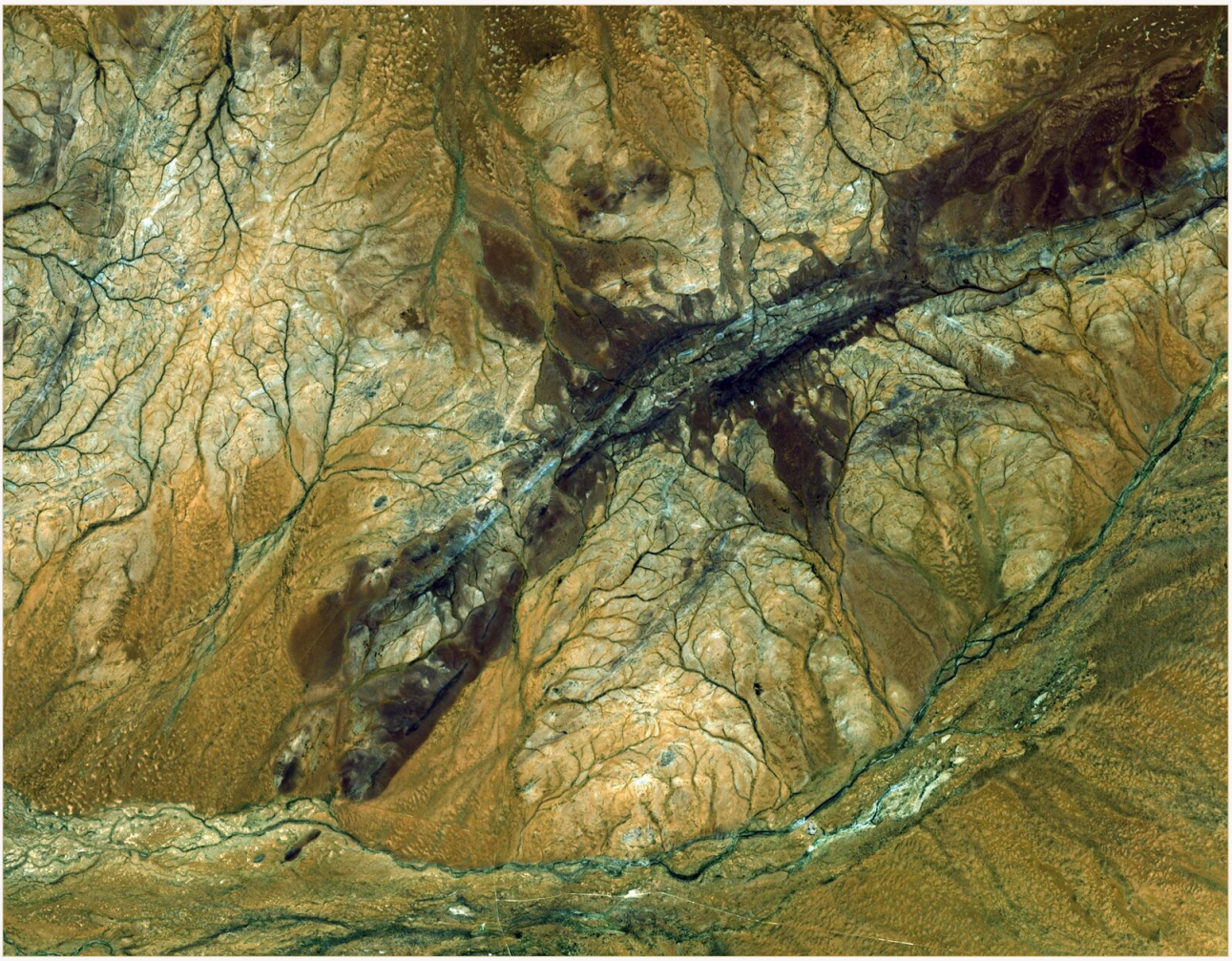
Saboda haka ne zaɓin marubutan na amfani da ƙididdiga masu taka-tsantsan yake da muhimmanci. Sun yi amfani da ƙananan iyakokin zafi, amma har yanzu suka sami ɓawon da yake narkewa sosai kusa da saman ƙasa. Saboda haka babban sakamakon — cewa ɓawon Hadean yana da zafi kuma yana da rauni — ba ya sauƙin ɓacewa idan aka canza wasu zaɓuɓɓukan samfurin. Abin da ba a ƙayyade sosai ba shi ne adadi dalla-dalla: ainihin geotherm, kaso na narkewa, da kaurin ɓawon. Ya fi dacewa a ɗauki **alkiblar sakamakon** a matsayin mai ƙarfi, amma a ɗauki ƙananan bambance-bambancen lambobi a matsayin na wucin gadi.

Abin da wannan binciken bai tabbatar ba

- Bai **gani kai tsaye** ga ɓawon Hadean ba. Kusan babu dutsen wannan zamani; sakamakon samfurin ne game da abin da ka'idojin zahiri suke nuna, ba ma'auni kai tsaye ba.
- Bai dogara da ra'ayin **"Late Heavy Bombardment"** ba. Yawan bugun da aka yi amfani da shi yana raguwa ne da lokaci kuma bugun suna zuwa bazuwar lokaci; ba a buƙatar wani tsalle guda na gaggawa.
- Bai warware muhawarar **plate tectonics** ba. Kalmar "ba ta da sauƙin yarda" a nan hujja ce mai tushe a kimiyyar zahiri wadda take goyon bayan farkon Duniya mai zafi da murfi marar motsi ko mai laushi, amma har yanzu masana suna muhawara kan irin tectonics da Hadean ya samu.
- Bai tabbatar cewa bugun duwatsun sararin samaniya ne **ya haifar** da bayyanar nahiyoyi a 4.0–3.9 Ga ba. Daidaiton lokutan yana da ƙarfi, kuma marubutan sun ce "mai yiwuwa ba daidaituwa kawai ba ce," amma wannan haɗuwa ce mai ban sha'awa, ba tabbataccen dalili da sakamako ba.
- Zircon na Jack Hills **ba nahiyoyi ne da suka tsira ba**. Ƙananan ƙwayoyin ma'adinai ne da suka nuna cewa felsic material da ruwa sun wanzu tun da wuri; manufar samfurin ita ce ɓawon da ya samar da su yawancinsa ya sake nutsewa ya ɓace.
- Bai sake gina cikakken tarihin farkon Duniya ba. Simulations ɗin an sauƙaƙa su: bayanan 1D da yankan 2D a kusa da equator, tare da bugun da aka takaita zuwa wannan yankin da aka ɗauka a wasu lokuta na musamman — ba cikakken samfurin duniya mai girma huɗu ba.

Yaya ƙarfin shaidar yake?

Ga babban ikirarin binciken — cewa zafin bugun duwatsun sararin samaniya ya kasance babban abin da ke sarrafa ɓawon Hadean, yana barinsa siriri kuma yana narkewa kusa da saman ƙasa — hujjar tana da haɗin kai kuma tana amfani da zato masu taka-tsantsan. An yi amfani da lambar geodynamics da aka gwada, shigarwar da suka dace da kimiyyar zahiri, da ƙananan iyakokin zafi; sannan an saka wata hanyar zafi da yawancin samfuran baya suka yi watsi da ita. Samfurin kuma yana ba da bayani guda ga abubuwa biyu da suka daɗe suna da wahalar fahimta: me ya sa kusan babu dutse da ya fi ~4 Ga tsufa da ya tsira, da kuma me ya sa ɓawon nahiyoyi mai ɗorewa ya fara bayyana daidai lokacin da bugun duwatsun sararin samaniya ya ragu.



Jack Hills a Yammacin Ostiraliya, kamar yadda na′urar ASTER ta NASA ta gani. Zircon daga wannan yanki suna cikin tsoffin abubuwan da suka tsira daga ƀawon Duniya na farko — ƙananan alamu daga wani zamani da kusan duk duwatsunsa suka ƀace.

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

Iyakokin binciken ma a sarari suke, kuma su ne irin iyakokin da duk samfurin zamanin da ya kamata ya samu: akwai samfurori da aka gina a kan wasu samfurori, suna jingina da kundin duwatsu mai matuƙar ƙaranci. Babban jumlar da za a fi ɗauka daga takardar — cewa "plate tectonics ba ta da sauƙin yarda" — **hasashe ne daga samfurin, ba abin da aka gani kai tsaye ba**. Don haka ya fi dacewa a ɗauki binciken a matsayin ƙaƙƙarfan hasashe mai hujja wanda ya sake tsara yadda za a tambayi Hadean, kuma wanda sauran masana za su iya gwada zato-zatonsa — musamman samfurin yawan bugun — ba a matsayin batun da aka rufe ba.

Takaitaccen ma'anar da ta fi amfani ba "haka Hadean yake" ba ce, kuma ba "simulation ne kawai" ba ce. Ita ce: **idan aka yi amfani da ka'idojin zahiri masu yiwuwa kuma masu taka-tsantsan, Duniya ta farko da ake ta bugawa da duwatsun sararin samaniya za ta kasance da ƀawo siriri, wani ƀangarensa narkakke, kuma yana sake zagayawa cikin mantle; wannan ra'ayi guda yana iya bayanin abubuwa da yawa daga ƙarancin shaidar da muka rage da ita.**

Me ya sa wannan yake da muhimmanci

Hoton farkon Duniya da ake yawan nunawa yana karkata zuwa ɗaya daga cikin bangarori biyu: ko duniya mai ruwa da plate tectonics mai kama da ta yau, ko kuma duniyar wuta da lava. Wannan binciken yana gabatar da wani hoto na tsakiya mai tushe a kimiyyar zahiri: ɓawo mai siriri wanda ake sake narkarwa daga zurfin kilomita kaɗan, ana lalata shi ana sake gina shi, yayin da tashe-tashen duwatsun sararin samaniya — ba kawai zafin cikin Duniya ba — ke tsara yanayinsa.

Wannan sabon tsarin tunani yana da amfani. Yana ba da wata hanya guda da za ta iya bayyana manyan abubuwa biyu game da yarintar Duniya — kusan ɓacewar kundin duwatsu da lokacin da nahiyoyin farko masu ɗorewa suka bayyana — kuma yana sanya zafin bugun duwatsun sararin samaniya, wani abu da aka saba watsi da shi, a tsakiyar labarin. Idan binciken ya jure gwaje-gwajen gaba, zai canza yadda muke tunani game da lokacin da Duniya ta zama duniyar nahiyoyi masu ɗorewa, kuma irin wannan tambayar tana shafar sauran duniyoyin duwatsu da suka samu nasu lokutan bugun.

Ba lallai ne wannan samfurin ya zama kalma ta ƙarshe ba. Abin da ake buƙata shi ne ya zama hasashe mai kyau da za a iya gwadawa — kuma ta hanyar haɗa shi da zircon da bayanan isotope da suka tsira, yana ba da wasu hanyoyin gwaji. Wannan shi ne ainihin ma'anar **"Hidden Hadean"**: zamani da a yau galibi sai ta hanyar samfuri za mu iya kaiwa gare shi, domin zamanin da kansa ya shafe yawancin shaidarsa.

Takaitaccen bayani

Zamanin farko na Duniya, Hadean (kafin ~4.03 Ga), ya bar mana kusan babu kundin duwatsu. Wannan binciken ya tambayi yadda ɓawon Duniya zai kasance idan aka saka wata hanyar zafi da ake yawan barinta a waje: **bugun duwatsun sararin samaniya**. Marubutan sun haɗa samfurin bugun da ke raguwa da lokaci da simulations na 1D da 2D na yadda zafi ke gudana a ɓawon Duniya da mantle, ciki har da zafin da magma mai tashi ke ɗauka. Sakamakon ya nuna cewa zafin bugun da aka tara da lokaci zai fi duk zafin cikin Duniya da aƙalla kusan sau goma a yawancin Hadean. Wannan zai bar ɓawon ƙasa siriri — ƙasa da ~5 km — kuma wani ɓangarensa yana narkewa a zurfin kilomita kaɗan; a kusan 5 km, samfurin ya nuna fiye da 30% na dutse yana narkewa, yanayin da ya yi rauni sosai ga plate tectonics. Irin wannan ɓawo zai sake nutsewa cikin mantle akai-akai, abin da zai iya bayyana me ya sa ƙalilan daga duwatsun Hadean suka tsira. Da bugun ya ragu a tsakanin 4.0–3.9 Ga, ɓawon nahiyoyi mai ɗorewa ya sami damar bayyana kusan a lokacin da tsofaffin duwatsun felsic da suka tsira suka fara fitowa. Saboda marubutan sun yi amfani da ƙananan iyakokin zafi, babban sakamakon yana da ɗan juriya ga canje-canjen zato, amma ainihin lambobi ba su da tabbaci sosai. Wannan **ƙaƙƙarfan samfurin farkon Duniya ne, ba kallo kai tsaye ga Hadean ba**.

Bincike ba tare da ƙarin gishiri ba

Abin da takardar ta nuna: A simulations masu tushe a kimiyyar zahiri waɗanda suka haɗa zafin bugun duwatsun sararin samaniya da ɗaukar zafi ta magma, ɓawon Hadean ya fito siriri kuma yana narkewa a zurfin kilomita kaɗan. Zafin bugun ya fi zafin cikin Duniya tasiri, yawancin ɓawon kuma yana sake zagayawa cikin mantle; a cikin wannan

samfurin, yanayin bai dace da plate tectonics ba.

Abin da yake yiwuwa amma ba a tabbatar ba: Bugun duwatsun sararin samaniya ne ya taimaka wajen ƙayyade lokacin da ɓawon nahiyoyi mai ɗorewa ya fara bayyana; Hadean ya kasance duniya mai murfi marar motsi ko mai laushi maimakon plate tectonics; kuma kusan duk duwatsun Hadean sun ɓace ne saboda ɓawon da ya narke yana sake zagayawa cikin mantle.

Abin da binciken bai nuna ba: Ma'auni kai tsaye na ɓawon Hadean; amsa ta ƙarshe ga muhawarar plate tectonics; tabbataccen dalili da sakamako tsakanin raguwar bugun da bayyanar nahiyoyi; cewa zircon na Jack Hills nahiyoyi ne da suka tsira; ko cikakken samfurin farkon Duniya.

Manyan iyakoki: Kundin duwatsun Hadean yana da matuƙar ƙaranci, don haka sakamakon ya dogara da jerin samfura — yawan bugun → geodynamics → daidaiton narkewar dutse. Samfurin yawan bugun kansa zaɓi ne mai yiwuwa amma ba shi kaɗai ba. Simulations ɗin kuma an sauƙaƙa su zuwa bayanan 1D da yankan 2D da aka ɗauka a lokuta kaɗan. Zato masu taka-tsantsan suna ƙarfafa babban sakamakon, amma ba su sa ainihin geotherm ko kaurin ɓawon ya zama tabbatacce ba.

Yawan amincewar da ya dace ga mai karatu na gama gari: Babba cewa, a ƙarƙashin waɗannan ka'idojin zahiri masu yiwuwa, farkon Duniya da ake ta bugawa zai kasance da ɓawo mai zafi, siriri kuma yana narkewa kusa da saman ƙasa. Matsakaici cewa wannan yana sa plate tectonics a Hadean ya zama mai wuya kuma yana iya bayyana ɓacewar kundin duwatsu. Ƙasa ga duk wani ikirari cewa binciken ya tabbatar yadda nahiyoyi suka samu ko ainihin lokacin da hakan ya faru.

Majiyoyi

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