Global accretionary orogenesis triggered the Cambrian Explosion of life

Mingshuai Zhu (zhumingshuai@mail.iggcas.ac.cn)
Institute of Geology and Geophysics, Chinese Academy of Sciences
Fuqin Zhang
Institute of Geology and Geophysics, Chinese Academy of Sciences
Yinggang Zhang
School of Earth Sciences and Engineering, Nanjing University
Daniel Pastor-Galán
Department of Geodynamics, Universidad de Granada
Benjamin Mills
University of Leeds https://orcid.org/0000-0002-9141-0931
Matthijs Smit
University of British Columbia
Carl Guilmette
Laval University https://orcid.org/0000-0001-7196-522X
Laicheng Miao
Institute of Geology and Geophysics, Chinese Academy of Sciences
Shun Li
School of Oceanography, Shanghai Jiao Tong University
Shunhu Yang
Chinese Academy of Sciences https://orcid.org/0000-0003-3724-3404
Ariuntsetseg Ganbat
Department of Earth Science, Graduate School of Science, Tohoku University
Zeli Wang
Shandong Key Laboratory of Depositional Mineralization and Sedimentary Minerals, Shandong University of Science and Technology

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Abstract

The Cambrian Explosion (541-515 Myr ago) is arguably the most significant evolutionary transition after the origin of life1-2. A variety of environmental perturbations have been correlated to this rapid animal species diversification1-3. Increased weathering fluxes from the continents to the oceans are hypothesized to cause these perturbations4-6, but why such enhanced weathering occurred is unknown. We document two newly discovered eclogite occurrences within the Central Asian Orogenic Belt (CAOB). These eclogites recorded Cambrian deep subduction of continental crust and consequent mountain building during arc-continent collisions concomitant to the Cambrian Explosion. Correlative metamorphic belts of the same age occur across the CAOB indicating a continental subduction front (>3,500 km) larger than that of the modern Himalaya. The CAOB, along with Gondwana's peripheral orogens, provide a unique and unrecognized global accretionary orogen (>18,500 km) for the Cambrian Earth, larger than the so-far recognized Cambrian collisional orogen during Gondwana assembly4. Our biogeochemical modelling results suggest that the increased weathering of phosphorus from these accretionary orogenic belts would stimulate marine primary productivity, increase atmospheric O2, and promote the expansion of shallow-ocean oxygenation at a time coincident with the Cambrian Explosion.

Main Text

The early Cambrian marks a turning point in Earth history, when most animal phyla emerged in the fossil record[1]. Various environmental, developmental, and ecological hypotheses have been proposed to explain this Cambrian explosion of life[2–3]. Among them, the evolution of the environment is often seen as the crucial initiating event[2], and likely involved rising oxygen levels in atmosphere and oceans[7–8], changes in ocean chemistry[9] and increased bio-essential elements[4,10]. The favoured mechanism for these congruent changes is an enhanced weathering flux from the continents to the oceans[4–6]. Weathering fluxes could directly provide the essential nutrients for the explosion of life[4,11] and oxidant for the euxinic ocean[12]. In addition, the increased nutrient inputs could produce a feedback loop where primary production and organic carbon burial would lead a rise in oceanic oxygen levels[4–5], which further spurs on biological diversification.

Several hypotheses explain the enhanced weathering fluxes from the continents to the oceans during Cambrian. One hypothesis proposes that erosion of glaciers and high chemical weathering rates during deglaciation in the aftermath of Snowball Earth led to higher flux delivery to seawater[11]. However, the Cryogenian glaciations occurred too early to account for the Cambrian Explosion[1], and the Ediacaran Gaskiers glaciation was too short and of a much lesser extent to have produced a significant enough weathering event[13]. Another hypothesis suggests that the formation of the large-scale Ediacaran-Cambrian unconformity ('Great Unconformity') provides an unusually high flux of continental weathering products to the Cambrian oceans during the Sauk transgression[6], but recent results indicate that the diachronous Great Unconformities represent regional tectonic features rather than a synchronous global phenomenon[14]. In addition, detrital zircon dating constrains that the Sauk marine transgression took place during an interval 505 to 500 Myr ago[15], and therefore post-dates the Cambrian Explosion. A third hypothesis is that erosion of the Pan-African collisional orogens that formed during Gondwana assembly released large amounts of continental sediments to the ocean[4–5]. However, Gondwana was largely assembled before ca. 610 Myr ago[16–17], and thus much of the tectonics associated with building the Pan-African mountain chain occurred too early to account for the Cambrian Explosion[1]; only the Kuunga collisional sub-system, which is exposed in southern Africa and along the eastern Indian subcontinent, remained active during the Cambrian[17–18].

Recently, accretionary orogenesis and associated magmatism at intra-oceanic and continental convergent plate boundaries are proposed to exert the strongest control on global chemical weathering fluxes[19–21]. Accretionary orogenic belts combine significant topographic relief, high rates of precipitation, large surface and subsurface water fluxes, and exposure of large volumes of highly weatherable mafic-ultramafic rocks[20–21]. For example, the Southeast Asian islands represent ca. 1.9% of the terrestrial surface, but contribute 14% of the total chemical weathering fluxes and 16.8% of the global phosphorous (P)-release[22]. During the Cambrian period, a very large proportion of orogenesis occurred in archipelago-style accretionary margins at the periphery of older cratons[23] rather than in a supercontinent collisional setting. Nevertheless, neither contribution nor causal link of accretionary orogens to the global Cambrian environmental evolution has ever been proposed.

Here, we reconstruct the Cambrian accretionary processes of the CAOB, and compare them with the Gondwana's peripheral accretionary orogens to explore the hypothesis that the Cambrian global accretionary orogenesis is causally linked to the Cambrian Explosion. The CAOB is one of the largest accretionary orogens worldwide, which was formed through multiple convergence and collision events of various orogenic components between 1250 and 250 Myr ago, a time of significant growth of new continental crust[24]. In this system, records of high-pressure (HP), low-temperature (LT) metamorphism, which mark major accretionary and collisional processes in the modern orogens, are sparse and thus tectonic reconstructions of the CAOB are uncertain. We report the discovery of two occurrences of Cambrian HP continent-type eclogite in the western Mongolia of the CAOB (Fig. 1a, b). One of these eclogites represents ca.770 – 740 Myr-old mafic rocks produced in a continental rift setting, whereas the other comprises ca. 853 Myr-old subduction-accretion complex (see Supplementary Information).

Regardless of their protolith difference, both eclogites occur along the west margins of the CAOB microcontinents, and were synchronously subducted and metamorphosed to eclogite-facies conditions (ca. 520 Myr ago) along a similar P-T path (Fig. 1c; Supplementary Information). Combined with the Tsakhir Uul continent-type eclogite found along the southwest margin of the Baydrag microcontinent (metamorphic age of ca. 540 Myr)[25,30], these three eclogite localities form a continental scale Cambrian HP metamorphic belt that stretches for > 1,000 km (Fig. 1) and records arc-continent collisions[31] along this plate boundary within a very narrow time window of ~ 20 Myr. The belt provides a HP/LT complement to the Cambrian granulite facies metamorphism and HP metamorphism that has affected the southern margin of the Siberian craton and various microcontinents across the CAOB[26–29], for instance the > 1,300 km Cambrian granulite-bearing Khondalite Belt[28] of NE China, the > 1,000 km granulite-bearing metamorphic belt at the southern margin of the Siberia[29] and the > 150 km Kokchetav continent-type high- and ultrahigh pressure terrane[26]. Altogether makes the CAOB the second largest accretionary orogenic system of the Cambrian Earth, and has a proved continental subduction front of over 3,500 km (larger in size than that of the present-day Himalaya). Deep subduction of felsic continental crust leads to major crust thickening, and the buoyancy of these deep crustal roots is thought to give rise to significant mountain topography[32]. Considering the apparent scale and synchronicity of these tectonic processes, it is to be assumed that huge mountain chains developed during the Cambrian accretions in the CAOB.

The timing of the Cambrian mountain building in the CAOB coincides exactly with that of accretionary orogenesis in Gondwana's peripheral orogens. In the northern margin of Gondwana, the Avalonian - Cadomian Orogen with an along-strike length as much as 8,000–10,000 km, represents one of the dominant orogens on the late Neoproterozoic-Cambrian Earth[33]. The cessation of subduction, widespread deformation and metamorphism, and the angular unconformity indicate the orogenesis took place at ca.550 – 520 Myr[33]. In the eastern Terra Australis Orogen, the well-known Ross–Delamerian accretionary orogenesis extends about 5,000–6,000 km along the Transantarctic Mountains, as well as in southeastern Australia, Tasmania and the South Island of New Zealand, and the main pulse of the orogenesis occurred at ca. 540–490 Myr[34]. In the western Terra Australis Orogen, the Pampean orogenesis extends for over 1,100 km and resulted from terrane accretion between ca. 545 and 520 Myr[35]. In the North Indo-Australie Orogen, the ca.520 – 490 Myr North Qinling and South Altyn Tagh HP/UHP continental - type metamorphism indicates a Cambrian orogenesis in the northern margin of Gondwana[36–37]. The widespread development of mountain chains along with the CAOB document a very specific setting of global mountain building (> 18,500 km) for the Cambrian Earth, which is unusual, if not unique, in the history of the Earth (Fig. 2a). Palaeogeographical reconstructions show that these periphery Cambrian accretionary orogenesis generally took place at low latitudes[38], which are where chemical weathering rates are at a global maximum[20–21]. Based on these observations, we argue that the erosion of the over 18,500 km long accretionary orogeny formed during Cambrian accretion is the most effective mechanism capable of weathering the vast amounts of mafic rocks required to drive the Cambrian Explosion, rather than the collisional orogens in the interior of Gondwana, where deep, indurated soil profiles in tropical drainage basins likely lead to very low (transport-limited) weathering intensity[22]. Rapid increases of seawater $^{87}Sr/^{86}Sr$ to the highest levels in Earth's history and decline of average seawater εNd to a long-term minimum provide supporting evidence for enhanced weathering of continental crust during the Cambrian accretionary orogenesis[6] (Fig. 2b).

We defend that the global accretionary orogen and the coincident Cambrian Explosion (Fig. 2c) is causal. As the nutrition concentration in seawater primarily controls the marine primary productivity[11], we investigate the impacts of P supply from these accretionary orogens on the Cambrian Earth system by using the Carbon–Oxygen–Phosphorous–Sulfur–Evolution (COPSE) global biogeochemical model[40].

The estimates of accretionary orogenic area and weathering rate can be used to quantify the annual P supply during the Cambrian, and geological records can provide constraints for the duration of mountain building in different segments of the Cambrian accretionary orogens (see Methods). We assume that the propagation rate and mean width of these orogens range from 60 to 100 km/Myr and 100–300 km, respectively, as evidenced in young accretionary orogens (e.g., Taiwan and Papua New Guinea)[41]. Then we can estimate the area time-variation of the accretionary orogenic belts. The oxygen isotope ($\delta^{18}O$) composition combined with distribution of climate sensitive lithology indicates the Cambrian global average surface temperature is about 6–10°C higher than present day[42], and modelling studies indicate the atmospheric CO_2 during Cambrian is about 1,800–2,800 ppm[43]. According to commonly used expressions of climatic dependency of silicate weathering at the global scale (see Methods), the P-release average rate of these Cambrian accretionary orogenic belts could be 3–6 times the present-day P-release rate in accretionary orogenic belts (the present-day P-release rate is 66.3 kg km^{-2} y^{-1}; ref. [22]). Using this flux per unit area estimate, we run COPSE to explore how the contribution of P weathering from accretionary orogenic belts in different scenarios (Fig. 3a) might affect global biogeochemical cycles and isotope ratios. The background model setup follows the latest model version[40], with the exception that sediment bioturbation is not altered through the model run. The timing of the initiation of meaningful sediment bioturbation is highly uncertain[44] and the current model initiates this during the Cambrian Explosion, thus we hold this forcing constant here to focus on the input of phosphorus alone.

The model outputs (Fig. 3) show that the increased P release from weathering of accretionary orogenesis is sufficient to cause large-scale changes in climate and biogeochemistry of the Cambrian Earth system. For example, in the moderate 300 km width and treble weathering rate (W300km*3R) P nutrient input scenario, atmospheric oxygen concentration is predicted to increase by around two times during the Cambrian period, reaching a maximum of ~ 8 atm% at ca. 520 Myr (Fig. 3c). In this scenario, the extent of marine anoxia decreases significantly (Fig. 3d). Given the global well-mixed ocean assumed in COPSE, we would expect shelf anoxia to decrease by a larger fraction than this. This increase in oxygen is primarily due to a higher marine primary productivity stimulated by the increased P input, where the explosion of algae and cyanobacteria in shallow peri-continental waters[5], and increased sedimentation and burial of organic carbon[4–5] together cause a sustained increase in atmospheric oxygen.

The increased burial of organic carbon also results in an increase in seawater $\delta^{13}C$ values (Fig. 3b), which is consistent with the recorded increasing $\delta^{13}C$ baseline during the early Cambrian[45]. Our atmospheric O_2 modelling results coincide with the curve of global genus-level diversity of marine animals[46] peaking at ca. 520Ma (Fig. 3c), and are also consistent with the suggestion of widespread ocean oxygenation based on the increased sedimentary molybdenum isotope data ($\delta^{98/95}Mo$) and U concentrations peaking at ca. 520 Ma[7]. The Cambrian accretionary orogenesis is also predicted to result in global cooling due to the consumption of carbon dioxide through silicate weathering[20–21] (Fig. 3e), and this cooler temperature would increase the total number of physiological ecotypes living in the shelf environments that can contribute to biodiversity[47]. In addition to rising O_2, erosion of these > 18,500 km mountain belts released a large flux of essential nutrients that triggered a bloom of primitive life that in turn provided abundant food for the Cambrian radiation of animals[4–5]. Though the Cambrian Explosion is likely to have been the result of a complex interplay of biotic and abiotic processes[2], the global Cambrian accretionary orogenesis must be regarded as a major environmental trigger.

Declarations

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Author contributions:

M.Z. and F.Z designed the project and wrote the original manuscript. Y. Z. and B. M. performed model simulations. D.P.G., B.M., M.A.S. and C.G. prepared the revised manuscript. M.Z., F.Z., L.M., S.Y. and A.G. conducted the mapping and sampling. M.Z., S.L. and Z.W. finished all the analyses. All authors contributed to the interpretation of the results.

Competing financial interests

The authors declare no competing financial interests.

Additional information

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Figures

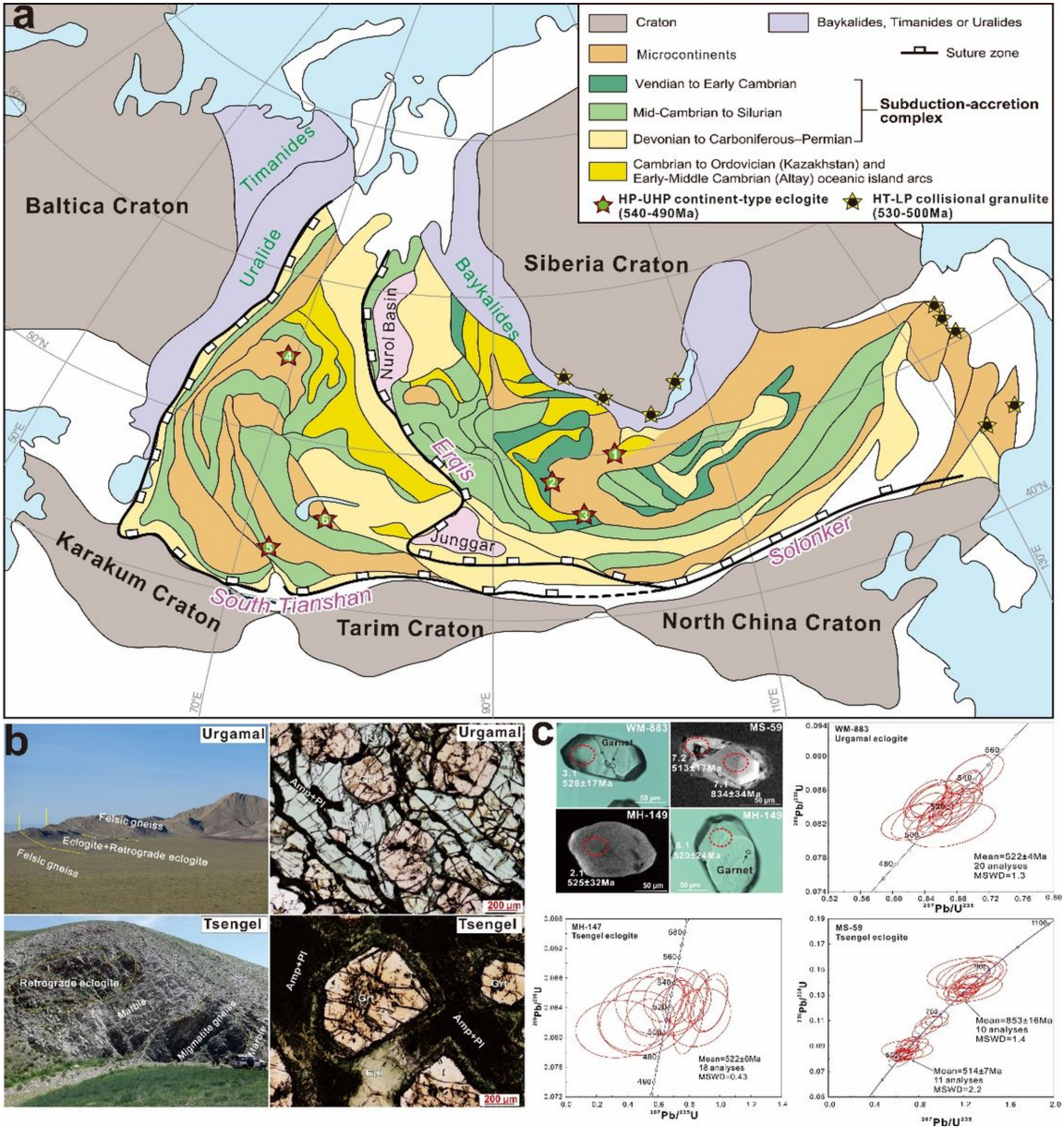

Figure 1

Tectonic map of the CAOB and major results of the two newly - discovered eclogites.

a, Tectonic map showing the main tectonic units of the CAOB (modified from Xiao et al.[24]). The Cambrian HP-UHP metamorphic rocks are indicated by red stars.1-Tsengel; 2-Urgamal; 3-Tsakhir Uul[25]; 4-Kokchetav[26]; 5- Makbal[27]; 6-Anrakhai[27]. The Cambrian granulitic metamorphic rocks along margins of

Siberian Craton and the Khondalite belt in NE China are indicated by yellow stars (refs. 26, 27). **b**, Field occurrences and microphotographs of the two eclogites. Grt - garnet, Amp - amphibole, Omp - omphacite, Pl - plagioclase, Rt - rutile, Epi - epidote. **c**, CL images of zircons and U-Pb concondia diagrams of the two eclogites.

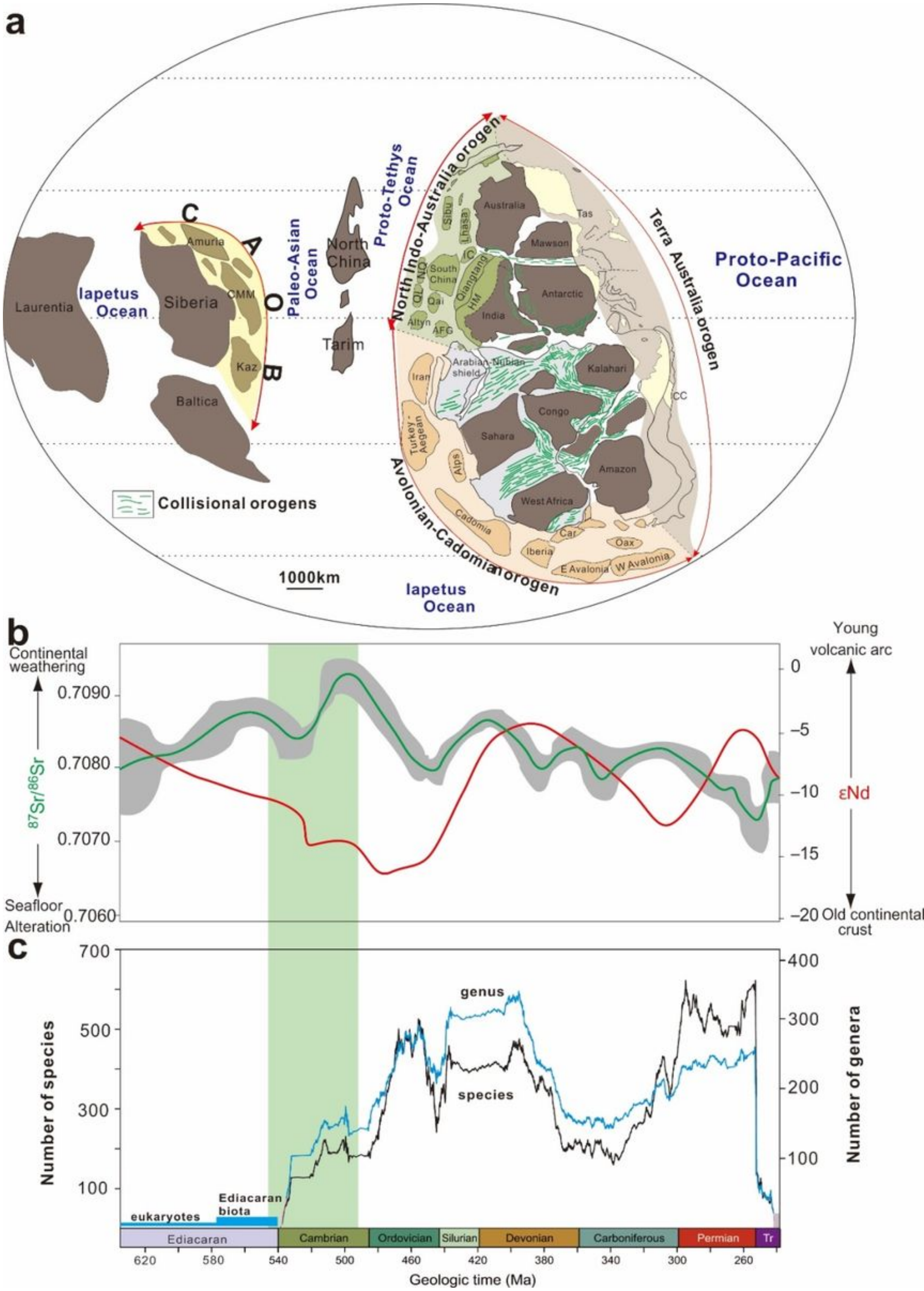

Figure 2

Global accretionary orogenesis, ocean chemical changes and the biodiversity during the Cambrian. a, Reconstruction of the global accretionary orogenesis during Cambrian (modified from Cawood et al.[23] and Zhao et al.[17]) . **b,** Global $^{87}Sr/^{86}Sr$ and mean εNd estimates from ref. 6 and references therein. **c,** General trajectories of Paleozoic genus and species diversity after ref.39. Green bar shows duration of the Cambrian accretionary orogenesis. Abbreviations: Afg – Afghanistan; Car – Carolina; CC – Cuyania and Chilenia; Fl – Florida; IC – Indochina; HM – Himalayas; Mad – Madagascar; Oax – Oaxaquia; SF – San Francisco; Tas – Tasmania; QL–Qilian; Qai–Qaidam; NQ–North Qinling; CMM-Central Mongolian microcontinents; Kaz-Kazakstan.

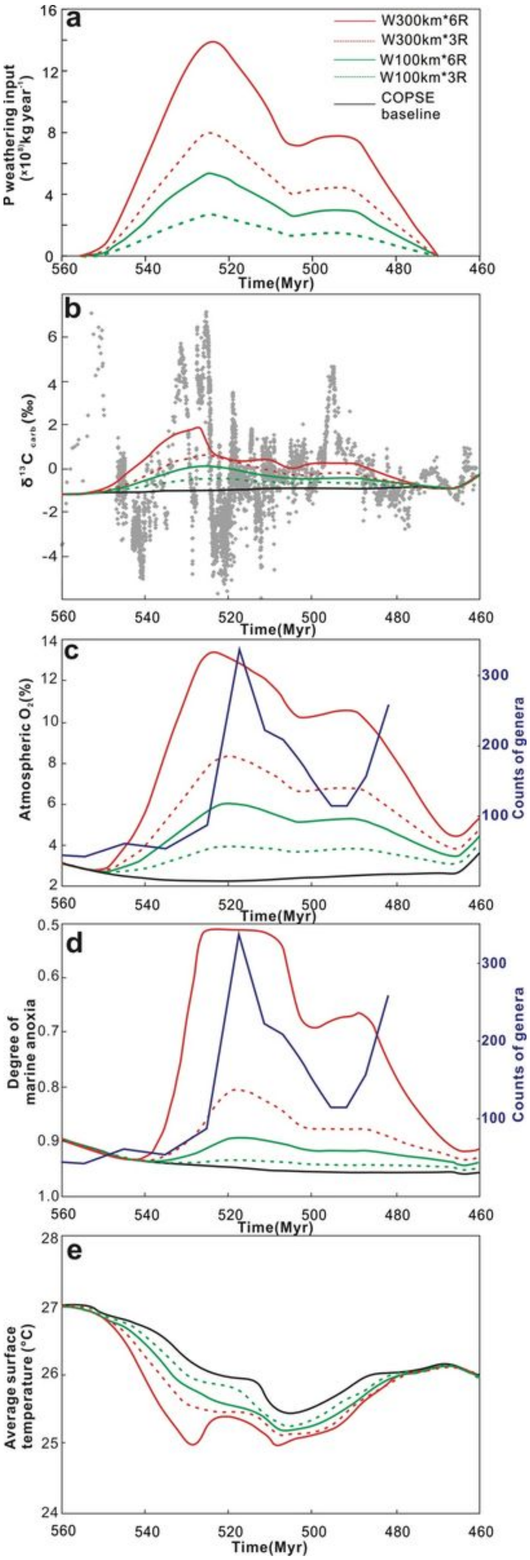

Figure 3

Biogeochemical model outputs for impacts of weathering of the Cambrian accretionary orogens. COPSE model baseline runs[40] plus P supply from the weathering flux. **a**, The P input from the Cambrian accretionary orogens. **b**, Modelled $\delta^{13}C$ of carbonates. **c**, Modelled atmospheric O_2, and global genus-level diversity of marine animals[46]. **d**, Degree of marine anoxia (represented as the modelled proportion of anoxic seafloor). **e**, Modelled global average surface temperature. ‘W100km*3R’ represents that the average width of the orogens are 100 km, and the weathering rate is three times the present day. ‘W300km*6R’ represents that the average width of the orogens are 300 km, and the weathering rate is six times the present day.

Supplementary Files

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