



Perth, September 2026

Review of manuscript “PyBacktrack 1.5: A community 1 tool for reconstructing paleobathymetry of drill sites, geohistory and global paleobathymetry”; submitted to Geoscientific Model Development

Dear editor,

I want to thank the authors for having produced an easy to read, and well-illustrated manuscript, which presents the updated PyBackTrack 1.5 package developed by Müller et al. These results are indeed incredibly valuable for the scientific communities indeed, specifically for palaeoclimate researcher and tectonicists. I would also emphasises that tools such as PyBackTrack 1.5 could certainly help applied research to refine subsurface-property distribution for hydrogen storage, carbon capture and storage, geothermal energy, aquifer management, mineral exploration, or hydrocarbon production.

The paper is well written, and should be considered for publications pending minor revisions.

I would recommend the authors to address three main points in addition to the listed suggestions in the attached commented PDF:

1. No Wheeler diagram and no need to rename the known concept of burial history diagrams

The manuscript presents one of new feature of PyBackTrack 1.5 as being “geohistory curves”, referencing them as “Wheeler” diagrams. First, the reference to Wheeler diagrams is misplaced. Wheeler diagrams transform 2D cross sections plotted in the spatial space (length + depth) to a spatial and temporal space, where depth is replaced by time (Wheeler, 1958). I would recommend deleted any mention of Wheeler diagrams from the manuscript as non of the presented material are, in fact, Wheeler diagrams.

The curves presented, notably in Fig. 8 of the paper, are classic burial history curves (e.g., Guidish et al., 1985), with a twist of adding the tectonic subsidence and sea-level curves on top of it. I would argue that renaming a known concept would only disservice the manuscript by hiding it from the community that would routinely produce/utilise such burial history curves.

2. Broaden the concept of bathymetry, subsidence, and their impact on sediment routing in the introduction

The manuscript starts by defining “paleobathymetry” as “the past water depth of seafloor or continental margin locations”. This definition is quite obtuse, as palaeobathymetry refers to any ancient, submerged surface, i.e., also including lacustrine and fluvial setting. I would recommend introducing the term in a broader manner than currently done, and include continental settings as well, as these could also be impacted by similar mechanical and thermal subsidence processes.

Secondly, the introduction states that the “bathymetry (...) changes through time in response to (...) thermal subsidence”. It omits that mechanical subsidence driven by fault movement/tectonic activity, especially in extensional settings, kicks in prior to thermal subsidence.

Finally, there is no mention on the impact of palaeobathymetry (and the change of thereof) on sediment routing. I would recommend the author adding a few words on this in addition to their list of impacted processes, as the deposited sediments would serve as primal input for palaeoclimate analyses, and the authors’ own burial history analyses indeed.

3. Figure updates

Figures are generally of high standards. However, several of them require minor updates to help the reader. The authors use a lot of geological time names (e.g., Early Cretaceous, Oligocene, etc.). However, none of these names are plotted anywhere. Therefore, please add the names of geological epochs and ages to Fig. 4-6-7-8-9-11.

The log of the Asteras well should be added to the paper, either next to Fig. 5, or 7 or 8.

Fig. 5 needs the following additional updates: add all the geographical names of the area called in the paper. Add the extent of Fig. 10 on the map.

The second parenthesis on the red y-axis is missing on Fig. 6.

Finally, on Fig. 10, would it be possible to add the major faults associated with the rifting episodes to the map, the check how the modelled subsidence fit the structural framework of the area?

4. Comparison of subsidence maps with published results

I would also like to understand better is how does PyBackTrack subsidence maps (Fig. 10) compare to published subsidence maps for the areas (e.g., Makuluni et al., 2024). Given that Makuluni et al. (2024) used 258 wells for the North Carnarvon Basin, how does the modelled subsidence from fewer, further spaced wells compare to published reconstructions. I appreciate that part of the discussion incorporates some of the published mechanisms to explain the modelled trends, but it would be useful to know how do these maps benchmark against published data.

5. Reorganised chapter 5.1

My last point might be a “deformation professionnelle”, but I would suggest reorganising chapter 5.1 from the oldest to the youngest, building the geological history from the start rather than the other way around. This is because the older geological history (i.e., location of the faults, localisation of the subsidence, etc.) impact the next step(s) of the basin evolution.

To address the formal journal criteria:

Scientific significance: excellent (1)

Scientific quality: good (2)

Scientific reproducibility: excellent (1)

Presentation quality: good (2)

I invite the authors to contact me directly if they have request for clarification with regards to my comment.

Sincerely,

Valentin Zuchuat

Reference:

Guidish et al., 1985: <https://doi.org/10.1306/AD461B97-16F7-11D7-8645000102C1865D>

Makuluni et al., 2024: <https://www.sciencedirect.com/science/article/pii/S004019512400057X#f0015>

Wheeler, 1958: <https://doi.org/10.1306/0BDA5AF2-16BD-11D7-8645000102C1865D>



PyBacktrack 1.5: A community tool for reconstructing paleobathymetry of drill sites, geohistory and global paleobathymetry

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Abstract

PyBacktrack is a Python community software package that reconstructs the paleo-water depth (paleobathymetry) of ocean drill sites and industry wells through time by combining a model of tectonic subsidence with sediment decompaction and isostatic correction. Since the release of pyBacktrack 1.0, the software has undergone substantial development that culminates in pyBacktrack 1.5. The package now (i) runs on Python 3 and is distributed via the Python Package Index, conda-forge and Docker; (ii) includes a new paleobathymetry gridding module that reconstructs and backtracks all submerged present-day crust through geological time to produce time-dependent paleobathymetry grids; (iii) uses an updated default oceanic age-to-depth model, a globally complete set of rift start/end age grids derived from a deforming plate model, an updated total sediment thickness grid and an updated present-day age grid; (iv) supports both mantle and paleomagnetic reference frames and allows the gridded paleobathymetry to be optionally merged with externally produced paleobathymetry on synthetic, subducted crust; and (v) ships with expanded sea-level model and dynamic topography model libraries. We illustrate pyBacktrack 1.5 with three applications: (1) paleobathymetry reconstructions since the Early Cretaceous of the North Atlantic and the Southern Ocean; (2) one-dimensional backstripping and geohistory analysis at a long-record industry well on the Australian North West Shelf in three configurations (including or omitting eustatic sea level, and including a joint sea level and dynamic topography correction); and (3) a margin-scale gridded tectonic-subsidence-rate analysis of 109 Australian Northwest Shelf industry wells, quantifying how much of the inferred tectonic subsidence rate is dependent on eustatic and dynamic-topographic corrections in space and time. Together, these developments make pyBacktrack 1.5 a more accessible, extensible and globally applicable framework for reconstructing paleobathymetry and testing the tectonic, sedimentary, sea-level and dynamic-topographic controls on basin evolution.

1. Introduction

Paleobathymetry, the past water depth of seafloor or continental margin locations, is a fundamental boundary condition for reconstructing the long-term evolution of ocean basins, continental margins, marine gateways, ocean circulation and the carbon cycle. The bathymetry at any site of marine sedimentation changes through time in response to several superimposed processes, including thermal subsidence of oceanic and rifted continental crust, compaction-driven progressive porosity reduction of the sediment column, isostatic adjustment to the changing sediment load, mantle-flow driven dynamic topography, and eustatic sea-level change (Allen and Allen, 2005; Müller et al., 2018). Quantitative recovery of paleobathymetry at a drill site or in a basin therefore demands an integrated workflow that brings these processes together in a single, reproducible framework.



Beyond its role in basin analysis, paleobathymetry is a first-order boundary condition for the broader community that models the deep-time Earth system. In paleoclimate and paleoceanographic simulations, the depth and width of marine gateways, the location and depth of mid-ocean ridges, and the elevation of submarine plateaus together control the geometry of the major ocean basins, the routes available to deep and intermediate water masses, and the partitioning of meridional and zonal flow (Hutchinson et al., 2018; Lunt et al., 2021; Sauermilch et al., 2021; Sijp et al., 2014). Paleobathymetry sets the position of the carbonate compensation depth (CCD), modulates organic-carbon burial efficiency and the storage of dissolved inorganic carbon (Pälike et al., 2012; Crampton et al., 2018; Dutkiewicz and Müller, 2022), and thereby couples solid-Earth tectonics to the long-term carbon cycle (Müller et al., 2022). It determines which shelves are flooded and which are emergent, which in turn controls biogeographic dispersal corridors, marine connectivity, productivity patterns and the extent of epicontinental seas (Allen and Allen, 2005; Kocsis and Scotese, 2020; Poblete et al., 2021). It is also the geometry on which mantle-flow simulations of dynamic topography are tested and compared (Gurnis, 1993; Müller et al., 2017; Braz et al., 2021). For all of these applications time-dependent paleobathymetry grids are required.

PyBacktrack (Müller et al., 2018) is an open-source Python package that implements such a workflow. It provides depth backtracking on both oceanic and continental crust, a library of compaction relationships for common marine lithologies, and a treatment of mantle-flow-derived dynamic topography drawn from a curated bundle of global models. Other open-source tools address related problems, but with different design priorities. For example, PALEOSTRIP is a MATLAB, GUI-based tool designed for user-controlled 1-D, 2-D and 3-D paleobathymetric backtracking, with a particular emphasis on 2-D and 3-D flexural isostasy for mapped stratigraphic surfaces, seismic transects and basin-scale sensitivity tests (Colleoni et al., 2021). PyBacktrack, by contrast, is built around reproducible Python workflows that are directly linked to plate reconstructions, global oceanic and continental subsidence models, dynamic topography corrections and the generation of time-dependent paleobathymetry grids. A central design choice of pyBacktrack, retained in 1.5, is that the tool exposes the underlying physical model as a transparent, modular Python application rather than as a closed-form executable. Every lithology, every sea-level curve and every dynamic-topography model is either a bundled text/NetCDF file or a user-supplied file. This makes pyBacktrack a useful pedagogical and exploratory tool as well as a production research instrument: users can substitute alternative tectonic-subsidence relationships or compaction laws without modifying the core algorithms. PyBacktrack 1.5 preserves and extends this design philosophy.

In the seven years since the 1.0 release, three developments have made a substantial revision of pyBacktrack desirable. First, the broader plate-tectonic modelling community has migrated to Python 3 and to richer, deformation-aware global plate models (e.g., Müller et al., 2019; Cao et al., 2021; Zahirovic et al., 2022). Second, the observational underpinnings of pyBacktrack, including present-day ocean-floor age grids, global total sediment thickness grids and oceanic age–depth relationships, have been refined (Straume et al., 2019; Seton et al., 2020; Richards et al., 2020). Third, a recurring request from users has been to use pyBacktrack to generate not only the depth history of a single site but two-dimensional, time-dependent paleobathymetry grids over entire ocean basins.

PyBacktrack 1.5 addresses these needs. We have ported the package to Python 3, integrated up-to-date age and sediment-thickness grids and an updated default oceanic age-to-depth model (Richards et al., 2020). We have added a paleobathymetry gridding module that reconstructs every present-day submerged grid point back through time, decompacts its sediment column at each reconstruction time and (optionally) merges the result with externally generated paleobathymetry on synthetic, since-subducted crust. We have made the rift start/end age grids,



93 that underpin the continental subsidence model, globally complete and have based them on the
 94 Zahirovic et al. (2022) deforming plate model. PyBacktrack 1.5 is distributed through the
 95 Python Package Index, conda-forge and a Docker image; example data, notebooks and a fully
 96 documented application programming interface are available at pybacktrack.readthedocs.io.
 97 Selected paleobathymetry grid sets are distributed via the EarthByte GPlates data repository
 98 and are linked from the pyBacktrack 1.5 documentation. This paper documents the new and
 99 updated features in pyBacktrack 1.5 and demonstrates how they can be applied.

100 2 PyBacktrack 1.5 architecture

101 The pyBacktrack package consists of several modules that can be either called from the
 102 command line as built-in scripts (using `python -m pybacktrack.<module>_cli`) or imported
 103 into user Python code for finer-grained control. The four modules are:

- 104 1) `'backtrack'` — reconstructs paleo-water depth at a single drill site, given a
 105 stratigraphic file of lithologies and ages and a chosen tectonic-subsidence model.
 106 Used for sites where the present-day water depth is known but the paleo-water depths
 107 are not.
- 108 2) `'backstrip'` — recovers tectonic subsidence at a single passive-margin site from a
 109 stratigraphic file that includes minimum and maximum estimates of paleo-water depth
 110 (typically derived from benthic microfossil assemblages). Used to isolate the tectonic
 111 contribution to subsidence.
- 112 3) `'paleo_bathymetry'` — new in pyBacktrack 1.4 and substantially extended in 1.5, this
 113 module generates two-dimensional, time-dependent paleobathymetry grids by
 114 reconstructing every present-day submerged grid point back through time and
 115 applying the same physics as the one-dimensional backtrack workflow.
- 116 4) `'age_to_depth'` — converts ocean-floor age to ocean-basement depth using one of
 117 three bundled relationships (RHCW18 (Richards et al., 2020), GDH1 (Stein and
 118 Stein, 1992) or Crosby_2007 (Crosby, 2007).

119 These modules are supported by utility modules that expose sediment decompaction routines,
 120 sea-level and dynamic-topography samplers and stratigraphic depth-to-age conversion (new
 121 since 1.0). They are configured by a bundle of data shipped with the package: lithology
 122 definitions, a present-day age and bathymetry grid, a total sediment thickness grid, a crustal
 123 thickness grid, dynamic-topography model grids, sea-level curves and the reconstruction model
 124 (rotation files and static polygons).

125 A new utility module `'stratigraphic_depth_to_age'` has been added in the 1.x series. It
 126 interpolates the ages of user-specified stratigraphic depths from a piecewise-linear age–depth
 127 model. The `'age_to_depth'` module has been generalised to accept user-supplied age–depth
 128 tables and additional bundled models. The `'interpolate'` script of pyBacktrack 1.0 remains
 129 available and unchanged. Both new modules are available as command-line scripts and as
 130 Python functions.

131 PyBacktrack's physical model is unchanged in 1.5 relative to 1.0. On oceanic crust, the tectonic
 132 subsidence at a site is computed from a user-selected age–depth relationship together with the
 133 present-day unloaded basement depth (water depth minus an isostatic correction for the
 134 present-day sediment thickness). On continental crust, tectonic subsidence is modelled with a
 135 McKenzie-style uniform-stretching model (McKenzie, 1978) in which the syn-rift and post-
 136 rift subsidence is determined from the present-day sediment thickness and from the rift start
 137 and end ages, following Jarvis and McKenzie, 1980). Decompaction of the sediment column
 138 at each time step uses the porosity–depth relationships from Müller et al. (2018).



139 **3 New features and improvements since pyBacktrack 1.0**

140 PyBacktrack 1.5 inherits all features of the 1.0 release but introduces numerous additions,
 141 replaces several default models with more recent alternatives and changes the installation
 142 footprint. We group the changes thematically below. Where a change was first introduced in
 143 an earlier 1.x release we indicate the version explicitly.

144 **3.1 Python 3, packaging and installation**

145 PyBacktrack 1.0 supported only Python 2.7, which has been end-of-life since 2020.
 146 PyBacktrack 1.5 supports Python 3.8 and above, and depends on pyGPlates (Mather et al.,
 147 2024). The package is now installable from the Python Package Index (`pip install`
 148 `pybacktrack`), from conda-forge (`conda install -c conda-forge pybacktrack`) and as a Docker
 149 image (`earthbyte/pybacktrack`). Example data, example drill sites and five Jupyter notebooks
 150 (`backstrip`, `backtrack`, `geohistory_analysis`, `paleobathymetry` and
 151 `reconstruct_drill_sites_on_paleobathymetry`) are bundled in a separate, optional install step
 152 (`python -c "import pybacktrack; pybacktrack.install_examples()"`). A separate
 153 `install_supplementary` script bundles supplementary tooling including the
 154 `generate_rift_grids.py` script used to regenerate the built-in rift grids. The continuous-
 155 integration test suite runs on Linux, macOS and Windows with all supported Python versions
 156 on every push, and the documentation is rebuilt automatically on each commit at
 157 `pybacktrack.readthedocs.io`.

158 PyBacktrack 1.5 has been refactored around `pyproject.toml`-driven modern packaging,
 159 allowing automated wheel builds and SCM-driven versioning. The new packaging removes the
 160 need for users to install the dependency library pyGPlates manually, since both PyPI and
 161 conda-forge now distribute pyGPlates for the major platforms. As a result, a fresh install of
 162 pyBacktrack 1.5 on Linux, macOS or Windows is a one-line `pip install pybacktrack`
 163 operation.

164 **3.2 New paleobathymetry gridding module**

165 A prominent addition in pyBacktrack 1.4 and 1.5 is the `paleo_bathymetry` module. Where the
 166 original 1.0 release backtracked single one-dimensional drill sites, `paleo_bathymetry`
 167 generates two-dimensional paleobathymetry grids by treating every submerged grid point at
 168 present day as a virtual drill site. At each user-selected grid spacing (default 6 arc-minutes), a
 169 single lithology (default `Average_ocean_floor_sediment`; previously `Shale`) is assigned an
 170 initial compacted thickness from the total sediment thickness grid and is progressively
 171 decompacted back through time. Loading the decompacted thickness onto the modelled
 172 tectonic subsidence (oceanic where the grid point lies inside the age grid, continental where it
 173 does not) together with optional dynamic topography and sea-level contributions yields a
 174 paleo-water depth at each grid point and each reconstruction time. Each grid point is
 175 reconstructed using a global plate model and the reconstructed locations, together with their
 176 paleo-water depths, are interpolated onto a regular output grid at every output time.

177 Trench-adjacent grid points produce spuriously deep paleobathymetry when reconstructed
 178 back into accreted forearc settings. To suppress this artefact, pyBacktrack 1.5 ships with a per-
 179 trench exclusion mask that omits, by default, present-day grid points within 60 km of the
 180 subducting plate side of each trench. The exclusion distances were hand-tuned for each trench
 181 based on the resultant paleobathymetry and can be over-ridden by the user with `--`
 182 `exclude_distances_to_trenches_kms`.

183 The module further supports merging the pyBacktrack-derived grids with externally produced
 184 paleobathymetry on synthetic (now-subducted) crust. Because pyBacktrack only generates



185 paleobathymetry for crust that persists at present day, the merging operation fills the inevitable
 186 gaps over the former Pacific, Tethys and Neo-Tethys oceans. The traditional paleobathymetry
 187 workflow used to fill these gaps is described by Wright et al. (in prep.).

188 **3.3 Updated default oceanic age-to-depth model**

189 The default age-to-depth model was updated in pyBacktrack 1.4 from GDH1 (Stein and Stein,
 190 1992) to the plate model of Richards et al. (2020; “RHCW18”). The preferred RHCW18
 191 parameters used by pyBacktrack are a mantle potential temperature of 1333 °C, a plate
 192 thickness of 130 km and a zero-age ridge depth of 2500 m. Both GDH1 and the Crosby (2007)
 193 model remain available via the ‘-m’ command-line option. RHCW18 was selected as the
 194 default because it more accurately reproduces depth–age data on undeformed seafloor that has
 195 not been thermally rest older than ~80 Myr than GDH1 (Richards et al., 2020) and yields global
 196 oceanic depth residuals that are more nearly isotropic with respect to age and plate identity
 197 (Hoggard et al., 2017; Richards et al., 2018). However, much of the preserved seafloor
 198 underlain by ocean crust has been thermally rejuvenated by volcanism, reheating and
 199 shallowing (Stein and Stein, 1992). Therefore, depending on the user's preferences or
 200 applications, GDH-1 often remains a viable choice.

201 **3.4 Updated reconstruction model and reference-frame support**

202 The default plate reconstruction model used by ‘paleo_bathymetry’ in pyBacktrack 1.5 is
 203 Zahirovic et al. (2022), replacing the Müller et al. (2019) model used in 1.4 and earlier. The
 204 two models are nearly identical for the period 0–250 Ma; the Zahirovic et al. (2022) model
 205 additionally incorporates South China deformation from Cao et al. (2021), which produces a
 206 slightly different optimised mantle reference frame for that interval. PyBacktrack 1.5 supports
 207 any plate reference frame, including mantle reference frames (often expressed by anchor plate
 208 0, the default) and the paleomagnetic reference frame of Zahirovic et al. (2022), here expressed
 209 by anchor plate 701701; the paleomagnetic frame is preferred for paleoclimate-related
 210 research. Users may supply their own static polygons and rotation files via the ‘--
 211 static_polygon_filename’ and ‘--rotation_filenames’ options; only the present-day grid-point
 212 reconstruction is affected — the dynamic-topography sampling uses each model’s own internal
 213 reconstruction.

214 **3.5 Globally complete rift start/end age grids**

215 PyBacktrack’s continental subsidence model requires the rift start and end ages at each
 216 location. PyBacktrack 1.0 obtained these from the drill-site file. PyBacktrack 1.4 introduced
 217 built-in rift start/end age grids generated from the Müller et al. (2019) deforming plate model,
 218 restricted to present-day submerged continental crust. In 1.5 the rift grids have been regenerated
 219 from the Zahirovic et al. (2022) deforming model and, crucially, extended to global coverage:
 220 every grid point that is not on actively deforming continental crust inherits the rift start and end
 221 ages of its nearest deforming grid point. This decouples the rift grids from the default age grid
 222 and from the default total sediment thickness grid, so that paleobathymetry can be regenerated
 223 with alternative grids (for example, a user-supplied age grid with a slightly different continent–
 224 ocean boundary, or a sediment thickness grid with a slightly different coastline) without leaving
 225 sliver gaps at grid boundaries. The script that generates the rift grids — ‘generate_rift_grids.py’
 226 in pybacktrack/supplementary — is documented in the user manual and can be rerun for any
 227 user-supplied deforming plate model.

228 **3.6 Updated default age and sediment-thickness grids, lithology and sea level curves**



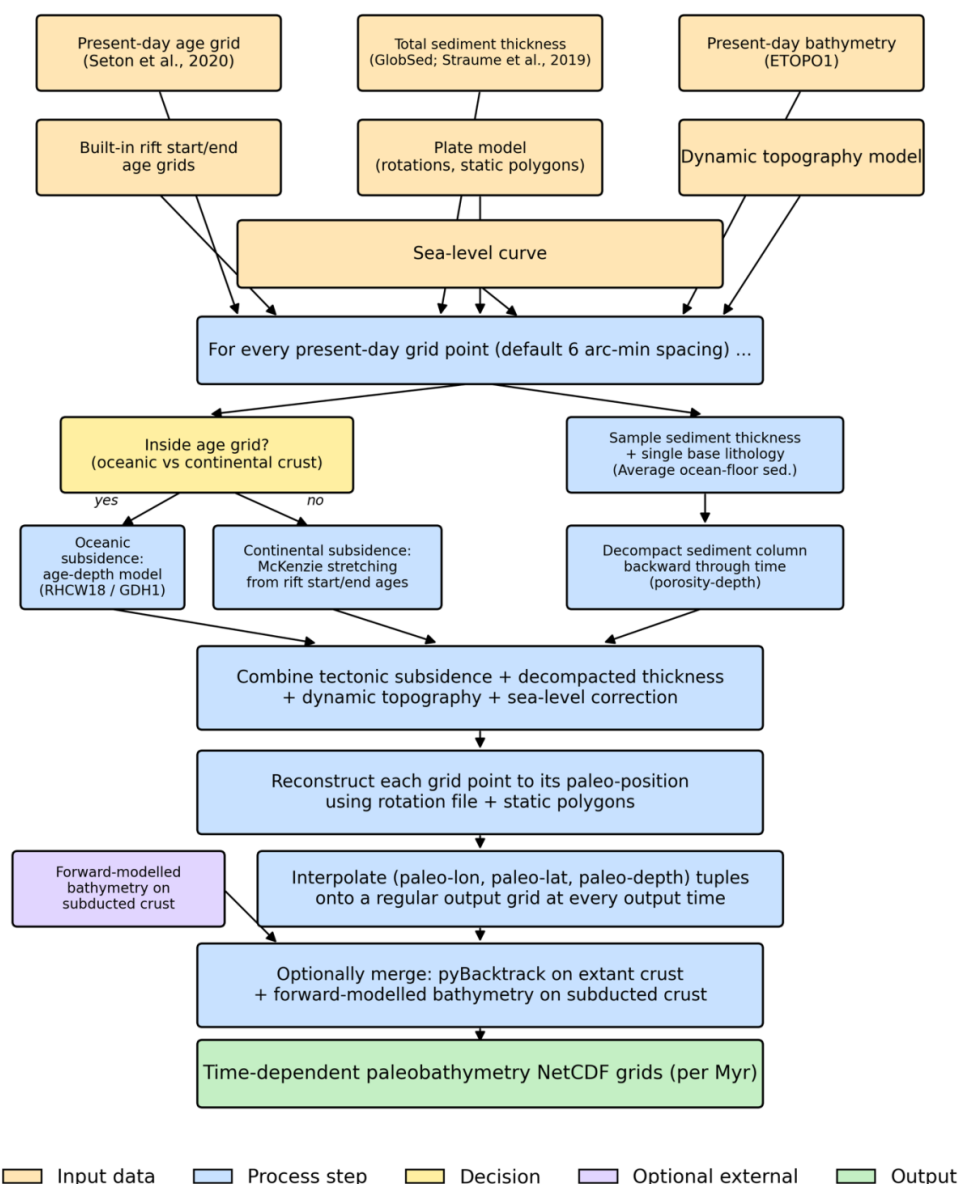
The default present-day age grid was updated in pyBacktrack 1.4 from the Müller et al. (2008) compilation to the 6 arc-minute compilation of Seton et al. (2020), which uses the Gee and Kent (2007) timescale and incorporates the seafloor-spreading parameters of Müller et al. (2016b) and Wright et al. (2016). The default total sediment thickness grid was updated in pyBacktrack 1.4 from the NOAA NGDC 5 arc-minute compilation to GlobSed (Straume et al., 2019), which provides a more accurate global compilation of sediment thicknesses with substantially improved coverage of high-latitude oceans. The bundled lithology library in pyBacktrack consists of two files. The “primary” file (16 entries) provides the porosity–depth relations for the lithologies tabulated in Müller et al. (2018) and remains unchanged. The “extended” file in pyBacktrack 1.5 ships 11 additional lithologies including anhydrite, chert, conglomerate, dolostone, grainstone, mafic igneous rocks, marl, organic mud, reef carbonate, rhyolite, salt and tuff. Users may continue to supply their own lithology definitions via the ‘-l’ option. PyBacktrack 1.5 ships several bundled sea-level curves: the standard and long-term curves of Haq et al. (1987), Miller et al. (2020) and a composite curve of three published curves by Haq and Ogg (2024) (0–66 Ma), Haq (2014) (66–140 Ma) and Haq (2017) (140.1–205 Ma).

4 Application examples

We illustrate pyBacktrack 1.5 with three complementary applications. The new paleobathymetry-gridding workflow is the single most novel addition since version 1.0, and we present it as a reproducible flowchart (Fig. 1). We illustrate its products with time-dependent paleobathymetry maps of the North Atlantic Ocean (Fig. 2) and the Southern Ocean (Fig. 3), and benchmark the released grids (Fig. 4) against the independent Straume et al. (2020) Cenozoic forward model. We apply the pyBacktrack workflow for individual drill sites to a regional, well-constrained passive margin, the Australian North West Shelf, where we (i) map the well coverage on a vertical-gravity-gradient basemap (Fig. 5), (ii) show the long-term sea-level and dynamic-topography time series that drive the corrections at the featured well asteras (Fig. 6), (iii) demonstrate one-dimensional backstripping at that single long-record well in three configurations (Fig. 7), (iv) present a geohistory (“Wheeler”) diagram for the same well (Fig. 8), and (v) generalise the workflow to margin-scale gridded tectonic-subsidence rates across all 109 wells (Figs. 9–12). All figure scripts are bundled with the paper in ‘figures/scripts/'. Figures 1, 4, 5, 6, 7, 8, 9, 10, 11 and 12 are produced with pyGMT or matplotlib (Uieda et al., 2024); Figures 2 and 3 follow the canonical plotting pattern of the bundled pyBacktrack notebook ‘reconstruct_drill_sites_on_paleobathymetry.ipynb’ (matplotlib + cartopy + ‘gplately.Raster’ + ‘gplately.PlotTopologies’ (Mather et al., 2024)).

4.1 Paleobathymetry-gridding workflow

The most novel addition in pyBacktrack 1.5 - relative to pyBacktrack 1.0 (Müller et al., 2018) - is the module that generates time-dependent two-dimensional paleobathymetry grids by reconstructing and backtracking every present-day submerged grid point. The workflow integrates the original 1.0 one-dimensional physics (oceanic and continental subsidence, sediment decompaction, sea-level correction, dynamic-topography correction) with three new building blocks: (i) globally complete rift start/end age grids; (ii) plate reconstruction of every grid point using a user-selected deforming plate model (default Zahirovic et al., 2022); and (iii) optional merging with externally generated forward-modelled paleobathymetry on synthetic, since-subducted crust. Figure 1 summarises the data flow and the algorithmic steps.



272

273 **Figure 1.** *pyBacktrack 1.5 paleobathymetry-gridding workflow. Peach boxes are input data*
 274 *(present-day age, sediment thickness, bathymetry; rift start/end age grids; plate model;*
 275 *dynamic-topography model; sea-level curve). Blue boxes are processing steps (decompaction;*
 276 *oceanic/continental subsidence; plate reconstruction; grid interpolation). The yellow box is*
 277 *the per-grid-point decision between oceanic and continental crust based on the oceanic crustal*
 278 *age grid used. The lavender box is the optional traditional-paleobathymetry input for*

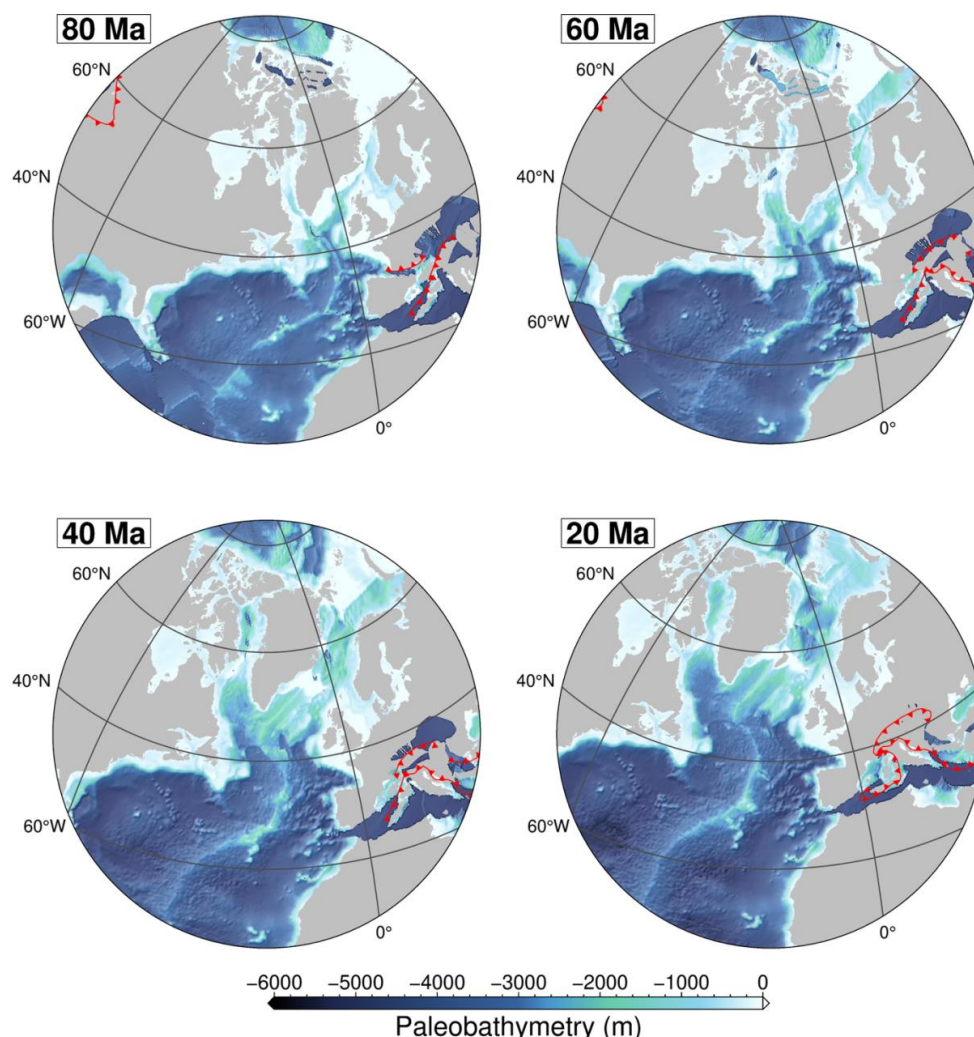


279 *subducted crust (involving grid merging). The green box is the final output as NetCDF*
 280 *paleobathymetry grids.*

281 Each grid point at present day (default 6 arc-min spacing) is classified as oceanic (inside the
 282 present-day age grid) or continental (outside). Oceanic points use a user-selected age-depth
 283 model (default RHCW18) to compute tectonic subsidence at every reconstruction time.
 284 Continental points use a McKenzie-style uniform-stretching model parameterised by the rift
 285 start and end ages sampled from the built-in rift grids. Each point is assigned an initial
 286 compacted sediment thickness from the GlobSed total-sediment-thickness grid (Straume et al.,
 287 2019) and a single base lithology (default 'Average_ocean_floor_sediment'). The column is
 288 decompacted backward through time using the porosity-depth relationship of the base
 289 lithology, and the decompacted thickness is combined with the modelled tectonic subsidence
 290 and the optional dynamic-topography and sea-level contributions to obtain a paleo-water depth
 291 at every reconstruction time. Each present-day grid point is then reconstructed to its paleo-
 292 position using the plate model, and the resulting (paleo-lon, paleo-lat, paleo-water depth) tuples
 293 are interpolated onto a regular output grid at every output time. Optionally, the pyBacktrack
 294 output is merged with externally produced traditional paleobathymetry on subducted crust to
 295 obtain globally complete paleobathymetry grids. The procedure is implemented in
 296 'pybacktrack/paleo_bathymetry.py' and is exposed both as a command-line script ('python -m
 297 pybacktrack.paleo_bathymetry_cli') and as a Python function
 298 ('pybacktrack.reconstruct_paleo_bathymetry_grids'). There are merged paleobathymetry grids
 299 available for the default plate model in pyBacktrack (Zahirovic 2022) for ages 0 to 170 Ma.
 300 They grid used in this paper is in the paleomagnetic reference frame (anchor plate 701701). The
 301 exact paleomagnetic-reference-frame palaeobathymetry grids used in Figs. 2–4 are archived
 302 with the paper's reproducibility package (Müller et al., 2026b).

303 **4.2 Cretaceous-Cenozoic paleobathymetry of the Atlantic-Tethys-Arctic realm**

304 Time-dependent paleobathymetry grids are essential boundary conditions for paleoclimate
 305 models, biogeographic dispersal analyses and ocean-circulation reconstructions (Kennett,
 306 1977; Sijp et al., 2014; Hutchinson et al., 2018; Lunt et al., 2021). We use the released
 307 pyBacktrack 1.5 paleobathymetry grids at 120, 80, 60 and 40 Ma to illustrate, respectively, the
 308 wide-open Cretaceous Tethys, the maximum extent of the Late Cretaceous oceans, the early
 309 Cenozoic Atlantic opening, and the mid-Eocene establishment of the modern Southern Ocean.
 310 The view is a Lambert azimuthal equal-area projection centred in the mid-North Atlantic (0
 311 deg E, 45 deg N) with a 50 deg horizon cap. The visible region therefore covers the entire
 312 western Tethys (Mediterranean and Caribbean realm), the full North Atlantic, the Arctic Ocean
 313 (well past the pole) and extends south to roughly the equator; equal-area, so ocean-basin sizes
 314 can be compared visually without distortion.



315

316 **Figure 2.** Paleobathymetry from the *pyBacktrack 1.5* at (a) 120 Ma, (b) 80 Ma, (c) 60 Ma and
 317 (d) 40 Ma. Reconstructed coastlines and plate boundaries and the underlying paleobathymetry
 318 grids are based on the Zahirovic et al. (2022) plate model in the paleomagnetic reference
 319 frame. Lambert azimuthal equal-area projection centred in the mid-North Atlantic (-20° E,
 320 45° N) with a 50° horizon cap enabling regional ocean-basin comparison with minimal
 321 distortion.

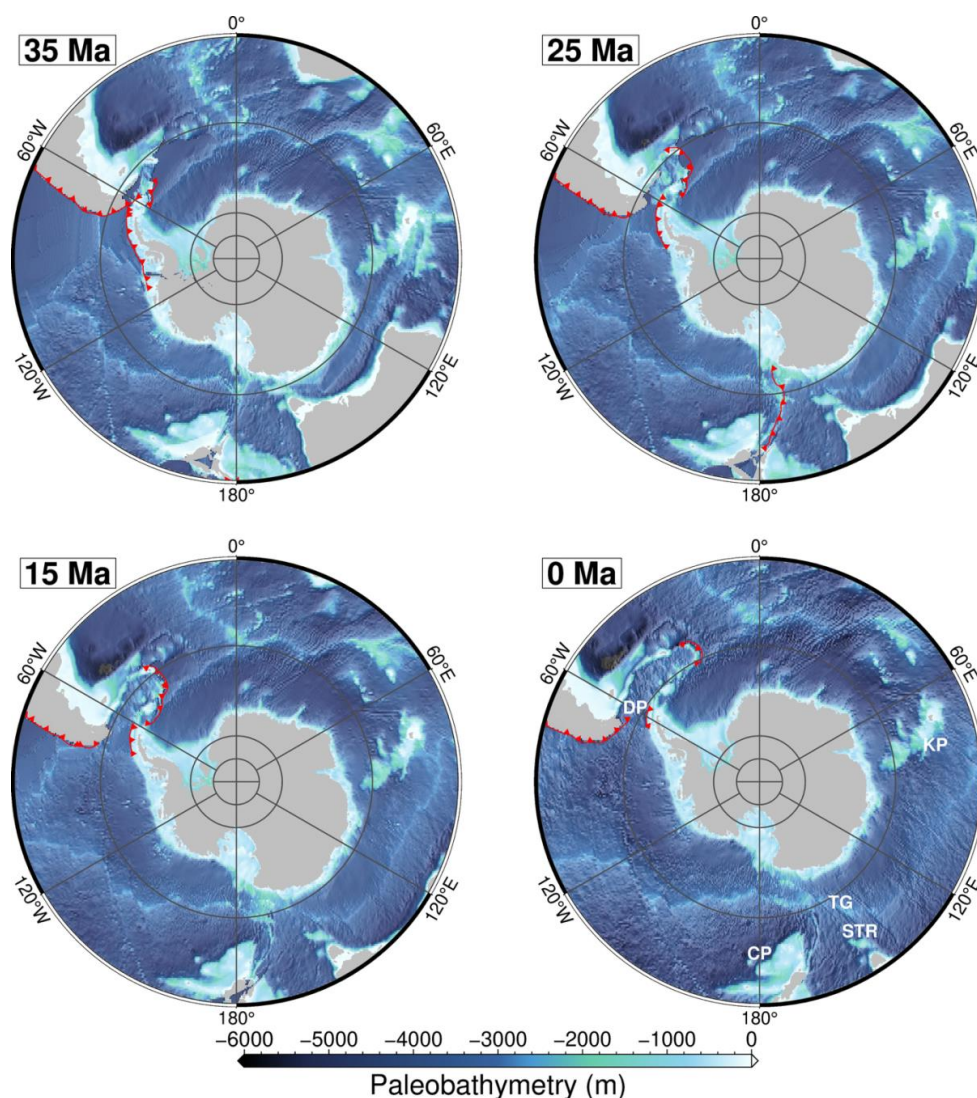
322 The four panels capture key Mesozoic-Cenozoic events of the North Atlantic and Tethyan
 323 systems: the deep central Atlantic conduit between a still narrow proto-North Atlantic and the
 324 southern Atlantic at 120 Ma; the equatorial Tethys deep seaway connecting the Atlantic and
 325 the Pacific realms at 80 Ma; the closing of the Western Interior Seaway and the opening of the
 326 Labrador Sea at 60 Ma; and, by 40 Ma, the constriction of the Tethys to its modern
 327 Mediterranean and Persian Gulf remnants while the North Atlantic and Norwegian-Greenland
 328 Sea reach near-modern bathymetric configurations.



329 **4.3 Southern Ocean paleobathymetry through time**

330 The southern high latitudes are central to Cenozoic climate evolution. Through the late Eocene
331 the South Tasman Rise and the Tasmanian land bridge separated the proto-Indian Ocean from
332 the proto-Pacific, and the Drake Passage between South America and the Antarctic Peninsula
333 was either closed or shallow. The progressive subsidence of the South Tasman Rise from the
334 late Eocene onward (Stickley et al., 2004; Bijl et al., 2013) and the deepening of the Drake
335 Passage during the Oligocene-Miocene (Lawver and Gahagan, 2003; Eagles and Jokat, 2014)
336 opened progressively deeper through-flows between the southern Atlantic, Indian and Pacific
337 basins and established the conditions for the Antarctic Circumpolar Current (ACC). The ACC
338 thermally isolates Antarctica from the warmer middle-latitude gyres, and the formation of a
339 continuous, deep circum-Antarctic current is widely held to have triggered or amplified the
340 onset of large-scale Antarctic glaciation at the Eocene-Oligocene boundary (Oi-1 event, ~33.7
341 Ma) (Kennett, 1977; Coxall et al., 2005; Houben et al., 2019), with the gateway depth playing
342 a critical role in setting the strength of the ACC and therefore the magnitude of southward heat
343 transport (Sauermilch et al., 2021). Reconstructing the bathymetry of these southern gateways
344 through time is therefore a basic ingredient of any Cenozoic paleoclimate or paleocean-
345 circulation model. We show pyBacktrack 1.5 grids at 35, 25, 15 and 0 Ma on a south-pole-
346 centred orthographic projection (Fig. 3) to illustrate how the Southern Ocean bathymetric
347 configuration evolved across this interval. The panels show the progressive opening and
348 deepening of the Tasman Gateway, the opening of the Drake Passage, and the widening of the
349 Southern Ocean, leading to the establishment of the modern circum-Antarctic deep water
350 circulation.

351



352

353 **Figure 3.** Southern Ocean view of pyBacktrack 1.5 paleobathymetry at (a) 35, (b) 25, (c) 15
 354 and (d) 0 Ma. The plate model used follows Fig. 2. White text acronyms are: DP – Drake
 355 Passage, KP – Kerguelen Plateau, TG – Tasman gateway, STR – South Tasman Rise, CP –
 356 Campbell Plateau. Lambert azimuthal equal-area projection centred on the south pole with a
 357 50° horizon cap.

358 4.4 Comparison with the Straume et al. (2020) Cenozoic forward-modelled 359 paleobathymetry

360 We compare our pyBacktrack-derived paleobathymetry against independent grids whose
 361 methodology differs from ours in almost every respect. Straume et al. (2020) published a
 362 Cenozoic (1–65 Ma, 1 Myr) global paleobathymetry + paleotopography grid set with explicit
 363 emphasis on the Northern Hemisphere oceanic gateways. Their approach is a five-step forward
 364 physical model anchored at each time slice on the plate-kinematic reconstruction of Straume



et al. (2019), updated from Seton et al. (2012): (i) oceanic lithospheric age from the rotated age grid → basement depth from the Crosby and McKenzie (2009) thermal-subsidence formula; (ii) residual bathymetry of reconstructed large igneous provinces and microcontinents added on top; (iii) sediment thickness from an empirical age and latitude regression (Straume et al., 2019) with isostatic loading; (iv) regression-based continental margins with reverse-time sediment removal; (v) a global eustatic sea-level correction. Crucially, Straume et al. (2020) make explicit manual adjustments in four regional gateways — the Fram Strait, the Greenland–Scotland Ridge, the Tethys Seaway and the Central American Seaway — so that the modelled paleobathymetry honours geological and paleo-oceanographic constraints from the regional literature (e.g. Iceland mantle-plume support of the Greenland–Scotland Ridge, sub-aerial Hovgård microcontinent restricting Fram Strait deep-water exchange until the Early Pliocene).

pyBacktrack1.5 is fundamentally different. Rather than predicting depth at time t from a thermal-subsidence formula anchored on the plate reconstruction, the workflow takes the present-day age, sediment-thickness and bathymetry grids and back-tracks every submerged grid point through reversed subsidence, decompaction, sea-level and dynamic-topography corrections to the time of interest. Two consequences follow. First, the released pyBacktrack 1.5 grids reproduce whatever fine-scale fabric is present in the present-day source data on every patch of preserved crust — mid-ocean-ridge axes, fracture-zone offsets, abyssal-hill orientation, seamount provinces — in their kinematically reconstructed past positions, with no smoothing back to a formula. Second, the workflow is by construction unable to reconstruct bathymetry on seafloor that has since been subducted: it has no present-day grid point to back-track from. However, this is alleviated by merging pyBacktrack paleobathymetry for a forward model with some in-principle similarity to that used by Straume et al. (2020) for now subducted ocean crust. Straume et al. (2020), being a plate-reconstruction-driven forward model, suffers neither limitation — and applies manual gateway corrections on top — but at the cost of a smoother, globally-uniform-formula representation of basin-scale depth and a complete absence of the small-scale heterogeneity preserved by backtracking.

We compare the distribution of bathymetric values at each time slice using each product's own ocean mask. Figure 4 (top) shows the median ocean depth and the median ± 1 MAD (median absolute deviation; a robust analogue of standard deviation, in metres) envelope for both products through the 1–65 Ma common window; the bottom panel overlays the full depth-distribution histograms at 40 Ma. Three observations stand out: (a) the pyBacktrack reconstruction has a consistently shallower median ocean depth than Straume et al. (2020) by roughly 300–450 m through the Cenozoic, with the offset modestly larger in the Eocene; (b) the two products have comparable MADs (~970–1090 m for pyBacktrack, ~900–985 m for Straume), so the bulk shapes of the depth distributions are similar; and (c) the Straume reconstruction covers a slightly larger ocean-area fraction of its native grid (~0.70 vs ~0.66 for pyBacktrack), consistent with its ability to place depth on subducted seafloor and with its globally smoother continental-margin representation.

404

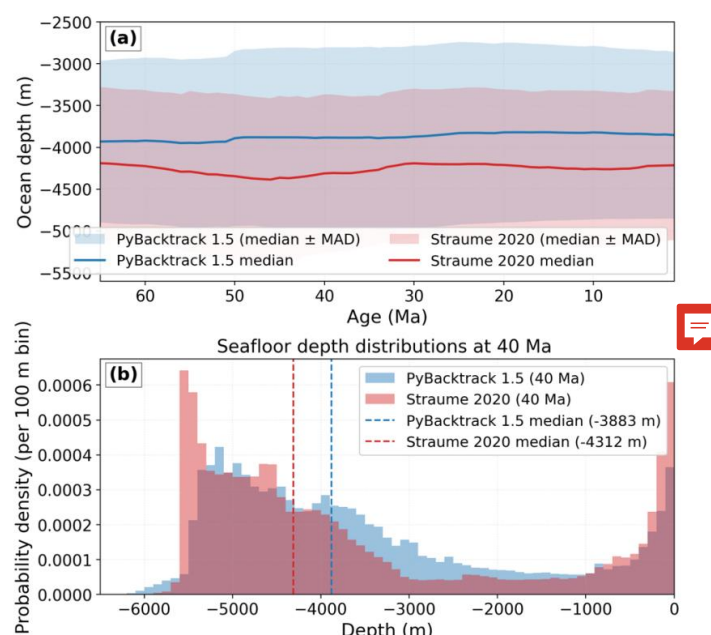


Figure 4. Comparison of the pyBacktrack 1.5 paleobathymetry based on the (Zahirovic et al., 2022) plate model against the Straume et al. (2020) Cenozoic forward-model paleobathymetry over the common window 1-65 Ma. TOP: time-series of the median ocean depth (solid lines) and median ± 1 MAD (median absolute deviation, the robust analogue of standard deviation, in metres) envelope (shaded bands) for each product. BOTTOM: depth-distribution histograms at 40 Ma, with the per-product median marked as a dashed vertical line. Each product is summarised on its own ocean mask (PyBacktrack: cells where the grid is finite; Straume: cells where $z < 0$).

The methodological and quantitative differences should not be read as one product being right and the other wrong. Each is fit for a different purpose. Straume et al.'s grids (2020) are suitable when the application is gateway-resolution paleo-ocean circulation modelling and when the user wants the benefit of literature-evaluated regional corrections. PyBacktrack is preferable when the application needs a self-consistent reconstruction whose physical assumptions can be audited end-to-end, or when the user wants the fine-scale fabric preserved on present-day-preserved crust, or when the analysis is augmented by individual wells where back-stripping is the appropriate tool. Merging the strengths of the two approaches — pyBacktrack-style back-tracking on preserved crust and Straume-style forward modelling on subducted crust — is our preferred method for complete paleobathymetry reconstruction.

4.5 NW Shelf data overview and well selection

For the regional and one-dimensional examples we use the Australian North West Shelf. The margin spans roughly 3000 km from the Carnarvon Basin in the southwest to the Browse Basin further north and the Bonaparte Basin in the Arafura Sea in the northeast (Fig. 5). It is one of the largest and most extensively drilled passive margins in the world. It developed through multiple Permian-Mesozoic rifting episodes including Permian-Triassic extension associated with the early break-up of Pangea, latest Triassic-Early Jurassic extension along what later became the western Australian margin, Late Jurassic-Early Cretaceous rifting and continental



break-up between Greater India and Western Australia, and the post-break-up opening of the Argo, Gascoyne, Cuvier and Perth abyssal plains (Gibbons et al., 2012, 2013). The Cenozoic record is dominated by passive thermal subsidence under a widespread carbonate platform that drowned and stepped down to the modern outer shelf during the Neogene. The NW Shelf is also a globally significant hydrocarbon province (Longley et al., 2002; Cathro et al., 2003), which is why an unusually dense industry-drilling effort has produced consistent, lithology-coded stratigraphy with paleobathymetry indicators derived from benthic foraminiferal assemblages - exactly the input that pyBacktrack needs. Its combination of long stratigraphic record, multi-phase tectonic history, dense well coverage, and well-resolved plate-tectonic context makes the NW Shelf an ideal natural laboratory for testing margin-scale backstripping workflows.

The well data used here (Fig. 5) were compiled by Müller et al. (2000). For the one-dimensional examples we feature a single long-record well, *asteras*, whose 20 stratigraphic horizons span 24 to 146 Ma, which is within the 0-150 Ma coverage of our preferred dynamic-topography model D10_gmcm9 (Braz et al., 2021) used in this context.

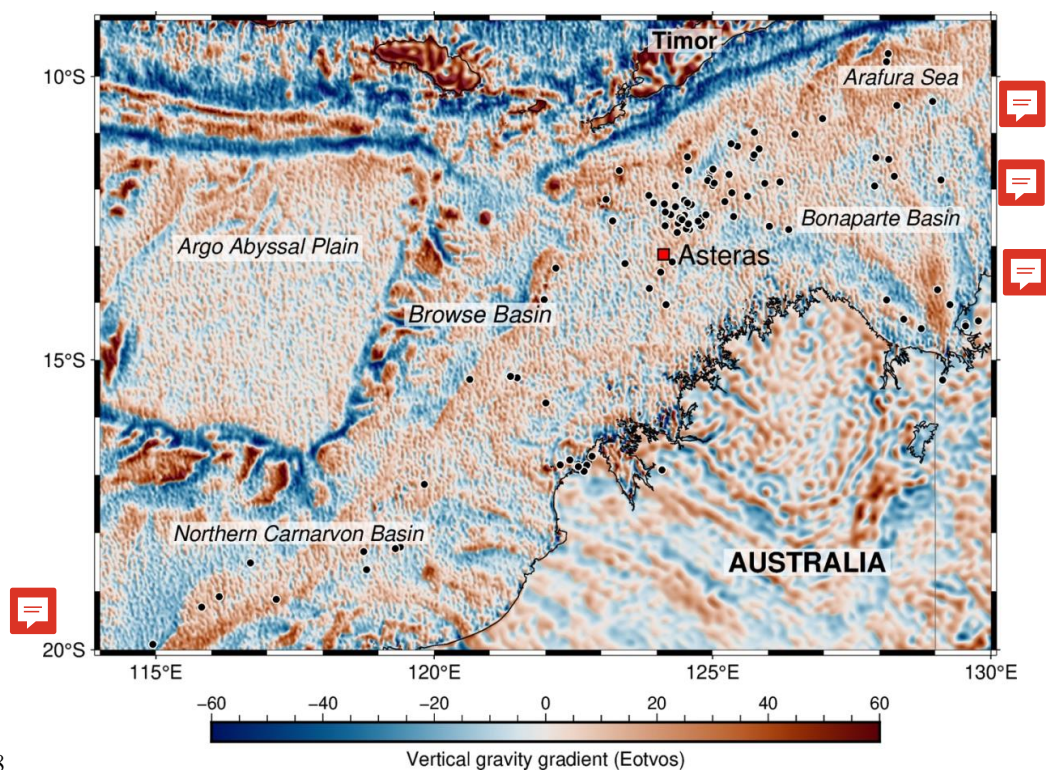
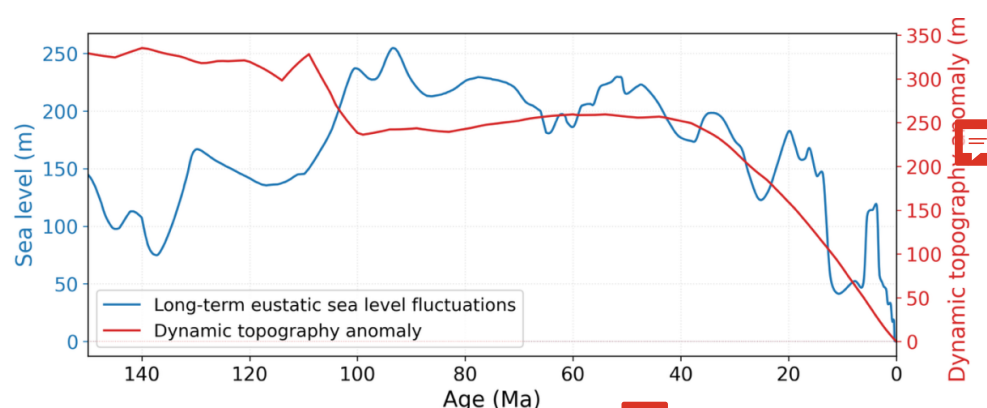


Figure 5. Location map of 109 NW Shelf industry wells used in this paper compiled by Müller et al. (2000). Black dots mark the wells; the featured well, *asteras*, used for the one-dimensional examples (Figs. 6, 7 and 8) is highlighted with a red square and label. Background: Satellite vertical-gravity-gradient (Sandwell et al., 2014) exposes the structural fabric (rifted margins, fracture zones, abyssal-plain topography).

4.6 Sea-level and dynamic-topography forcings used in backstripping



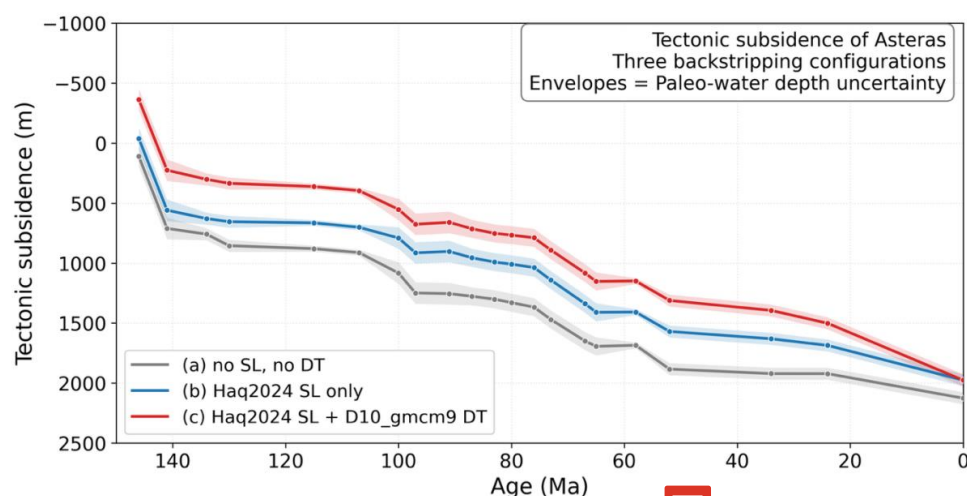
455 The tectonic subsidence inferred from well data depends on whether eustatic sea level
 456 fluctuations and/or mantle convection-driven dynamic topography through time is considered.
 457 Long-term eustatic sea level and dynamic topography via pyBacktrack as time series were
 458 sampled at the well location using the bundled Haq2024 long-term hybrid sea-level curve and
 459 the D10_gmcm9 dynamic-topography model of Braz et al. (2021), whose 0-150 Ma coverage
 460 spans the entire asteras stratigraphic record (oldest horizon 146 Ma). Figure 6 shows both
 461 forcings evaluated at the asteras location across the 150-0 Ma window used for every
 462 subsequent figure.



463
 464 **Figure 6.** Examples of eustatic sea-level and dynamic topography models at the featured NW
 465 Shelf well, asteras (see Fig. 5 for well site). Left y-axis: Haq2024 long-term sea-level curve as
 466 implemented in pyBacktrack 1.5 (Haq and Ogg (2024) (0–66 Ma), Haq (2014) (66–140 Ma)
 467 and Haq (2017) (140.1–150 Ma) (solid blue). Right y-axis: D10_gmcm9 dynamic-topography
 468 elevation anomaly at the well location relative to present (dashed orange; Braz et al., 2021).

469 4.7 Backstripping in three configurations

470 Mirroring the bundled `pybacktrack/notebooks/backstrip.ipynb` workflow, we run
 471 `pybacktrack.backstrip\_well` for the featured well asteras in three configurations: (a) no sea
 472 level and no dynamic topography (the raw decompacted record); (b) Haq2024 long-term hybrid
 473 sea level only, which isolates the eustatic correction; and (c) Haq2024 sea level together with
 474 the D10_gmcm9 dynamic-topography model of Braz et al. (2021), the full external correction
 475 set used throughout the rest of the paper. All three curves are overlaid on a single panel for
 476 direct comparison; each carries its min/max paleo-water-depth uncertainty envelope.



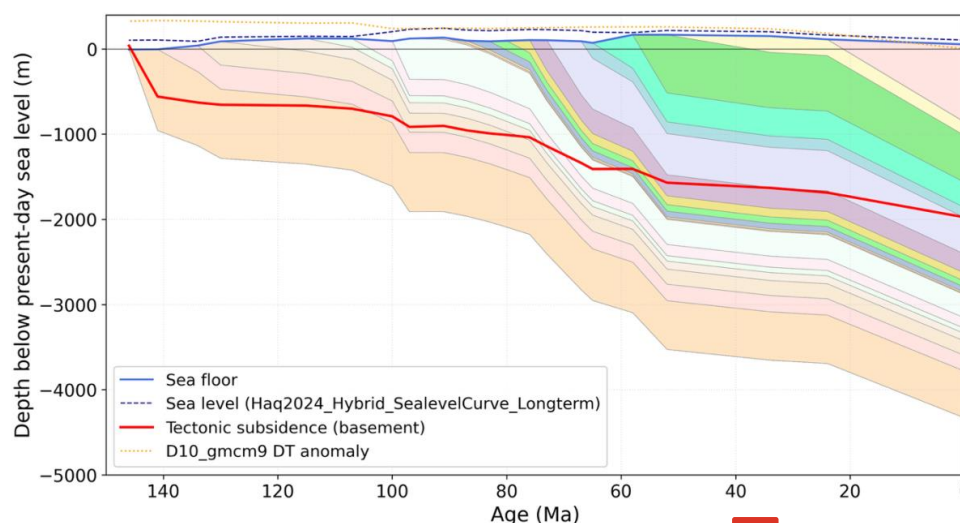
477

478 **Figure 7.** Tectonic subsidence at industry well *asteras*, computed by *pyBacktrack* in three
 479 backstripping configurations overlaid on a single panel: (a) no sea level and no dynamic
 480 topography (grey); (b) Haq2024 long-term sea level only (blue); (c) Haq2024 sea level
 481 together with the D10_gmcm9 dynamic-topography model of Braz et al. (2021) (red). Shaded
 482 bands: min/max envelope implied by the paleo-water-depth uncertainty range in the well file.
 483 Markers: the twenty stratigraphic horizons at which the well is defined. Y-axis auto-scaled to
 484 the deepest envelope (positive-down); the top of the axis extends a small distance above
 485 present-day sea level so the configurations that briefly cross above zero in early history are
 486 not clipped.

487 The well displays the characteristic two-stage subsidence pattern of a rifted passive margin: a
 488 rapid early phase in the Jurassic-Early Cretaceous and a more gradual post-rift thermal
 489 subsidence from the Late Cretaceous onward. The comparison between configurations (a), (b)
 490 and (c) shows that the eustatic correction has only a minor effect on the inferred tectonic
 491 subsidence (a few tens of metres over the well record), while the D10_gmcm9 dynamic-
 492 topography correction shifts the inferred subsidence by several hundred metres across the
 493 Cretaceous-Cenozoic interval where the model has its largest amplitude at this latitude. The
 494 width of the envelope is narrowest in well intervals constrained by shallow-shelf benthic
 495 assemblages and widest in the mid- to outer-shelf clay-dominated intervals - a direct
 496 visualisation of the most important uncertainty in 1D backstripping.

497 **4.8 Geohistory analysis at the featured well**

498 **Geohistory** or "**Wheeler**" diagrams visualise the through-time configuration of the sediment
 499 column relative to sea level, the sea floor and the basement. *PyBacktrack* returns, at each unit
 500 boundary, the decompacted thickness of every stratigraphic unit and the inferred water depth;
 501 we combine these to draw stacked, time-dependent stratigraphic units between the basement
 502 (tectonic subsidence) and the sea floor, following the structure of the bundled
 503 `'geohistory_analysis.ipynb'` notebook. The diagram is plotted in the standard geological
 504 positive-up sign convention: sea-level highstands plot above the zero datum, sea-floor and
 505 basement plot below it, and the dynamic-topography anomaly is shown relative to present.



506

507 **Figure 8.** Geohistory analysis of the featured well *asteras*. Coloured polygons show the
 508 decompacted thicknesses of the twenty individual stratigraphic units stacked downward from
 509 the time-dependent sea floor (royal-blue solid line). The dashed dark-blue line shows the
 510 Haq2024 long-term sea-level curve; the red line shows the basement (tectonic-subsidence)
 511 elevation; the dotted orange line shows the D10_gmcm9 dynamic-topography elevation
 512 anomaly relative to present (Braz et al., 2021).

513 The geohistory diagram resolves the slow Cretaceous sedimentation episode and the relatively
 514 rapid Cenozoic carbonate-platform accumulation, with the sediment column thickening to
 515 modern values during the Neogene drowning of the shelf. The combined representation of sea-
 516 level curve, sea floor, basement and dynamic-topography anomaly makes the role of relative
 517 sea level in driving facies changes immediately legible, a feature that is particularly useful for
 518 teaching and outreach.

519 4.9 Gridded NW Shelf tectonic-subsidence rates

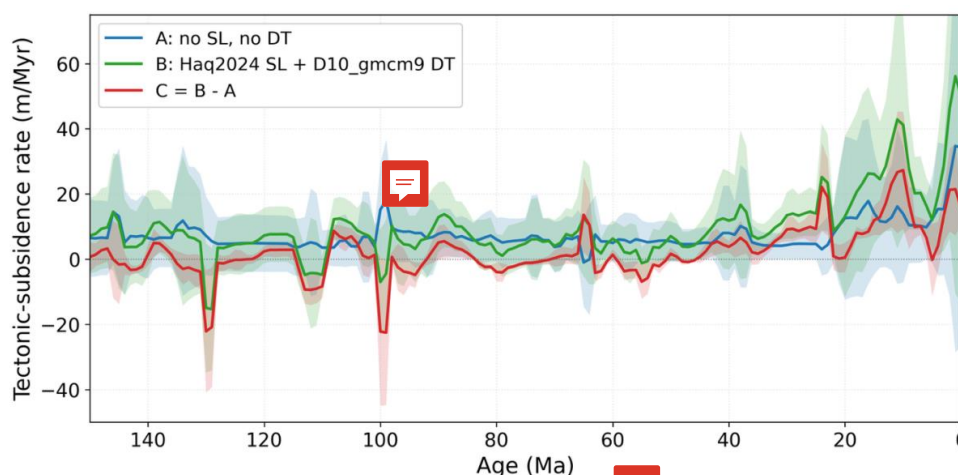
520 Generalising the one-dimensional workflow to all 109 NW Shelf wells lets us interpolate the
 521 inferred tectonic subsidence at any time slice into a margin-scale grid. To isolate the **rate** at
 522 which subsidence is accumulating, rather than its cumulative amount, we differentiate the per-
 523 well subsidence time-series with a forward 1 Myr finite difference and grid the resulting rate
 524 field. We do this in two configurations: (A) no sea level and no dynamic topography; and (B)
 525 the Haq2024 long-term hybrid sea level together with the D10_gmcm9 dynamic-topography
 526 model (Braz et al., 2021). The difference between the two rate fields quantifies how much of
 527 the apparent subsidence rate is absorbed by the combined eustatic + dynamic-topographic
 528 corrections.

529 At each time slice we grid the (lon, lat, rate) point cloud with the GMT *surface* algorithm under
 530 a tension of 0.5 (a balanced compromise between the pure minimum-curvature spline at T=0
 531 and the pure harmonic solution at T=1) and clip the result with a concave-hull (alpha-shape)
 532 mask of the 109 well locations, dilated by 80 km, so that no extrapolation into the deep ocean
 533 or far into the Australian craton is produced. The well population thins back through time (109
 534 wells at 50 Ma, 107 at 100 Ma, 68 at 200 Ma); we only generate grids for time slices where at
 535 least 10 wells contribute and the contributing wells span at least 3 degrees in longitude and



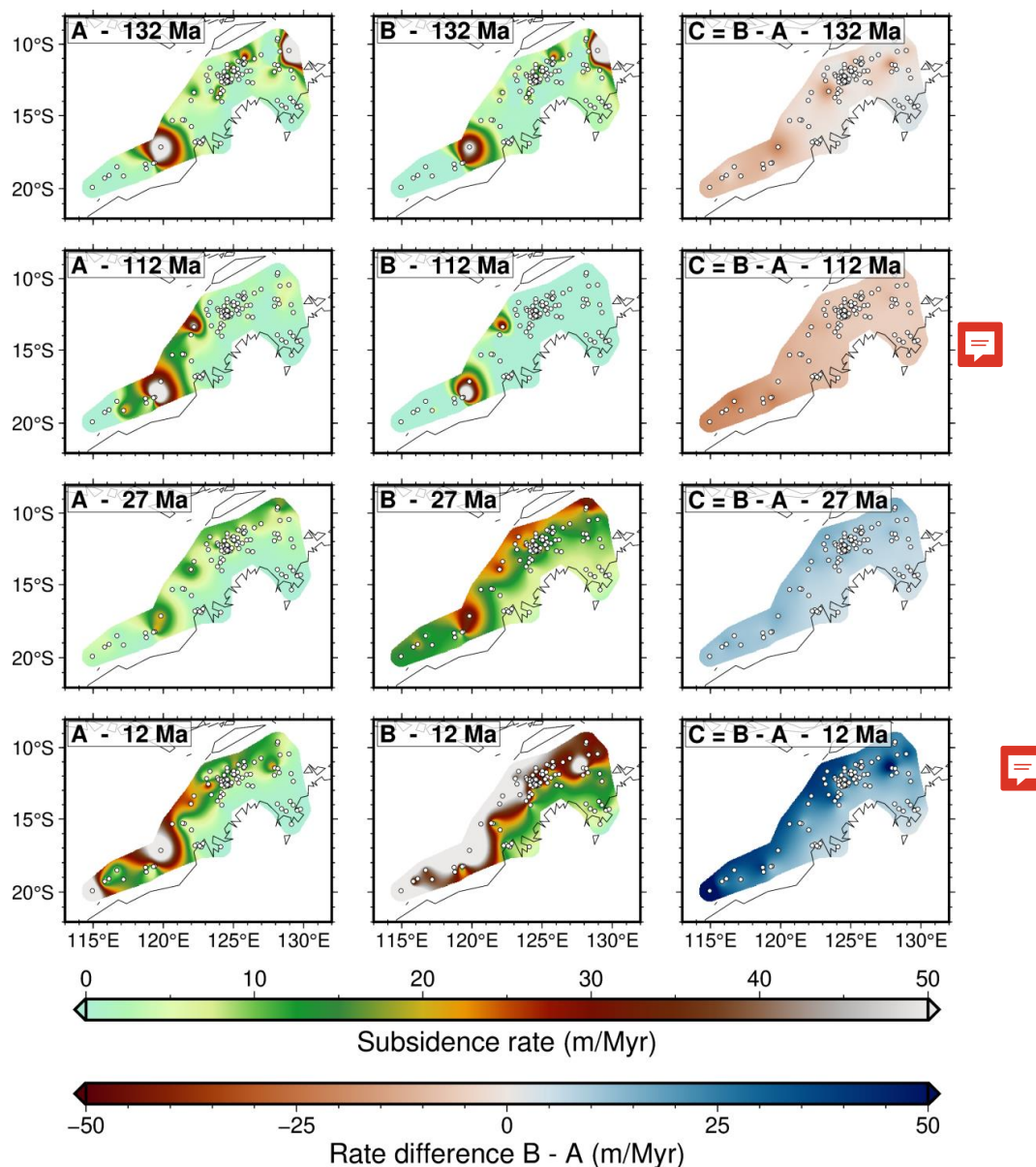
latitude. The oldest time based on this criterion is written by the workflow into
 'cutoff_time_Ma.txt'; the panels below are automatically clipped to this cutoff. The full
 workflow is implemented in 'figures/scripts/07a_backstrip_all_nwshelf.py'.

A compact summary of the margin-scale rate behaviour is obtained by reducing the per-well
 rate point clouds to a time series of mean $\pm$ one standard deviation across the contributing
 wells at every 1 Myr time slice (Fig. 9). Plotting both configurations on a single axis makes the
 magnitude of the eustatic + dynamic-topographic correction immediately visible as the
 displacement between the two mean curves; the shaded bands show the spread of subsidence-
 rate values across the NW Shelf at each Myr.



545

Figure 9. Northwest Shelf tectonic-subsidence rate time series: across-well mean (solid line)
 $\pm$ 1 standard deviation (shaded band) at every 1 Myr time slice for which at least 15 wells
 contribute, for configuration A (no sea level, no dynamic topography; blue), configuration C
 (Haq2024 long-term sea level + D10_gmcm9 dynamic topography, Braz et al., 2021; red) and
 the difference rate $D = rate_A - rate_C$ (green). Dashed grey line: zero rate (uplift above,
 subsidence below).



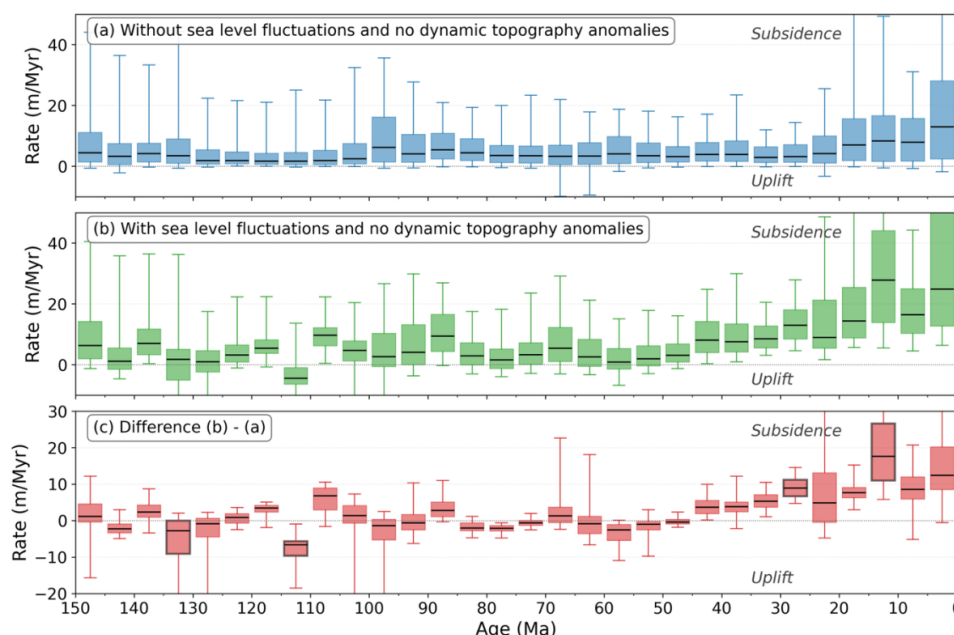
552

553 **Figure 10.** Combined NW Shelf tectonic-subsidence rate fields at four selected 5 Myr intervals
 554 highlighted in Fig. 11(c) (centres 12, 27, 112 and 132 Ma) at which differences between
 555 tectonic subsidence rate without (A) and with (B) sea level and dynamic topography correction
 556 are maximised. Columns: (A) no sea level, no dynamic topography; (B) Haq2024 long-term
 557 hybrid sea level plus D10_gmcm9 dynamic topography (Braz et al., 2021); (C = B - A) the
 558 difference field. In column C, positive values (blue) denote excess subsidence introduced by
 559 the sea level and dynamic topography correction and negative values (warm) denote excess
 560 uplift. White-filled circles on every panel mark the 109 well locations. The rate field is



561 interpolated with GMT `surface` (tension 0.5) and clipped to a concave-hull mask of the well
 562 distribution, extended by 80 km to create a buffer around the well data coverage.

563



564

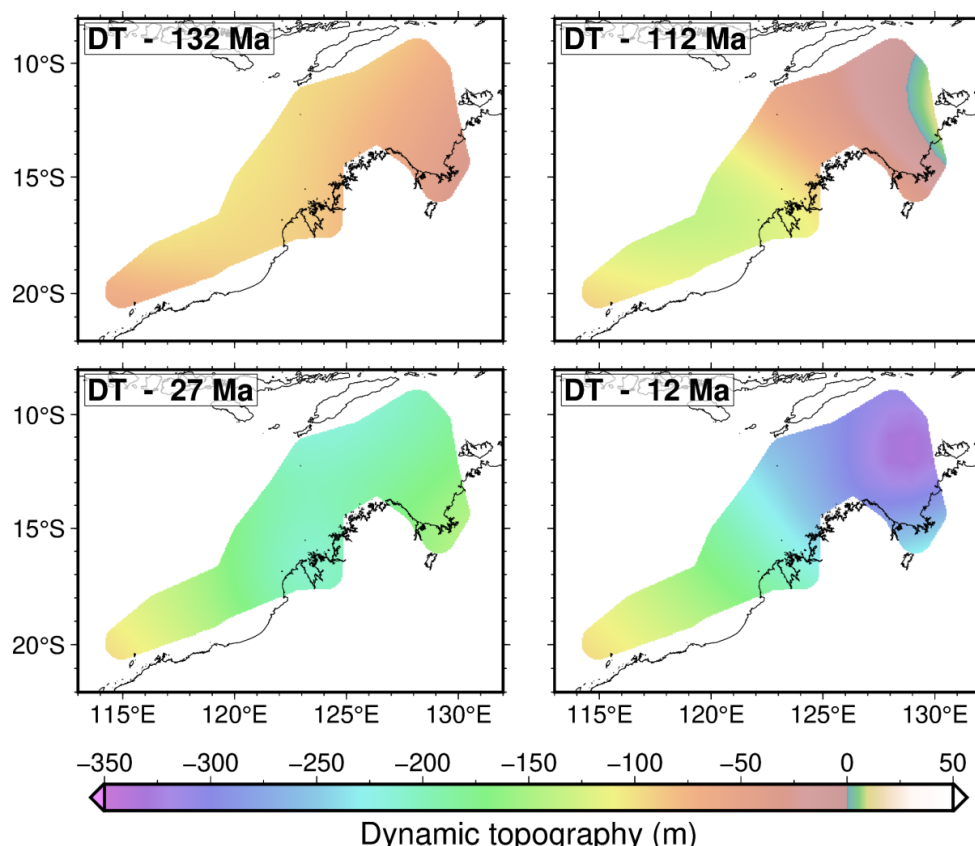
565 **Figure 11.** NW Shelf tectonic-subsidence rate distribution through time, summarised as box
 566 plots at 5 Myr intervals. Three stacked panels: (a) configuration A (no SL, no DT); (b)
 567 configuration B (Haq2024 long-term hybrid sea level plus D10_gmcm9 dynamic topography,
 568 Braz et al., 2021); (c) the difference $C = B - A$. Each box pools every 1 Myr rate grid whose
 569 age falls inside the 5 Myr window, so each summarises spatial and within-interval temporal
 570 variability simultaneously. Box = inter-quartile range, central line = median, whiskers = 5th-
 571 95th percentile. The four boxes in panel (c) with thicker black edges (10-15, 25-30, 110-115
 572 and 130-135 Ma) mark the five-Myr intervals with the largest mean $|C|$; their middle ages (12,
 573 27, 112 and 132 Ma) are mapped in Figs. 10 and 12. Sign convention: positive = subsiding,
 574 negative = uplifting.

575 The combined rate-field matrix and box plots (Figs. 10, 11) make the spatial pattern of the
 576 D10_gmcm9 dynamic-topography signal at the NW Shelf (Fig. 12) directly comparable to the
 577 well-based rate-difference field. The box-plot summary in Fig. 11 quantifies how the entire
 578 spatial distribution of the rate shifts when the SL + DT correction is applied, and identifies four
 579 5 Myr intervals -- 10-15, 25-30, 110-115 and 130-135 Ma -- where this shift is largest (thicker-
 580 edged boxes in panel c). Each interval is mapped in Fig. 10 at its middle integer age (12, 27,
 581 112 and 132 Ma), and the same four times are revisited in Fig. 12 to compare with the
 582 underlying DT field. Animations at 1 Myr resolution for the rate fields are produced by
 583 `10a\_make\_subsidence\_videos.py` and are distributed alongside the paper.

584 4.10 Dynamic-topography



585 The tectonic subsidence difference field (Fig. 10, right column) shows how the modelled
 586 subsidence rate is altered when imposing combined sea-level and dynamic-topography
 587 correction at each pixel and each selected time, but the spatial structure is filtered through the
 588 distribution of the 109 NW Shelf wells. To complement this with a view that depends only on
 589 the dynamic-topography model itself, Fig. 12 plots the raw bundled D10_gmcm9 elevation
 590 anomaly (Braz et al., 2021) over the same NW Shelf region and at the same four selected times.



591

592 *Figure 12. PyBacktrack-bundled D10_gmcm9 dynamic-topography elevation anomaly (Braz*
 593 *et al., 2021) over the NW Shelf at the same four times picked for Fig. 10: 12, 27, 112 and 132*
 594 *Ma (top-left, top-right, bottom-left, bottom-right). Positive values (warm) denote locations that*
 595 *were higher than today (uplifted relative to present); negative values (cool) denote locations*
 596 *that were lower than today. The bundled 5 Myr DT grids are linearly interpolated in time and*
 597 *up-sampled to 0.05 deg through GMT 'blockmedian' -> 'surface' (tension 0.5), the same*
 598 *workflow used as for the well-based rate fields of Fig. 10. The same concave-hull mask of the*
 599 *109 well locations is applied so the spatial footprint matches Fig. 10.*

600 The dynamic topography fields are uniformly negative across the bulk of the NW Shelf,
 601 reflecting that the region is placed over a long-lived mantle downwelling, particularly in the
 602 last 100 Ma (Fig. 12). The amplitude and spatial extent of this negative anomaly migrate
 603 northeastward through the Cretaceous and intensify during the Cenozoic, consistent with
 604 Australia moving towards a subduction-related downwelling province.



605 5 Discussion

606 5.1 NW Shelf subsidence-rate variability and competing causes

607 The pyBacktrack 1.5 workflow lets us compare two alternative reconstructions of tectonic
 608 subsidence at the same well: configuration A, which ignores eustatic sea-level fluctuations and
 609 dynamic topography, and configuration B, which applies the Haq2024 long-term hybrid sea-
 610 level curve and the D10_gmcm9 dynamic-topography model (Braz et al., 2021). Each
 611 reconstruction is a model with its own shortcomings. On the one hand we know that long-term
 612 eustatic sea-level fluctuations and mantle-driven dynamic topography demonstrably influence
 613 shelf-scale paleo-water depths through time (Müller et al., 2008; Spasojevic and Gurnis, 2012;
 614 Haq and Ogg, 2024), so omitting them must introduce bias into the inferred tectonic
 615 subsidence. On the other hand the sea-level curve and the dynamic-topography model are
 616 themselves uncertain: eustatic reconstructions disagree on both amplitude and timing, and
 617 global mantle-flow models differ in their NW Shelf signature depending on assumed mantle
 618 viscosity structure, plate-motion history and initial condition. Configuration B is therefore not
 619 automatically the better estimate; if either correction is locally wrong, applying it adds noise
 620 rather than removing it.

621 Rather than attempt a full evaluation here, we ask a narrower, more tractable question: at the
 622 times when the sea level and dynamic topography correction has its largest effect on the
 623 inferred tectonic-subsidence rate on the NW Shelf, do independent geological constraints
 624 provide reasonable grounds to believe that configuration B is closer to the truth than
 625 configuration A? Ranking the 30 five-Myr intervals across 0-150 Ma by the spatial mean of
 626 the tectonic subsidence difference $|C| = |\text{rate}_B - \text{rate}_A|$, with a 15 Myr non-maximum
 627 suppression to avoid clustering in time, selects four intervals with rather different fingerprints
 628 in the Miocene, Oligocene and Cretaceous, highlighted as thicker-edged boxes in Fig. 11c.
 629 Their middle integer ages (12, 27, 112 and 132 Ma) are mapped in Figs. 10 and 12. The middle-
 630 Miocene interval dominates the ranking by a factor of 2-3 over the other three; the two Early
 631 Cretaceous intervals have comparable spatial means but very different spreads, which itself is
 632 diagnostic, as discussed below. We examine each interval in turn.

633 The 10-15 Ma interval (middle Miocene) has by far the largest mean $|C|$ of the four (21.4 m/Myr
 634 -- more than twice the next-largest interval) and the highest IQR (16 m/Myr). Geologically, it
 635 coincides with foreland-style flexural loading driven by the collision of Australia with the
 636 Banda Arc and Timor (Müller et al., 2000; Cunneen et al., 2003; Harrowfield and Keep, 2005;
 637 Grahame and Cole, 2021). Broad-amplitude basement subsidence up to ~500 m has been
 638 documented inboard of the **Timor Trough, propagating into the Roebuck, Browse, Vulcan and**
 639 **Argo-margin domains**. Independently, Czarnota et al. (2013) document a regional pulse of
 640 accelerated subsidence near 9 Ma that they attribute to mantle convective drawdown, and
 641 Makuluni et al. (2022) and Young et al. (2020) link this Cenozoic acceleration to Australia's
 642 transit from an upwelling province to a subduction-related downwelling province above the
 643 southwest-Pacific slab system. Both flexural loading and mantle drawdown predict the kind
 644 of long-wavelength tectonic-subsidence anomaly that the D10_gmcm9 correction in
 645 configuration B explicitly removes. That a margin-wide ~20 m/Myr signal is large, regionally
 646 coherent (high IQR, comparatively low maximum-to-mean ratio of ~4-5) and aligned with two
 647 converging independent lines of evidence makes the middle Miocene the strongest a priori case
 648 for configuration B being closer to the true tectonic subsidence than configuration A.

649 The 25-30 Ma (latest Oligocene) interval has a mean $|C|$ of 9.3 m/Myr, max $|C|$ of 45 m/Myr
 650 and IQR of only 5 m/Myr -- a smaller-amplitude but still spatially organised signal. It coincides
 651 with the early stages of Australia's continental-scale tilt above the long-lived south-west Pacific



652 slab system (Müller et al., 2018; Makuluni et al., 2022; Young et al., 2020), a long-wavelength,
 653 low-frequency mantle-flow signal that drives gentle shelf-scale subsidence in the Northern
 654 Carnarvon Basin. The mantle-flow signature at this latitude in the D10_gmcm9 model has the
 655 appropriate sign and amplitude to capture this signal (Fig. 12, top-right panel). The supporting
 656 evidence is less pronounced than for the middle Miocene flexural-plus-drawdown case and the
 657 amplitude of the correction is smaller, but the consistency between the predicted continental-
 658 tilting direction and the D10_gmcm9 DT field offers reasonable grounds that configuration B
 659 is preferable here too.

660 The 110-115 Ma interval (Aptian) has the smallest IQR of the four (4 m/Myr) and the lowest
 661 max $|C|$ (43 m/Myr) -- a flat, spatially uniform, low-amplitude signal. Geologically, Aptian-
 662 Albian to Cenomanian post-rift sequences in the Northern Carnarvon Basin are generally
 663 interpreted as a passive-margin succession of marine flooding, condensation, open-ocean
 664 circulation and thermal subsidence (Winata et al., 2023), with no compelling independent
 665 evidence for a discrete tectonic uplift pulse at ~110 Ma. The spatially uniform, low-IQR
 666 fingerprint is consistent with the absence of any distinct event: the modest mean $|C|$ here is
 667 most plausibly the residue of long-wavelength differences between the SL and DT model
 668 outputs themselves rather than evidence of a real tectonic correction. In this interval neither
 669 configuration is strongly supported by external data and we cannot judge which is closer to the
 670 truth. This is the weakest of the four cases.

671 The 130-135 Ma (Hauterivian-Valanginian) interval has a mean $|C|$ of 7.6 m/Myr but a max $|C|$
 672 of 94 m/Myr -- a maximum-to-mean ratio above 12, indicating that the signal is carried by
 673 isolated spikes rather than a regionally coherent trend. The IQR is intermediate (9 m/Myr).
 674 This statistical fingerprint matches the geological evidence remarkably well. Recent seismic-
 675 stratigraphic and burial-history work identifies multiple Early Cretaceous unconformities on
 676 the **Gascoyne-Cuvier margin** and the Northern Carnarvon Basin -- an intra-Valanginian
 677 unconformity at 134.98-133.74 Ma, a top-Valanginian unconformity at ~134-133 Ma, and an
 678 intra-Hauterivian unconformity at ~132.5-131 Ma (Reeve et al., 2022) -- and Valanginian uplift
 679 in the southern Exmouth Sub-basin beneath the KV seismic event (Longley et al., 2002).
 680 Independent compaction and vitrinite-reflectance modelling indicates removal of up to ~800
 681 m of section from the flanks of the **Exmouth, Barrow and Dampier** sub-basins, attributed to
 682 depth-dependent extension and magmatic intrusion during the final stages of breakup between
 683 Australia and Greater India (Makuluni et al., 2024). These events fall directly within our 130-
 684 135 Ma box-plot interval, but they are intrinsically spatially heterogeneous: rift-flank uplifts
 685 vary at the structural-block scale, not at the long-wavelength scale at which dynamic-
 686 topography corrections operate (Reeve et al., 2022). The high-max, low-mean signature in Fig.
 687 11(c) is therefore exactly what we would expect if the 132 Ma signal is a real but block-scale
 688 tectonic phenomenon that the long-wavelength dynamic topography correction cannot resolve.
 689 At face value the choice between A and B is therefore more difficult to defend than for the
 690 Cenozoic intervals, although the spatial-statistical fingerprint helps with highlighting the
 691 underlying mechanism for observed tectonic subsidence anomalies at this time.

692 Taken together, the four largest-difference intervals span the full spectrum of confidence: a
 693 strong case for configuration B at 10-15 Ma (consistent independent evidence for both flexural
 694 loading and mantle drawdown); a reasonable case at 27 Ma (consistent with continental-tilting
 695 evidence at lower confidence); an unclear case at 112 Ma (no compelling independent evidence
 696 either way). and a weak case at 132 Ma (real but spatially heterogeneous rift-flank uplift not
 697 captured by long-wavelength DT models). The pyBacktrack 1.5 workflow is built to make this
 698 kind of honest comparison straightforward: producing the side-by-side A vs B time series,
 699 gridded rate fields and per-interval box-plot summaries takes minutes, and Fig. 11(c) localises
 700 the intervals where the question matters most.



701 5.2 Limitations and recommendations

702 Several limitations remain. PyBacktrack only generates paleobathymetry for crust that is
 703 preserved at present day; reconstructions of subducted crust must continue to be drawn from
 704 an external workflow and merged at output time. Continental subsidence is modelled with a
 705 single, uniform lithospheric stretching model that does not capture lithospheric heterogeneity,
 706 multiple rift episodes within a single basin, or the contribution of magmatic underplating. The
 707 dynamic-topography contribution remains uncertain at the few-hundred-metre level (Hoggard
 708 et al., 2017; Müller et al., 2018; Cao et al., 2019); the bundle of eight global models in
 709 pyBacktrack permits the user to characterise this uncertainty. The default lithology assumed in
 710 the paleobathymetry gridding workflow is 'Average_ocean_floor_sediment', which is
 711 appropriate for most of the open ocean but biases the decompacted thicknesses on shelves
 712 dominated by carbonate facies. Users requiring regional fidelity in those settings should
 713 override the default with the '-b' option or use a regional rift-grid file with locally appropriate
 714 lithology choices.

715 PyBacktrack 1.5 also makes more visible an issue that has long been implicit in 1D
 716 backtracking: the choice of dynamic-topography model can systematically shift paleo-water
 717 depths by several hundred metres. We recommend that users always compute their backtracked
 718 or backstripped results with at least two different dynamic-topography models from the eight
 719 bundled with pyBacktrack and report the resulting range as an additional source of uncertainty.
 720 Dynamic topography model-specific time limits are documented in the pyBacktrack reference
 721 documentation. All eight dynamic-topography models bundled with pyBacktrack, together
 722 with a growing library of additional published DT and plate-tectonic data sets, can be browsed
 723 interactively in 3D and downloaded from the GPlates Portal at <https://portal.gplates.org>
 724 (Müller et al., 2016a), so users can explore the model fields visually before choosing which to
 725 apply in pyBacktrack.

726 5.3 Current state and future development

727 PyBacktrack 1.5 represents a substantial generalisation of the original 1.0 tool from a one-
 728 dimensional drill-site backtracker to an integrated one- and two-dimensional paleobathymetry
 729 workflow. The new paleobathymetry gridding capability allows pyBacktrack to be used
 730 directly as a boundary-condition generator for climate, biogeographic and sedimentary-system
 731 models. The migration to Python 3 and to a multi-channel distribution (PyPI, conda-forge,
 732 Docker) lowers the barrier to use, and the move to a globally complete set of rift grids removes
 733 a common source of frustration when applying the package to user-supplied age or sediment-
 734 thickness grids.

735 Future development of pyBacktrack will focus on three areas: (i) incorporation of a workflow
 736 for generating paleobathymetry for now subducted crust; and (ii) introduction of probabilistic
 737 uncertainty propagation, so that the paleobathymetry grids carry per-grid-point uncertainty
 738 estimates derived from the uncertainties in the input present-day grids, the chosen subsidence
 739 model and the chosen dynamic-topography model.

740 6 Conclusions

741 PyBacktrack 1.5 is a major revision of the original pyBacktrack 1.0 community tool for
 742 reconstructing paleobathymetry on oceanic and continental crust. The package has been
 743 migrated to Python 3 and is now distributed via PyPI, conda-forge and Docker. The most
 744 significant scientific addition is the 'paleo_bathymetry' gridding module, which reconstructs
 745 and backtracks every present-day submerged grid point to produce time-dependent, two-
 746 dimensional paleobathymetry grids that can be optionally merged with externally produced



747 grids for now subducted ocean crust. Default models have been updated to reflect a decade of
 748 community progress: the RHCW18 oceanic age-to-depth relationship, the Seton et al. (2020)
 749 age grid, the Straume et al. (2019) GlobSed sediment thickness grid and the Zahirovic et al.
 750 (2022) deforming plate model. PyBacktrack 1.5 supports both the mantle and paleomagnetic
 751 reference frames, ships globally complete rift start/end-age grids, and includes an expanded
 752 library of sea-level curves and lithology entries.

753 **Code and data availability**

754 PyBacktrack version 1.5.0 is archived at Zenodo (Müller et al., 2026a;
 755 <https://doi.org/10.5281/zenodo.20809733>) under the GNU General Public License v2.0. The
 756 code, locally held input data and figure-generation workflow used to produce the results in
 757 this paper are archived at Zenodo (Müller et al., 2026b;
 758 <https://doi.org/10.5281/zenodo.20810168>). This reproducibility package includes the tagged
 759 companion applications repository, the 109 Australian North West Shelf well files, regional
 760 vertical-gravity-gradient and D10_gmcm9 dynamic-topography data, dependency
 761 specifications, and the exact palaeobathymetry grids used for Figs. 2–4. The archived grid set
 762 spans 0–170 Ma and is based on the Zahirovic et al. (2022) deforming plate model in the
 763 paleomagnetic reference frame (anchor plate 701701). Provenance, licences and citation
 764 requirements for included data are documented in the archive.

765 **Author contributions**

766 RDM conceived the project, supervised the development of pyBacktrack 1.5, designed the
 767 application examples and drafted the manuscript. JC led the software engineering, implemented
 768 the paleobathymetry gridding module, the rift gridding scripts and the migration to Python 3,
 769 and produced the bundled documentation. SW and NMW contributed to algorithm design, and
 770 AD curated the lithology library. All authors contributed to interpretation and revision of the
 771 manuscript.

772 **Competing interests**

773 The authors declare that they have no competing interests.

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