The geological record following the c. 2.3 billion years old Great Oxidation Event includes evidence for anomalously high burial of organic carbon and the emergence of widespread mountain building. Both carbon burial and orogeny occurred globally over the period 2.1 to 1.8 billion years ago. Prolific cyanobacteria were preserved as peak black shale sedimentation and abundant graphite. In numerous orogens, the exceptionally carbonaceous sediments were strongly deformed by thrusting, folding, and shearing. Here an assessment of the timing of Palaeoproterozoic carbon burial and peak deformation/metamorphism in 20 orogens shows that orogeny consistently occurred less than 200 million years after sedimentation, in a time frame comparable to that of orogens through the Phanerozoic. This implies that the high carbon burial played a critical role in reducing frictional strength and lubricating compressive deformation, which allowed crustal thickening to build Palaeoproterozoic mountain belts. Further, this episode left a legacy of weakening and deformation in 2 billion year-old crust which has supported subsequent orogenies up to the building of the Himalayas today. The link between Palaeoproterozoic biomass and long-term deformation of the Earth’s crust demonstrates the integral relationship between biosphere and lithosphere.
Orogeny involves the building of mountains by plate tectonic processes in which the lithosphere is deformed under compression. Several lines of evidence mark the Palaeoproterozoic as the time when mountain building commenced in the forms which have continued to the present day. This is evident in a rapid increase in the frequency of collisional orogens, an increase in the preservation of continental crust as recorded by the earliest large lateral plate motions, the earliest global subduction network at 2 Ga, the predominance of steep subduction zones, and the first appearance of ophiolites about 2 Ga. The Palaeoproterozoic also saw a marked increase in the biomass in the oceans, and consequent burial of organic carbon in the crust, which are recorded in the geochemical anomalies of the Lomagundi-Jatuli and Shunga events. The earliest Palaeoproterozoic carbon burial occurred at the passive margins of fragmenting supercratons as plate tectonics emerged. The increase in abundance may have been a unique response to the c. 2.3 Ga Great Oxidation Event (GOE), and/or a series of regional responses to widespread igneous activity that provided increased nutrients. The result was prolific oxygen-tolerant cyanobacteria that left globally widespread carbon-rich sediment. The additional carbon allowed easier deformation of the crust, in a manner that built mountain belts, and thereby plate margins characteristic of modern plate tectonics.

Results and discussion
Lubricating the growth of orogens: organic matter and mountain building. The formation of plate margins, where orogens develop, is enhanced by sediment, which confers low strength. Wet sediment and metasediment increase the lubrication of subduction. Sediment containing carbonaceous matter is particularly effective in allowing deformation to occur, due to the ductile nature of organic-rich shales, overpressure weakening due to maturation of organic matter, and metamorphism to low-friction graphite. Sediments rich in organic matter are relatively common in collisional orogens due to the incorporation of thrust platform sequences. Consequently, numerous studies identify organic material as a critical control on the weakening of faulted rocks in orogens. Only small amounts (few%) of carbon are required to dominate the frictional strength of the rock and allow seismic slip. Upon graphitization of the carbon, the frictional strength is further reduced to about 0.3 times the normal stress for carbonaceous pelitic rocks. Critically, low frictional strength enhances thrust-stacking in collisional orogens, thus promoting crustal thickening during mountain building.

Direct evidence for the deformation potential of highly carbonaceous rocks in orogens is found in an examination of major detachment surfaces in the younger Phanerozoic record. Twenty examples of thrust detachments that supported orogenic deformation (10 s to 100 s km extent), aged Cambrian to Paleogene, are consistently facilitated by shales containing a few percent TOC (Supplementary Table 1). The critical importance of this high level of organic carbon concentration to allow deformation is evident in a data set of Devonian shales (n = 102), where shearing occurred in shales with mean TOC 2.8%, while no shearing occurred in shales with mean TOC 1.4%. When highly carbonaceous rocks occur on a global basis, their contribution to orogenic deformation is similarly widespread. Following the oceanic anoxic events of the Cretaceous, the resultant black shales became detachment surfaces in numerous orogens including in the Rockies, the Andes, Svalbard, central Europe, Indonesia, and Japan (Supplementary Table 1).

Given the link between organic matter and deformation evident in younger rocks, the scene was set for collisional orogenesis at ~2 Ga (Fig. 1) by the exceptional accumulation of...
organic carbon during the mid-Palaeoproterozoic (Figs. 1, 2). Abundant carbon is evident from a peak in black shale deposition24, and from the record of the world’s richest (highest % TOC) graphite deposits25. The maximum carbon contents in carbonaceous rocks in the Palaeoproterozoic orogens are consistently above 10%, and many are above 20% (Table 1). These values are much greater than typical values for carbonaceous rocks in Phanerozoic orogens (Supplementary Table 1). Most of the richest graphite deposits are Palaeoproterozoic25.

The marine cyanobacteria that are assumed to be responsible for enhanced carbon burial underwent several important developments following the GOE. Cyanobacteria became larger after the GOE, up to 50 µm diameter from <3 µm previously, and then developed sheaths26, potentially increasing the mass of cellular carbon that was buried. A 10 µm diameter cell has about 25 times as much carbon as a 2.5 µm cell, based on established relationships27. At this range of cell sizes, larger phytoplankton cells would also settle through the water column significantly faster, and would be more likely to flocculate8. This would enhance the burial of carbon by restricting the time when oxidation could occur28.

In many cases, the carbonaceous sediments were accompanied by platform limestones. The stromatolite record shows a peak at ~1.9 Ga, consistent with widespread sedimentation on broad shallow platforms29. The passage of anomalous quantities of carbonate into subduction zones at this time is recorded by widely distributed carbonatites in Palaeoproterozoic orogens30,31. The abundant carbonate would have further reduced friction in the Palaeoproterozoic crust32. Supracrustal sediments engender thin-skinned tectonics, which is characterized by high degrees of crustal shortening22,33. The wide distribution of supracrustal sediments deposited at ~2.0 Ga was therefore available to confer a high degree of shortening to the immediately subsequent orogens.

Palaeoproterozoic orogens: widespread mountain building.
A peak in orogenesis during the Palaeoproterozoic at ~2 Ga is marked by a large number of individual orogens34, the overall preserved orogen length34, and a high incidence of metamorphism35. The first widespread formation of high mountains is inferred at this time, from a peak in the production of S-type granites from 1.95-1.65 Ga and a high incidence of metamorphic rocks36.

Global deformation of the Palaeoproterozoic lithosphere is shown by the response to abundant carbon in numerous individual orogens. Twenty orogens with very highly carbonaceous rocks, of Palaeoproterozoic age distributed worldwide (Fig. 1), each record deformation focussed in pelitic/graphitic metasediments, including thrusting, imbrication, isoclinal folding, and shear zones that characterise crustal shortening (Table 1, Supplementary Note 1). The maximum period between sedimentation and deformation in the Palaeoproterozoic data set (measured from the onset of sedimentation to end of orogeny) was mostly less than 200 Myr, notwithstanding uncertainties in dating (Fig. 3; Table 1). The period ranges from 60 to 120 Myr for five orogens in North America, where more age data is available, suggesting that this is a good guide to typical times for consumption of oceanic lithosphere in the Palaeoproterozoic.

Most subducting lithosphere today is Late Cretaceous or younger, with a mean age of about 65 Ma37, and the time interval between Phanerozoic shale sedimentation and orogeny is usually less than 200 Myr and often less than 100 Myr (Supplementary Table 1). The consumption of seafloor sediment in the Palaeoproterozoic was, thus, at a similar rate to today, which has several implications. The similarity is consistent with the establishment of global subduction, and cycling of carbon via subduction zones.

Fig. 2 Occurrence of carbonaceous sediment and orogeny through time. Sediments (curves coloured blue) were recorded by graphite deposits weighted by mean carbon content25, the abundance of black shales24, and stromatolite occurrences as a measure of carbonate platform abundance25. Orogeny (curves coloured red) was recorded by the incidence of metamorphism35, abundance of orogens dated by the onset of deformation22, and preserved length of orogens34. Peak occurrence in sediment input coincides with a peak in orogenic activity, emphasized by the toned bar at 2.0 to 1.8 Ga.
Table 1 Carbon contents of carbonaceous units which accommodated deformation in orogens.

| Orogen (age t₀)                      | Carbonaceous Unit (age tₐ)                      | Maximum Δt (tₐ-t₀) | Carbon content                  |
|--------------------------------------|------------------------------------------------|--------------------|---------------------------------|
| Pine Creek Orogen, Australia (2.02-1.85 Ga) | Whites Fm. (2.02 Ga); Koolpin Fm. (1.88 Ga)   | 170 Myr            | Up to 10.4; 11.7 % TOC          |
| Kimban Orogen, Australia (1.85-1.70 Ga)   | Hutchison Group (1.87 Ga)                        | 170 Myr            | Up to 30 % TOC, Graphite ore    |
| Aravalli Orogen, India (1.8-1.74 Ga)      | Aravalli Supergroup (1.9-1.7 Ga)                 | 160 Myr            | Up to 15 % TOC, Graphite ore    |
| Trans-North China Orogen, China (1.95-1.85 Ga) | Khondalite belt (2.0-1.95 Ga)                   | 150 Myr            | Up to 30 % TOC, Graphite ore    |
| Jiao-Liao-Ji Orogen, China (1.94-1.86 Ga)  | Laode/Jingshan Groups (2.05-1.94 Ga)            | 190 Myr            | Graphite ore                    |
| Akritkan Orogen, Russia (2.0-1.91 Ga)     | Khaspian Group, Udokan Series (2.1-1.9 Ga)       | 190 Myr            | Up to 23 % TOC, Graphite ore    |
| Wopmay Orogen, Canada (1.9-1.8 Ga)        | Coronation Supergroup (1.88 Ga)                 | 80 Myr             | Up to 91 % TOC                  |
| Foxe Orogen, Canada (1.88-1.84 Ga)       | Piling Group, Bravo Lake Formation (1.92-1.89 Ga)| 80 Myr             | Up to 5.6 % TOC                 |
| Trans-Hudson Orogen, USA-Canada (1.83-1.79 Ga) | Kissenryan Gneiss (1.85-1.84 Ga)               | 60 Myr             | Graphite ore                    |
| Penokean Orogen, USA (1.89-1.82 Ga)      | Animike and Baraga Groups (1.88-1.83 Ga)        | 60 Myr             | Up to 44 % TOC                  |
| Tornagat Orogen, Canada (1.91-1.82 Ga)    | Tasiyak Gneiss (1.94-1.88 Ga)                    | 120 Myr            | Up to 30 % TOC, Graphite ore    |
| Nagssugtoidian Orogen, Greenland (1.88-1.83 Ga) | Siptorq Supracrustals (2.00-1.92 Ga)      | 170 Myr            | Up to 24 % TOC                  |
| Ketilidian Orogen, Greenland (1.85-1.80 Ga) | Sortis and Vallen Groups (2.0-1.9 Ga)           | 200 Myr            | Graphite ore                    |
| Lawfordian Orogen, UK (1.9-1.87 Ga)      | Lewisian supracrustals (2.0-1.9 Ga)             | 130 Myr            | Up to 97 % TOC                  |
| Svecofennian Orogen, Finland-Sweden-Norway (1.88-1.79 Ga) | Multiple graphic schists (1.91-1.88 Ga) | 120 Myr            | Up to 25 % TOC, Graphite ore    |
| East Sarmatian Orogen, Belarus (2.10-2.07 Ga) | Vorontssova series (2.24-2.10 Ga)              | 170 Myr            | Up to 18 % TOC, Graphite ore    |
| Birmanian Orogen, West Africa (2.18-2.06 Ga) | Lower Birmanian (2.19-2.10 Ga)                  | 90 Myr             | Up to 25 % TOC, Graphite ore    |
| Ebuneian Orogen, Gabon-Congo (2.04-2.0 Ga) | Ogoue complex, Francovillian (2.12-2.04 Ga)    | 120 Myr            | Up to 17 % TOC                  |
| Magondi Orogen, Zimbabwe (2.06-1.96 Ga)   | PinWiri Group (2.2-2.06 Ga)                     | 240 Myr            | Graphite ore                    |
| Minas Orogen, Brazil (2.1-2.01 Ga)       | Irapacera khondalites (2.08-2.07 Ga)            | 70 Myr             | Up to 35 % TOC, Graphite ore    |

TOC = Total Organic Carbon.
Data sources in Supplementary Note 1.

Fig. 3 Chronology of carbonaceous sediments and deformation in 20 Palaeoproterozoic orogens. Details in Table 1. The maximum interval between carbonaceous rocks (blue colour) and orogenic deformation (purple colour) is consistently <200 Myr, comparable to Phanerozoic orogens.
at ~2 Ga. As the carbon contents of the sediment were anomalously high in the Palaeoproterozoic, the flux of carbon into subduction zones was greater, and hence deformation could take place more readily than had been possible hitherto. As inferred above, an anomalous episode of global carbon concentration on the ocean floor can support deformation by decollement in multiple orogens within 100 Myr. The availability of abundant carbon on the Palaeoproterozoic seafloor therefore allowed widespread orogenesis, as occurred subsequently in the Phanerozoic. The increasing database of ages implies a consistent speed of subduction, which supports the inference that Palaeoproterozoic plate convergence occurred at a similar rate to the present day.

The 20 examples chosen are all collisional orogens, involving continent-continent collision, or they have a mixed accretionary and collisional history. The role played by carbonaceous rocks in contractional deformation is evident in cross-sections through Palaeoproterozoic orogenic belts, which show imbricate thrust slices detached in pelitic/graphitic sediments, often stacked near-vertically.

The role of graphitic sediments in mountain building. In at least fifteen of the twenty orogens in Fig. 1, the deformed rocks contain graphite ore bodies. In ore-grade graphite, the organic carbon content is very high, enriched above the levels in unaltered carbonaceous sediments. In some cases, enrichment is a consequence of the mobilization of organic carbon during deformation and metamorphism. In some other Palaeoproterozoic graphite deposits, carbon is added from mantle carbon dioxide or due to the metamorphic decarbonation of marbles. These alternatives can be distinguished by the carbon isotopic composition of the graphite, which would be relatively light or heavy, respectively. All of the twenty orogens have known isotopic compositions for their graphitic sediments, which are consistently light (Supplementary Note 1, Fig. 5), indicating a biological origin for the carbon in the orogens rather than from an abiotic source.
Evidence that the graphitic sediments localized and enhanced deformation takes two forms. Firstly, the concentration of graphite on shear surfaces is a direct consequence of carbon mobility during fault slip\textsuperscript{15–18}. In some cases (Fig. 4), there is evidence for structural thickening of the graphite due to local redistribution (e.g. in Kimban and Ketilidian orogens), and...
graphite is a noted component in subduction zones (e.g. in Trans-North China and Penokean orogens). Secondly, data from relatively young plate margins, including the Pacific rim\(^{40}\), show that fault slip in graphitic rocks can cause a decrease in order in the graphite structure. This so-called strain-induced amorphization of graphite\(^{19,40}\) is an exception to the assumed irreversibility of the graphitisation process. The anomalous disorder indicates a potential signature for graphite that facilitated deformation in the deep geological record. Graphite that had been involved in deformation could be less ordered (lower maturation and inferred palaeotemperature) than the background graphitic metasediment.

Spectroscopic data from graphite in several Palaeoproterozoic orogens\(^8,11-43\) including the Pine Creek Orogen (Australia), Birimian Orogen (Ghana), Minas Orogen (Brazil), and Svecofennian Orogen (Finland), distinguish between a component in the country rock representing metamorphosed organic matter, and a component in fault rocks which was mobilized from the country rock (Fig. 6). Exceptionally, the mobilized graphite in all four orogens is less ordered than the country rock, as deduced from standard measurements using Raman spectroscopy and/or X-ray diffraction, expressed as palaeotemperature-equivalents for comparison. The consistent pattern of disorder in mobilized carbon in fault rocks in the Palaeoproterozoic orogens strongly indicates that the carbon was directly involved in the Palaeoproterozoic deformation.

The long-term legacy of the Palaeoproterozoic. As the consequence of carbon burial in the Palaeoproterozoic seas was the incorporation of refractory graphite during orogenesis, much carbon became locked into the geological cycle. This left a legacy for mountain building through subsequent geological history. The properties that enhanced deformation and crustal shortening during the Palaeoproterozoic are just as likely to do so where 2 Gt sediments are present in much younger orogens. Accordingly, degrees of crustal shortening in Phanerozoic orogens are high where they are rooted in Palaeoproterozoic crust\(^22\). In the Himalayas, Palaeogene thrusting was focussed in the graphitic sediments of the ~2 Ga Lesser Himalaya Sequences, which had already focussed crustal shortening during the Palaeoproterozoic\(^44\). The intervening 2 Gyr record includes, for example, detachment on Palaeoproterozoic shale units during the 1.0 Ga Grenvillian Orogen in Labrador\(^45\) and the 0.43 Ga Caledonian Orogen in Norway\(^46\). Pressure-temperature (P-T) trajectories for Palaeoproterozoic granulitic metapelites (Fig. 7) reflect reactivation involving compositional uplift of the granulites, either during normal exhumation or during a younger orogenic event. Palaeoproterozoic pelites were reactivated during the main periods of orogenesis over the last 2 Gyr (Fig. 8, Table 2). The exceptional Palaeoproterozoic biomass was thus reflected not only in mountain building during the Palaeoproterozoic but also in mountain building ever since.

**Methods**

The relationship between carbon burial and plate margin deformation was evidenced by the review of data available in the published literature. The link was demonstrated in young (Phanerozoic) rocks using 20 case studies where detachment on organic-rich beds is documented. The case studies were characterised using the age of sedimentation, carbon contents of sediment, and age of deformation. The characterization was repeated for 20 Palaeoproterozoic orogens, with the additional documentation of organic carbon isotope composition to prove biogenicity. The periods between sedimentation and deformation were then compared between the Phanerozoic and Palaeoproterozoic data sets.

Strain composition of graphite was inferred using published spectroscopy data for carbonaceous matter in 4 Palaeoproterozoic orogens where components in the country rocks and remobilized in fault rocks were both available.

**Data availability**

The data tables used to produce the results of this article can be accessed at the National Geoscience Data Centre (https://doi.org/10.5285/d101a9c6-55f5-4a35-be6b-92a4eb76b38), entitled ‘Data tables for global Palaeoproterozoic black shales’, linked to NERC grant NE/M010953/1.

Received: 25 June 2021; Accepted: 22 October 2021; Published online: 26 November 2021

**References**

1. Abbott, D., Drury, R. & Smith, W. H. F. Flat to steep transition in subduction style. *Geology* **22**, 937–940 (1994).
2. Mitchell, R. N. et al. Plate tectonics before 2.0 Ga: evidence from paleomagnetism of cratons within supercontinent Nuna. *Amer. J. Sci.* **314**, 878–894 (2014).
3. Wan, B. et al. Seismological evidence for the earliest global subduction network at 2 Ga ago. *Sci. Adv.*, eabc5491 (2020).
4. Weller, O. M. & St-Onge, M. R. Record of modern-style plate tectonics in the Palaeoproterozoic Trans-Hudson orogen. *Nat. Geosci.* **10**, 305–311 (2017).
5. Condie, K. C. A planet in transition: the onset of plate tectonics on Earth between 3 and 2 Ga? *Geosci. Front.* **9**, 51–60 (2018).
6. Brown, M. & Johnson, T. Metamorphism and the evolution of subduction on Earth. *Amer. Min.* **104**, 1065–1082 (2019).
7. Martin, A. P. et al. Multiple Palaeoproterozoic carbon burial episodes and excursions. *Earth Planet. Sci. Letts.* **424**, 226–236 (2015).
8. Kamennyia, N. A. et al. High P CO2-induced exopolysaccharide-rich ballast aggregates of planktonic cyanobacteria could explain Palaeoproterozoic carbon burial. *Nat. Commun.* **9**, 2116 (2018).
9. Canfield, D. E. Carbon cycle evolution before and after the great oxidation of the atmosphere. *Amer. J. Sci.* **321**, 297–331 (2021).
10. Brown, M., Johnson, T. & Gardiner, N. J. Plate tectonics and the Archean–Palaeoproterozoic transition. *Amer. Min.* **108**, 76–96 (2020).
11. Eguchi, J., Seales, J. & Dasgupta, R. Great oxidation and lomagundi events linked by deep cycling and enhanced degassing of carbon. *Nat. Geosci.* **13**, 71–76 (2020).
12. Behr, W. M. & Becker, T. W. Sediment control on subduction plate speeds. *Earth Planet. Sci. Letts.* **502**, 166–173 (2018).
13. Sobolev, S. V. & Brown, M. Surface erosion events controlled the evolution of plate tectonics on Earth. *Nature* **570**, 52–57 (2019).
14. Morley, C. K. et al. Review of major shale-dominated detachment and thrust characteristics in the diagenetic zone: Part II, rock mechanics and microscopic scale. *Earth-Sci. Rev.* **176**, 19–50 (2018).
15. Butter, E. H. et al. Reduction of friction on geological faults by weak-phase smearing. *J. Struct. Geol.* **51**, 52–60 (2013).

**Table 2 Examples of reworking of Palaeoproterozoic metapelites during deformation in younger orogenies (Fig. 6).**

| Location   | Palaeoproterozoic Orogeny          | Younger Orogeny          |
|------------|-----------------------------------|--------------------------|
| East Africa| Ubendian (metapelites 1830–1820 Ma\(^{61}\)) | Kibaran (1180–1090 Ma\(^{61}\)) |
| Labrador   | New Quebec (metapelites 1.84–1.77 Ga) | Pan-African (570–550 Ma\(^{62}\)) |
| Northwest India | Aravalli (metapelites metamorphism 1.85 Ga\(^{63}\)) | Grenville (1010 Ma\(^{35}\)) |
| North Norway | Svecofennian/Svekokarelian (peak metamorphism 1850 Ma\(^{65}\)) | Delhi (~1000 Ma\(^{64}\)) |
| Central Australia | Strangways (sediments 1.82–1.78 Ga\(^{66}\); Subduction ~1.77 Ga) | Caledonian (430 Ma\(^{46}\)) |
| Korea      | Hwacheon Granulite Complex (metapelites 1.87 Ga\(^{53}\)) | Alice Springs (0.4–0.3 Ga\(^{57}\)) |
| Himalaya   | Wangtu (arc magmatism ~1.85 Ga\(^{68}\)) | Permoo-Triassic Collisional (240–225 Ma\(^{52}\)) |
|            |                                   | Himalayan (~50 Ma onwards\(^{68}\)) |
16. Ohashi, K., Hirose, T. & Shimamoto, T. Graphite as a lubricating agent in fault zones: an insight from low- to high-velocity friction experiments on a ZnO-modified graphite-sandstone composite. J. Geophys. Res. 118, 2067–2084 (2013).

17. Craw, D. & Upton, P. Graphite reaction weakening of fault rocks, and uplift of the Annapurna Himal, central Nepal. Geosphere 10, 720–731 (2014).

18. Luu, M., Cao, S., Neubauer, F., Li, J. & Cheng, X. Deformation fabrics and strain localization mechanisms in graphitic-bearing rocks from the Akihe Fault, Japan. J. Geophys. Res. 121, 3962–3981 (2016).

19. Cooper, C. M., Lenardic, A., Levander, A. & Moresi, L. Creation and preservation of cratonic lithosphere: seismic constraints and geodynamic models. Geophysical Monograph Series, Archean Geodynamics and Environments 164, 75–88 (2006).

20. Morehead, F., Watts, A. B. & Burov, E. Structure of orogenic belts controlled by lithospheric age. Nat. Geosci. 6, 785–789 (2013).

21. Enomoto, C. B., Coleman, J. L., Swezey, C. S., Niemeyer, P. W. & Dulong, F. T. Geochemical and mineralogical sampling of the Devonian shales in the Broadtop Synclinorium, Appalachian Basin, in Virginia, West Virginia, Maryland, and Pennsylvania. U.S.G.S. Open-File Report 2015-1061 (2015).

22. Condie, K. C., Des Marais, D. J. & Abbott, D. Precambrian superplumes and tectonic evolution of the Hwaechon Granulite Complex, Central Korea: Composite P-T path resulting from two distinct crustal-thickening events. J. Petrol. 44, 197–225 (2003).

23. Van Kranendonk, M. J. Tectonic evolution of the Paleoproterozoic Torngat Orogen: evidence from pressure-temperature-time deformation paths in the North River map area, Labrador. Tectonics 15, 843–869 (1996).

24. Keeling, J. Graphite: properties, uses and South Australian resources. MESA J. 84, 28–41 (2017).

25. Kaur, P., Zeh, A. & Chaudhri, N. Palaeoproterozoic continental arc in the North River map area, Labrador. Precamb. Res. 288, 56–78 (2017).

26. Skipton, D. R., St-Onge, M. R., Schneider, D. A. & McFarlane, C. R. M. Tectonomerothermal evolution of the middle crust in the Trans-Hudson Orogen, Baffin Island, Canada: Evidence from petrology and monazite geochronology of metagranitoids in the Mill Ameri granite. J. Petrol. 47, 1437–1462 (2006).

27. Childs, J. A. & Figueredo, C. C. Phytoplankton settling depends on cell size: evidence from the Late Mesoproterozoic of Tamaulipas, Mexico. Limnol. Ocean. 53, 1313–1334 (2008).

28. Xu, C. et al. Cold deep subduction recorded by remnants of a Paleoproterozoic carbonated slab. Nat. Commun. 9, https://doi.org/10.1038/s41467-018-01540-5 (2018).

29. Kurzawski, R. et al. Earthquake nucleation in weak subducted carbonates. Nature Geosci. 9, 717–722 (2016).

30. Pfeiffer, O. A. Thick-skinned and thin-skinned tectonics: a global perspective. J. Geol. 97, 677–697 (1989).

31. Condie, K. C. & Puetz, S. J. Time series analysis of mantle cycles Part II: The geologic record in zircons, large igneous provinces and mantle lithosphere. Geosci. Front. 10, 1327–1336 (2019).

32. Brown, M. & Johnson, T. Secular change in metamorphism and the onset of global plate tectonics. Amer. Min. 103, 181–196 (2018).

33. Zhu, Z., Campbell, T. H., Allen, C. M. & Burnham, A. D. S. T-type granites: their origin and distribution through time as determined from detrital zircons. Earth Planet. Sci. Lett. 536, 151140 (2020).

34. Seton, M. et al. A global data set of present-day oceanic crustal age and seafloor spreading parameters. Geochem. Geophys. Geosyst. 21, e2020GC003214 (2020).

35. Kribek, B. et al. The origin and hydrothermal mobilization of carbonaceous matter associated with Paleoproterozoic orogenic-type gold deposits of West Africa. Precambrian Research 270, 300–317 (2015).

36. Luque, F. J. et al. Vein graphite deposition: geological settings, origin, and economic significance. Mineral. Dep. 49, 261–277 (2014).

37. Nakamura, Y., Ohashi, K., Toshinoishi, T., Kato, M. & Aki, J. Strain-induced amorphization of graphite in fault zones of the Hidaka metamorphic belt, Hokkaido, Japan. J. Geophys. Res. 72, 142–161 (1967).

38. Mirasol-Robert, A. et al. Evidence and origin of different types of sedimentary organic matter associated with a Paleoproterozoic orogenic Au deposit. Precamb. Res. 299, 319–338 (2016).

39. Miranda, D. A., de Oliveira Chaves, A., Campello, M. S. & de Moraes Ramos, S. L. L. Origin and thermometry of graphites from Itapecerica supracrustal succession of the southern São Francisco Craton by C isotopes, X-ray diffraction, and Raman spectroscopy. Int. Geol. Rev. 61, 1864–1875 (2019).

40. Prando, F. et al. Fluid-mediated brittle-ductile deformation at seismic deformation front Part 2: stress history and fluid pressure variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland). Solid Earth 11, 489–511 (2020).

41. Saha, D. Lesser Himalayan sequences in Eastern Himalaya and their deformation: Implications for Paleoproterozoic tectonic activity along the Ophiolite Belt. J. Geol. Front. 4, 289–304 (2013).

42. Van Gool, J. A. M., Rivers, T. & Calon, T. Grenville front zone, Gagnon terrane, southwestern Labrador: configuration of a midcrustal foreland fold-thrust belt. Tectonics 27, TC1004 (2008).

43. Torgersen, E., Viola, G. & Sandstad, J. S. Revised structure and stratigraphy of the Arkose Frontal Thrust Tectonic Window, northern Norway. Norw. J. Geol. 95, 397–421 (2015).

44. Furnes, H., de Wit, M. & Dilek, Y. Precambrian greenstone belts host different ophiolite types. In: Dilek, Y. & Furnes, H. (eds.) Evolution of Archean Crust and Early Life. Modern Approaches in Solid Earth Sciences 7, Springer Science, Dordrecht, https://doi.org/10.1007/978-94-007-7613-9_1 (2014).

45. Torgersen, E. & Frontal thrust of Waypapa Orogen, Taku lake map area, District of Mackenzie. Current Research, Part A, Geological Survey of Canada, Paper 82-1A, 119–122 (1982).

46. Trelaž, P. J. The geological evolution of the Magondi mobile belt, Zimbabwe. Precamb. Res. 38, 55–73 (1988).

47. Lucas, S. B. & Byrne, T. Footwall involvement during arc-continent collision, Ungava orogeny, northern Canada. J. Geol. Soc. Lond. 149, 237–248 (1992).

48. Tirrul, R. Frontal thrust zone of Wopmay Orogen, Takijuq lake map area, Northwest Territories, Canada, U.S.G.S. Open-File Report 2015-1061 (2015).

49. Kaur, P., Zeh, A. & Chaudhri, N. Palaeoproterozoic continental arc in the North River map area, Labrador. Precamb. Res. 288, 56–78 (2017).

50. Bendaou, A. et al. Geochronology and metamorphic P-T-X evolution of the Ebenee granulite-facies metametapelites of Tidjouenine (Central Hoggar, Algeria); witness of the LATEA metacratonic evolution. Geol. Soc. Lond. Spec. Pubs. 297, 111–146 (2008).

51. Keeling, J. Graphite: properties, uses and South Australian resources. MESA J. 84, 28–41 (2017).

52. Boniface, N., Schenk, V. & Appel, P. Paleoproterozoic eclogites of MORB-type chemistry and three Proterozoic orogenic belts in the Uibelend Belt (Tanzania): Evidence from monazite and zircon geochronology, and geochemistry. Precamb. Res. 192-195, 16–33 (2012).

53. Coelho, R. M. & de Oliveira Chaves, A. Pressure-temperature-time evolution of Paleoproterozoic khalduites from Claudio shear zone (southern São Francisco craton, Brazil): Links with khlandite belt of the North China craton. J. South Amer. Earth Sci. 94, 102250 (2019).

54. Treloar, P. J. The geological evolution of the Magondi mobile belt, Zimbabwe. Precamb. Res. 38, 55–73 (1988).

55. Kribs, B. et al. Neoproterozoic reworking of the Ubendian Belt crust: New constraints from in situ zircon U-Pb-Hf isotope geochronologic evidence from the Paleoproterozoic Nussir Deposit, Finnmark, Arctic Norway. Precambrian Research 298, 208–225 (2015).
Acknowledgements
The work was partially supported by NERC grant NE/M010953/1. The manuscript benefited by advice from Michael Brown and Ross Mitchell.

Author contributions
Data were collated and interpreted by J.P. and C.B. Both authors have contributed to the paper, written by J.P.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-021-00313-5.

Correspondence and requests for materials should be addressed to John Parnell.

Peer review information Communications Earth & Environment thanks Michael Brown and Ross Mitchell for their contribution to the peer review of this work. Primary Handling Editors: João Duarte, Joe Aslin, Heike Langenberg. Peer reviewer reports are available.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2021