GLACIAL CYCLES

Arc-continent collisions in the tropics set Earth's climate state

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On multimillion-year time scales, Earth has experienced warm ice-free and cold glacial climates, but it is unknown whether transitions between these background climate states were the result of changes in carbon dioxide sources or sinks. Low-latitude arc-continent collisions are hypothesized to drive cooling by exhuming and eroding mafic and ultramafic rocks in the warm, wet tropics, thereby increasing Earth's potential to sequester carbon through chemical weathering. To better constrain global weatherability through time, the paleogeographic position of all major Phanerozoic arc-continent collisions was reconstructed and compared to the latitudinal distribution of ice sheets. This analysis reveals a strong correlation between the extent of glaciation and arc-continent collisions in the tropics. Earth's climate state is set primarily by global weatherability, which changes with the latitudinal distribution of arc-continent collisions.

Over geological history, Earth's climate has varied between warm ice-free climate states, and cold glacial climate states in which polar continents were covered in ice (*1*, *2*). Through the Phanerozoic Eon [past 540 million years (Ma)], Earth's climate has been predominantly nonglacial (~75%), with relatively brief, ~3- to 60-Ma intervals of glacial climate (*1*, *3*). Similarly, aside from Snowball Earth events, much of the preceding Proterozoic Eon was also characterized by a nonglacial climate state (*3*). Given that a warm, nonglacial climate is the most common climate state for Earth, what processes have caused cooling trends on million-year time scales resulting in glacial climate states, like that observed today?

Earth's climate state is set by the balance between geological sources and sinks of carbon to the ocean-atmosphere system, but their relative importance is uncertain (*4*–*8*). On long time scales, CO_2 is emitted primarily by volcanism and consumed primarily by chemical weathering of silicate rocks, which delivers alkalinity through rivers to the ocean and sequesters carbon via the precipitation of carbonate rocks. Prolonged imbalances between the magnitude of the sources and sinks would catastrophically manifest in either the onset of a Snowball Earth or a runaway greenhouse (*7*). The relative clemency of Phanerozoic climate requires that CO_2 sinks scale with changes in the sources, which can be explained through the silicate weathering feedback where increased CO_2 leads to higher temperatures and invigorated hydrological cycling that enhances chemical weathering and vice versa (*4*). Because of the silicate weathering feedback, a decrease in the CO_2 flux to the atmosphere leads to decreased weathering until a new steady state is achieved at lower CO_2 concentrations in the atmosphere (*4*, *7*). CO_2 levels also vary as a result of changes in global weatherability—the cumulative factors that affect chemical weathering aside from climate (*8*). Global weatherability is the product of variables such as lithology, topography, and paleolatitude (*8*, *9*). An increase in global weatherability also results in cooling as the consumption of carbon through silicate weathering will match that of volcanic input at lower concentrations of atmospheric CO_2.

Present-day global CO_2-consumption estimates emphasize the importance of highly weatherable areas: ~10 to 20% of land area is responsible for ~50 to 75% of CO_2 consumption through silicate weathering (*10*, *11*). These highly weatherable areas, e.g., Southeast Asia, are mainly situated in the warm, wet tropics with substantial topographic relief and are composed of Ca- and Mg-rich mafic and ultramafic rocks, which have faster dissolution rates than felsic rocks (*8*–*12*). In general, basaltic watersheds in the tropical rain belt have about two-orders-of-magnitude higher CO_2-consumption rates than granitic watersheds outside of the tropics (*13*).

In the modern climate, the annual migration of the intertropical convergence zone results in a tropical rain belt within 10° to 20° of the equator (fig. S5). The tropical rain belt is below the ascending branch of the Hadley circulation, which has been confined to low-latitude throughout Earth's history (*14*). Thus, geological data coupled with paleogeographic reconstructions can be used to estimate changes in topography and lithology within the tropical rain belt through time. Notably, as climate warms or cools, the tropics remain relatively warm and wet with high weathering rates such that global weatherability is particularly sensitive to paleogeographic changes in the tropics (*15*–*17*).

Phanerozoic cooling trends have been previously attributed to a decrease in CO_2 output from volcanism (*6*, *18*), or an increase in global weatherability through mountain building (*2*, *5*, *8*), or the drift of mafic rocks associated with large igneous provinces (LIPs) through the tropics (*15*). Recently, it was proposed that low-latitude arc-continent collisions combine these processes by terminating subduction-related volcanic CO_2 outgassing along the collided segment, while also increasing global weatherability by actively exhuming volcanic arcs in the warm, wet tropics (*19*).

During arc-continent collisions volcanic arcs are obducted onto continents, creating ophiolites, which are preserved along suture zones and mark the position of former oceans. Arcs and ophiolites are composed predominantly of basalt and ultramafic rocks that are Ca- and Mg-rich and effective at consuming CO_2 through silicate weathering (*8*–*13*, *20*). Ophiolites in collisional belts can extend tens of thousands of kilometers along strike and be progressively exhumed as they are thrust over a continental margin. The combination of high chemical weathering rates in the tropics and the generation of topography during exhumation makes low-latitude arc-continent collisions particularly effective at liberating the large quantities of cations in arcs to the ocean, thereby increasing global weatherability and driving global cooling (*19*).

The process of arc-continent collision in the tropics has been invoked to explain specific cooling episodes during the Ordovician and Late Cretaceous to Oligocene (*19*, *21*), but are intervals of extensive tropical suture length specifically associated with intervals of cool climate? To test this hypothesis, we created a database of Phanerozoic ophiolite-bearing sutures associated with arc-continent collisions that we reconstructed with paleogeographic models (*22*). These geological reconstructions (Fig. 1, fig. S1, and movie S1) provide a framework for analyzing the relationships between the latitudinal distribution of highly weatherable lithologies and Phanerozoic climate change. Particularly, we compare the length of active sutures in the tropics through time with the Phanerozoic record of glaciation (Fig. 2 and fig. S2). Ophiolite obduction along a suture was deemed active from the time of the first evidence of arc exhumation, such as the appearance of ophiolite detritus in the foreland, to the age of the final collision, preferably defined by the cessation of foreland deposition.

Our results show that global active suture zone length varied through the Phanerozoic between 0 and 30,000 km. Peaks in total suture length (between 10,000 and 30,000 km) are associated with major tectonic events such as the Taconic (~465 to 440 Ma), early Uralian (~375 to 358 Ma), Hercynian (~340 to 300 Ma), Central Asian (~250 to 220 Ma), Himalayan (~50 to 0 Ma), and Indonesian (~20 to 0 Ma) orogenies (Fig. 2A). Some of these orogenic events resulted in extensive

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ophiolite obduction within the tropics (Fig. 2B) as these collisions occurred at low latitude in roughly east-west oriented orogenic belts. Because of their geometry, the Taconic, Hercynian, Himalayan, and Indonesian orogenies had 5000- to 15,000-km-long sutures that were within 15° of the equator. By contrast, the early Uralian and Central Asian orogenies occurred at mid- to high latitudes, with less than 3000-km suture length exposed in the tropics (Fig. 2B).

To characterize Earth's climate state through the Phanerozoic, we use the latitudinal extent of continental ice sheets, which were compiled with updated age constraints (Fig. 2C and table S3). Although extent of glaciation is an imperfect proxy for global climate, Phanerozoic $p\text{CO}_2$ (partial pressure of CO_2) estimates are very uncertain (*23*). Over the Phanerozoic, there have been three major glacial intervals, in the Late Ordovician (~455 to 440 Ma), Permo-Carboniferous (~335 to 280 Ma), and the Cenozoic (~35 to 0 Ma), with a smaller glacial advance in the Late Devonian (~360 Ma). Similarly, the major peaks in the record of suture length in the tropics are in the Late Ordovician, the Permian-Carboniferous, and the Cenozoic (Fig. 2B). Notably, there are no major tropical suture length peaks during extended periods of nonglacial climate (e.g., the Mesozoic; 250 to 65 Ma).

To provide a statistical test of the correlation between arc-continent collisions in the tropics and glaciation, we evaluated whether suture length (*22*) correlates better with the real ice-extent record than with randomly generated synthetic records of ice extent (i.e., simulating the null hypothesis that ice extent is independent of the proposed forcing). Synthetic ice-extent records with 5-Ma resolution were generated by randomly varying the timing of four glacial episodes (Late Ordovician, Late Devonian, Permo-Carboniferous, and Cenozoic) over the past 520 Ma (fig. S6). We also compared the percent of overlap between records, i.e., time steps containing both glaciation and significant suture length (fig. S7). This analysis reveals that ice extent correlates strongly with tropical (r = 0.66 to 0.59) and total (r = 0.57) suture length, with statistical significance relative to the null-hypothesis ($p < 0.01$), and that ice extent lacks correlation with high-latitude sutures ($r = -0.06$, $p = 0.55$) (fig. S8 and table S4). The strongest correlation is between ice extent and sutures <20° of latitude (r = 0.66), where under the null hypothesis, only 0.002% of the random simulations of ice extent correlate as well as the observed data (table S4); results are similar for sutures within 15° of the equator. Correlations were found to be relatively insensitive to age uncertainties when age errors in aggregate suture length were simulated by using a random walk scaled to a maximum of 5 or 10 Ma (fig. S8).

The peaks in suture length within the tropics that correspond with the three major glacial intervals are each ~10,000 km. This is approximately the length of present-day sutures in the tropics in the Indonesian orogenic system, including New Guinea and the Philippines. Currently, this region, which includes two of the three largest ophiolites on Earth (*24*), is estimated to account for ~9 to 14% of the modern global carbon sink (*10*, *11*). We propose that the increasing exhumation of the ophiolite-bearing sutures in Indonesia and New Guinea has been a major factor in Middle Miocene to present cooling by increasing global weatherability.

From the present maximum in suture length in the tropics, there is a local minimum in active sutures at ~25 Ma (Fig. 2B). This minimum broadly coincides with the Late Oligocene to Middle Miocene warm interval. A second Cenozoic peak in suture length in the tropics occurs during the Eocene leading up to the initiation of Antarctic glaciation. The two-pronged cooling trend from the Late Cretaceous to Eocene (*25*) has been attributed to low-latitude arc-continent collision (*19*) and corresponds with local maxima in suture length in the tropics (Fig. 2B).

The Permo-Carboniferous glaciations have classically been related to an increase in carbon storage on land (*26*). Recently, it was proposed that the low-latitude Hercynian orogeny was sufficient to initiate glaciation (*17*). Our data broadly support the latter hypothesis but highlight the importance of a specific phase of mountain building, that is, the exhumation of ophiolites in the tropics. Our results also confirm that Late

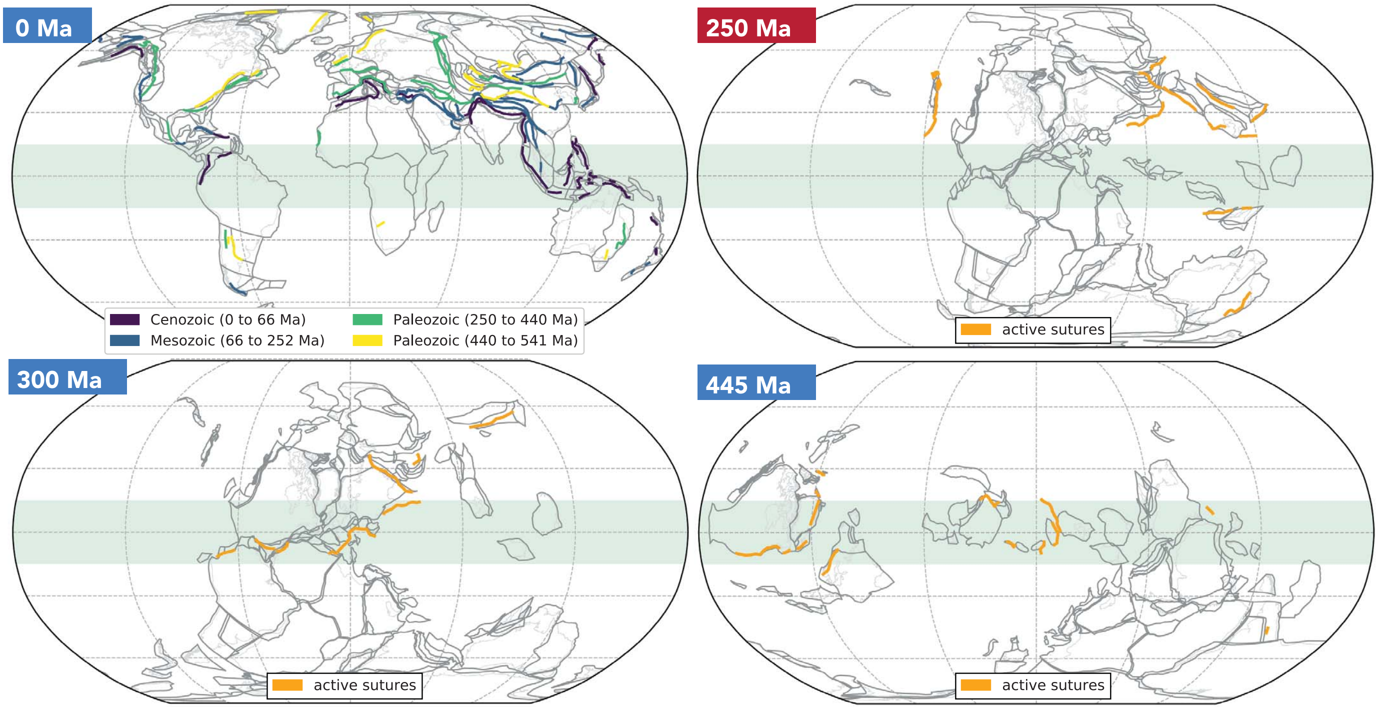

Fig. 1. Reconstructions of ophiolite-bearing sutures. All sutures within the compilation are shown in present-day coordinates in the 0 Ma map and are color-coded by age. The tropical rain belt is shaded green. Continental outlines shown are tectonic units of Torsvik and Cocks (*30*). Paleogeographic reconstructions of these tectonic units and actively exhuming sutures are shown at the times of peaks in total suture length (Fig. 2). The Triassic (250 Ma) peak in total suture length is at a nonglacial interval (red) with minimal suture length in the tropics. The Carboniferous (300 Ma) and Ordovician (445 Ma) peaks are both during glacial intervals (blue) and have extensive suture length in the tropics.

Ordovician glaciation was coincident with low-latitude arc-continent collision in the Taconic orogeny (*21*), Kazakh terranes, Tarim, and North China (*27*).

Like the Eocene, the Early Ordovician increase in suture length in the tropics precedes glaciation by ~10 Ma. This lag may be due to warm background climate states and low global weatherability during the early Cenozoic and early Paleozoic, such that substantial and prolonged increases in global weatherability were necessary to drive cooling and initiate glaciation. Indeed, oxygen isotope records from both the Eocene and Ordovician demonstrate long-term cooling trends prior to glaciation (*21*, *25*).

The Cenozoic seawater rise in radiogenic Sr and Os isotopes appears inconsistent with our hypothesis, as arcs contain relatively unradiogenic Sr and Os. However, these trends can be attributed to the differential exhumation of Greater and Lesser Himalayan lithologies (*28*). That isotopically distinct source rocks can drive seawater Sr and Os isotope records complicates their use as a global radiogenic to juvenile weathering proxy.

The hypothesis evaluated here, that Earth's climate state is set by the presence or absence of arc-continent collisions in the tropics, is analogous to proposals that have linked the drift of LIPs into the tropics as a driver for Cenozoic (*15*) and Neoproterozoic cooling (*16*). We have performed a similar analysis of the paleolatitude of LIPs through time (figs. S3 and S4), in which we imposed two postemplacement scenarios, one with exponential decay of LIP areas with a 120-Ma half-life, and a second in which there is also burial of LIPs associated with rifting and subsidence (*22*). In both scenarios, area of total LIPs at all latitudes and LIPs above and below 15° have a weakly negative to zero correlation with ice extent, with the exception of the decay plus burial scenario at <15°, which has a weakly positive correlation coefficient of $r = 0.10$ (fig. S9 and table S4). The lack of a clear relationship between LIP area and climate state (fig. S4) may be due to regolith development and soil shielding in the absence of active exhumation (*10*). By contrast, arc-continent collisions create active topography, limiting the effect of shielding and facilitating high local weathering rates.

Because arc-continent collisions terminate subduction-related volcanism along the collided segment, cooling may also be due to reduced volcanic activity and CO_2 output (*19*). However, the high total suture length related to the Central Asian and the early Uralian orogenies during nonglacial intervals demonstrate that reduction in arc length and volcanic CO_2 output alone are not sufficient to push the global climate into a glacial climate state. These results indicate that changes in chemical weatherability due to low latitude arc-continent collision and associated ophiolite obduction are the primary driver of global cooling trends, and reduction in volcanic CO_2 output is of secondary importance.

Alternatively, it has been proposed that the extent of continental arc-volcanism is responsible for long-term climate change by modulating CO_2 outgassing (*18*, *29*). To quantify the strength of this proposed correlation, Phanerozoic ice extent was compared to a compilation of continental arc length (*29*). A Mesozoic peak and Cenozoic low in continental arc length results in a significantly weaker correlation with arc length ($r = 0.38$) than that for the suture records (<15° $r = 0.64$, <20° $r = 0.66$) (fig. S9 and table S4).

Although we acknowledge that volcanic outgassing must have changed through time and that organic carbon burial also had an impact on long-term climate, our analysis suggests that global weatherability has provided the first-order control on Earth's climate state. Particularly, arc-continent collisions in the tropics, such as the Indonesian orogenic system today, are ephemeral on geological time scales, and when they drift out of the tropics or exhumation ceases and topography is eroded away, Earth returns to a nonglacial climate state. Thus, our model accounts for both the initiation and termination of ice ages. This pattern has repeated at least three times throughout the Phanerozoic—when there have been abundant tracts of ophiolites being exhumed and eroded in the tropics, Earth has been in a glacial climate state, and when not, Earth has been in a nonglacial climate state.

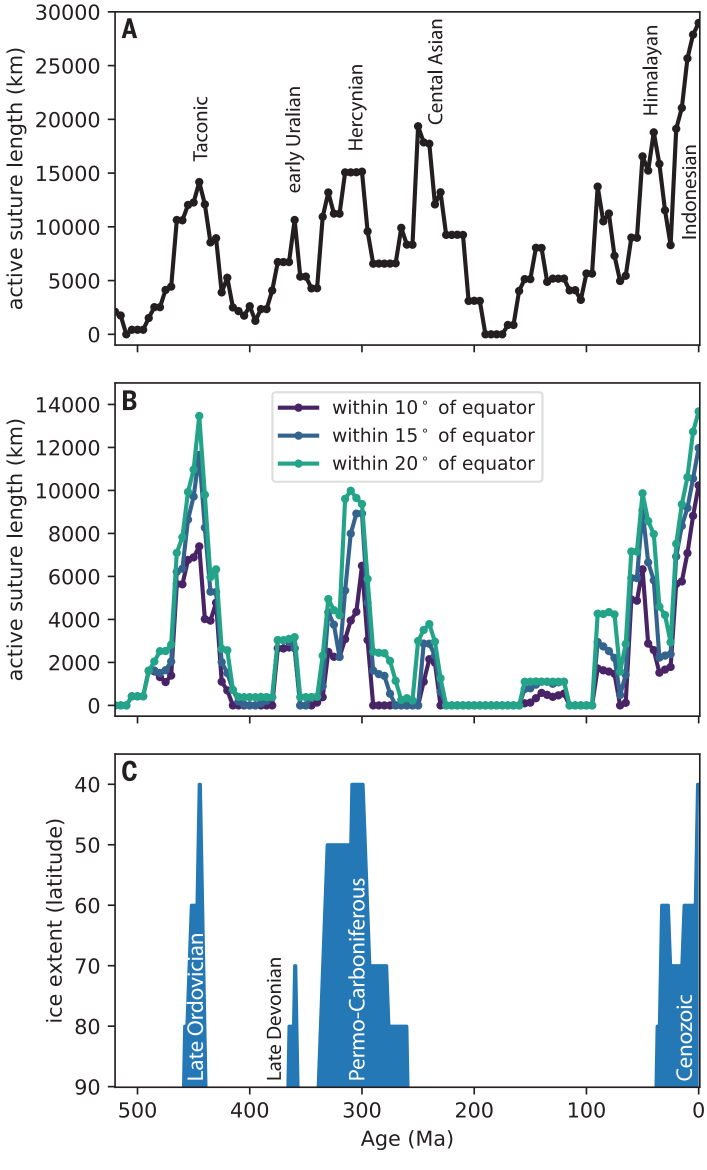

Fig. 2. Phanerozoic suture length in the tropics compared to the latitudinal extent of continental glaciation. (**A**) Total length of active suture length. (**B**) Total length of active sutures that are reconstructed to be within 10°, 15°, and 20° of the equator over the past 520 million years. (**C**) Blue marks the latitudinal extent of continental ice sheets, excluding Alpine glaciers (table S3).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/364/6436/181/suppl/DC1
Materials and Methods
Figs. S1 to S9
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Controlling cooling

On million-year time scales, Earth's climate state is determined by sources and sinks of carbon to the ocean-atmosphere system. But which specific mechanisms are important in controlling the timing of glacial intervals? Macdonald *et al.* identify arc-continent collisions in the tropics as a primary control (see the Perspective by Hartmann). They compiled a database of Phanerozoic arc-continent collisions and the latitudinal distribution of ice sheets, showing that ice coverage was greatest when those collisions were most widespread, maximizing global weatherability.

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