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Peer Review File

Increased biomass and carbon burial 2 billion years ago triggered mountain building

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

3rd Sep 21

Dear Dr. Parnell,

Please allow me to apologise for the delay in sending a decision on your manuscript titled "Elevated biomass at 2 Ga triggered mountain building". It has now been seen by 2 reviewers, and I include their comments at the end of this message.

As you will see, they find your work novel and of interest to the geosciences community, and provide some relatively minor suggestions for improvements that we would like you to address. I fully agree with the reviewers and we are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

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We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Joao Duarte, PhD
Editorial Board Member

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Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review of: COMMSENV-21-0396-T

By: Michael Brown

This paper proposes that increase in carbon in passive margin sedimentary sequences consequent upon the GOE facilitated Paleoproterozoic mountain building. I found the paper novel and of interest; it should be of interest to the community at large. The study is convincing and the paper will influence conceptual understanding about mountain building processes.

My comments below are keyed by page/line number (I converted the pdf to a Word docx file; the pages/lines do not match perfectly, but a copy of the docx file is appended).

2/1-3. The first two sentences are highly unlikely to be correct (indeed, your own Figure 3 shows collision occurring before or by 2.1 Ga). It is the breakup of several supercratons in the early Paleoproterozoic that provide the passive margins along the trailing edges of cratons where organic carbon was buried prior to incorporation in the collisional orogens that suture Nuna and, eventually, Columbia. So, the logic must be that plate tectonics (i.e. a fragmented rigid lithosphere and a network of weak plate boundaries, with motion driven by stable subduction) had emerged by, say, c. 2.2 Ga or slightly earlier. The diachronous stabilization of cratons from c. 3.1 to c. 2.4 Ga or so and the 'mixed' signals in various geological datasets during that period suggest (to this reviewer) that the period down to c. 2.4 Ga or so was one of transition from the pre-plate tectonics mode to the present (global) plate tectonics mode (consistent with the (slightly tongue-in-cheek) 1 Ga transition proposed by Bercovici and Ricard, 2014, Nature). See Brown et al., 2020, AnnRevEarthPlanetSci, for discussion. I doubt that supercraton breakup, stable subduction and craton drift have anything (much) to do with the rise of oxygen, but these steps must precede (even if not by much) the consequent burial of organic carbon.

2/15 Suggest delete "continental"

2/17 Suggest delete "plate tectonics, and" (or modify with an addition sentence)

2/19 Take care with "an increase in the production of continental crust as recorded by zircon ages"! First, the oldest (double) peak in zircon ages is in the Neoarchean. Second, the debate about production vs preservation goes back to Hawkesworth et al., 2009, Science, and is not resolved. I suggest you simply leave out this clause.

2/21-22 In the references, Weller & St Onge is a study of a single eclogite boudin (it is set in a global context in their Figure 6 using the dataset of Brown, 2014). So, similar to the compilation of seismic images from multiple orogens by Wan et al., 2020, a reference to the most recent global dataset and discussion would be more appropriate (Brown and Johnson, 2019, American Mineralogist).

2/28 Plate tectonics must precede the development of high biomass (discussed above).

4/5 To avoid duplication, I would replace the first use of "exceptional" with "collisional"

4/25 Suggest "marble" --> "carbonate"

5/10 Figure 5G in Zhu et al. is based on the dataset of Brown and Johnson (2019, Mineralogical Magazine), and the peak in the 30 pt moving mean in the Paleoproterozoic is determined by 2 outliers at 7 GPa. These are 2 of 4 data that record low T/P conditions (i.e. blueschists, low-T eclogites and UHP metamorphism) prior to the late Tonian, and low T/P metamorphism relates to subduction rather than to collision. The moving mean of P for collision-related metamorphism is shown in the top panel of Figure 11 in Brown and Johnson (2019, Mineralogical Magazine). There is an gradual increase of P in the Paleoproterozoic.

6/2-4 Widespread orogeny is driven by plate tectonics that amalgamated the cratons into Nuna and, eventually, Columbia. The modern style of orogenesis is facilitated by the "abundant carbon"!

8/6-10. This is an overinterpretation of the data that this reviewer cannot follow. Of the 7 localities for which P-T paths are shown in Supp. Fig. 6, only 2 appear to involve a younger event (Korea and Algeria). Of the other 5, 4 show P-T paths consistent with 'normal' rates of exhumation for the Paleoproterozoic, but I could not confirm the 5th (Trans-Hudson), which does not seem to come from the reference quoted (Skipton et al., 2017). This figure does not seem to provide strong support for the point the authors are trying to make.

Reviewer #2 (Remarks to the Author):

COMMSENV-21-0396-T
Parnell and Brolly
CEE

Review by Ross N. Mitchell, Ph.D. ross.mitchell@mail.iggcas.ac.cn

The authors claim a peak in marine biomass at ca. 2.1–2.0 Ga (Lomgagundi–Jatulit positive d13C excursion and shungite deposits to follow) helped facilitate the immediately subsequent impressive orogenic peak of the Orosirian Period. Although I was compelled by the spatiotemporal link between the carbon-rich seds indeed showing up as graphite in Orosirian orogens, I initially had my doubts about their being a causal links between the two phenomena. But the authors have won me over in their diligent approach to testing their fascinating hypothesis and any way they can think of. Surely others will find other means to do so upon reading this intriguing work once it is published.

This is a fascinating and well-executed paper that should be published as soon as possible. The authors build off their recent compilation work (Parnell+21_Geo-Mag) to devise an incredible hypothesis. Unbelievably, they even seem to back it up with impressive knowledge of the relevant literature and exposition in effective figures and tables. I have made edits in the annotated PDF that hopefully improve the otherwise already excellent paper. My recommendation is thus to accept pending minor revisions. Some additional suggestions that might improve the paper are offered below too.

The abstract is good, but I'm not sure it does full justice to the depth of research the authors have done into the specific feasibility of the mechanism they propose. I know you want to be as broad/general as possible, but for those who will be immediately skeptical that spatiotemporal link doesn't mean a causative link (I had by doubts at first too!), a little more "meat on the bone" upfront might be nice. Consider editing the abstract a bit.

Figure 2: The time axis in figure 2 runs the opposite way to those in Figures 3 and 4 and it should be consistent. I personally prefer adopting the time moving forward to the right as in Figures 3 and 4.

Figure 3: To make a stronger visual link between the sediment and orogen phase for each place, I'd recommend leaving no space between these two bars for each place (i.e., red right below blue without any space between the two records for each place).

Supp Figure 3: Neat figure. quite convincing. if not published before, perhaps consider including in the main text?

Supp Figure 5: To make a stronger visual link between the two sources for each place, I'd recommend leaving no space between these two bars for each place (i.e., red right below black without any space between the two records for each place).

Elevated biomass at 2 Ga triggered mountain building

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The geological record following the c. 2.3 Ga Great Oxidation Event includes evidence for an anomalously high burial of organic carbon, and the emergence of modern plate tectonics. Both occurred globally over the period 2.1 to 1.8 Ga. In numerous orogens, highly carbonaceous sediments focussed deformation by thrusting, folding and shearing. Here an assessment of the timing of Palaeoproterozoic carbon burial and peak deformation/metamorphism shows that orogeny consistently occurred less than 200 Myr after sedimentation, in a time frame comparable to that of orogens through the Phanerozoic. This implies that the high carbon burial played a key role in lubricating compressive deformation, and it allowed the crustal thickening that built Palaeoproterozoic mountain belts. Further, this episode left a legacy of weakening and deformation in 2 Gyr-old crust, which has supported orogeny up to the building of the Himalayas today.

Orogeny involves the building of continental mountains by plate tectonic processes in which the lithosphere is deformed under compression. Several lines of evidence mark the Palaeoproterozoic as the time when plate tectonics, and mountain building, commenced in the form which has continued to the present day. This is evident in a rapid increase in the frequency of collisional orogens, an increase in the production of continental crust as recorded by zircon ages, 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 (Abbott et al. 1994, Weller & St-Onge 2017, Condie 2018, Wan et al. 2020). The Palaeoproterozoic also saw a marked increase in the biomass in the oceans, and consequent burial of organic carbon in the crust (Martin et al. 2015, Kamennaya et al. 2018). This may have been a unique response to the c. 2.3 Ga Great Oxidation Event (GOE), or a series of regional responses to widespread igneous activity that provided increased nutrients (Martin et al. 2015). The result was prolific oxygen-tolerant cyanobacteria that left globally widespread carbon-rich sediment. An analysis of the time interval between burial of organic carbon and orogeny indicates that the developments of high biomass and plate tectonics are linked. 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.

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 (Behr & Becker 2018, Sobolev & Brown 2019). 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 (Morley et al. 2018). Sediments rich in organic matter are relatively common in collisional orogens due to the incorporation of thrusted platform sequences (Morley et al. 2018). Consequently, numerous studies identify organic material as a critical control on the weakening of faulted rocks in orogens (Rutter et al. 2013, Oohashi et al. 2013, Craw & Upton 2014, Lyu et al. 2020). Only small amounts (few %) of carbon are required to dominate the frictional strength of the rock and allow seismic slip (Kaneki & Hirono 2019). Upon graphitization of the carbon the frictional strength is further reduced to about 0.3 times the normal stress for carbonaceous pelitic rocks (Yamasaki et al. 2016). Critically, low frictional strength enhances thrust-stacking in collisional orogens (Cooper et al. 2006), i.e. it allows crustal thickening during mountain building (Mouthereau et al. 2013).

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 (10s to 100s 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 % (Enomoto et al. 2015). 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 exceptional 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 deposition (Condie et al. 2001), and from the record of the world's richest (highest % TOC) graphite deposits. 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). 28 of the richest 33 graphite deposits are Palaeoproterozoic (Parnell et al. 2021; Supplementary Fig. 1, Supplementary Table 3).

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 sheaths (Sánchez-Baracaldo 2015), 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 relationships in Mullin 1966). At this range of cell sizes, larger phytoplankton cells would also settle through the water column significantly faster and thereby enhance survival of oxidation to bury more carbon (Chindia & Figueredo 2018).

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 platforms (Condie et al. 2000). The passage of anomalous quantities of carbonate into subduction zones at this time is recorded by widely distributed carbonatites in Palaeoproterozoic orogens (Xu et al. 2018). The abundant marble would have further reduced friction in the Palaeoproterozoic crust (Supplementary Fig. 2). Supracrustal sediments engender thin-skinned tectonics, which is characterized by high degrees of crustal shortening (Mouthereau et al. 2013). 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 orogens (Condie & Puetz 2019), the overall preserved orogen length (Condie & Puetz 2019), and a high incidence of metamorphism (Brown & Johnson 2018). 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 an anomalously high peak pressure of metamorphic rocks (Zhu et al. 2020).

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 Table 2). The maximum period between sedimentation and deformation in the Palaeoproterozoic data set (measured from 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 consumption times in the Palaeoproterozoic. Most subducting lithosphere today is Late Cretaceous or younger, with a mean age of about 65 Ma, and the time interval between Phanerozoic shale sedimentation and orogeny is usually less than 200 Myr and often less than 100 Myr (Supplementary Table 2). The consumption of sea floor 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, at ~2 Ga (Wan et al. 2020). 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 sea floor therefore created the opportunity for widespread orogeny. Less direct measurements (palaeomagnetism, palaeogeography) suggest that plate speeds have increased over the last 2 billion years (Condie et al. 2015), but the increasing database of ages implies a consistent speed of subduction.

The 20 examples chosen are all collisional orogens, i.e. they involved continent-continent collision, or they have a mixed accretionary and collisional history (Condie & Puetz 2019). 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 (Supplementary Fig. 3).

The role of graphitic sediments

In at least fifteen of the twenty orogens in Figure 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 (e.g. Kribek et al. 2015). In some other Precambrian graphite deposits, carbon is added from mantle carbon dioxide or due to the metamorphic decarbonation of marbles (Luque et al. 2014). These alternatives can be distinguished by the carbon isotopic composition of the graphite, which would be relatively light or heavy respectively (Luque et al. 2014). All of the twenty orogens have known isotopic compositions for their graphitic sediments, which are consistently light (Table 1, Supplementary Fig. 4), 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 (Rutter et al. 2013, Oohashi et al. 2013, Craw & Upton 2014, Lyu et al. 2020). In some cases 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 (Nakamura et al. 2015), 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 (Nakamura et al. 2015, Kaneki & Hirono 2019) 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 (Kribek et al. 2015, Mirasol-Robert et al. 2017, Miranda et al. 2019, Prando et al. 2020), 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 (Supplementary Fig. 5). 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 Ga sediments are present in much younger orogens. Accordingly, degrees of crustal shortening in

Phanerozoic orogens are high where they are rooted in Palaeoproterozoic crust (Mouthereau et al. 2013). 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 (Saha 2013). The intervening 2 Gyr record includes, for example, detachment on Palaeoproterozoic shale units during the 1.0 Ga Grenvillian Orogeny in Labrador (van Gool et al. 2008) and the 0.43 Ga Caledonian Orogeny in Norway (Torgersen et al. 2015). Pressure-temperature (P-T) trajectories for Palaeoproterozoic granulitic metapelites (Supplementary Fig. 6) reflect reactivation involving compressional uplift and exhumation of the granulites, and show that Palaeoproterozoic pelites were reactivated during the main periods of orogenesis over the last 2 billion years (Fig. 4, Supplementary Table 4). The exceptional Palaeoproterozoic biomass was reflected not only in mountain building during the Palaeoproterozoic but ever since.

Acknowledgements

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Author contributions

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

Competing interests

The authors declare no competing interests

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Figure 1. **Palaeoproterozoic orogens, distributed globally, exhibiting significant deformation within highly carbonaceous rocks**. Orogenies all commenced 2.1 to 1.8 Ga. Details in Table 1.

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Figure 4. **Reactivation of Palaeoproterozoic pelites during younger orogenies**. Pelites deformed during subduction-related collision in the Palaeoproterozoic were deformed further during younger continental collision, particularly during episodes of widespread orogenesis (measured by Condie & Puetz 2019). Details of orogenies in Supplementary Table 4.

Elevated biomass at 2 Ga triggered mountain building

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The geological record following the c. 2.3 Ga Great Oxidation Event includes evidence for ~~an~~ anomalously high burial of organic carbon, and the emergence of ~~modern plate tectonics,~~ Both occurred globally over the period 2.1 to 1.8 Ga. In numerous orogens, highly carbonaceous sediments focussed deformation by thrusting, folding and shearing. Here an assessment of the timing of Palaeoproterozoic carbon burial and peak deformation/metamorphism shows that orogeny consistently occurred less than 200 Myr after sedimentation, in a time frame comparable to that of orogens through the Phanerozoic. This implies that the high carbon burial played a key role in lubricating compressive deformation, and it allowed the crustal thickening that built Palaeoproterozoic mountain belts. Further, this episode left a legacy of weakening and deformation in 2 Gyr-old crust, which has supported orogeny up to the building of the Himalayas today.

Orogeny involves the building of continental mountains by plate tectonic processes in which the lithosphere is deformed under compression. Several lines of evidence mark the Palaeoproterozoic as the time when plate tectonics, and mountain building, commenced in the form which has continued to the present day. This is evident in a rapid increase in the frequency of collisional orogens, an increase in the ~~production~~ of continental crust as recorded by zircon ages, 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 (Abbott et al. 1994, Weller & St-Onge 2017, Condie 2018, Wan et al. 2020). The Palaeoproterozoic also saw a marked increase in the biomass in the oceans, and consequent burial of organic carbon in the crust (Martin et al. 2015, Kamennaya et al. 2018). This may have been a unique response to the c. 2.3 Ga Great Oxidation Event (GOE), or a series of regional responses to widespread igneous activity that provided increased nutrients (Martin et al. 2015). The result was prolific oxygen-tolerant cyanobacteria that left globally widespread carbon-rich sediment. An analysis of the time interval between burial of organic carbon and orogeny indicates that the developments of high biomass and plate tectonics are linked. 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.

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 (Behr & Becker 2018, Sobolev & Brown 2019). 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 (Morley et al. 2018). Sediments rich in organic matter are relatively common in collisional orogens due to the incorporation of thrusted platform sequences (Morley et al. 2018). Consequently, numerous studies identify organic material as a critical control on the weakening of faulted rocks in orogens (Rutter et al. 2013, Oohashi et al. 2013, Craw & Upton 2014, Lyu et al. 2020). Only small amounts (few %) of carbon are required to dominate the frictional strength of the rock and allow seismic slip (Kaneki & Hirono 2019). Upon graphitization of the carbon the frictional strength is further reduced to about 0.3 times the normal stress for carbonaceous pelitic rocks (Yamasaki et al. 2016). Critically, low frictional strength enhances thrust-stacking in collisional orogens (Cooper et al. 2006), ~~i.e. it allows~~ crustal thickening during mountain building (Mouthereau et al. 2013).

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 (10s to 100s 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 % (Enomoto et al. 2015). 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 exceptional 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 deposition (Condie et al. 2001), and from the record of the world's richest (highest % TOC) graphite deposits. 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). 28 of the richest 33 graphite deposits are Palaeoproterozoic (Parnell et al. 2021; Supplementary Fig. 1, Supplementary Table 3).

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 sheaths (Sánchez-Baracaldo 2015), 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 relationships in Mullin 1966). At this range of cell sizes, larger phytoplankton cells would also settle through the water column significantly faster and thereby enhance survival of oxidation to bury more carbon (Chindia & Figueredo 2018).

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 platforms (Condie et al. 2000). The passage of anomalous quantities of carbonate into subduction zones at this time is recorded by widely distributed carbonatites in Palaeoproterozoic orogens (Xu et al. 2018). The abundant marble would have further reduced friction in the Palaeoproterozoic crust (Supplementary Fig. 2). Supracrustal sediments engender thin-skinned tectonics, which is characterized by high degrees of crustal shortening (Mouthereau et al. 2013). 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 orogens (Condie & Puetz 2019), the overall preserved orogen length (Condie & Puetz 2019), and a high incidence of metamorphism (Brown & Johnson 2018). 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 an anomalously high peak pressure of metamorphic rocks (Zhu et al. 2020).

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 Table 2). The maximum period between sedimentation and deformation in the Palaeoproterozoic data set (measured from 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 consumption times in the Palaeoproterozoic. Most subducting lithosphere today is Late Cretaceous or younger, with a mean age of about 65 Ma, and the time interval between Phanerozoic shale sedimentation and orogeny is usually less than 200 Myr and often less than 100 Myr (Supplementary Table 2). The consumption of sea floor 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, at ~2 Ga (Wan et al. 2020). 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 sea floor therefore created the opportunity for widespread orogeny. Less direct measurements (palaeomagnetism, palaeogeography) suggest that plate speeds have increased over the last 2 billion years (Condie et al. 2015), but the increasing database of ages implies a consistent speed of subduction.

The 20 examples chosen are all collisional orogens, i.e. ~~they involved~~ continent-continent collision, or they have a mixed accretionary and collisional history (Condie & Puetz 2019). 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 (Supplementary Fig. 3).

The role of graphitic sediments

In at least fifteen of the twenty orogens in Figure 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 (e.g. Kribek et al. 2015). In some other Precambrian graphite deposits, carbon is added from mantle carbon dioxide or due to the metamorphic decarbonation of marbles (Luque et al. 2014). These alternatives can be distinguished by the carbon isotopic composition of the graphite, which would be relatively light or heavy respectively (Luque et al. 2014). All of the twenty orogens have known isotopic compositions for their graphitic sediments, which are consistently light (Table 1, Supplementary Fig. 4), 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 (Rutter et al. 2013, Oohashi et al. 2013, Craw & Upton 2014, Lyu et al. 2020). In some cases 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 (Nakamura et al. 2015), 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 (Nakamura et al. 2015, Kaneki & Hirono 2019) 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 (Kribek et al. 2015, Mirasol-Robert et al. 2017, Miranda et al. 2019, Prando et al. 2020), 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 (Supplementary Fig. 5). 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 Ga sediments are present in much younger orogens. Accordingly, degrees of crustal shortening in Phanerozoic orogens are high where they are rooted in Palaeoproterozoic crust (Mouthereau et al. 2013). 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 (Saha 2013). The intervening 2 Gyr record includes, for example, detachment on Palaeoproterozoic shale units during the 1.0 Ga Grenvillian Orogeny in Labrador (van Gool et al. 2008) and the 0.43 Ga Caledonian Orogeny in Norway (Torgersen et al. 2015). Pressure-temperature (P-T) trajectories for Palaeoproterozoic granulitic metapelites (Supplementary Fig. 6) reflect reactivation involving compressional uplift and exhumation of the granulites, and show that Palaeoproterozoic pelites were reactivated during the main periods of orogenesis over the last 2 ~~billion years~~ (Fig. 4, Supplementary Table 4). The exceptional Palaeoproterozoic biomass was reflected not only in mountain building during the Palaeoproterozoic but ever since.

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Author contributions

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

Competing interests

The authors declare no competing interests

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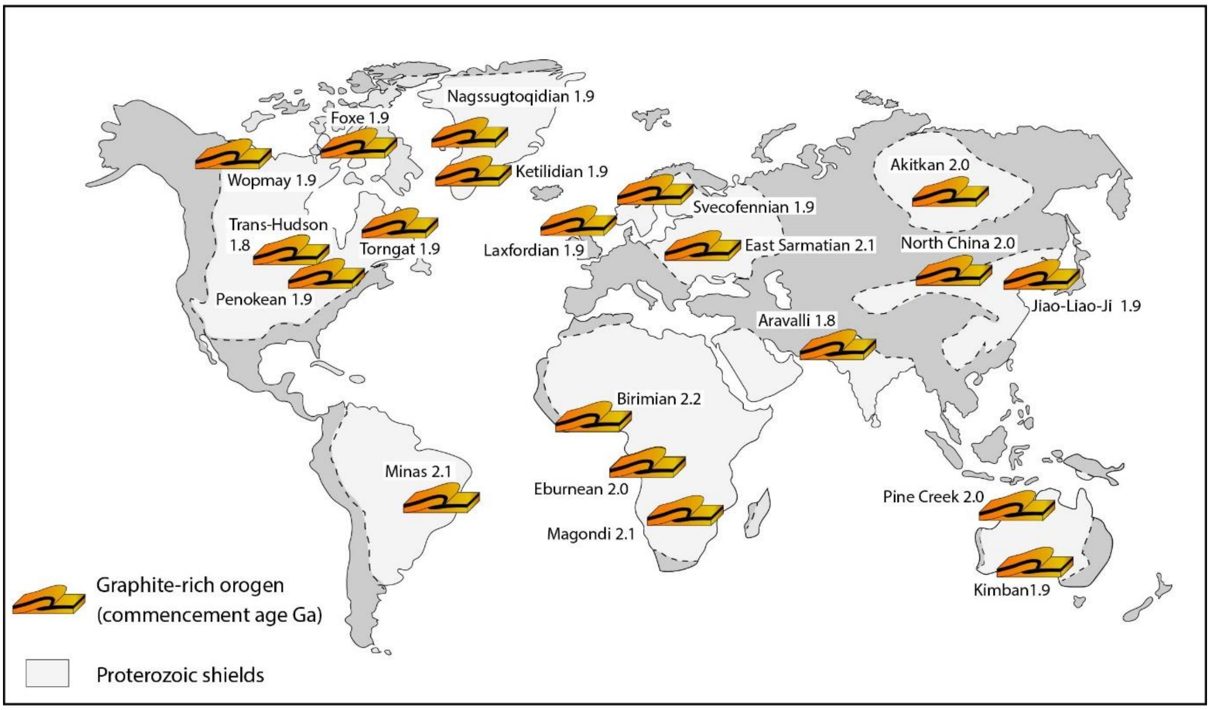
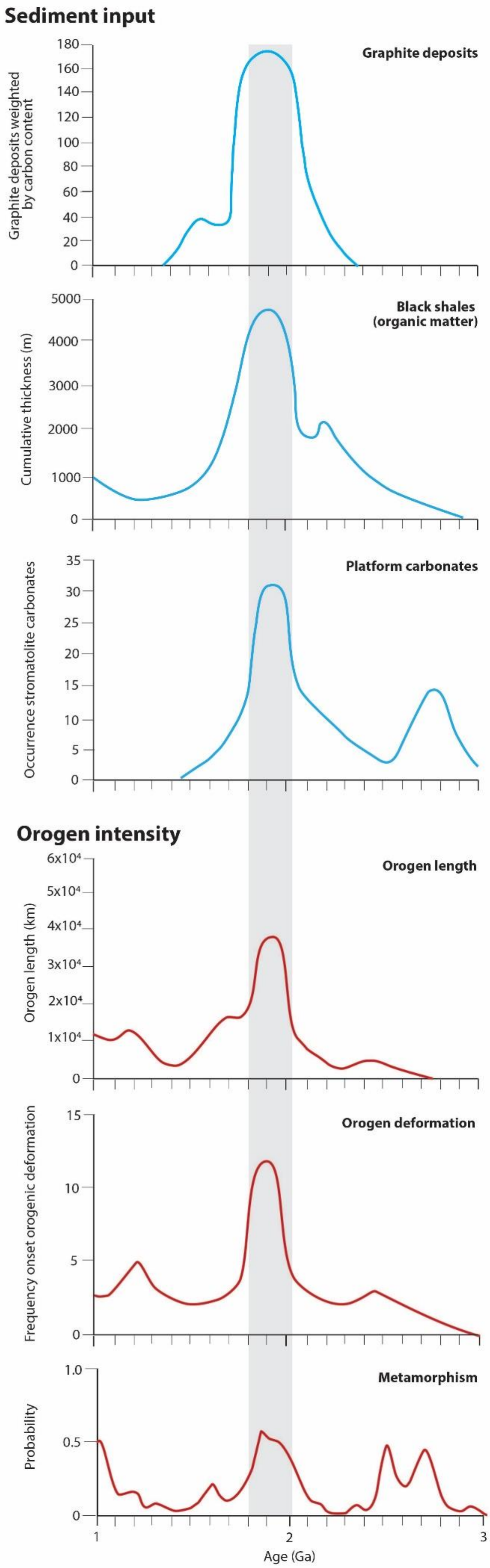
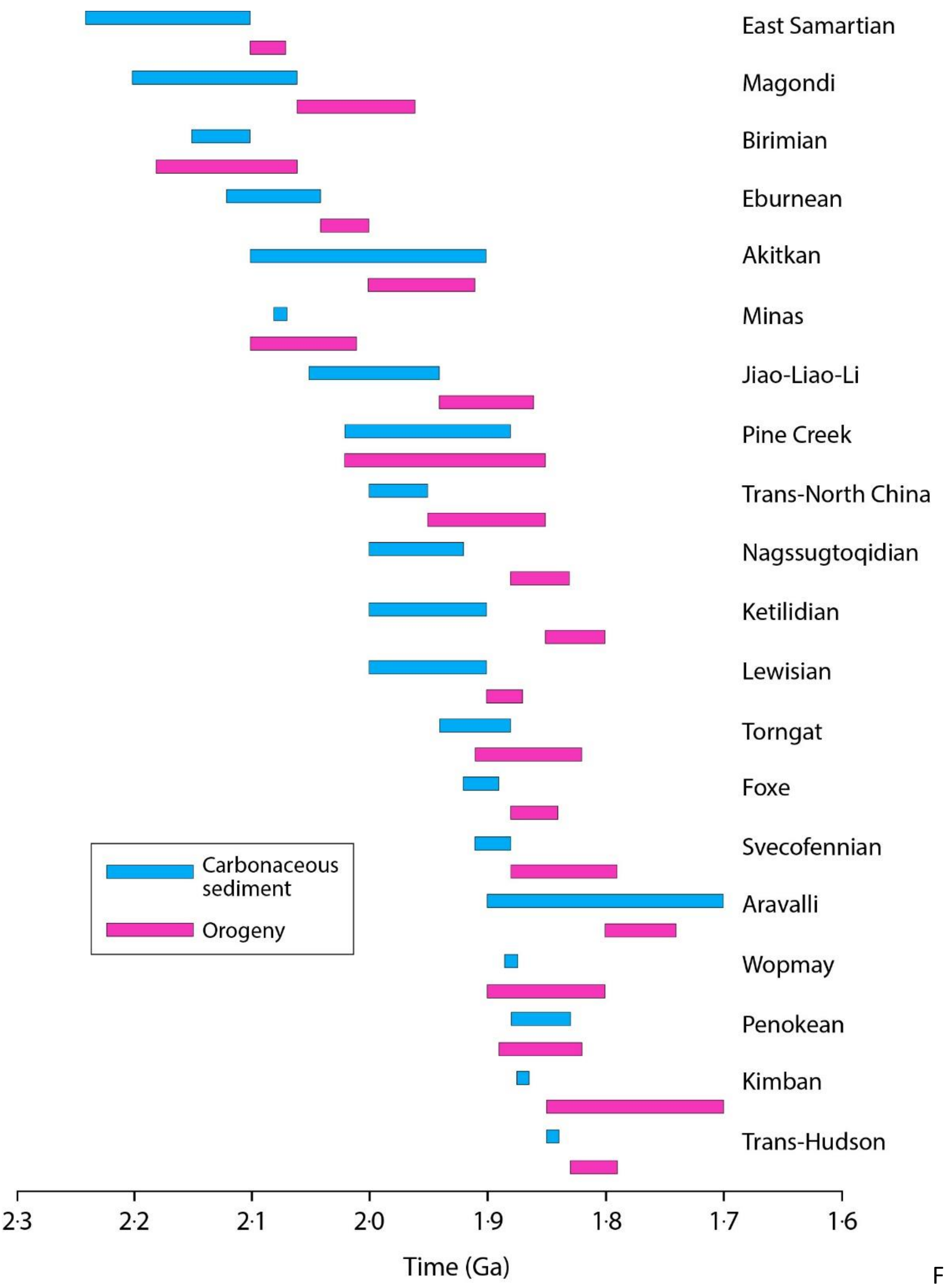


Fig. 1



Sediment input
Graphite deposits
Graphite deposits weighted by carbon content
Black shales (organic matter)
Cumulative thickness (m)
Platform carbonates
Occurrence stromatolite carbonates
Orogen intensity
Orogen length
Orogen length (km)
Orogen deformation
Frequency onset orogenic deformation
Metamorphism
Probability
Age (Ga)

Fig. 2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Ketilidian
Lewisian
Torngat
Foxe
Svecofennian
Aravalli
Wopmay
Penokean
Kimban
Trans-Hudson
Carbonaceous sediment
Orogeny
2·3
2·2
2·1
2·0
1·9
1·8
1·7
1·6
Time (Ga)

Fig. 3

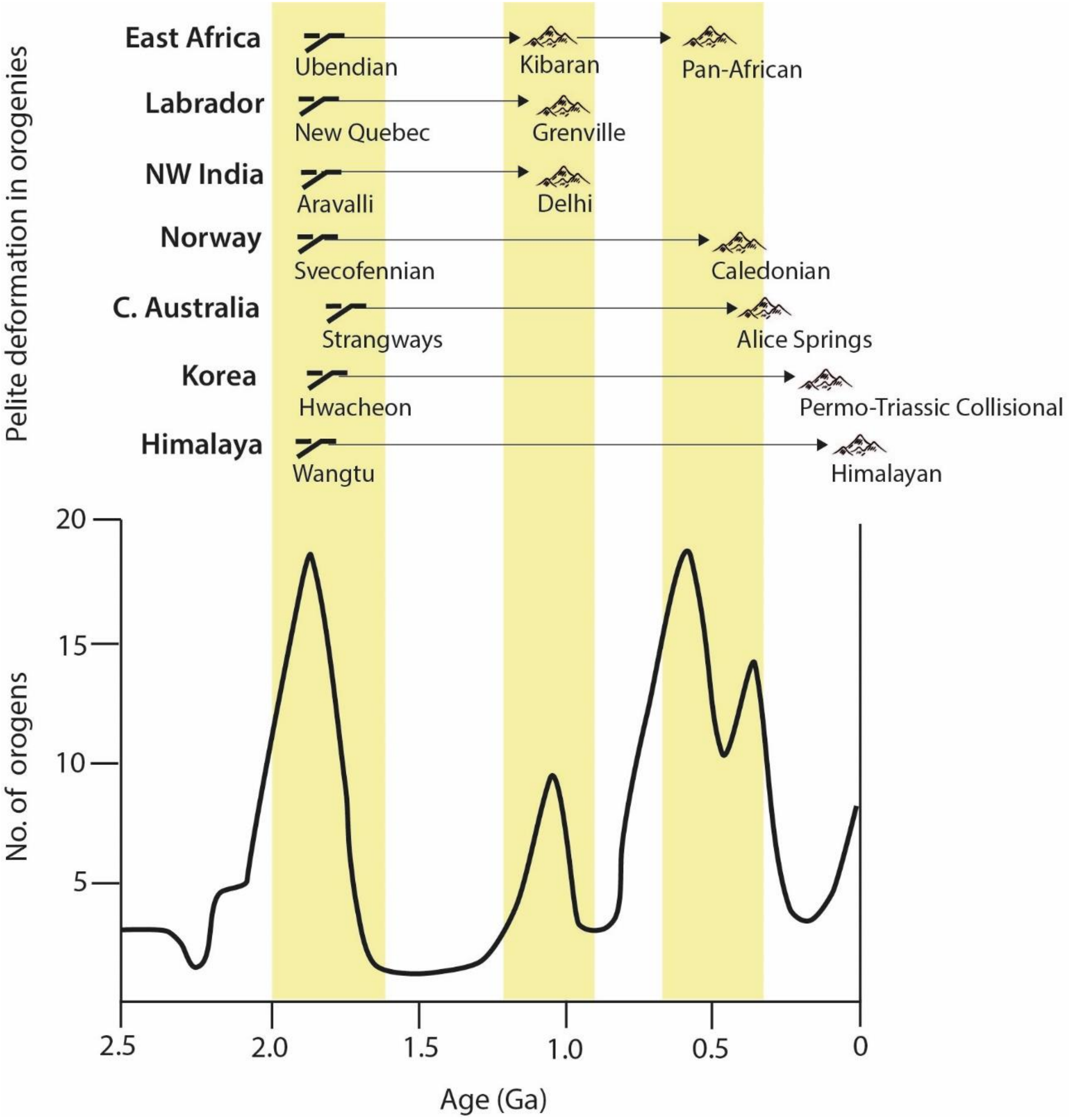
East Africa
Ubendian
Kibaran
Pan-African
Labrador
New Quebec
Grenville
NW India
Aravalli
Delhi
Norway
Svecofennian
Caledonian
C. Australia
Strangways
Alice Springs
Korea
Hwacheon
Permo-Triassic Collisional
Himalaya
Wangtu
Himalayan
Pelite deformation in orogenies
No. of orogens
20
15
10
5
2.5
2.0
1.5
1.0
0.5
0
Age (Ga)

Fig. 4

Table 1. Carbon contents and isotope compositions of carbonaceous units which accommodated deformation in orogens.

Data sources in Supplementary Table 2.

Orogen (age t_o)	**Carbonaceous Unit (age t_c)**	**Maximum Δt (t_c-t_o)**	**Carbon content**	**Carbon isotope composition (‰)**	**Response in orogen**
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	Koolpin -27.6 to -31.1	B, F, S, T
Kimban Orogen, Australia (1.85-1.70 Ga)	Hutchison Group (1.87 Ga)	170 Myr	Up to 30+ % TOC, Graphite ore	-13.0 to -29.0	F, G, I, S, T
Aravalli Orogen, India (1.8-1.74 Ga)	Aravalli Supergroup (1.9-1.7 Ga)	160 Myr	Up to 15 % TOC, Graphite ore	-21.1 to -25.9	F, I, S, T
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	-24.6 to -29.0	F, G, S, T
Jiao-Liao-Ji Orogen, China (1.94-1.86 Ga)	Liaohe/Jingshan Groups (2.05-1.94 Ga)	190 Myr	Graphite ore	-18.6 to -21.7	D, F, S, T
Akitkan Orogen, Russia (2.0-1.91 Ga)	Khapchan Group, Udokan Series (2.1-1.9 Ga)	190 Myr	Up to 23 % TOC, Graphite ore	-29.2 to -31.6	F, S, T
Wopmay Orogen, Canada (1.9-1.8 Ga)	Coronation Supergroup (1.88 Ga)	80 Myr	Up to 9.1 % TOC	-14.5 to -26.5	B, I, T
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	-27.5 to -27.8	F, I, S, T

Trans-Hudson Orogen, USA-Canada (1.83-1.79 Ga)	Kisseynew Gneiss (1.85-1.84 Ga)	60 Myr	Graphite ore	-17.9 to -29.8	F, I, S, T
Penokean Orogen, USA (1.89-1.82 Ga)	Animikie and Baraga Groups (1.88-1.83 Ga)	60 Myr	Up to 44 % TOC, Graphite ore	-22.4 to -32.2	D, G, I, T
Torngat Orogen, Canada (1.91-1.82 Ga)	Tasiuyak Gneiss (1.94-1.88 Ga)	120 Myr	Up to 30 % TOC, Graphite ore	-24.8 to -31.7	B, F, I, T
Nagssugtoqidian Orogen, Greenland (1.88-1.83 Ga)	Siportoq Supracrustals (2.00-1.92 Ga)	170 Myr	Up to 24 % TOC, Graphite ore	-18.1 to -31.0	B, F, I, S, T
Ketilidian Orogen, Greenland (1.85-1.80 Ga)	Sortis and Vallen Groups (2.0-1.9 Ga)	200 Myr	Up to 29 % TOC, Graphite ore	-22.3 to -32.5	F, G, I, S, T
Laxfordian Orogen, UK (1.9-1.87 Ga)	Lewisian supracrustals (2.0-1.9 Ga)	130 Myr	Up to 10.7 % TOC	-21.6 to -24.6	F, I, S, T
Svecofennian Orogen, Finland-Sweden-Norway (1.88-1.79 Ga)	Multiple graphitic schists (1.91-1.88 Ga)	120 Myr	Up to 25 % TOC, Graphite ore	-19.2 to -27.0	F, I, S, T
East Sarmatian Orogen, Belarus (2.10-2.07 Ga)	Vorontsovska series (2.24-2.10 Ga)	170 Myr	Up to 18 % TOC, Graphite ore	-27.4 to -31.1	S, T
Birimian Orogen, West Africa (2.18-2.06 Ga)	Lower Birimian (2.15-2.10 Ga)	90 Myr	Up to 25 % TOC, Graphite ore	-23.5 to -31.1	I, T
Eburnean Orogen, Gabon-Congo (2.04-2.0 Ga)	Ogooue ́complex, Francevillian (2.12-2.04 Ga)	120 Myr	Up to 17 % TOC	-27.1 to -46.2	D, F, T

Magondi Orogen, Zimbabwe (2.06-1.96 Ga)	PiriWiri Group (2.2-2.06 Ga)	240 Myr	Graphite ore	-23.6 to -24.2	B, F, I, T
Minas Orogen, Brazil (2.1-2.01 Ga)	Itapecerica khondalites (2.08-2.07 Ga)	70 Myr	Up to 35 % TOC, Graphite ore	-21.2 to -27.9	B, F, S, T

TOC = Total Organic Carbon. B, basal decollement; D, decollement; F, isoclinal folding; G, graphite thickening/in subduction zones; I, imbrication; S, shear zones; T, thrusting (especially bedding-parallel).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

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- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

Elevated biomass at 2 Ga triggered mountain building

Response to Reviewers (Responses in BOLD)

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COMMSENV-21-0396-T
Parnell and Brolly
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Review by Ross N. Mitchell, Ph.D. ross.mitchell@mail.iggcas.ac.cn

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22nd Sep 21

Dear Professor Parnell,

Thank you for submitting your revised manuscript titled "Elevated biomass at 2 Ga triggered mountain building". I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

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orcid.org/0000-0001-7505-3690

Increased biomass and carbon burial 2 billion years ago triggered mountain building

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(all responses made at previous review stage)

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