Comparison of basin-scale in situ and meteoric $^{10}$Be erosion and denudation rates across a rainfall, slope, and elevation gradient at George River, northeast Tasmania, Australia

Leah VanLandingham$^1$, Eric W. Portenga$^1$, Edward C. Lefroy$^2$, Paul R. Bierman$^3$, Alan J. Hidy$^4$

$^1$Geography and Geology Department, Eastern Michigan University, Ypsilanti, MI 48197, United States
$^2$Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 98, Hobart 7001, Australia
$^3$Rubenstein School for Natural Resources and the Environment, University of Vermont, Burlington, VT 05405, United States
$^4$Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA 94550, United States

Correspondence to: Eric W. Portenga (eric.portenga@emich.edu), Paul R. Bierman (paul.bierman@uvm.edu)

Abstract. Long-term erosion rates in Tasmania, at the southern end of Australia’s Great Dividing Range, are poorly known, yet such knowledge is critical for making informed land-use decisions and improving ecological health of coastal ecosystems. Here, we present the first quantitative, geologically-relevant estimates of erosion rates for the George River basin, in northeast Tasmania, based on in-situ produced $^{10}$Be ($^{10}$Be$^i$) measured from stream sand at two trunk channel sites and seven tributaries (average 10.5 mm kyr$^{-1}$). These new $^{10}$Be$^i$-based erosion rates are strongly related to mean annual precipitation rates and elevation, and we suggest that the current East-West precipitation gradient across George River greatly influences erosion in northeast Tasmania. This stands in contrast to erosion rates along the mainland portions of Australia’s Great Dividing Range, which are more strongly related to basin slope. We also extract and measure meteoric $^{10}$Be ($^{10}$Be$^m$) from sediment grain coatings of the stream sand at each site, which we use to estimate $^{10}$Be$^m$-based erosion and denudation rates for George River. $^{10}$Be$^m$-based erosion and denudation metrics, particularly those from the central and eastern tributaries, are also closely related to elevation and precipitation in the same manner as $^{10}$Be$^i$ erosion rates. Although $^{10}$Be$^m$-based denudation rates replicate $^{10}$Be$^i$ erosion rates within a factor of two, $^{10}$Be$^m$-based erosion rates are systematically 5–6x higher than $^{10}$Be$^i$ erosion rates. $^{10}$Be$^m$ erosion and denudation metrics for the westernmost headwater catchments are significantly lower than expected and have likely been affected by intensive and widespread topsoil erosion related to forestry, which delivers large volumes of sediment rich in $^{10}$Be$^m$ to tributary streams. The $^{10}$Be$^i$ erosion rates presented in this study may be useful for land managers seeking to restore ecological health of Tasmania’s estuaries by reducing sediment input to levels prior to landscape disturbance.

1 Introduction

Erosion rates of river basins derived from measurements of the in-situ produced cosmogenic isotope, $^{10}$Be$^i$, have been used to elucidate and infer topographic, tectonic, and climate drivers of landscape evolution for thousands of individual river basins (Codilean et al., 2018; Harel et al., 2016; Mishra et al., 2019; Portenga and Bierman, 2011; Wittmann et al., 2020). Recently, erosion rates from individual studies have been compiled and analyzed at the scale of entire continental orogens to demonstrate...
primary and secondary controls on erosion across thousands to tens of thousands of years (Aguilar et al., 2014; Carretier et al., 2018; Codilean et al., 2021; Delunel et al., 2020; Starke et al., 2020). For example, Delunel et al. (2020) find that \(^{10}\text{Be}\) erosion rates across the European Alps are strongly linked to mean basin slope and influenced by uplift and glaciations. A number of north-south latitudinal studies from the South American Andes show that some segments of the range are driven by uplift (Carretier et al., 2015; Starke et al., 2017) and slope (Carretier et al., 2018) but not necessarily rainfall unless one considers the effects of vegetation in driving soil weathering rates (Carretier et al., 2015; Starke et al., 2020).

A new compilation and analysis of \(^{10}\text{Be}\) erosion rates across the Great Dividing Range on eastern Australia, however, is the first to analyze landscape dynamics across a continent-spanning, passive, post-orogenic rift margin and finds that basin slope is most closely related to erosion at all spatial scales, more so than any other potential driver of erosion (Codilean et al., 2021). While Codilean et al.’s (2021) analysis comprises erosion rates from the Western and Eastern flanks of the Great Dividing Range – northern tropics to temperate southeast Australia – it is restricted to mainland Australia. Here, we supplement Codilean et al.’s (2021) study with the first \(^{10}\text{Be}\)-based erosion rates from the southernmost end of the eastern Australian passive margin on the island-state of Tasmania and the first presented for temperate rainforests in the Southern Hemisphere (Fig. 1; cf. Adams and Ehlers, 2017; Belmont et al., 2007). Furthermore, important quantitative erosion rate data for Tasmania and many of its fluvial systems are currently lacking (Jerie et al., 2003; Koehnken, 2001), and providing new erosion rate data will provide useful information for land managers and estuary restoration efforts.

Figure 1: Generalized tectonic map of the eastern Southern Ocean/southwest Pacific Ocean, surrounding Tasmania, including large-scale geologic structures in southeast Australia and Tasmania. Inset shows normalized island-wide precipitation gradient across Tasmania with darker shades of blue being areas with more precipitation. The Central Highlands establishes a pronounced rainfall shadow on the east side of the island. The Ben Lomond Plateau promotes a secondary, more-localized East-West precipitation gradient for northeast Tasmania where the field area for this study is located; the main George River basin is shown outlined in yellow. Major estuaries are indicated: Derwent Estuary (DE), Macquarie Harbour (MH), Tamar Estuary (TE), Georges Bay (GB). Cities are shown with black dots for reference: Hobart (H), Launceston (L), St. Helens (SH).
1.1 Importance of Erosion of George River and the Georges Bay Watershed

Applications of $^{10}$Be, erosion studies in Australia often are set within the context of assessing the impact of sediment delivery to sensitive offshore coastal environments, primarily the Great Barrier Reef (Croke et al., 2015; Nichols et al., 2014). Recently, efforts to conserve and restore estuarine environments across Australia have gained significant traction, particularly because estuaries link terrestrial fluvial systems to coastal environments and act as a biogeochemical buffer and sediment trap between the two environments (Creighton et al., 2015; Fitzsimmons et al., 2015; Wolanski and Ducrotoy, 2014). These restoration efforts include hundreds of Tasmanian estuaries (Coughanowr and Whitehead, 2013; Edgar et al., 2000; Murphy et al., 2003), which suffer from centuries of human-caused degradation resulting from urbanization, introduction of invasive species, forestry, mining, fishing, agriculture, and tourism (Augustineus et al., 2010; Butler, 2006; Davis and Kidd, 2012; Edgar and Barrett, 2000; Ellison and Sheehan, 2014; Jones et al., 2003; Martin-Smith and Vincent, 2005; Nanson et al., 1994; Seen et al., 2004). Active conservation, restoration, and monitoring efforts are underway at many Tasmanian estuaries (Beard et al., 2008; Crawford and White, 2005; Creighton et al., 2015); none quantify geologically-relevant erosion rates nor sediment delivery, despite a recognized need to lower sediment delivery in order to reduce nutrient and pollutant loads, improve water clarity, and prevent burial of hard surfaces important for marine life (Elliott et al., 2007; Geist and Hawkins, 2016; Noe et al., 2020; Verdonschot, 2013).

This study focuses on the Georges Bay estuary in northeast Tasmania, which is known for its oyster stocks (Mitchell et al., 2000) but has been degraded by a history of timber production, tin mining, and agriculture. Historical land-use practices have supplied $>10^6$ m$^3$ of sediment to Georges Bay’s primary tributary, the George River (no “s”), since the late 19th century (Knighton, 1991) and continue to supply pollutants to Georges Bay (Bleaney et al., 2015; Crawford and White, 2005). The intensive historical industrial use of the land in the George River catchment and the threat of excess sediment delivery to the fragile estuarine environment in Georges Bay has driven state and local municipalities to focus restoration and conservation efforts on the bay. As elsewhere, the success of these efforts relies in part, on reducing sediment delivery from George River to Georges Bay (Batley et al., 2010; Crawford and White, 2005; Kragt and Newham, 2009; McKenny and Shepherd, 1999; Mount et al., 2005).

1.2 In situ $^{10}$Be and meteoric $^{10}$Be erosion and denudation metrics

The primary goal of this study is to provide background rates (over millennia) of landscape change and sediment delivery from the George River to Georges Bay using the in situ cosmogenic isotope beryllium-10 ($^{10}$Be) in fluvial sediment (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). $^{10}$Be, production decreases exponentially with depth in rock and sediment at Earth’s surface such that $^{10}$Be concentrations at depths $>2$ m is negligible compared to that measured closer to Earth’s surface (Gosse and Phillips, 2001; Lal, 1991); $^{10}$Be, produced by muons dominates at depths $>2$ m (Braucher et al., 2003; Gosse and Phillips, 2001; Heisinger et al., 1997), but muogenic $^{10}$Be, production is generally negligible when compare to
spallogenic $^{10}$Be production, except in rapidly eroding landscapes or landscapes with steep terrain (e.g. Dethier et al., 2014; Fellin et al., 2017; Rosenkranz et al., 2018; Scherler et al., 2014; Siame et al., 2011) or in paleoerosion studies (e.g. Schaller et al., 2001, 2004, 2016). Bioturbation homogenizes $^{10}$Be concentrations in soils (Brown et al., 1995; Granger et al., 1996; Schaller et al., 2018), and $^{10}$Be erosion rates are therefore considered to be insensitive to widespread shallow erosion. This insensitivity allows $^{10}$Be erosion rates to be a useful gauge of pre-disturbance rates of landscape change (Ferrier et al., 2005; Portenga et al., 2019; Schmidt et al., 2018; Vanacker et al., 2007); exceptions have been noted where human land use is intensive (i.e. Schmidt et al., 2016) or the effects of human land use are exacerbated by climate extremes (i.e. Rosenkranz et al., 2018).

Pre-disturbance $^{10}$Be erosion data can inform approaches to reducing sediment delivery from George River and support efforts to improve the ecological health of Georges Bay estuary and possibly other watersheds in northeast Tasmania that share similar bedrock and topographic characteristics.

Whereas $^{10}$Be is produced in rock and sediment, $^{10}$Be is also produced via spallation of oxygen in the atmosphere; this $^{10}$Be rains out or falls to Earth’s surface (meteoric $^{10}$Be; $^{10}$Be$_{m}$) where it is readily adsorbed into sediment grain coatings and traditionally used to trace sediment through landscapes (Brown et al., 1988; Heikkilä and von Blanckenburg, 2015; Helz et al., 1992; Monaghan et al., 1986; Portenga et al., 2017; Reusser et al., 2010b; Valette-Silver et al., 1986). Recently derived equations allow erosion rates and denudation rates to be calculated from measurements of $^{10}$Be$_{m}$ and the chemically-similar, non-cosmogenic $^{9}$Be, which is weathered out of mineral grains ($^{9}$Be$_{reac}$; Willenbring and von Blanckenburg, 2010; von Blanckenburg et al., 2012). $^{10}$Be$_{m}$ erosion and $^{10}$Be$_{m}/^{9}$Be$_{reac}$ denudation rates have been used to quantify landscape evolution over a variety of spatial scales for long-established river basins (Dannhaus et al., 2018; Deng et al., 2020; Harrison et al., 2021; Portenga et al., 2019; Rahaman et al., 2017; Wittmann et al., 2012, 2015) and has shown particular promise in quantifying landscape dynamics in quartz-poor landscapes (Deng et al., 2020; Rahaman et al., 2017).

Here, we consider erosion to be the physical mass loss from a landscape and denudation to be the sum of physical and chemical mass loss. Conceptually, and with regards to $^{10}$Be, Portenga et al. (2019) suggested that if soil thickness approximates the zone of $^{10}$Be production (<2 m) and if pH values in the environment are high (>3.9, Graly et al., 2010) such that no $^{10}$Be$_{m}$ desorbs from sediment grain coatings, erosion and denudation rates derived from measurements of $^{10}$Be$_{i}$ and $^{10}$Be$_{m}/^{9}$Be$_{reac}$ should be comparable and should measure landscape dynamics similarly. Although replication between $^{10}$Be$_{i}$ and $^{10}$Be$_{m}$ erosion and denudation rates at individual sites is poor (Portenga et al., 2019; Rahaman et al., 2017; Wittmann et al., 2015), average rates from $^{10}$Be$_{i}$ and $^{10}$Be$_{m}/^{9}$Be$_{reac}$ erosion and denudation datasets tend to be similar in magnitude, and similar spatial patterns of landscape change emerge from both $^{10}$Be$_{i}$ and $^{10}$Be$_{m}$ datasets across large regions (Deng et al., 2020; Portenga et al., 2019; Wittmann et al., 2015). Further use of the $^{10}$Be$_{m}/^{9}$Be$_{reac}$ denudation method in landscapes where $^{10}$Be$_{i}$ erosion can be measured and compared is important for evaluation the veracity of $^{10}$Be$_{m}$ erosion and $^{10}$Be$_{m}/^{9}$Be$_{reac}$ denudation calculations.
The small size and relatively uniform bedrock geology of George River basin provide an ideal location to compare $^{10}$Be$_i$ erosion rates with erosion and denudation rates derived using $^{10}$Be$_m$ and $^{10}$Be$_m$/Be$_{rec}$, respectively (Willenbring and von Blanckenburg, 2010; von Blanckenburg et al., 2012); additionally, measured soil pH values in the catchment range from 4.0–5.5 (Kidd et al., 2015), thereby suggesting that $^{10}$Be$_m$ loss to chemical weathering is not a concern in George River. Thus, a secondary goal of this study is to compare $^{10}$Be$_m$ erosion and denudation rates to $^{10}$Be$_i$ erosion rates as a means of assessing the efficacy of the $^{10}$Be$_m$ erosion and $^{10}$Be$_m$/Be$_{rec}$ denudation methods in a landscape that minimizes geological heterogeneity, which otherwise may introduce scatter to larger datasets covering larger, more geologically-diverse landscapes (i.e. Deng et al., 2020; Portenga et al., 2019; Rahaman et al., 2017). Although George River has a simple bedrock geology, it also has a long history of intensive lode and placer tin mining that has, in the past, disturbed its fluvial systems (Knighton, 1991; Preston, 2012). Given that intensive land-use histories have affected results of $^{10}$Be$_m$ calculations elsewhere (Portenga et al., 2019), we explore how mining in George River affects our interpretations of $^{10}$Be-based erosion and denudation calculations throughout this study.

Figure 2: A. Shaded relief map of the topography of George River basin. Areas of historic mining are shown (Knighton, 1991), the action of which delivered $>10^6$ m$^3$ to the George River delta in Georges Bay (GB). B. Bedrock geology map of George River shows the widespread occurrence of Devonian felsic intrusions of the Blue Tier Batholith, which underlies the vast majority of the field area. Note that basins TG-2, TG-4, TG-5, and TG-8 are almost entirely underlain by...
2 Field Area

Tasmania separated from mainland Australia during Cretaceous rifting of Antarctica and Australia and sits at the southern end of the Great Australian Escarpment – a steep arch-type escarpment that formed during the separation of Zealandia from mainland Australia in the Mid- to Late-Cretaceous (Fig. 1; Codilean et al., 2021; Crowder et al., 2019; Etheridge et al., 1987; Gaina et al., 1998; Griffiths, 1971; Gunn, 1975; Hayes and Ringis, 1973; Lanyon et al., 1993; Matmon et al., 2002; McDougall and van der Lingen, 1974; Mortimer et al., 2017; Persano et al., 2002; Sutherland et al., 2001; Weissel and Hayes, 1977). Bedrock of George River basin comprises granodiorite and granite associated with the Blue Tier Batholith, which were contemporaneously emplaced into sediments of the Mathinna Supergroup in the Devonian (Fig. 2; Foster et al., 2000; Gee and Groves, 1971; Gray and Foster, 2004; Higgins et al., 1985; McCarthy and Groves, 1979; Seymour et al., 2006). Siluro-Devonian sedimentary rocks and Neogene basalts underlie small areas, primarily along drainage divides in the central and western George River basin (Seymour et al., 2006).

George River basin is of modest size (557 km²) in northeastern Tasmania with low elevation (mean = 386 m) and gentle hillslopes (mean = 10°) that drain the eastern slopes of the Rattler Range, which currently has a warm, temperate climate (Kottek et al., 2006). Despite eastern Tasmania being in the rain shadow of the central Tasmanian Highlands and western coast...
ranges, the local topography of the Ben Lomond Plateau induces a moderate east-west precipitation gradient across George River basin (1,261–970 mm yr⁻¹; Fig. 3; Table 1; BoM, 2021; Fick and Hijmans, 2017).

Table 1. Sample locations and basin data

| Sample ID | River name          | Sample Location | Elevation (m) | Basin Area (km²) | Relief (m) | Mean weighted slope (°) | Mean annual precipitation (mm yr⁻¹) |
|-----------|---------------------|-----------------|---------------|------------------|------------|-------------------------|------------------------------------|
| TG-1      | George River        | -41.29017       | 148.22217     | 346              | 397.25     | 1127                    | 10                                 |
| TG-2      | Forester Creek      | -41.27181       | 148.19925     | 141              | 40.21      | 298                     | 6                                  |
| TG-3      | Powers Creek        | -41.28286       | 148.13247     | 265              | 55.56      | 670                     | 10                                 |
| TG-4      | Groves Creek        | -41.25511       | 148.08317     | 364              | 34.39      | 439                     | 11                                 |
| TG-5      | Ransom River        | -41.25364       | 148.08239     | 347              | 27.71      | 709                     | 10                                 |
| TG-6      | North George River  | -41.28067       | 148.00697     | 439              | 65.84      | 790                     | 12                                 |
| TG-7      | South George River  | -41.32208       | 147.92172     | 652              | 42.53      | 753                     | 9                                  |
| TG-8      | Mt. Albert Rivulet  | -41.32178       | 147.92592     | 596              | 20.42      | 631                     | 10                                 |
| TG-9      | George River @ St. Helens | -41.31350 | 148.26531     | 331              | 426.88     | 1174                    | 10                                 |

* Based or derived from Satellite Radar Topography Mission data, 90 m resolution (Gallant et al., 2011)

* Rainfall data are modelled precipitation rates from the WorldClim dataset, 1 km² resolution (Fick and Hijmans, 2017)

Aboriginal Australians crossed to Tasmania from mainland Australia >35 ka (Cosgrove, 1995; Cosgrove et al., 1990), possibly corresponding to subaerial exposure of the Bass Strait ~56–40 ka (McIntosh et al., 2006) and localized ice advances in the central Tasmanian highlands (Barrows et al., 2001, 2002; Macintosh et al., 2006). Ecological habitat suitability models, based on characteristics and locations of thousands of archaeological sites across Tasmania indicate that Aboriginal communities were located close to freshwater sources and coastal resources, such as the landscapes around Georges Bay and the lower elevations within George River tributaries (Jones et al., 2019). Human arrival in Tasmania has been linked to widespread erosion events in mid-elevation landscapes (McIntosh et al., 2009).

Historically, decades of intensive tin lode mining in isolated headwaters of some tributaries and pockets of hydraulic sluice mining for tin in lowland floodplains introduced >10⁶ m³ of tailings to George River and its tributaries (Fig. 2a), decreasing the average grain size of alluvium from 30–50 mm to 1–2 mm (Knighton, 1991). Bedload characteristics have since returned to pre-disturbance levels following widespread alluvium storage in floodplains and aggradation at the George River delta in Georges Bay (Knighton, 1991; Cheetham and Martin, 2018). Despite George River’s return to pre-disturbance channel and bedload characteristics, a study from an experimental forest in the Gentle Annie tributary to George River shows that sediment yields from logged plots relative to unlogged plots continues to contribute sediment to the George River system (Wilson, 1999). More recently, land use within George River basin in 2008, at the time of sample collection, consisted primarily of forestry production from relatively natural environments and secondarily of conservation land (Fig. 4); intensive land use (i.e. built structures, permanent land alteration) and agricultural production from unirrigated land occur in equal proportion, though much less than the primary and secondary land uses; a small percentage of George River is used for agricultural production from irrigated lands (ABARES, 2016).
3 Methods

Sediment samples for this study were collected in 2008 from several locations along the trunk \((n = 2)\) and tributaries \((n = 7)\) of George River (Fig. 2). At each site, sediment was collected from the streambed and/or in-channel bars to ensure active fluvial transport and mixing. Samples were sieved in the field to the 250–850 μm grain-size fraction. Although this grain-size is finer than the mean natural grain size \((30–50 \text{ mm}; \text{Knighton, 1991})\), previous studies show that \(^{10}\text{Be}\) grain-size bias is minimal or not present in small, low-elevation, low-relief, temperate landscapes where landslides are uncommon (van Dongen et al., 2001).
et al., 2019); thus, \(^{10}\)Be, measured from the 250–850 μm grain-size fraction can be interpreted as geological erosion rates. \(^{10}\)Be\(_m\) and the weathered and in situ phases of \(^{9}\)Be (\(^{9}\)Be\(_{\text{rec}}\), \(^{9}\)Be\(_{\text{min}}\), respectively) were measured from the 250–850 μm grain-size fraction from all seven tributary sites and one of the trunk channel sites.

\(^{10}\)Be\(_i\) was extracted from quartz from each sample at the University of Vermont following standard methods, during which a known amount of \(^{9}\)Be carrier (\(^{9}\)Be\(_{\text{car}}\)) was added to each sample (Kohl and Nishiizumi, 1992; Corbett et al., 2016); no native beryllium was detected in quartz concentrates from any sample, which can otherwise lead to significant overestimates of \(^{10}\)Be\(_r\)-based erosion rates (Portenga et al., 2015). \(^{10}\)Be/\(^{9}\)Be\(_{\text{car}}\) ratios were measured by accelerator mass spectrometry at the Lawrence Livermore National Laboratory CAMS facility (Table 2); \(^{10}\)Be\(_i\) measurements were blank-corrected (the average ratio of three blanks was subtracted from the ratio of unknown sample) and normalized to the 07KNSTD3110 AMS \(^{10}\)Be standard material, which has a nominal \(^{10}\)Be/\(^{9}\)Be ratio of 2.85 x 10\(^{-12}\) (Nishiizumi et al., 2007). \(^{10}\)Be production was averaged across all sampled basins to a single point following Portenga and Bierman (2011), and the CRONUS on-line erosion rate calculator (Balco et al., 2008) was used to derive \(^{10}\)Be erosion rates following the Lal (1991) and Stone (2000) scaling schemes (\(\epsilon\), Table 3); here, \(\epsilon\) is presented in units of mm kyr\(^{-1}\). As in Portenga et al. (2019), we present \(^{10}\)Be\(_r\)-based sediment flux rates in this study (Appendix A), which we present as the factor of \(\epsilon\) and \(\rho\) in units of Mg km\(^{-2}\) yr\(^{-1}\), so as to compare to \(^{10}\)Be\(_m\)/\(^{9}\)Be\(_{\text{rec}}\)-based denudation rates (see below). Muogenic production of \(^{10}\)Be is incorporated into \(^{10}\)Be\(_r\) based erosion rates; however, muogenic \(^{10}\)Be is negligible relative to spallogenic \(^{10}\)Be production given George River’s post-orogenic, low-elevation, low-relief setting.

| In situ Sample ID | UVM Batch No. | Quartz mass (g) | Carrier mass (μg) | LLNL Sample ID | \(\text{^{10}Be/^{9}Be}_{\text{car}}\) | \(\pm 1\sigma\) | \(\text{^{10}Be}_{\text{i}}\) (atoms g\(^{-1}\)) | \(\pm 1\sigma\) |
|-------------------|----------------|----------------|------------------|----------------|---------------------|----------|----------------|----------|
| TG-1 432\(^a\) | 20.099 | 250.791 | BE28820 | 4.37E-12 | 7.83E-15 | 3.64E+05 | 6.52E+03 |
| TG-2 438\(^b\) | 20.100 | 249.506 | BE29129 | 6.83E-13 | 9.31E-15 | 5.66E+05 | 7.72E+03 |
| TG-3 438 | 22.423 | 249.704 | BE29130 | 4.79E-13 | 1.41E-14 | 3.97E+05 | 1.17E+04 |
| TG-4 438 | 19.288 | 248.814 | BE29131 | 3.10E-13 | 8.41E-15 | 2.56E+05 | 6.95E+03 |
| TG-5 438 | 20.702 | 250.296 | BE29133 | 4.37E-13 | 1.02E-14 | 3.63E+05 | 8.48E+03 |
| TG-6 446\(^c\) | 20.532 | 249.209 | BE29303 | 2.81E-13 | 6.11E-15 | 2.33E+05 | 5.05E+03 |
| TG-7 446 | 20.156 | 249.111 | BE29304 | 2.28E-13 | 6.76E-15 | 1.86E+05 | 5.60E+03 |
| TG-8 446 | 20.747 | 249.704 | BE29305 | 2.99E-13 | 7.35E-15 | 2.48E+05 | 6.10E+03 |
| TG-9 446 | 20.169 | 250.791 | BE29306 | 4.94E-13 | 1.19E-14 | 4.11E+05 | 9.92E+03 |

| Meteoric Sample ID | UVM Batch No. | Sample mass (g) | Carrier mass (μg) | LLNL Sample ID | \(\text{^{10}Be/^{9}Be}_{\text{car}}\) | \(\pm 1\sigma\) | \(\text{Q}\) (tons cm\(^2\) yr\(^{-1}\) (atoms g\(^{-1}\)) | \(\pm 1\sigma\) | \(\text{^{9}Be}_{\text{rec}}\) (atoms g\(^{-1}\)) | \(\pm 1\sigma\) | \(\text{^{9}Be}_{\text{min}}\) (atoms g\(^{-1}\)) | \(\pm 1\sigma\) |
|-------------------|----------------|----------------|------------------|----------------|---------------------|----------|----------------|----------|----------------|----------|----------------|----------|
| TG-2 MB-15\(^d\) | 0.463 | 328.71 | BE27783 | 1.51E-12 | 2.07E-14 | 8.12E+05 | 7.16E+07 | 9.83E+05 | 2.51E+16 | 1.32E+16 |
| TG-3 MB-15 | 0.497 | 298.02 | BE27784 | 1.50E-12 | 2.26E-14 | 8.92E+05 | 5.99E+07 | 9.05E+05 | 3.19E+16 | 1.06E+16 |
| TG-4 MB-15 | 0.497 | 296.04 | BE27785 | 1.12E-12 | 1.55E-14 | 9.73E+05 | 4.84E+07 | 6.89E+05 | 3.29E+16 | 1.08E+16 |
| TG-5 MB-15 | 0.491 | 300.00 | BE27786 | 1.05E-12 | 1.46E-14 | 9.79E+05 | 4.29E+07 | 5.95E+05 | 2.84E+16 | 1.06E+16 |
| TG-6 MB-15 | 0.466 | 300.99 | BE27787 | 4.30E-12 | 5.79E-14 | 1.01E+08 | 1.85E+08 | 2.50E+06 | 4.54E+16 | 4.06E+16 |
| TG-7 MB-15 | 0.487 | 299.01 | BE27788 | 5.06E-12 | 6.09E-14 | 1.06E+06 | 2.30E+08 | 2.50E+06 | 3.09E+16 | 5.82E+16 |
| TG-8 MB-15 | 0.487 | 300.00 | BE27789 | 5.35E-12 | 5.83E-14 | 1.01E+06 | 2.20E+08 | 2.40E+06 | 2.71E+16 | 5.54E+16 |
| TG-9 MB-15 | 0.541 | 299.01 | BE27790 | 1.19E-12 | 1.64E-14 | 9.28E+05 | 4.39E+07 | 6.06E+05 | 1.53E+16 | 1.08E+16 |

\(^a\) In situ Batch 432 Blank \(\text{^{10}Be/^{9}Be}_{\text{car}}\) ratio = 1.25 x 10\(^{-12}\) ± 5.87 x 10\(^{-13}\)
\(^b\) In situ Batch 438 Blank \(\text{^{10}Be/^{9}Be}_{\text{car}}\) ratio = 1.22 x 10\(^{-12}\) ± 1.82 x 10\(^{-13}\)
\(^c\) In situ Batch 446 Blank \(\text{^{10}Be/^{9}Be}_{\text{car}}\) ratio = 1.27 x 10\(^{-12}\) ± 6.70 x 10\(^{-13}\)
\(^d\) Meteoric Batch MB-15 Blank \(\text{^{10}Be/^{9}Be}_{\text{car}}\) ratio = 1.65 x 10\(^{-12}\) ± 1.72 x 10\(^{-13}\)
10Be$_m$ was extracted following Stone’s (1998) fusion method and a 9Be carrier solution was added to each sample. 10Be$_m$/9Be$_{car}$ ratios of these fusion extracts were measured at the Lawrence Livermore National Laboratory CAMS facility, blank-corrected (ratio of one blank was subtracted from ratio of unknown samples; Table 2) and normalized to the 07KNSTD3110 standard material (Nishizumi et al., 2007). Sample material used to calculate 9Be$_{rec}$ was first subject to strong acid leaching to remove sediment grain coatings (Greene, 2016; Portenga et al., 2019 supplement); it was then fully digested in HF and 9Be$_{min}$ was measured in that solution. Both 9Be$_{rec}$ from sediment grain coatings and 9Be$_{min}$ from the remaining mineral material were measured by inductively coupled plasma-optical emission spectrometry (ICP-OES) at the University of Vermont. In this study, E and D$_m$ are presented in units of mm kyr$^{-1}$ and Mg km$^{-2}$ yr$^{-1}$, respectively.

| Sample ID | $\epsilon^a$ (mm kyr$^{-1}$) ± 2σ | Integration duration (kyr) | Sed Flux (Mg km$^{-2}$ yr$^{-1}$) ± 2σ | E (mm kyr$^{-1}$) ± 2σ | D$_m$ (Mg km$^{-2}$ yr$^{-1}$) ± 2σ |
|-----------|----------------------------------|-----------------------------|------------------------------------------|--------------------------|----------------------------------|
| TG-1      | 9.6 1.6 61.8 25.9               |                             |                                          |                          |                                  |
| TG-2      | 4.8 0.8 122.5 13.1             |                             |                                          |                          |                                  |
| TG-3      | 8.1 1.4 73.7 21.7             |                             |                                          |                          |                                  |
| TG-4      | 14.1 2.4 42.1 38.1             |                             |                                          |                          |                                  |
| TG-5      | 9.6 1.6 62.0 25.8            |                             |                                          |                          |                                  |
| TG-6      | 16.7 2.8 35.5 45.1            |                             |                                          |                          |                                  |
| TG-7      | 24.5 4.2 24.2 66.2            |                             |                                          |                          |                                  |
| TG-8      | 17.6 3.0 33.7 47.5            |                             |                                          |                          |                                  |
| TG-9      | 8.3 1.4 71.5 22.4            |                             |                                          |                          |                                  |

$^a$ 10Be$_m$ erosion rates calculated using the CRONUS erosion rate calculator version 3.0, wrapper version 3.0 rates version 3.0, muons version 3.1 (Balco et al., 2008)

E and D$_m$ presented in this study (Table 3) are calculated using values of Q that range from 8.12 x 10$^5$ atoms cm$^{-2}$ yr$^{-1}$ to 1.06 x 10$^6$ atoms cm$^{-2}$ yr$^{-1}$ (Appendix A; Graly et al., 2011). Values of Q used here are of the same order of magnitude as 10Be$_m$ accumulation rates measured from a similar latitude in New Zealand (1.68 to 1.72 x 10$^5$ atoms cm$^{-2}$ yr$^{-1}$; Reusser et al., 2010a), those integrated throughout the Holocene (1.0–1.5 x 10$^6$ atoms cm$^{-2}$ yr$^{-1}$; Heikkilä and von Blanckenburg, 2015), and atmospheric-depth integrated rates of Q (~7 x 10$^5$ atoms cm$^{-2}$ yr$^{-1}$; Masarik and Beer, 2009; Willenbring and von Blanckenburg, 2010). We choose to use Graly et al.’s (2011) approach to deriving values of Q for this study since they are specific to the latitude and rainfall for each basin.

We compare $\epsilon$, sediment flux, E, and D$_m$ to various topographic and climatic factors to assess dominant processes driving or related to background landscape evolution in George River (Table 1). Topographic data are derived from the SRTM 90-m resolution global dataset (Gallant et al., 2011). We use mean annual precipitation data from the updated WorldClim global dataset instead of precipitation from meteorological stations because of its greater spatial coverage, but we note that while WorldClim rainfall values are nominally lower than measured precipitation, both datasets show increased rainfall at higher elevations (Fig. 3c; BoM, 2021). Ratings of soil erosivity have been derived for Tasmania (Kidd et al., 2014, 2015) and are strongly tied to hillslope angle within George River basin (Fig. 5); thus, comparing erosion and denudation metrics against
basin slope metrics provides an adequate assessment of whether models of hillslope erodibility influence erosion in George River.

4 Results

4.1 \(^{10}\text{Be}\) erosion rates, \(\varepsilon\)

Erosion rates, \(\varepsilon\), based on measured concentrations of in situ \(^{10}\text{Be}\) (Table 3) range from 4.8 to 24.5 mm kyr\(^{-1}\) (Appendix A), and we find that the average \(\varepsilon\) from tributaries (13.6 \(\pm\) 1.0 mm kyr\(^{-1}\); 2\(\sigma\)) is greater than either of the trunk channel samples (TG-1 = 9.6 \(\pm\) 1.6 mm kyr\(^{-1}\); TG-9 = 8.3 \(\pm\) 1.4 mm kyr\(^{-1}\); 2\(\sigma\)). Tributary values for \(\varepsilon\), and \(\varepsilon\)-based sediment flux rates are greater in the high-elevation, western headwaters of George River basin and decrease systematically, eastwards towards the lower-elevation coast (Fig. 6). This eastward decrease in \(\varepsilon\) also corresponds to a decrease in rainfall along the precipitation gradient (\(R^2 = 0.82\)); relationships between \(\varepsilon\) and basin relief, basin-weighted slope, and the percent of each basin that is categorized as being greater than or equal to High Erosivity are weak (Fig. 7; \(R^2 = 0.39\), \(R^2 = 0.17\), \(R^2 = 0.05\), respectively).

Taking the product of \(\varepsilon\) and the area of each catchment provides the average annual volume of sediment exported from each catchment over millennia. Summing these volumes, shows that a similar volume of sediment passes through the trunk channel sample sites annually as the sum of sediment exiting sampled tributaries (TG-1 = 3.8 \(\pm\) 0.7 km\(^3\) yr\(^{-1}\); TG-9 = 3.5 \(\pm\) 0.7 km\(^3\) yr\(^{-1}\); tributaries = 3.9 \(\pm\) 0.3 km\(^3\) yr\(^{-1}\); 2\(\sigma\)). Trunk channel samples, TG-1 and TG-9, should also incorporate erosion from their respective subcatchments – the area upstream of the sample site, but downstream of all tributary sample points. Using regression equations for \(\varepsilon\) and longitude, elevation, and precipitation, each, an average modelled \(\varepsilon\) for TG-1 is 9.6 \(\pm\) 3.0 mm kyr\(^{-1}\) and an average modelled \(\varepsilon\) for TG-9 is 1.1 \(\pm\) 3.1 mm kyr\(^{-1}\). The average volume of sediment these subcatchments contribute to annual sediment loads, based on modelled \(\varepsilon\) data are TG-1 = 1.1 \(\pm\) 0.4 km\(^3\) yr\(^{-1}\) and TG-9 = 0.0 \(\pm\) 0.1 km\(^3\) yr\(^{-1}\).
Figure 5: A. Map of hillslope angle across George River basin, derived from 90 m SRTM digital elevation models. B. Map of hillslope erosivity across George River basin, from Kidd et al. (2014, 2015). C. Analysis of variance, showing hillslope angles associated with categories of landscape erosivity (Kidd et al., 2014, 2015) at George River. Box-and-whiskers cover ±1.5x the interquartile range; black dot is the mean slope for the erosivity category. Comparison of means for each category indicate that the means of erosivity categories are all significantly different from each other (i.e. no categories are linked by the same letter in the Connecting Letters Report); we use hillslope angle as a quantitative proxy for erosivity at George River.
Figure 6: $^{10}$Be$_i$ based erosion rates ($\varepsilon$, top row, black circles), $\varepsilon$-based sediment fluxes (top row, gray squares), $^{10}$Be$_m$-based erosion rates ($E$, bottom row, black circles), and $^{10}$Be$_m$/Be$_{crust}$-based denudation rates ($D_m$, bottom row, gray squares) from George River tributaries compared to mean basin longitude, mean basin elevation, and mean annual precipitation within each basin. $\varepsilon$ for all tributaries and $E$ and $D_m$ for the central and eastern tributaries (orange and blue ellipses, respectively) are strongly correlated with each variable, likely owing to the East-West precipitation gradient projected across the catchment (Fig. 3). Unbracketed $R^2$ values reflect correlation of all data whereas bracketed $R^2$ values indicate correlations for $^{10}$Be$_m$-based metrics only in the central and eastern tributaries. All error bars show 2$\sigma$ uncertainties.
Figure 7: $^{10}$Be$_i$ based erosion rates ($\varepsilon$, top row, black circles), $\varepsilon$-based sediment fluxes (top row, gray squares), $^{10}$Be$_m$-based erosion rates ($E$, bottom row, black circles), and $^{10}$Be$_m$/$^{9}$Be$_{reac}$-based denudation rates ($D_m$, bottom row, gray squares) from George River tributaries compared to mean basin longitude, mean basin elevation, and mean annual precipitation within each basin. Moderate relationships exist between $\varepsilon$ and basin relief and between $D_m$ and the percent of each basin that is designated High Erosivity or greater (Kidd et al., 2014, 2015). All error bars show $2\sigma$ uncertainties.

4.2 $^{10}$Be$_m$ erosion rates, $E$, and denudation rates, $D_m$

$^{10}$Be$_m$-based erosion rates, $E$, range from 17.0 to 78.3 mm kyr$^{-1}$ and replicate values for $\varepsilon$ well in the three westernmost headwater catchments, but not in the lower-elevation, center and easternmost tributaries, where $E$ is systematically ~5–6x higher than $\varepsilon$ (Fig. 8). $^{10}$Be$_m$/$^{9}$Be$_{reac}$-based denudation rates, $D_m$, range from 22.7 to 53.7 Mg km$^{-2}$ yr$^{-1}$. Except for TG-4 and TG-9, values for $D_m$ do not replicate sediment fluxes derived from $\varepsilon$, although the central and easternmost tributaries plot much...
closer to a 1:1 line than the samples from the three western-most headwater tributaries (Fig. 8). TG-4 was collected at the mouth of Groom River, upstream of which activities at the long-closed Anchor Mine significantly altered the topography. The meteoric erosion rate for the trunk channel site TG-9, $E = 78.3 \pm 2.2$ mm kyr$^{-1}$ is significantly higher than $\varepsilon$ for the same site ($10.7 \pm 1.7$ mm kyr$^{-1}$), but the denudation rate at TG-9, $D_m = 33.0 \pm 0.9$ Mg km$^{-2}$ yr$^{-1}$, replicates the $\varepsilon$-based sediment flux ($28.9 \pm 4.5$ Mg km$^{-2}$ yr$^{-1}$).

In general, $^{10}$Be$_m$-based measures of $E$ and $D_m$ are not significantly related to any topographic or climatic metric (Figs. 6, 7). However, the observed relationships between $E$ and $D_m$ and longitude, elevation, and precipitation are similar to those observed with $\varepsilon$ in the central and eastern tributaries (Fig. 6); $E$ and $D_m$ in the western tributaries do not follow the spatial trends that $\varepsilon$ exhibits.

Figure 8: $^{10}$Be$_i$-based erosion rates, $\varepsilon$, compared to $^{10}$Be$_m$-based erosion rates, $E$ (black circles) and $\varepsilon$-derived sediment fluxes compared to $^{10}$Be$_m$/Be$_{rec}$-based denudation rates, $D_m$, (gray squares) for the same sample sites. Erosion rates for the trunk-channel sample, TG-9 are indicated by the magenta circle and denudation rates are indicated by the cyan square. All error bars show 2\(\sigma\) uncertainties. Solid colored lines indicate 1-fold through 6-fold differences between erosion and denudation metrics using the $^{10}$Be$_i$ and $^{10}$Be$_m$ methods. $^{10}$Be$_m$ erosion rates are ~5–6x greater than $^{10}$Be$_i$ erosion rates in the central and eastern tributaries. $^{10}$Be$_m$/Be$_{rec}$ denudation rates replicate $^{10}$Be$_i$ sediment fluxes with much greater accuracy than $^{10}$Be$_m$ erosion rates.

5 Discussion

Erosion in George River is strongly related to basin longitude, elevation, and mean annual precipitation east of the Rattler Range and the prominent Ben Lomond Plateau (Fig. 6), and we find no evidence to suggest that $\varepsilon$ is related to slope in George River over millennial timescales. This result differs from most studies, which show strong correlations between $\varepsilon$ and mean basin slope at a global scale (Portenga and Bierman, 2011), at regional scales, across the Great Dividing Range on Australia’s mainland (Fig. 9; Codilean et al., 2021; Nichols et al., 2014), and despite prior assessments of George River that suggest slope
imparts a large control over erosion and sediment generation in the catchment (Jerie et al., 2003; Kragt and Newham, 2009). Instead, our finding is consistent with Mishra et al.’s (2018) suggestion that in low-slope, low-elevation, post-tectonic settings, the relationship between slope and erosion becomes secondary to precipitation, and this study presents one of the clearest examples of erosion along a topographically induced precipitation gradient in $^{10}$Be erosion literature.

Figure 9: A. Map of river basins draining east off the Great Australian Escarpment, where $^{10}$Be erosion rate data are available; adapted from Codilean et al. (2021). Filled circles are trunk streams and open circles are tributaries. Orange data include previously-published data (Codilean et al., 2021; Croke et al., 2015; Fülöp et al., 2020; Godard et al., 2019; Nichols et al., 2014; Tomkins et al., 2007). Blue data are new data presented in this study from George River, Tasmania. The average $^{10}$Be erosion rates from George River (10.5 mm kyr$^{-1}$) is consistent with erosion rates from southeast mainland Australia (average 11.6 mm kyr$^{-1}$; Codilean et al., 2021). B. Comparison of $^{10}$Be erosion rates from George River (blue circles) and the eastern flanks of the Great Australian Escarpment (orange circles) to basin average slope. B. Comparison of $^{10}$Be erosion rates from George River (blue circles) and the eastern flanks of the Great Australian Escarpment (orange circles) to mean annual precipitation.

The very strong relationship between precipitation and ε would likely not have emerged had our $^{10}$Be samples been affected by clast attrition (Carretier et al., 2009), deep-seated landslides (Aguilar et al., 2014; Gonzalez et al., 2016; Puchol et al., 2014), or intensive erosion associated with mining, forestry, or agriculture (Barreto et al., 2014; Neilson et al., 2017). Even intensive
tin mining, which supplied $>10^6$ m$^3$ to George River over the last two centuries (Knighton, 1991) seems to not have not had a long-lasting diluting effect on $^{10}$Be in sampled stream sediment. It is possible that mining efforts, especially the sluice mining, did not lead to $^{10}$Be dilution because of the homogenizing effect of $^{10}$Be in well-bioturbated soils (Brown et al., 1995) or that the size of George River was large enough to buffer the effects of mining efforts in a similar way that large catchments can buffer the effects of landslide material (Niemi et al., 2005; Yanites et al., 2009). It is also possible that mining activity did lead to $^{10}$Be dilution, but that these effects have since recovered along with bedload characteristics (Knighton, 1991) similar to the rapid, two-year recovery of $^{10}$Be concentrations following storm-triggered landslides in Puerto Rico (Grande et al., 2021). Overall, the close relationship between $^{10}$Be, erosion rates and mean annual precipitation across George River demonstrates how well $^{10}$Be, erosion rates can reflect background, geologically-meaningful rates of landscape evolution on millennial timescales, even in areas with long histories of intensive human land-use.

Higher values of $\epsilon$ where there is more rainfall suggests that more sediment is being generated in the western portion of the catchment where larger volumes of rainfall can facilitate the generation, erosion, entrainment, and delivery of sediment to trunk channels than in the eastern portion of the catchment. However, we recognize that perhaps $\epsilon$ is not necessarily related to precipitation, but rather $\epsilon$ and precipitation may both be more directly influenced by elevation. Although no part of George River was ever glaciated, cirque development and periglacial activity was active to the southwest of George River, across the Ben Lomond Plateau during the Last Glacial Maximum and previous glaciations (Barrows et al., 2002; Colhoun, 2002), in which case $\epsilon$ may be greater at higher elevations due to greater amounts of periglacial weathering.

High $^{10}$Be, erosion rates have been linked to greater amounts of periglacial activity elsewhere (e.g. Delunel et al., 2010; Hancock and Kirwan, 2007; Marshall et al., 2017); however, periglacial activity in northeast Tasmania was typically limited to elevations $>1,100$ m (Colhoun, 2002), and it is therefore unlikely that periglacial processes would have increased erosion rates in George River’s western tributaries, all of which are below this elevation. Alternatively, higher $\epsilon$ at higher elevations may be due to greater amounts of rock exhumation for inland northeast Tasmania relative to the coasts throughout the Cenozoic, interpolated from apatite fission track cooling ages across Tasmania (Kohn et al., 2002). This is also unlikely, however, as landscape lowering over millions of years has slowed from an early Cenozoic peak rates of 30–50 m Myr$^{-1}$ to late Cenozoic rates of $<10$ m Myr$^{-1}$, and rock exhumation rates are presently comparable, if not slower than new $^{10}$Be based erosion rates presented in this study. We therefore remain confident that the relationship between $\epsilon$ and elevation and rainfall in this study are real and reflective of the influence of rainfall in driving landscape evolution over millennial timescales in George River.

Since pre-disturbance stream flow and bedload conditions were re-established by the 1990s (Knighton, 1991), it appears the greatest risk of future excesses of sediment flux from George River to Georges Bay comes from land-use changes involving the widespread disturbance of surficial soils, such as through forestry (Wilson, 1999). The percentage of land used for
Production forestry in native environments has been decreasing throughout the 21st century (Fig. 4), and while some of this land use is being supplanted by Conservation and Protected Native Land Cover, which could buffer the effects of widespread erosion, much is being replaced by grazing and agriculture, which would only serve to increase erosion, particularly in the headwater catchments where geological erosion rates are naturally high (Fig. 4). Given recent land-use trends, the $^{10}\text{Be}$ erosion rates presented here may provide a useful benchmark level of sediment delivery to George River, Georges Bay, and other fluvial systems in northeast Tasmania that share topographic and geologic characteristics similar to those at George River.

5.1 Considerations of $\varepsilon$ for trunk channel versus tributary sites

A mass-balance comparison of the volume of sediment passing through the trunk channels ($\varepsilon \times$ upstream area; 3.8 ± 0.7 km$^3$ yr$^{-1}$ at TG-1 and 3.5 ± 0.7 km$^3$ yr$^{-1}$ at TG-9) versus the summed volume of sediment exiting tributaries (3.9 ± 0.3 km$^3$ yr$^{-1}$) suggests that little erosion (and therefore addition of sediment) is occurring in the trunk channel subcatchments. Average modelled $\varepsilon$ for trunk channel sites, calculated using the regression equations and mean longitude, the mean elevation, and mean annual precipitation values for the TG-1 and TG-9 subcatchments (9.6 ± 3.0 mm kyr$^{-1}$ and 1.1 ± 3.1 mm kyr$^{-1}$, respectively), however, suggests that the TG-1 subcatchment should be contributing at least ~1 km$^3$ of sediment more to George River annually. Given that the mass of sediment leaving the tributaries is equal to the mass of sediment passing through TG-1 and TG-9, we make the interpretation that the $^{10}\text{Be}$ measured at TG-1 and TG-9 trunk channel locations is effectively dominated by erosion in the tributaries, with little input from the subcatchments or George River floodplain, and $\varepsilon$ at trunk channel sites should be considered minimum estimates of erosion for the upstream contributing area. Our interpretation of erosion at trunk streams being dominated by headwater input has been made elsewhere, albeit in much larger river basins (i.e. Wittmann et al. 2009, 2011, 2016). The average erosion rate we therefore present for George River is the average of $\varepsilon$ at TG-1, TG-9, and the average of $\varepsilon$ from the seven tributaries combined (10.5 ± 0.8 mm kyr$^{-1}$); we do not consider $\varepsilon$ of trunk channel samples, modelled or measured, when considering spatial statistics of erosion in George River basin.

Compared to measurements of $\varepsilon$ on the Australian mainland, the mean value of $\varepsilon$ for George River (10.5 ± 0.8 mm kyr$^{-1}$) is of similar magnitude as the median erosion rate for all catchments draining the eastern flanks of the Great Dividing Range passive margin of mainland Australia (15.9 mm kyr$^{-1}$; Fig. 9; Codilean et al., 2021). Average $\varepsilon$ from George River is most consistent, however, with the erosion rates of mainland basins at the southernmost extent of the Great Dividing Range, across the Bass Strait, which are those that share similar topographic characteristics and geological histories as George River (Codilean et al., 2021). The similarity between the geology, climate, and topography of newly-sampled basins and derived $^{10}\text{Be}$ erosion rates in Tasmania and those from southeast mainland Australia suggests that evolution of landscapes that share similar climatic, topographic, and geologic characteristics is driven by common forces.
5.2 Comparing $^{10}$Be$_i$-based and $^{10}$Be$_{reac}$-based erosion and denudation metrics

The strong relationship between $^{10}$Be$_i$ erosion rates and topographically-induced precipitation across Georges River (Fig. 6) suggests that $^{10}$Be$_i$ erosion rates, $e$, are geologically accurate and meaningful. The small, geologically-homogeneous landscape of George River, therefore allows us to test a previous hypothesis (Portenga et al., 2019) that measured $^{10}$Be$_{reac}$-based erosion rates, $E$, and $^{10}$Be$_{reac}$/Be$_{reac}$-based denudation rates, $D_m$, to replicate $e$ or $e$-based sediment fluxes, respectively. At first glance, $E$ replicates $e$ only in the headwater catchments and $D_m$ replicates $e$-based sediment fluxes relatively well in all tributaries except for the headwater catchments (Fig. 8). Overall, values of $E$ and $D_m$ do not replicate the spatial patterns or yield the same relationships with topographic and climate parameters that we observe with $e$ and $e$-based sediment fluxes (Figs. 6, 7).

However, when only $E$ and $D_m$ from tributaries in the central and eastern areas of George River (TG-2 through TG-5) are considered, a consistent relationship between $E$ and $D_m$ and basin longitude, elevation, and precipitation emerges and is similar to the relationships we observe between longitude, elevation, and precipitation and $e$ (Fig. 6). Despite this small sample subset ($n = 4$), we suggest that $E$ and $D_m$ reflect the same patterns of landscape dynamics in George River as $e$. Moreover, the similarity of $D_m$ and $e$-based sediment fluxes for central and eastern tributaries provides support our hypothesis that $^{10}$Be$_{reac}$/Be$_{reac}$ based denudation rates should more closely replicate $^{10}$Be$_i$-based erosion rates in small river basins where geological heterogeneity is minimized. Our findings also, generally, support the continued exploration and application of $^{10}$Be$_{reac}$/Be$_{reac}$ denudation rates in geomorphological studies (Dannhaus et al., 2017; Deng et al., 2020; Portenga et al., 2019; Rahaman et al., 2017; Wittmann et al., 2012, 2015). Interestingly, measured values of $E$ are systematically ~4–5x greater than $e$, and thus while $E$ may be influenced by the same geomorphological processes in George River as $e$ and $D_m$, it does not appear to reflect accurate rates of landscape change.

The similarity of the spatial patterns of $E$ and $D_m$ with longitude, elevation, and precipitation in the central and eastern tributaries with those exhibited by $e$ across the whole George River basin suggests that $E$ and $D_m$ in the headwater catchments (TG-6, TG-7, and TG-8) significantly underestimate accurate or realistic values of $E$ and $D_m$ for these tributaries. Of all of the variables and measurements required to derive both $E$ and $D_m$, excess amounts of measured $^{10}$Be$_{reac}$ is the only common factor that would lead to erroneously low calculated values of $E$ and $D_m$. Once delivered to Earth’s surface, meteoric $^{10}$Be$_{reac}$ concentrates in uppermost soil horizons (Graly et al., 2010; Willenbring and von Blanckenburg, 2010), and thus any disturbance and excavation of large volumes of topsoil (i.e. agriculture, forestry, wildfire erosion, or mining activities) could strip soil with the highest concentrations of $^{10}$Be$_{reac}$ in its grain coatings entering and introduce them into a stream’s bedload, a process similar to that identified following early land-use changes and deforestation in the Chesapeake Bay and San Francisco Bay (Valette-Silver et al., 1986; van Geen et al., 1999). Mining activities in George River were restricted to lower catchment areas and tributaries where $^{10}$Be$_{reac}$ based metrics demonstrate the same relationships to topography and climate as $e$ (Fig. 2), and no wildfires nor prescribed fires have burned through the headwater catchments (Fig. 4).
At the time of sample collection for this study in 2008, forestry from natural environments and from production plantations was the largest land use designation within George River. Elsewhere in George River, rainfall and runoff experiments carried out in the Gentle Annie experimental catchment, a tributary to TG-2 (Fig. 4), showed that rills and gullies developed in hillslope plots that were heavily disturbed by forestry machinery, yielding significantly more sediment during simulated rainfall events than soil plots that were burned and more sediment than plots where soils were left undisturbed (Wilson, 1999). Although there are no detailed records of when plots of land in George River were timbered, we invoke Wilson’s (1999) findings to suggest it is plausible that active forestry had disturbed soils in the headwater catchments at or shortly prior to the timing of sample collection, significantly disturbing $^{10}\text{Be}_m$-rich top soils, and delivering large volumes of sediment with excess $^{10}\text{Be}_m$ to sample collection sites, which subsequently resulted in the calculated values of $E$ and $D_m$ that are much lower than otherwise expected based on the trends of $E$ and $D_m$ in other tributaries. Following this interpretation, we suggest that measures of $E$ and $D_m$ may reflect spatial patterns or replicate $\varepsilon$ rates in geologically homogeneous landscapes, respectively, but caution should be taken when applying $^{10}\text{Be}_m$ erosion and denudation metrics in landscapes with intensive soil disturbances (Portenga et al., 2019).

6 Conclusions

$^{10}\text{Be}_i$ erosion rates throughout the George River basin, and $^{10}\text{Be}_m$ erosion and denudation rates in its central and eastern tributaries, are closely related to a topographically-induced East-West precipitation gradient across the catchment. Tasmanian landscapes differ from the Great Dividing Range where erosion rates and slope are closely linked. The average $^{10}\text{Be}_i$ erosion in George River, 13.6 mm kyr$^{-1}$, reflects erosion in tributaries to George River where precipitation is greatest; little sediment is generated in trunk channel subcatchments. These findings support the notion that precipitation imparts more influence on landscape development in low-slope, low-elevation landscapes (Mishra et al., 2018), which often tend to be in post-orogenic, passive margin settings.

Although sediment erosion associated with mining, agricultural, and forestry land-use practices occurred in the George River basin during the 19th and 20th Centuries, $^{10}\text{Be}_i$ based erosion rates in the basin appear to reflect pre-disturbance rates of landscape change. Such rates are useful as part of Tasmania’s current efforts to re-establish healthy and sustainable ecological conditions in its many estuarine environments, particularly those in northeast Tasmania where estuary tributaries have similar geological and topographic characteristics to those found at George River. The pace of erosion in the George River basin is similar to that at the southern end of the Great Dividing Range on the Australian mainland, which has similar bedrock and climate characteristics.

$^{10}\text{Be}_m$-based erosion and denudation in the central and eastern tributaries of George River generally replicates spatial patterns of $^{10}\text{Be}_i$-based erosion and denudation. Low $^{10}\text{Be}_m$-based erosion and denudation rates calculated in three headwater tributaries demonstrate the sensitivity of meteoric $^{10}\text{Be}_i$-based calculation to recent and intensive land use that disturbs and erodes topsoils.
Data from the George River basin support application of $^{10}$Be methods in small, lithologically homogeneous basins with limited amounts of topsoil disturbance.

Appendices

### Appendix A: Erosion rate and denudation rate equations

| $^{10}$Be | Erosion Rate |
| --- | --- |
| $\epsilon = \frac{1}{\rho} \left( \frac{\Lambda}{P_0} - \lambda \right)$ |

| Variable | Description | Unit |
| --- | --- | --- |
| $\epsilon$ | $^{10}$Be erosion rate | cm yr$^{-1}$ |
| $\Lambda$ | Attenuation length for cosmic-ray penetration | cm |
| $P_0$ | Production rate of $^{10}$Be at Earth’s surface | atoms g$^{-1}$ yr$^{-1}$ |
| $N$ | Measured concentration of in-situ produced $^{10}$Be | atoms g$^{-1}$ |
| $\lambda$ | $^{10}$Be decay constant | yr$^{-1}$ |
| $\rho$ | Rock density | g cm$^{-3}$ |
| $E$ | $^{10}$Be$_{\text{er}}$-based erosion rate | cm yr$^{-1}$ |
| $Q$ | Atmospheric $^{10}$Be$_{\text{er}}$ delivery rate | atoms cm$^{-2}$ yr$^{-1}$ |
| $^{10}$Be$_{\text{er}}$ | Measured concentration of $^{10}$Be$_{\text{er}}$ extracted from sediment grain coatings | atoms g$^{-1}$ |
| $D_{\text{er}}$ | $^{10}$Be$_{\text{er}}$/Be$_{\text{er}}$-based denudation rate | g cm$^{-2}$ yr$^{-1}$ |
| $^{10}$Be$_{\text{er}}$ | Measured concentration of Be still within mineral grains | atoms g$^{-1}$ |
| $^{10}$Be$_{\text{er}}$ | Assumed concentration of $^{10}$Be in crustal bedrock | $1.67 \times 10^{17}$ atoms g$^{-1}$ |

| $^{10}$Be$_{\text{er}}$/Be$_{\text{er}}$ | Denudation Rate |
| --- | --- |
| $D_{\text{er}} = \frac{Q}{\rho} \frac{^{10}{\text{Be}}_{\text{er}} + 1}{^{10}{\text{Be}}_{\text{er}}}$ |

### Appendix B: CRONUS Entry Data

| CRONUS ID | Lat. | Long. | Meas. | Meas. Error | Age | Ref. |
| --- | --- | --- | --- | --- | --- | --- |
| TG-1 | -41.29017 | 148.22217 | 346 | std | 1 | 2.7 | 0 | 2008 |
| TG-1 | Be-10 | Quartz | 3.64E+05 | 6.52E+03 | 07KNSTD |
| TG-2 | -41.27183 | 148.19925 | 141 | std | 1 | 2.7 | 0 | 2008 |
| TG-2 | Be-10 | Quartz | 5.66E+05 | 7.72E+03 | 07KNSTD |
| TG-3 | -41.28286 | 148.13247 | 265 | std | 1 | 2.7 | 0 | 2008 |
| TG-3 | Be-10 | Quartz | 3.97E+05 | 1.17E+04 | 07KNSTD |
| TG-4 | -41.25514 | 148.08317 | 364 | std | 1 | 2.7 | 0 | 2008 |
| TG-4 | Be-10 | Quartz | 2.56E+05 | 6.95E+03 | 07KNSTD |
| TG-5 | -41.25364 | 148.08239 | 347 | std | 1 | 2.7 | 0 | 2008 |
| TG-5 | Be-10 | Quartz | 3.63E+05 | 8.48E+03 | 07KNSTD |
| TG-6 | -41.26067 | 148.00697 | 439 | std | 1 | 2.7 | 0 | 2008 |
| TG-6 | Be-10 | Quartz | 2.33E+05 | 5.05E+03 | 07KNSTD |
| TG-7 | -41.32208 | 147.92172 | 652 | std | 1 | 2.7 | 0 | 2008 |
| TG-7 | Be-10 | Quartz | 1.88E+05 | 5.60E+03 | 07KNSTD |
| TG-8 | -41.32178 | 147.92592 | 586 | std | 1 | 2.7 | 0 | 2008 |
| TG-8 | Be-10 | Quartz | 2.48E+05 | 6.10E+03 | 07KNSTD |
| TG-9 | -41.31350 | 148.26531 | 331 | std | 1 | 2.7 | 0 | 2008 |
| TG-9 | Be-10 | Quartz | 4.11E+05 | 9.92E+03 | 07KNSTD |
Data Availability

All data used in this study, and all data needed to reproduce our findings are presented in Tables 1-3 and the equations we use to work with data to calculate erosion rates, sediment fluxes, denudation rates, and integration times are presented in Appendix A. Data entry for calculating erosion rates from the CRONUS online erosion rate calculator, formatted for text entry, are given in Appendix.

Author Contribution

The conceptual analysis of the data presented in this paper comes from LV’s Undergraduate Honors Thesis (2020) at Eastern Michigan University. EWP contributed to post-thesis manuscript revisions, data analysis, and figure drafting. Samples and the $^{10}$Be data presented here were collected and facilitated by PRB and ECL in 2008. $^9$Be and $^{10}$Be data were first presented in Sophie E. Greene’s Master’s Thesis (2016) at the University of Vermont; SEG declined a request to participate in the writing and publication of this paper. AJH verified Lawrence Livermore National Laboratory’s measurement of beryllium at the Center for Accelerator Mass Spectrometry in 2009. This work was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This is LLNL-JRNL-825534.

References

ABARES, 2016, The Australian Land Use and Management Classification Version 8: Australian Bureau of Agricultural and Resource Economics and Sciences, https://www.agriculture.gov.au/abares/aclump/land-use/alum-classification.

Adams, B. A., and Ehlers, T., 2017, Deciphering topographic signals of glaciation and rock uplift in an active orogen: A case study from the Olympic Mountains, USA: Earth Surface Processes and Landforms, v. 42, no. 11, p. 1680-1692.

Aguilar, G., Carretier, S., Regard, V., Vassallo, R., Riquelme, R., and Martinod, J., 2014, Grain size-dependent 10Be concentrations in alluvial stream sediment of the Huasco Valley, a semi-arid Andes region: Quaternary Geochronology, v. 19, p. 163-172.

Augustinus, P., Barton, C. E., Zawadzki, A., and Harle, K., 2010, Lithological and geochemical record of mining-induced changes in sediments from Macquarie Harbour, southwest Tasmania, Australia: Environmental Earth Sciences, v. 61, no. 3, p. 625-639.

Belmont, P., Pazzaglia, F., and Gosse, J. C., 2007, Cosmogenic 10Be as a tracer for hillslope and channel sediment dynamics in the Clearwater River, western Washington State: Earth and Planetary Science Letters, v. 264, no. 1-2, p. 123-135.
Bierman, P., and Steig, E. J., 1996, Estimating rates of denudation using cosmogenic isotope abundances in sediment: Earth surface processes and landforms, v. 21, no. 2, p. 125-139.

Bleaney, A., Hickey, C. W., Stewart, M., Scammell, M., and Senjen, R., 2015, Preliminary investigations of toxicity in the Georges Bay catchment, Tasmania, Australia: International Journal of Environmental Studies, v. 72, no. 1, p. 1-23.

BoM, 2021, Climate Data Online: Australia Bureau of Meteorology, http://www.bom.gov.au/climate/data/.

Braucher, R., Brown, E., Bourliès, D., and Colin, F., 2003, In situ produced 10Be measurements at great depths: implications for production rates by fast muons: Earth and Planetary Science Letters, v. 211, no. 3-4, p. 251-258.

Brown, E. T., Stallard, R. F., Larsen, M. C., Raisbeck, G. M., and Yiou, F., 1995, Denudation rates determined from the accumulation of in situ-produced 10Be in the Luquillo Experimental Forest, Puerto Rico: Earth and Planetary Science Letters, v. 129, no. 1-4, p. 193-202.

Brown, L., Pavich, M. J., Hickman, R. E., Klein, J., and Middleton, R., 1988, Erosion of the eastern United States observed with 10Be: Earth Surface Processes and Landforms, v. 13, no. 5, p. 441-457.

Butler, E. C., 2006, The tail of two rivers in Tasmania: the Derwent and Huon estuaries, Estuaries, Springer, p. 1-49.

Carretier, S., Regard, V., and Soual, C., 2009, Theoretical cosmogenic nuclide concentration in river bed load clasts: Does it depend on clast size?: Quaternary Geochronology, v. 4, no. 2, p. 108-123.

Carretier, S., Tolorza, V., Regard, V., Aguilar, G., Bermúdez, M. A., Martinod, J., Guyot, J. L., Hérail, G., and Riquelme, R., 2018, Review of erosion dynamics along the major NS climatic gradient in Chile and perspectives: Geomorphology, v. 300, p. 45-68.

Carretier, S., Tolorza, V., Rodríguez, M., Pepin, E., Aguilar, G., Regard, V., Martinod, J., Riquelme, R., Bonnet, S., and Brichau, S., 2015, Erosion in the Chilean Andes between 27 S and 39 S: tectonic, climatic and geomorphic control: Geological Society, London, Special Publications, v. 399, no. 1, p. 401-418.

Cheetham, M. D., and Martin, J. C., 2018, Hope for the best, plan for the worst: Managing sediment input in the upper catchment whilst preparing for avulsion at the mouth, 9th Australian Stream Management Conference: Hobart, Tasmania, Australia, p. 8.

Codilean, A. T., Fülöp, R.-H., Munack, H., Wilcken, K. M., Cohen, T. J., Rood, D. H., Fink, D., Bartley, R., Croke, J., and Fifield, L., 2021, Controls on denudation along the East Australian continental margin: Earth-Science Reviews, p. 103543.

Colhoun, E. A., 2002, Periglacial landforms and deposits of Tasmania: Periglacial and Permafrost Research in the Southern Hemisphere: South African Journal of Science, v. 98, no. 1, p. 55-63.

Corbett, L. B., Bierman, P. R., and Rood, D. H., 2016, An approach for optimizing in situ cosmogenic 10Be sample preparation: Quaternary Geochronology, v. 33, p. 24-34.

Cosgrove, R., 1995, Late Pleistocene behavioural variation and time trends: the case from Tasmania: Archaeology in Oceania, v. 30, no. 3, p. 83-104.

Cosgrove, R., Allen, J., and Marshall, B., 1990, Palaeo-ecology and Pleistocene human occupation in south central Tasmania: Antiquity, v. 64, no. 242, p. 59-78.

Coughanowr, C., and Whitehead, J., 2013, The Derwent Estuary Program: A collaborative model for science-based management, Tasmania, Australia: Ocean & Coastal Management, v. 86, p. 110-118.

Crawford, C., and White, C., 2005, Establishment of an integrated water quality monitoring framework for Georges Bay. Creighton, C., Boon, P. I., Brookes, J. D., and Sheaves, M., 2015, Repairing Australia's estuaries for improved fisheries production – what benefits, at what cost?: Marine and Freshwater Research, v. 66, no. 6, p. 493-507.

Croke, J., Bartley, R., Chappell, J., Austin, J. M., Fifield, K., Tims, S. G., Thompson, C. J., and Furuichi, T., 2015, 10Be-derived denudation rates from the Burdekin catchment: The largest contributor of sediment to the Great Barrier Reef: Geomorphology, v. 241, p. 122-134.

Crowder, E., Rawlinson, N., Pilia, S., Cornwell, D. G., and Reading, A. M., 2019, Transdimensional ambient noise tomography of Bass Strait, southeast Australia, reveals the sedimentary basin and deep crustal structure beneath a failed continental rift: Geophysical Journal International, v. 217, no. 2, p. 970-987.

Dannhaus, N., Wittmann, H., Krám, P., Christl, M., and von Blanckenburg, F., 2018, Catchment-wide weathering and erosion rates of mafic, ultramafic, and granitic rock from cosmogenic meteoric 10Be/9Be ratios: Geochemica et Cosmochimica Acta, v. 222, p. 618-641.
Davis, J., and Kidd, I. M., 2012, Identifying Major Stressors: The Essential Precursor to Restoring Cultural Ecosystem Services in a Degraded Estuary: Estuaries and Coasts, v. 35, no. 4, p. 1007-1017.

Delunel, R., Schlunegger, F., Valla, P. G., Dixon, J., Glotzbach, C., Hippe, K., Kober, F., Molliex, S., Norton, K. P., Salcher, B., Wittmann, H., Akçar, N., and Christl, M., 2020, Late-Pleistocene catchment-wide denudation patterns across the European Alps: Earth-Science Reviews, v. 211, p. 103407.

Delunel, R., van der Beek, P. A., Carcaillet, J., Boulès, D. L., and Valla, P. G., 2010, Frost-cracking control on catchment denudation rates: Insights from in situ produced 10Be concentrations in stream sediments (Ecrins–Pelvoux massif, French Western Alps): Earth and Planetary Science Letters, v. 293, no. 1-2, p. 72-83.

Deng, K., Yang, S., von Blanckenburg, F., and Wittmann, H., 2020, Denudation Rate Changes Along a Fast-Eroding Mountainous River With Slate Headwaters in Taiwan From 10Be (Meteoric)/9Be Ratios: Journal of Geophysical Research: Earth Surface, v. 125, no. 2, p. e2019JF005251.

Dethier, D. P., Ouimet, W., Bierman, P. R., Rood, D. H., and Balco, G., 2014, Basins and bedrock: Spatial variation in 10Be erosion rates and increasing relief in the southern Rocky Mountains, USA: Geology, v. 42, no. 2, p. 167-170.

Edgar, G., and Barrett, N., 2000, Effects of Catchment Activities on Macrofaunal Assemblages in Tasmanian Estuaries: Estuarine, Coastal and Shelf Science, v. 50, no. 5, p. 639-654.

Edgar, G. J., Barrett, N. S., Graddon, D. J., and Last, P. R., 2000, The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study: Biological Conservation, v. 92, no. 3, p. 383-397.

Elliot, M., Burdon, D., Hemingway, K. L., and Apitz, S. E., 2007, Estuarine, coastal and marine ecosystem restoration: confusing management and science—a revision of concepts: Estuarine, Coastal and Shelf Science, v. 74, no. 3, p. 349-366.

Ellison, J. C., and Sheehan, M. R., 2014, Past, present and futures of the Tamar Estuary, Tasmania, Estuaries of Australia in 2050 and Beyond, Springer, p. 69-89.

Etheridge, M. A., Branson, J. C., and Stuart-Smith, P. G., 1987, The Bass, Gippsland and Otway basins, southeast Australia: A branched rift system formed by continental extension: Sedimentary Basins and Basin-forming Mechanisms, v. Memoir 12, p. 147-162.

Fellin, M. G., Chen, C.-Y., Willett, S. D., Christl, M., and Chen, Y.-G., 2017, Erosion rates across space and timescales from a multi-proxy study of rivers of eastern Taiwan: Global and Planetary Change, v. 157, p. 174-193.

Ferrier, K. L., Kirchner, J. W., and Finkel, R. C., 2005, Erosion rates over millennial and decadal timescales at Caspar Creek and Redwood Creek, northern California Coast Ranges: Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, v. 30, no. 8, p. 1025-1038.

Fick, S. E., and Hijmans, R. J., 2017, WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas: International Journal of Climatology, v. 37, no. 12, p. 4302-4315.

Fitzsimons, J. A., Hale, L., Hancock, B., and Beck, M. W., 2015, Developing a marine conservation program in temperate Australia: determining priorities for action: Australian Journal of Maritime & Ocean Affairs, v. 7, no. 1, p. 85-93.

Foster, D. A., and Gray, D. R., 2000, Evolution and Structure of the Lachlan Fold Belt (Orogen) of Eastern Australia: Annual Review of Earth and Planetary Sciences, v. 28, no. 1, p. 47-80.

Füllöff, R.-H., Codilean, A. T., Wilcken, K. M., Cohen, T. J., Fink, D., Smith, A. M., Yang, B., Levchenko, V. A., Wacker, L., Marx, S. K., Stromsoe, N., Fujioka, T., and Dunai, T. J., 2020, Million-year lag times in a post-orogenic sediment conveyor: Science Advances, v. 6, no. 25, p. eaaz8845.

Gaina, C., Müller, D. R., Royer, J.-Y., Stock, J., Hardebeck, J., and Symonds, P., 1998, The tectonic history of the Tasman Sea: A puzzle with 13 pieces: Journal of Geophysical Research: Solid Earth, v. 103, no. B6, p. 12413-12433.

Gallant, J., Wilson, N., Dowling, T., Read, A., and Inskeep, C., 2011, SRTM-derived 1 Second Digital Elevation Models Version 1.0. Record 1: Geoscience Australia, Canberra, ACT, Australia.

Gee, R. D., and Groves, D. I., 1971, Structural features and mode of emplacement of part of the blue tier batholith in Northeast Tasmania: Journal of the Geological Society of Australia, v. 18, no. 1, p. 41-55.

Geist, J., and Hawkins, S. J., 2016, Habitat recovery and restoration in aquatic ecosystems: current progress and future challenges: Aquatic Conservation: Marine and Freshwater Ecosystems, v. 26, no. 5, p. 942-962.

Godard, V., Dosseto, A., Fleury, J., Bellier, O., and Siame, L., 2019, Transient landscape dynamics across the Southeastern Australian Escarpment: Earth and Planetary Science Letters, v. 506, p. 397-406.
Gonzalez, V. S., Bierman, P. R., Nichols, K. K., and Rood, D. H., 2016, Long-term erosion rates of Panamanian drainage basins determined using in situ 10Be: Geomorphology, v. 275, p. 1-15.

Gosse, J. C., and Phillips, F. M., 2001, Terrestrial in situ cosmogenic nuclides: theory and application: Quaternary Science Reviews, v. 20, no. 14, p. 1475-1560.

Graly, J. A., Bierman, P. R., Reusser, L. J., and Pavich, M. J., 2010, Meteoric 10Be in soil profiles – A global meta-analysis: Geochimica et Cosmochimica Acta, v. 74, no. 23, p. 6814-6829.

Graly, J. A., Reusser, L. J., and Bierman, P. R., 2011, Short and long-term delivery rates of meteoric 10Be to terrestrial soils: Earth and Planetary Science Letters, v. 302, no. 3, p. 329-336.

Grande, A., Schmidt, A. H., Bierman, P. R., Corbett, L. B., Lópeza-Lloreda, C., Willenbring, J., McDowell, W. H., and Caffee, M. W., 2021, Landslides, hurricanes, and sediment sourcing impact basin-scale erosion estimates in Luquillo, Puerto Rico: Earth and Planetary Science Letters, v. 562, p. 116821.

Granger, D. E., Kirchner, J. W., and Finkel, R., 1996, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediment: The Journal of Geology, v. 104, no. 3, p. 249-257.

Gray, D. R., and Foster, D. A., 2004, Tectonic evolution of the Lachlan Orogen, southeast Australia: Historical review, data synthesis and modern perspectives: Australian Journal of Earth Sciences, v. 51, no. 6, p. 773-817.

Greene, E. S., 2016, Comparing meteoric 10Be, in situ 10Be, and native 9Be across a diverse set of watersheds, Master’s Thesis, Geology Department, University of Vermont, Burlington, VT, United States, 118 p.

Griffiths, J. R., 1971, Continental margin tectonics and the evolution of south-east Australia: The APPEA Journal, v. 11, no. 1, p. 75-79.

Gunn, P. J., 1975, Mesozoic-Cainozoic Tectonics and Igneous Activity: Southeastern Australia: Journal of the Geological Society of Australia, v. 22, no. 2, p. 215-221.

Hancock, G., and Kirwan, M., 2007, Summit erosion rates deduced from 10Be: Implications for relief production in the central Appalachians: Geology, v. 35, no. 1, p. 89-92.

Harel, M.-A., Mudd, S., and Attal, M., 2016, Global analysis of the stream power law parameters based on worldwide 10Be denudation rates: Geomorphology, v. 268, p. 184-196.

Harrison, E. J., Willenbring, J. K., and Brocard, G. Y., 2021, Quaternary record of terrestrial environmental change in response to climatic forcing and anthropogenic perturbations, in Puerto Rico: Quaternary Science Reviews, v. 253, p. 106770.

Hayes, D. E., and Ringis, J., 1973, Seafloor Spreading in the Tasman Sea: Nature, v. 243, no. 5408, p. 454-458.

Heikilä, U., and von Blanckenburg, F., 2015, The global distribution of Holocene meteoric 10Be fluxes from atmospheric models. Distribution maps for terrestrial Earth’s surface applications, GFZ Data Services, doi:10.5880/GFZ.3.4.2015.001

Heisinger, B., Niedermayer, M., Hartmann, F., Korschinek, G., Nolte, E., Morteani, G., Neumaier, S., Petitjean, C., Kubik, P., and Synal, A., 1997, In-situ production of radionuclides at great depths: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, v. 123, no. 1-4, p. 341-346.

Helz, G. R., and Valette-Silver, N., 1992, Beryllium-10 in Chesapeake Bay sediments: An indicator of sediment provenance: Estuarine, Coastal and Shelf Science, v. 34, no. 5, p. 459-469.

Higgins, N. C., Solomon, M., and Varne, R., 1985, The genesis of the Blue Tier Batholith, northeastern Tasmania, Australia: Lithos, v. 18, p. 129-149.

Jerie, K., Houshold, I., and Peters, D., 2003, Tasmania’s river geomorphology: stream character and regional analysis: Nature Conservation Branch, DPIWE.

Jones, B., Chenhall, B., Debretsion, F., and Hutton, A., 2003, Geochemical comparisons between estuaries with non-industrialised and industrialised catchments: The Huon and Derwent River estuaries, Tasmania: Australian Journal of Earth Sciences, v. 50, no. 5, p. 653-667.

Jones, P. J., Williamson, G. J., Bowman, D. M. J. S., Lefroy, E. C., 2019, Mapping Tasmania’s cultural landscapes: Using habitat suitability modelling of archaeological sites as a landscape history tool: Journal of Biogeography, v. 46, no. 11, p. 2570-2582.

Kidd, D., Malone, B., McBratney, A., Minasny, B., Odgers, N., Webb, M., and Searle, R., 2014, A new digital soil resource for Tasmania, Australia, in Proceedings 20th World Congress of Soil Science, p. 612-613.

Kidd, D., Webb, M., Malone, B., Minasny, B., and McBratney, A., 2015, 80-metre resolution 3D soil attribute maps for Tasmania, Australia: Soil Research, doi. 10.1071/SR14268.
Knighton, A., 1991, Channel bed adjustment along mine-affected rivers of northeast Tasmania: Geomorphology, v. 4, no. 3-4, p. 205-219.

Koehnken, L., 2001, North-east rivers environmental review: A review of Tasmanian environmental quality data to 2001: Supervising Scientist Report 168, Australian Government Department of Agriculture, Water and the Environment, pp. 64.

Kohl, C. P., and Nishizumi, K., 1992, Chemical isolation of quartz for measurement of in-situ-produced cosmogenic nuclides: Geochimica et Cosmochimica Acta, v. 56, no. 9, p. 3583-3587.

Kohn, B. P., Gleadow, A. J. W., Brown, R. W., Gallagher, K., O'Sullivan, P. B., and Foster, D. A., 2002, Shaping the Australian crust over the last 300 million years: Insights from fission track thermotectonic imaging and denudation studies of key terranes: Australian Journal of Earth Sciences, v. 49, no. 4, p. 697-717.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F., 2006, World map of the Köppen-Geiger climate classification updated: Meteorologische Zeitschrift, v. 15, no. 3, p. 259-263.

Kragt, M. E., and Newham, L. T., 2009, Developing a water-quality model for the George catchment, Tasmania: Landscape Logic.

Lal, D., 1991, Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models: Earth and Planetary Science Letters, v. 104, no. 2-4, p. 424-439.

Land-Tasmania, 2020, Fire History [of Tasmania]: Tasmania Department of Primary Industries, Water and Environment, Hobart, Tasmania, Australia, https://www.thelist.tas.gov.au/app/content/data/geo-meta-data-record?detailRecordUID=b94d4388-995d-416a-9844-a39de2798bed.

Lanyon, R., Varne, R., and Crawford, A. J., 1993, Tasmanian Tertiary basalts, the Balleny plume, and opening of the Tasman Sea (southwest Pacific Ocean): Geology, v. 21, no. 6, p. 555-558.

Mackintosh, A. N., Barrows, T. T., Colhoun, E. A., and Fifield, L. K., 2006, Exposure dating and glacial reconstruction at Mt. Field, Tasmania, Australia, identifies MIS 3 and MIS 2 glacial advances and climatic variability: Journal of Quaternary Science, v. 21, no. 4, p. 363-376.

Marshall, J. A., Roering, J. J., Gavin, D. G., and Granger, D. E., 2017, Late Quaternary climatic controls on erosion rates and geomorphic processes in western Oregon, USA: GSA Bulletin, v. 129, no. 5-6, p. 715-731.

Martin, J., and Cheetham, M., 2018, Final Report: Lower George River Investigation: Lower George Riverworks Trust.

Martin-Smith, K. M., and Vincent, A. C., 2005, Seahorse declines in the Derwent estuary, Tasmania in the absence of fishing pressure: Biological Conservation, v. 123, no. 4, p. 533-545.

Masarik, J., and Beer, J., 2009, An updated simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere: Journal of Geophysical Research: Atmospheres, v. 114, no. D11.

Matmon, A., Bierman, P., and Enzel, Y., 2002, Pattern and tempo of great escarpment erosion: Geology, v. 30, no. 12, p. 1135-1138.

McCarthy, T. S., and Groves, D. I., 1979, The Blue Tier Batholith, Northeastern Tasmania: Contributions to Mineralogy and Petrology, v. 71, no. 2, p. 193-209.

McDougall, I., and van der Lingen, G. J., 1974, Age of the rhyolites of the Lord Howe Rise and the evolution of the southwest Pacific Ocean: Earth and Planetary Science Letters, v. 21, no. 2, p. 117-126.

McIntosh, P. D., Price, D. M., Eberhard, R., and Slee, A. J., 2009, Late Quaternary erosion events in lowland and mid-altitude Tasmania in relation to climate change and first human arrival: Quaternary Science Reviews, v. 28, no. 9, p. 850-872.

McKenny, C., and Shepherd, C., 1999, Ecological flow requirements for the George River: Report Series WRA 99/14, Department of Primary Industries, Water and Environment, Tasmania, pp. 31.

Mishra, A. K., Placzek, C., and Jones, R., 2019, Coupled influence of precipitation and vegetation on millennial-scale erosion rates derived from 10Be: PloS one, v. 14, no. 1, p. e0211325.

Mitchell, I. M., Crawford, C. M., and Rushton, M. J., 2000, Flat oyster (Ostrea angasi) growth and survival rates at Georges Bay, Tasmania (Australia): Aquaculture, v. 191, no. 4, p. 309-321.

Monaghan, M. C., Krishnaswami, S., and Turekian, K. K., 1986, The global-average production rate of 10Be: Earth and Planetary Science Letters, v. 76, no. 3, p. 279-287.

Mortimer, N., Campbell, H. J., Tulloch, A. J., King, P. R., Stagpoole, V. M., Wood, R. A., Rattenbury, M. S., Sutherland, R., Adams, C. J., Collot, J., and Seton, M., 2017, Zealandia: Earth’s hidden continent: GSA Today, v. 27, p. 27-35.

Mount, R., Crawford, C., Veal, C., and White, C., 2005, Bringing back the bay: marine habitats and water quality in Georges Bay.
700 Murphy, R., Crawford, C., and Barmuta, L., 2003, Estuarine Health in Tasmania, Status and Indicators: Water Quality: Tasmanian Aquaculture and Fisheries Institute.
Nanson, G. C., Von Krusenstierna, A., Bryant, E. A., and Renilson, M. R., 1994, Experimental measurements of river-bank erosion caused by boat-generated waves on the gordon river, Tasmania: Regulated Rivers: Research & Management, v. 9, no. 1, p. 1-14.
705 Neilson, T. B., Schmidt, A. H., Bierman, P. R., Rood, D. H., and Sosa Gonzalez, V., 2017, Efficacy of in situ and meteoric 10Be mixing in fluvial sediment collected from small catchments in China: Chemical Geology, v. 471, p. 119-130.
Nichols, K. K., Bierman, P. R., and Rood, D. H., 2014, 10Be constrains the sediment sources and sediment yields to the Great Barrier Reef from the tropical Barron River catchment, Queensland, Australia: Geomorphology, v. 224, p. 102-110.
Niemi, N. A., Oskin, M., Burbank, D. W., Heimsath, A. M., and Gabet, E. J., 2005, Effects of bedrock landslides on cosmogenically determined erosion rates: Earth and Planetary Science Letters, v. 237, no. 3, p. 480-498.
710 Nishiizumi, K., Imamura, M., Caffee, M. W., Southon, J. R., Finkel, R. C., and McAninch, J., 2007, Absolute calibration of 10Be AMS standards: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, v. 258, no. 2, p. 403-413.
Noe, G. B., Cashman, M. J., Skalak, K., Gellis, A., Hopkins, K. G., Moyer, D., Webber, J., Benthem, A., Maloney, K., and Brakebill, J., 2020, Sediment dynamics and implications for management: State of the science from long-term research in the Chesapeake Bay watershed, USA: Wiley Interdisciplinary Reviews: Water, v. 7, no. 4, p. e1454.
715 Persano, C., Stuart, F. M., Bishop, P., and Barford, D. N., 2002, Apatite (U-Th)/He age constraints on the development of the Great Escarpment on the southeastern Australian passive margin: Earth and Planetary Science Letters, v. 200, no. 1, p. 79-90.
720 Portenga, E. W., and Bierman, P. R., 2011, Understanding Earth's eroding surface with 10 Be: GSA Today, v. 21, no. 8, p. 4-10.
Portenga, E. W., Bierman, P. R., Duncan, C., Corbett, L. B., Kehrwald, N. M., and Rood, D. H., 2015, Erosion rates of the Bhutanese Himalaya determined using in situ-produced 10Be: Geomorphology, v. 233, p. 112-126.
Portenga, E. W., Bierman, P. R., Trodick, C. D., Jr., Greene, S. E., DeJong, B. D., Rood, D. H., and Pavich, M. J., 2019, Erosion rates and sediment flux within the Potomac River basin quantified over millennial timescales using beryllium isotopes: GSA Bulletin, v. 131, no. 7-8, p. 1295-1311.
Portenga, E. W., Bishop, P., Rood, D. H., and Bierman, P. R., 2017, Combining bulk sediment OSL and meteoric 10Be fingerprinting techniques to identify gully initiation sites and erosion depths: Journal of Geophysical Research: Earth Surface, v. 122, no. 2, p. 513-527.
730 Preston, K., 2012, Anchor tin mine, Tasmania: A century of struggle for profitability, Australasian Mining History Association, v. 10, p. 140-159.
Puchol, N., Lavé, J., Lupker, M., Blard, P.-H., Gallo, F., and France-Lanord, C., 2014, Grain-size dependent concentration of cosmogenic 10Be and erosion dynamics in a landslide-dominated Himalayan watershed: Geomorphology, v. 224, p. 55-68.
735 Rahaman, W., Wittmann, H., and von Blanckenburg, F., 2017, Denudation rates and the degree of chemical weathering in the Ganga River basin from ratios of meteoric cosmogenic 10Be to stable 9Be: Earth and Planetary Science Letters, v. 469, p. 156-169.
Reusser, L., Graly, J., Bierman, P., and Rood, D., 2010a, Calibrating a long-term meteoric 10Be accumulation rate in soil: Geophysical Research Letters, v. 37, no. 19.
740 Reusser, L. J., and Bierman, P. R., 2010, Using meteoric 10Be to track fluvial sand through the Waipaoa River basin, New Zealand: Geology, v. 38, no. 1, p. 47-50.
Rosenkranz, R., Schildgen, T., Wittmann, H., and Spiegel, C., 2018, Coupling erosion and topographic development in the rainiest place on Earth: Reconstructing the Shillong Plateau uplift history with in-situ cosmogenic 10Be: Earth and Planetary Science Letters, v. 483, p. 39-51.
745 Schaller, M., Blanckenburg, F., v., Hovius, N., Veldkamp, A., van den Berg, M. W., and Kubik, P., 2004, Paleoerosion rates from cosmogenic 10Be in a 1.3 Ma terrace sequence: response of the River Meuse to changes in climate and rock uplift: The Journal of geology, v. 112, no. 2, p. 127-144.
Schaller, M., Ehlers, T., Lang, K. A., Schmid, M., and Fuentes-Espoz, J., 2018, Addressing the contribution of climate and vegetation cover on hillslope denudation, Chilean Coastal Cordillera (26–38 S): Earth and Planetary Science Letters, v. 489, p. 111-122.

Schaller, M., Ehlers, T., Stor, T., Torrent, J., Lobato, L., Christl, M., and Vockenhuber, C., 2016, Spatial and temporal variations in denudation rates derived from cosmogenic nuclides in four European fluvial terrace sequences: Geomorphology, v. 274, p. 180-192.

Schaller, M., von Blanckenburg, F., Hovius, N., and Kubik, P., 2001, Large-scale erosion rates from in situ-produced cosmogenic nuclides in European river sediments: Earth and Planetary Science Letters, v. 188, no. 3-4, p. 441-458.

Scherler, D., Bookhagen, B., and Strecker, M. R., 2014, Tectonic control on 10Be-derived erosion rates in the Garhwal Himalaya, India: Journal of Geophysical Research: Earth Surface, v. 119, no. 2, p. 83-105.

Schmidt, A. H., Gonzalez, V. S., Bierman, P. R., Neilson, T. B., and Rood, D. H., 2018, Agricultural land use doubled sediment loads in western China’s rivers: Anthropocene, v. 21, p. 95-106.

Schmidt, A. H., Neilson, T. B., Bierman, P. R., Ouimet, W. B., and Sosa Gonzalez, V., 2016, Influence of topography and human activity on apparent in situ 10Be-derived erosion rates in Yunnan, SW China: Earth Surf. Dynam., v. 4, no. 4, p. 819-830.

Seen, A., Townsend, A., Atkinson, B., Ellison, J., Harrison, J., and Heijnis, H., 2004, Determining the History and Sources of Contaminants in Sediments in the Tamar Estuary, Tasmania, Using 210Pb Dating and Stable Pb Isotope Analyses: Environmental Chemistry, v. 1, no. 1, p. 49-54.

Seymour, D. B., Green, G. R., and Calver, C. R., 2006, The geology and mineral deposits of Tasmania: A summary: Mineral Resources Tasmania, https://www.mrt.tas.gov.au/products/publications/the_geology_and_mineral_deposits_of_tasmania_a_summary.

Siame, L., Angelier, J., Chen, R.-F., Godard, V., Derriex, F., Bourlès, D., Braucher, R., Chang, K.-J., Chu, H.-T., and Lee, J.-C., 2011, Erosion rates in an active orogen (NE-Taiwan): A confrontation of cosmogenic measurements with river suspended loads: Quaternary Geochronology, v. 6, no. 2, p. 246-260.

Starke, J., Ehlers, T., and Schaller, M., 2017, Tectonic and climatic controls on the spatial distribution of denudation rates in Northern Chile (18 S to 23 S) determined from cosmogenic nuclides: Journal of Geophysical Research: Earth Surface, v. 122, no. 10, p. 1949-1971.

-, 2020, Latitudinal effect of vegetation on erosion rates identified along western South America: Science, v. 367, no. 6484, p. 1358-1361.

Stone, J., 1998, A Rapid Fusion Method for Separation of Beryllium-10 From Soils and Silicates: Geochimica et Cosmochimica Acta, v. 62, no. 3, p. 555-561.

Sutherland, R., King, P., and Wood, R., 2001, Tectonic evolution of Cretaceous rift basins in south-eastern Australia and New Zealand: Implications for exploration risk assessment, Petroleum Exploration Society of Australia Eastern Australasian Basins Symposium: Melbourne, Victoria, Australia.

Tomkins, K. M., Humphreys, G. S., Wilkinson, M. T., Fink, D., Hesse, P. P., Doerr, S. H., Shakesby, R. A., Wallbrink, P. J., and Blake, W. H., 2007, Contemporary versus long-term denudation along a passive plate margin: the role of extreme events: Earth Surface Processes and Landforms, v. 32, no. 7, p. 1013-1031.

Valette-Silver, J. N., Brown, L., Pavich, M., Klein, J., and Middleton, R., 1986, Detection of erosion events using 10Be profiles: example of the impact of agriculture on soil erosion in the Chesapeake Bay area (U.S.A.): Earth and Planetary Science Letters, v. 80, no. 1, p. 82-90.

van Dongen, R., Scherler, D., Wittmann, H., and von Blanckenburg, F., 2019, Cosmogenic 10Be in river sediment: where grain size matters and why: Earth Surf. Dynam., v. 7, no. 2, p. 393-410.

van Geen, A., Valette-Silver, N. J., Luoma, S. N., Fuller, C. C., Baskaran, M., Tera, F., and Klein, J., 1999, Constraints on the sedimentation history of San Francisco Bay from 14C and 10Be: Marine Chemistry, v. 64, no. 1, p. 29-38.

Vanacker, V., von Blanckenburg, F., Govers, G., Molina, A., Poesen, J., Deckers, J., and Kubik, P., 2007, Restoring dense vegetation can slow mountain erosion to near natural benchmark levels: Geology, v. 35, no. 4, p. 303-306.

Verdonschot, P., Spears, B., Feld, C., Brucet, S., Keizer-Vlek, H., Borja, A., Elliott, M., Kernan, M., and Johnson, R., 2013, A comparative review of recovery processes in rivers, lakes, estuarine and coastal waters: Hydrobiologia, v. 704, no. 1, p. 453-474.
von Blanckenburg, F., Bouchez, J., and Wittmann, H., 2012, Earth surface erosion and weathering from the 10Be (meteoric)/9Be ratio: Earth and Planetary Science Letters, v. 351-352, p. 295-305.

Weissel, J. K., and Hayes, D. E., 1977, Evolution of the Tasman Sea reappraised: Earth and Planetary Science Letters, v. 36, no. 1, p. 77-84.

Wilson, C. J., 1999, Effects of logging and fire on runoff and erosion on highly erodible granitic soils in Tasmania: Water Resources Research, v. 35, no. 11, p. 3531-3546.

Wittmann, H., Malusà, M. G., Resentini, A., Garzanti, E., and Niedermann, S., 2016, The cosmogenic record of mountain erosion transmitted across a foreland basin: Source-to-sink analysis of in situ 10Be, 26Al and 21Ne in sediment of the Po river catchment: Earth and Planetary Science Letters, v. 452, p. 258-271.

Wittmann, H., Oelze, M., Gaillardet, J., Garzanti, E., and von Blanckenburg, F., 2020, A global rate of denudation from cosmogenic nuclides in the Earth's largest rivers: Earth-Science Reviews, v. 204, p. 103147.

Wittmann, H., von Blanckenburg, F., Dannhaus, N., Naumann, R., Christl, M., and Gaillardet, J., 2012, The dependence of meteoric 10Be concentrations on particle size in Amazon River bed sediment and the extraction of reactive 10Be/9Be ratios: Chemical Geology, v. 318-319, p. 126-138.

Wittmann, H., von Blanckenburg, F., Dannhaus, N., Bouchez, J., Gaillardet, J., Guyot, J. L., Maurice, L., Roig, H., Filizola, N., and Christl, M., 2015, A test of the cosmogenic 10Be(meteoric)/9Be proxy for simultaneously determining basin-wide erosion rates, denudation rates, and the degree of weathering in the Amazon basin: Journal of Geophysical Research: Earth Surface, v. 120, no. 12, p. 2498-2528.

Wittmann, H., von Blanckenburg, F., Guyot, J.-L., Maurice, L., and Kubik, P., 2011, Quantifying sediment discharge from the Bolivian Andes into the Beni foreland basin from cosmogenic 10Be-derived denudation rates: Revista Brasileira de Geociências, v. 41, no. 4, p. 629-641.

Wittmann, H., von Blanckenburg, F., Guyot, J. L., Maurice, L., and Kubik, P. W., 2009, From source to sink: Preserving the cosmogenic 10Be-derived denudation rate signal of the Bolivian Andes in sediment of the Beni and Mamoré foreland basins: Earth and Planetary Science Letters, v. 288, no. 3, p. 463-474.

Wolanski, E., and Ducrotoy, J.-P., 2014, Estuaries of Australia in 2050 and beyond–A synthesis, Estuaries of Australia in 2050 and beyond, Springer, p. 1-13.

Yanites, B. J., Tucker, G. E., and Anderson, R. S., 2009, Numerical and analytical models of cosmogenic radionuclide dynamics in landslide-dominated drainage basins: Journal of Geophysical Research: Earth Surface, v. 114, no. F1.