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Lack of a weathering signal with increased Cenozoic erosion?

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Abstract

The Late Cenozoic has been marked by large and rapid fluctuations in temperature. This cooling has been attributed to accelerated erosion, with concomitant increased chemical-weathering rates and CO_2 drawdown from the atmosphere. At the same time, much of the supporting evidence appears to be affected by a sampling bias, implying that global erosion and weathering have remained largely constant over the past millions of years. We suggest that sedimentary archives of geomorphic activity, such as grain size and the ratio of terrestrial to oceanic sedimentation, which show accelerated erosion are not subject to these biases. Furthermore, the active tectonic settings where these erosion increases were likely to have taken place are exactly those locations where chemical-weathering signals are least likely to faithfully follow physical erosion rates. A lack of evidence for an increase in chemical weathering does not necessarily preclude an increase in physical erosion. In this contribution, we suggest an alternative interpretation in which erosion rates have increased in the Late Cenozoic but without significantly increased silicate weathering, which can explain the meagre response of chemical-weathering proxies.

1 | INTRODUCTION

Many recent papers have highlighted a lack of consensus on our understanding of how, and even if, climate impacts landscape change over geological timescales (e.g. Herman and Champagnac, 2016; Willenbring and Jerolmack, 2016). Over the past few million years, climate cooled significantly (e.g. Lisiecki & Raymo, 2005) such that glaciers began to grow globally. Initially, geological records were interpreted to indicate that sedimentation rates (and by proxy erosion rates) increased at the same time (Hay et al. 1988; Kuhlemann et al., 2002; Zhang et al., 2001; Herman et al., 2013). These datasets seemed to support positive feedbacks between mountain building, climate and erosion (Molnar and England, 1990; Raymo and Ruddiman, 1992 among others). The most accepted version of this argument is that global cooling drove glacial advance, which in turn resulted in increased erosion and weathering rates (e.g. Molnar and England, 1990; Herman et al., 2013; Herman and Champagnac, 2016). These increased weathering rates would then result in CO_2 drawdown through silicate-mineral weathering (e.g. Raymo and Ruddiman, 1992; Berner & Kothaval, 2001). This scenario was consistent with the available data until it was suggested that a measurement bias existed in the geological record (Sadler, 1999; Schumer & Jerolmack, 2009; Sadler & Jerolmack, 2014; Willenbring and Jerolmack, 2016). If sedimentary records include not only periods of sedimentation but also periods of non-sedimentation and erosion then sedimentation rates would naturally appear to accelerate towards modern times. If this is indeed the case, then an acceleration of erosion (by proxy) never existed (Willenbring and von Blanckenburg, 2010; Willenbring and Jerolmack, 2016).

The purpose of this article is to propose an alternative view to the two dominant paradigms. We suggest that many sedimentary records that are not subject to an erosion bias (cf. Sadler, 1999) do indicate that erosion rates have increased in many sedimentary systems. For example, fan systems in the Andes and Nile delta have prograded during this time (Uba et al., 2007; Sestini, 1989) and grain sizes in both marine and continental environments (Zhang et al., 2001) became larger. Furthermore, the balance of terrestrial-derived to oceanic-derived sediment has increased (Hay et al., 1988). While these records individually are prone to a Sadler-effect bias (e.g. Willenbring and Jerolmack, 2016), their ratio should be independent and provides evidence for a shift towards a larger relative importance of clastic material in the stratigraphic record, particularly during the past few million years. Accordingly, we argue that there is geological evidence of increasing physical erosion in the Late Cenozoic. At the same time, proxies of chemical weathering have yielded mixed results showing both strong (Riebe et al., 2004 and Ferrier, Riebe, & Hahm, 2016 among others) and weak (e.g. Norton and von Blanckenburg, 2010; West et al., 2005) coupling between chemical weathering and erosion. The last decade has led us towards the understanding that chemical-weathering rates may not necessarily respond linearly to physical erosion rates, especially in tectonically active settings (West et al., 2005; Ferrier & Kirchner, 2008; Norton and von Blanckenburg, 2010), and that non-silicate weathering is important in many mountain settings, especially where granitic batholiths are scarce (Torres et al., 2016). We pursue these two lines of evidence to suggest that there was an increase in the supply of coarse-grained material and thus erosion rate during the Cenozoic and that this is not necessarily contradicted by a limited signal of increased chemical weathering. Accordingly, we propose that a middle ground may exist in reconciling increased erosion (Herman and Champagnac, 2016) and near-constant atmospheric CO_2 (e.g. Willenbring and Jerolmack, 2016) during the Cenozoic.

2 | SEDIMENTARY ARCHIVES

The hypothesis of an inferred increase in global erosion rates during the past few millions of years is mainly based on work by Zhang et al. (2001) and to some extent by Hay et al. (1988) (Figure 1a). These authors showed that sediment accumulation rates in the world's oceans (Hay et al., 1988) and in continental sedimentary basins (Zhang et al., 2001) increased substantially during the past c. 5 Ma. Recently, both of these sediment accumulation records have been challenged by Willenbring and von Blanckenburg (2010) and Willenbring and Jerolmack (2016) based on the 'Sadler effect' (e.g. an apparent increase in recent erosion rate caused by the existence of periods of erosion and non-deposition; Sadler, 1999). As such, erosion and non-deposition bias the geological record as the temporal scale of observations gets shorter. While erosional hiatuses do indeed appear to be a part of the sedimentary record, sediment calibre and sedimentary structures, which are indicative of the energy of the erosional and depositional environments, have also been recorded by many authors (Hay et al., 1988 and Zhang et al., 2001, among others) and are not subject to Sadler-type biases.

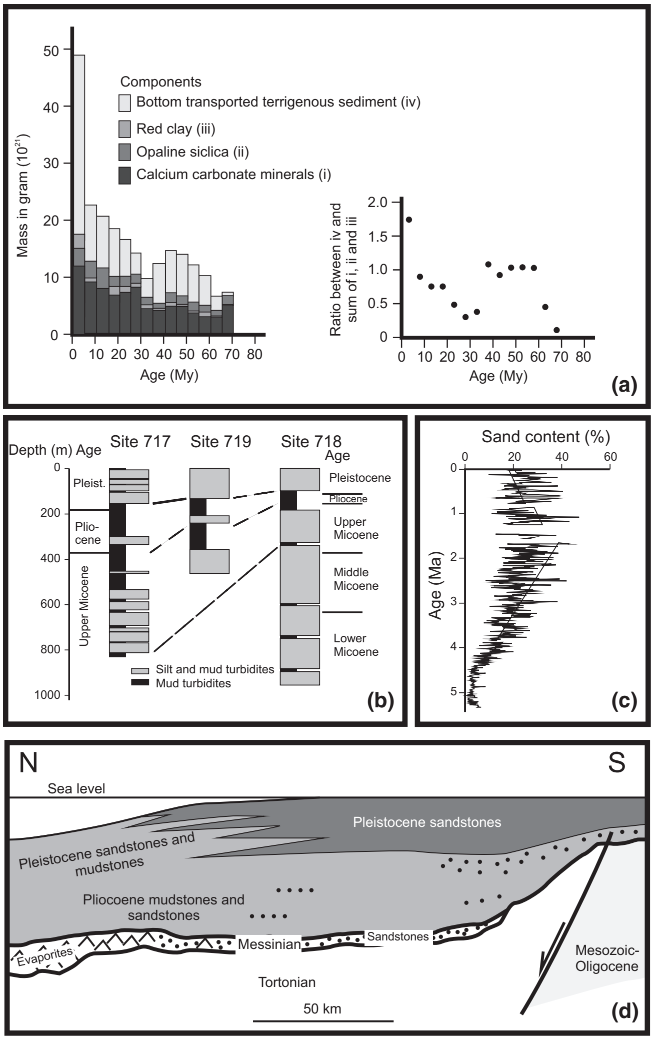

FIGURE 1 (a) Sediment accumulation rate data, taken from Hay et al. (1988), and the ratio between the contribution of bottom-transported terrigenous sediment (component iv) and the sum of calcium carbonate minerals (component i), opaline silica (component ii) and red clay (component iii). (b) IODP drillings through distal Bengal fan deposits. While trends in clastic sedimentation are lacking at IODP 718, sites 719 and 717 do show that the relative frequency of coarser grained turbidites was higher during the Pleistocene compared to the time span between the Upper Miocene and the Pliocene. This suggests progradation of the Bengal submarine fan. This also implies that the supply of sediment was increasing at the Pliocene–Pleistocene boundary, most likely driven by a larger sediment flux from the Himalaya (Stow et al., 1989). (c) Sand contents at the Caribbean ODP drilling site 999 and the DSPD site 502 (Prell, 1982; Haug & Tiedemann, 1998). (d) Schematic figure illustrating the temporal and spatial relationships between the depositional systems of the Nile delta. The figure shows that the delta continuously expanded into the Mediterranean after the Messinian salinity crisis. However, the progradation rates accelerated during the Pleistocene in response to a larger supply of coarser grained material (modified after Sestini (1989))

Grain size in fluvial systems is predominantly controlled by the style and magnitude of erosion in the catchment and by transport efficiency (Church, 2006), where the supply and transport of coarser grained material requires larger erosional and transport work to be accomplished (Paola et al., 1992). Zhang et al. (2001) highlighted a shift in the pattern of sedimentation around 2–4 Ma together with sediment accumulation rates, the latter of which has been challenged (see above). Fine-grained sediments that accumulated during the mid-Cenozoic give way to Plio-Quaternary conglomerates in regions as disparate as high Asia (Burbank et al., 1996) and the Southern Alps of New Zealand (Nathan et al., 1986), and a larger relative abundance of heavy minerals appears in sandstone interbeds (same authors). One could argue that conglomerates may become enriched in the geological record as pebbles are hard to break down. Accordingly, recycling of previously deposited conglomerates could potentially result in the accumulation of further conglomerates, thereby contributing to the increase in the relative abundance of this lithology through time, particularly for Quaternary sediments as examples from the foreland basin north of the European Alps have shown (Claude, 2016). In the case of the Himalayas, however, the gravel front is currently situated at the foothills of the mountain range and breakdown of gravels to sand has been shown to be very efficient (Dingle et al., 2017). Accordingly, for this particular case, we do not consider that recycling of previously deposited gravels and conglomerates contributes to a bias. Finally, Cochran (1990) reported a shift from mud-dominated towards silt-dominated turbiditic sedimentation at the Pliocene–Pleistocene boundary from three different IODP wells (sites 717, 718, 719) situated at the distal margin of the Bengal submarine megafan (Figure 1b). Submarine megafan progradation and increased grain size ultimately point to a larger supply of clastic material (e.g. Paola et al., 1992) through increased erosion from widely distributed basins.

The absolute sedimentation rates in ocean basins are prone to erosion biases; however, erosion or non-sedimentation would remove terrestrial and oceanic sediments indiscriminately. As such, we suggest that the ratio of terrestrial to oceanic material represents a more faithful record of subaerial erosion. Hay et al. (1988) differentiated between the various sedimentary components in their study (Figure 1a). These include: (1) calcium carbonate minerals, which are mostly of biogenic, pelagic origin where phyto- and zooplanktonic organisms have extracted dissolved elements from the ocean; (2) opaline silica, which is also mostly of pelagic origin and which has been fixed by diatoms and radiolarians in the sea water; (3) red clay, which could be of volcanic origin, or could have been transported as dust by wind, or alternatively could have accumulated through diagenetic processes and (4) bottom-transported terrigenous sediment, which was calculated as the residual of the total sediment if the other components are known. This approach adds a bias as the related volumes of terrigenous-derived material have not been independently constrained. But what is important in this context is the pattern of the ratio between component (4) and the sum of components (1) to (3), because this offers a proxy to infer a possible shift in the relative importance of physical vs chemical sedimentation. The limited temporal resolution of the original study plus uncertainties in the evaluation of deep-sea drilling (DSDP) data are factors that could add substantial limits, as a recent assessment has shown (Lyle, 2003). However, in our example, terrigenous/oceanic ratios ranged between 0.3 and 1 between 30 and 5 Ma, then increased to nearly 1.8 between 5 Ma and the present (Figure 1a). Hay et al. (1988) interpreted this increase as a response to continental glaciations, where lowered sea levels allowed fluvial systems to erode the continental margins, thereby supplying large volumes of clastic material to the ocean. Similar results have been reported from the Caribbean sites 999 and 502 of the Ocean Drilling Program (ODP) and the Deep Sea Drilling Project (DSDP), respectively, where the sand content increased from <10% prior to 4.5 Ma to nearly 20% thereafter (Prell, 1982; Haug and Tiedemann, 1998) (Figure 1c). These changes have been interpreted as a response to the intensification of the Gulf Stream after the closure of the Isthmus of Panama at 4.6 Ma (Haug and Tiedemann, 1998), potentially showing larger supply rates of terrigenous-derived material. This is supported by IODP drillings in the Pacific Ocean on the western margin of Africa at c. 23°S latitude that encountered a higher abundance of wind-blown dust and sand and a larger abundance of pollen in Pleistocene sediments (Ruddiman et al., 1989; Vallé et al., 2014). Despite the potential for biases in sediment accumulation rates, the changing relative abundance of clastic material in offshore archives suggests increasing terrestrial input at or after c. 5 Ma, which is consistent with an inferred increase in the ratio between physical and chemical sedimentation.

A clear glacial driver for this potential increased physical erosion as suggested by Herman and Champagnac (2016) is proving enigmatic as multiple sedimentary systems indicate an increase in sediment supply. Recent work by Ganti et al. (2016) suggests that glacial landscapes in particular might be prone to erosional hiatus biases and that it is important to use a chronometer that averages over the same time-scale. With this in mind, one strong piece of evidence for non-biased increased glacial erosion rates comes from Charreau et al. (2011) who used concentrations of in-situ ^{10}Be (which would tend to have similar or shorter averaging times than glacial/interglacial timescales) preserved in continental sediments of Central Asia to document a transience towards a larger supply of clastic material at the intensification of glaciations at ~2 Ma, showing that erosion can increase significantly with glacial activity. However, other archives are consistent with an increase in the supply rate of coarse-grained clastic material before the onset of major glaciations. Figueiredo et al. (2009) reported that delta sedimentation of the Amazon stream, one of the largest river systems on Earth, commenced in the Late Miocene between 12 and 11 Ma. Figueiredo et al. (2009) interpreted these changes as a response to a combination of Andean tectonism, global cooling and sea-level fall during the Late Miocene. Uba et al. (2007) also inferred an increase in sediment supply to the continental Chaco foreland basin on the eastern margin of the Central Andes, one of the largest foreland basins in a continental setting, based on high sediment accumulation rates paired with large-scale coarsening and thickening-upward megasequences. These changes in sedimentation patterns have been related to monsoon intensification and larger climate variability in South America. For example, faster incision rates in streams with sources on the eastern margin of the Andes have been linked to higher orographic rainfall (Lease and Ehlers, 2013). At the same time, stratigraphic data show that fluvio-deltaic deposits appear for the first time in the present delta area of the Nile delta in the Late Miocene (Sestini, 1989) with fast progradation yielding a large-scale coarsening-upward sequence since the Late Pliocene and particularly during the Pleistocene (Figure 1d). Kuhlemann et al. (2002) reported a larger sediment supply from the Central European Alps to the North Sea and the Mediterranean during the past ~2–4 Ma based on volumetric sediment budgets of circum-Alpine basins. However, some of this increase in flux was likely related to Sadler-type recycling of previously deposited foreland basin deposits (Baran et al., 2014). These archives, although incomplete in the time they cover and variable in the timing of inferred larger sediment fluxes with potentially different drivers, share the same observation that the relative importance of clastic material in numerous stratigraphic records in terrestrial, nearshore and offshore environments has increased at least since the Late Miocene and possibly earlier. In summary, there is ample evidence from nearly all continents, the largest onshore and offshore megafans and particularly from the Pacific Ocean that the supply of coarser grained material relative to the total volume of sediment has increased during the past few million years. The majority of these archives are from fluvial settings where potential glacial erosion hiatuses (cf. Ganti et al., 2016) would not affect the record. The timing of the onset of these shifts varies, but changes are consistent, pointing towards a change in either the transport or the erosional mechanisms at work, or a combination of both.

The mechanisms connecting the potential climate drivers to erosion are also unclear. Empirical (Gabet et al., 2004), analogue (Bonnet & Crave, 2003) and numerical (Tucker and Slingerland, 1997) models have all shown that increased precipitation can lead to a lowering of relief. There has been a large body of work showing the lasting effect of climate on landscape process and form. Roe et al. (2002) showed that orographic precipitation (which would likely be enhanced when westerly winds become stronger; see references in Herman and Champagnac, 2016) has a strong control on the relief of a mountain belt. Using a 1D model, they illustrated a twofold difference in relief generation for a given change in uplift rate when considering full orographic feedbacks. These examples show the direct influence of climate (precipitation in this case) on erosion through changing topography even without glacial erosion. Importantly, these transient erosional responses can persist for geologically significant intervals. Numerical modelling by Whipple (2009) suggests that system response times to changes in erosional efficiency can last on the order of 2–10 Ma or longer. If these systems are repeatedly perturbed, then long-term transience can be maintained (Schlunegger et al., 2011). In order for this to be sustained over the million-year timescales suggested by the data, one needs to invoke isostatic feedbacks such that elevation of the entire orogen is reduced as the crustal root is consumed (i.e. Molnar, 2004). Clearly, such a state cannot continue ad infinitum (e.g. Willenbring and Jerolmack, 2016), but the enhanced erosion implied by sedimentary records presented here and thermochronometric records presented by Herman et al. (2013) and discussed in Herman and Champagnac (2016) is viable given the current understanding of crustal response.

3 | CHEMICAL WEATHERING AND ARCHIVES

As is the case for the physical record, chemical proxies have yielded contradictory evidence for increased weathering. The lack of a weathering signal is not a priori proof of a lack of an erosional event. Indeed, the relationship between weathering and erosion is a point of ongoing debate. Climate proxies show a clear cooling of global temperatures over the past few million years (Lisiecki & Raymo, 2005); however, as described above, many geochemical-weathering proxies fail to show any such change.

Atmospheric pCO_2 records are variable and imply at most a modest decrease (Fedorov et al., 2013), with pCO_2 decreasing ~25% in the past 5 Ma (Beerling and Royer, 2011) but remaining constant within error from ~2 Ma until pre-industrial times. $^{10/9}$Be ratios also suggest at most a 20% increase in weathering rates (Willenbring and von Blanckenburg, 2010). This begs the question: what is the signature of different forms of weathering on the common geochemical markers?

One of the arguments against a Late Cenozoic increase in physical erosion is that there should be a concomitant increase in chemical-weathering rates (e.g. Willenbring and von Blanckenburg, 2010) based on the understanding that there is a roughly linear relationship between chemical weathering and physical erosion rates (Riebe et al., 2004; Ferrier et al., 2016). However, many authors over the past couple of decades have argued that chemical-weathering rates, especially in tectonically active areas, may not scale linearly with physical erosion rates, based on both empirical data (West et al., 2005; Dixon & von Blanckenburg, 2012; Norton and von Blanckenburg, 2010) and numerical modelling (Ferrier & Kirchner, 2008; Gabet and Mudd, 2009). While the exact relationship between weathering and erosion is still debated, it is most often treated as a power law function such that:

$$W = aD^{\alpha} \tag{1}$$

where W is weathering, a is a scalar, D is denudation and α controls the linearity of the weathering/erosion relationship. Reported values for α have ranged between 0.37 and 1 (Millot et al., 2002; Riebe et al., 2004; West et al., 2005). Ferrier et al.'s (2016) compilation of weathering intensity from mass loss in regolith suggests limited kinetic influences and $\alpha \sim 0.83$. The cosmogenic-nuclide-derived denudation rates used for weathering studies (Ferrier et al., 2016 and references therein) are inherently limited by analytical precision and the requirement for attainment of steady state. As such, these studies tend to cut off the fastest rates, potentially limiting the evidence for non-linear weathering/erosion relationships. The global compilation of chemical denudation from rivers by West et al. (2005) indicates that $\alpha = 0.42 \pm 0.15$. We suggest that the river load data are more comparable with the sedimentary archives used to determine sedimentation rates. In addition, because streams integrate patterns of sediment supply and erosion over broader spatial and also temporal scales, we suggest that sediment loads in these systems are more indicative, on average, of the erosional mechanisms at work in mountain belts than measurements of α ratios that were carried out for the hillslope scales. Accordingly, we tentatively prefer α values of c. 0.42 (West et al., 2005) compared with estimates closer to 1, where related α values are mainly based on studies for the hillslope scale.

We use the power law relationship above to calculate the global increase in weathering flux that would be expected for a given denudation rate increase assuming a variety of non-linear scalars and linear scaling. We estimate relative global erosion fluxes by calling on a non-linear relationship between mean relief and denudation rate (Montgomery and Brandon, 2002):

$$D \approx Ea + \frac{KR}{1-(R/R_{ref})^2} \tag{2}$$

where Ea is a background denudation rate, K is a scalar, R is the mean relief (in this case over a 10 km^2 moving window and binned into 1 m intervals) and R_{ref} is a reference relief determined by Montgomery and Brandon (2002) to be ~1500 m. While this approach is simple and is prone to biases of its own (see Willenbring et al. 2013; Kirchner and Ferrier, 2013), it provides a reasonable first check on the magnitude of weathered material that might be generated by different erosion rates. Following Montgomery and Brandon (2002), we apply Eq. 2 to a global relief dataset at 1 km (Figure 2). We calculate reference erosion rates and weathering rates for each relief class and sum them to determine the relative response of weathering to an increase in denudation. Because the non-linear equation does not allow for meaningful solutions at or above the reference relief, we limit the maximum erosion rate to the value at $R_{ref}-1$ for relief values greater than or equal to 1500 m (<2% of the total area). In this way we estimate the globally integrated response of weathering to denudation rate changes (Figure 2).

The $^{10/9}$Be archive allows for upwards of a 20% increase in weathering rates (Willenbring and von Blanckenburg, 2010). Based on a weathering/erosion relationship where $\alpha = 0.42$ (West et al., 2005) the twofold increase in erosion rates implied by Herman et al.'s (2013) work would result in only a 34% increase in global weathering flux (Figure 3). In the extreme case, if soils become kinetically limited (Ferrier & Kirchner, 2008; Norton and von Blanckenburg, 2010; Dixon and von Blanckenburg, 2012) then the global model predicts less than a 20% increase in global weathering flux for up to a sevenfold increase in physical weathering. A Cenozoic acceleration of erosion would likely be sourced in active tectonic settings. These locations are where one might be more likely to find kinetically limited soils (i.e. Norton and von

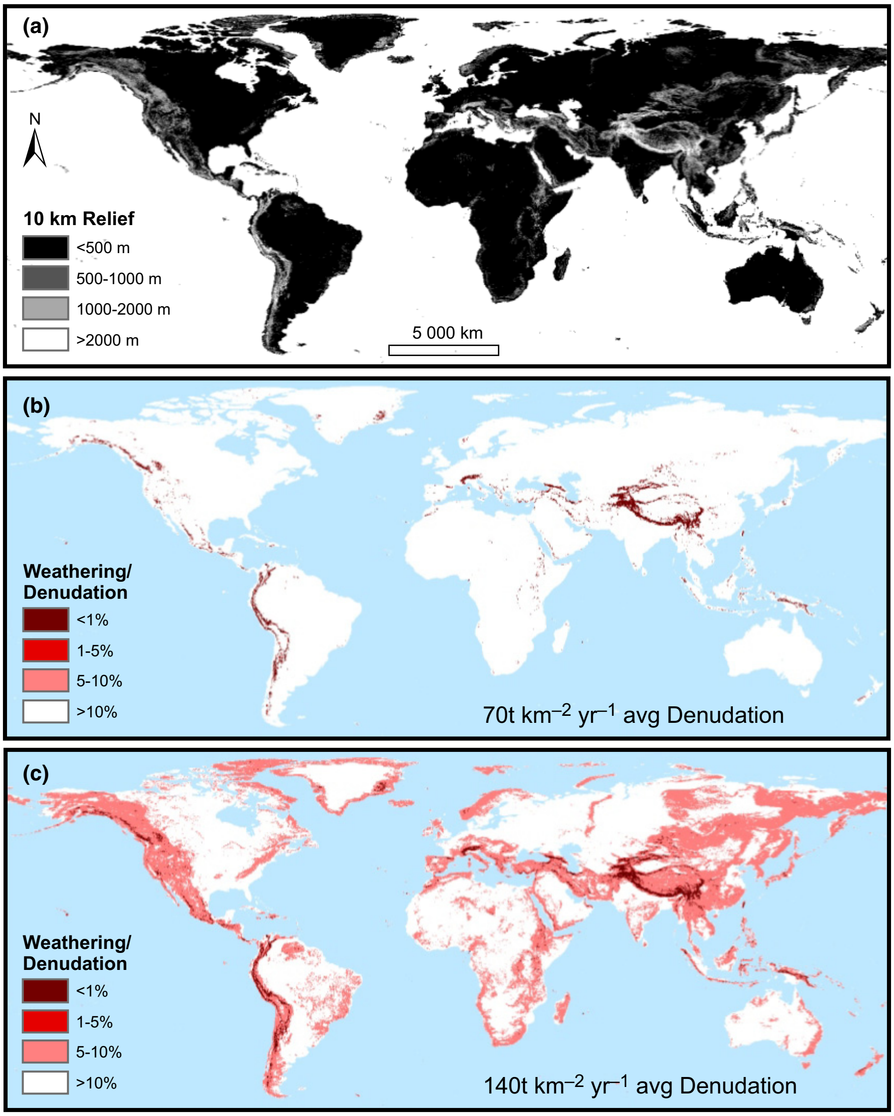

FIGURE 2 Global relief and per cent weathering contribution to total denudation. The relief calculated with a 10 km moving window (a) was used to calculate global denudation rates following Montgomery and Brandon (2002). Subfigures (b) and (c) show the per cent contribution of chemical weathering to the total denudation rate for $\alpha = 0.42$ (West et al., 2005) (b) under modern conditions ($Ea = 0.01$ mm/yr^{-1}, $K = 0.00025$, $R_{ref} = 1500$ m; Montgomery and Brandon (2002)) yielding an average global denudation rate of ~70 t km^{-2} yr^{-1} and (c) under a doubling of denudation rate. For non-linear weathering laws, increased denudation results in larger areas with a smaller relative weathering contribution (i.e. areal extent where chemical weathering is >10% of denudation is much larger for the modern climate with low denudation rates (b) compared to scenario (c) with higher denudation rates)

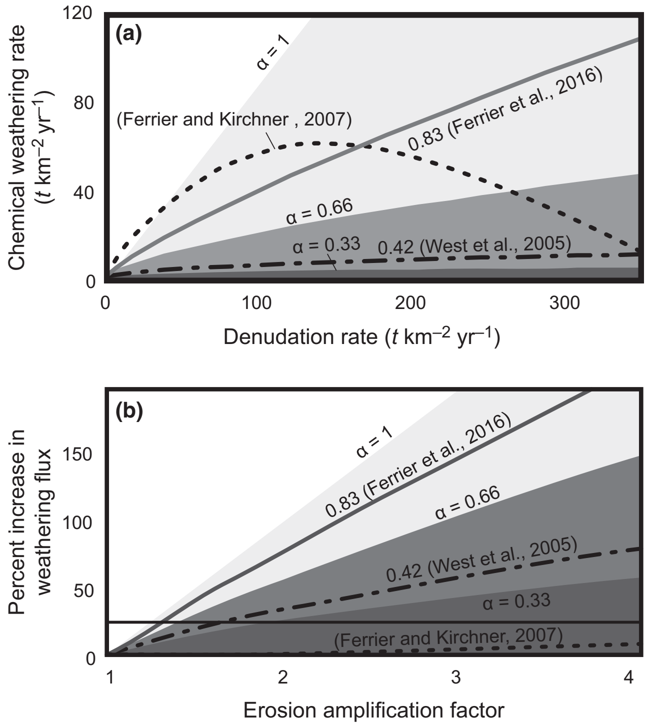

FIGURE 3 Global response of weathering to increased erosion. (a) Weathering vs. erosion for a range of exponents from 0.33 (dark grey) to 1 (light grey). The scaling exponents of West et al. (2005) and Ferrier et al. (2016) are indicated by solid and dashed lines respectively. (b) Per cent increase in global weathering flux vs. erosion amplification factor for different weathering exponents. The range of potential weathering increases from $^{10/9}$Be ratios and pCO_2 is shown with a black box. Near linear models imply minimal increase in erosion rates, while strongly non-linear models can accommodate as much as a two-fold increase in erosion without exceeding the weathering suggested by chemical archives

Blanckenburg, 2010), where bedrock is frequently exposed and hillslopes are at threshold angles (Ouimet et al., 2009). Modelled weathering responses using non-linear weathering/erosion relationships in primarily granitic landscapes suggest that under kinetic limits chemical-weathering fluxes may not increase appreciably with increasing erosion (Figure 3). Of course, in the case of a linear response, there is a doubling of chemical weathering for a doubling of erosion. However, the impact of such a response on atmospheric pCO_2 would still be dependent on the proportion of silicate rocks exposed in the catchment.

The dominance of silicate weathering itself has also recently been called into question. Jacobson et al. (2015) and Moore et al. (2013) suggested that weathering of trace calcite in mountain settings becomes more important with higher erosion rates. Moore et al. also illustrated that even large increases in erosion in the New Zealand Southern Alps or Himalaya Tibetan Plateau would not lead to appreciable CO_2 drawdown. These results from granitic landscapes can also be extended to other lithologies. For example, Jacobson et al. (2015) measured Ca isotopes in basaltic settings in Iceland. They found that calcite weathering makes up a large proportion of the total weathering flux, especially for glaciated catchments. Rapid erosion, such as in New Zealand and from glaciated areas, is not solely associated with rapid silicate mineral weathering, and instead carbonate minerals are increasingly efficiently weathered from the system. In addition, sulphide minerals in mountain settings have recently been shown to play a major role in the weathering (Torres et al., 2016). These authors showed that sulphide oxidation acts as a CO_2 source in the Andes and that the ratio of sulphide to silicate weathering increases with increasing erosion rate. This implies that the locations in which we expect to see increases in physical erosion are the very locations that are likely not to provide a coherent chemical-weathering signal.

These results are important for two reasons. First, they imply that some chemical-weathering pathways do not result in a decrease in pCO_2. Indeed, in some cases, mountain weathering may even contribute to atmospheric CO_2 (Torres et al., 2016). Second, chemical-weathering proxies may be insensitive to these forms of weathering. For example, ^{9}Be is delivered to the oceans through silicate mineral weathering but is largely absent from carbonates, with concentrations potentially on the order of tenths of a ppm (Turekian and Wedepohl, 1961), while the granitic rocks that are often taken to represent the crust have significantly higher ^{9}Be concentrations (~5 ppm vs a crustal average of ~2.8 ppm, Taylor, 1964). Because of this, the rapid calcite weathering that takes place in mountains will not be visible as a decrease in $^{10/9}$Be ratios in the oceans and will not result in a change to atmospheric CO_2 concentrations. The upshot of this is that the most common forms of weathering at very rapid erosion rates may be invisible to common archives of chemical weathering.

4 | CONCLUSION

Sedimentary archives show trends of increasing grain size and increasing terrestrial input over the Late Cenozoic. These trends are independent of non-deposition or erosion biases and suggest long-term transience, where physical fluxes have increased relative to chemical fluxes. Transience is a common feature of Earth's surface system: rivers incise and deposit, mountains grow and decay. When considering the question of a Late Cenozoic increase in erosion, the question becomes one of time-scale: can transience persist over the million-year timescales suggested by sedimentary archives? We suggest that this is indeed the case where long term erosional transience could be supported by isostatic response and slow removal of crustal roots.

Chemical-weathering models also suggest that there may be a minimal response to the inferred increased physical erosion. Hillslope scale weathering implies a nearly linear trend between weathering and erosion and is consistent with no more than a 20% increase in erosion. However, when considering global river databases, the weathering–erosion trend becomes much less linear, such that a nearly two-fold increase in erosion is consistent with current weathering archives and pCO_2. Added to this, recent work has shown the important role of calcite and sulphide weathering in rapidly eroding mountain settings, suggesting that ambiguous chemical-weathering archives are completely consistent with an increase in erosion rates within the past few million years.

A lack of a weathering signal has been taken to imply that erosion rates did not increase in the Late Cenozoic. We present an alternative scenario in which a non-linear trend and/or a major contribution from non-silicate rocks minimises the effect of increased erosion on archives of chemical weathering. We suggest that there is sufficient sedimentological evidence for widespread increases in erosion over the Late Cenozoic and therefore that there is no reason to necessarily expect weathering rates to increase significantly with increased erosion rates. If this is indeed the case, then the lack of a chemical-weathering signal is in keeping with the geological observations of increased erosion in at least some mountain ranges globally.

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