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iceHIST v1.0: a cosmogenic-nuclide model suite for testing glacier and ice-sheet histories

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Abstract. Cosmogenic-nuclide inventories in glaciated landscapes record changes in glaciers or ice sheets, and other surface processes. Scenario-based models can extract glacier and ice-sheet history information from these inventories, but many approaches remain specialised to a single site, data type, scenario structure, or inference method. Here I present iceHIST v1.0, a model suite for testing hypotheses about glacier and ice-sheet history using in situ 10Be, 14C and/or 26Al. iceHIST supports depth profiles (e.g. bedrock cores), surface samples as transects (vertical or horizontal), and combined core-plus-transect datasets, including modern subaerial and subglacial samples. Four scenario families define the tested histories: OneStage, DynamicPeriods, TimeSeries and IceSurface. These scenarios encompass simple cover histories, repeated exposure and burial intervals, thresholded time-series histories, and explicit or imported ice-surface histories. For each scenario, a common forward model integrates nuclide production over depth and time, accounts for radioactive decay, ice cover, and sample thickness, and includes options for snow shielding, subaerial and subglacial erosion, and inherited inventories. Model predictions are compared with data using Monte Carlo screening, Markov chain Monte Carlo (MCMC) posterior exploration, or likelihood weighting of fixed imported histories. Synthetic demonstrations illustrate surface and depth-profile recovery, time-series threshold recovery, thinner-than-present lowstand testing, a Monte Carlo-to-MCMC workflow, and ranking of imported ensemble histories. Applied in this manner, iceHIST can determine how long glaciers were larger or smaller than today, whether ice sheets thinned below current levels and subsequently re-thickened, and identify which glacier or ice-sheet simulations best match cosmogenic-nuclide observations.

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1 Introduction

1.1 Cosmogenic nuclides as integrated records of glacier and ice-sheet history

Cosmogenic-nuclide measurements provide direct geological constraints on past glacier and ice-sheet change. These nuclides, produced in near-surface minerals, record whether rock has been exposed to cosmic rays, shielded from them, buried long enough for radioactive decay, or affected by erosion and exhumation. Surface-exposure dating is the simplest and most widely used application of this concept (Gosse and Phillips, 2001; Lal, 1991), and has generated large datasets on glacier and ice-sheet change from glaciated landscapes worldwide. These datasets are valuable because glaciers and ice sheets are sensitive to temperature, precipitation, ice dynamics and sea level, and because their former extents provide geological tests of palaeoclimate and ice-sheet behaviour (Balco, 2020; Schaefer et al., 2022). However, the concentration measured in any sample is controlled by production, shielding, decay and denudation, rather than exposure duration alone. The same production-depth and decay systematics also allow cosmogenic data to record longer-term ice-cover frequency, ice-thickness variability along elevation transects and subsurface residence during erosion, but only when these processes are modelled explicitly (Balco, 2017; Halberstadt et al., 2023; Heisinger et al., 2002a, b; Nishiizumi et al., 1991; Spector et al., 2020).

This distinction is particularly important in glaciated landscapes. Ice can quarry fresh rock and reset cosmogenic inventories, but it can also shield surfaces without eroding them, thereby preserving nuclides inherited from earlier exposure (Balco, 2020). Snow, till, sediment and thin ice can reduce production without fully preventing it, while subaerial or subglacial erosion can remove high-concentration surface material and expose material with a different irradiation history. Apparent exposure ages can therefore differ from the timing of glacier retreat, moraine stabilisation, ice thinning or bedrock exposure.

The resulting non-uniqueness is central to cosmogenic-nuclide interpretation. A low concentration may reflect short exposure, long burial, thick cover, rapid erosion, or a small inherited inventory; a high

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concentration may reflect prolonged exposure, inheritance preserved beneath non-erosive ice, thin cover, or exhumation of previously irradiated material. Multi-nuclide measurements help because different nuclides retain different parts of the history. Long-lived ^{10}Be and ^{26}Al preserve cumulative exposure and inheritance over long timescales, whereas in situ ^{14}C, with its short half-life, is particularly sensitive to Holocene exposure, recent burial, and rapid changes in surface or ice-cover conditions (Balco, 2020; Goehring et al., 2011; Hippe, 2017; Schaefer et al., 2022).

These properties allow cosmogenic nuclides to address questions that are difficult to answer from landforms alone: how long glaciers were larger or smaller than present, whether ice sheets thinned below present and later re-thickened, whether bedrock was repeatedly exposed and buried or remained ice-free, how much erosion occurred beneath ice, and which climate or ice-sheet model histories are consistent with geological evidence. Answering these questions requires explicit comparison of measured concentrations with hypothesised histories. iceHIST aims to test which exposure, cover, burial, erosion and inheritance histories are consistent with the data, given defined assumptions.

1.2 Existing modelling approaches and the iceHIST gap

Previous studies have addressed parts of this interpretation problem through increasingly explicit cosmogenic-nuclide modelling. Geologically constrained Monte Carlo depth-profile models provided a practical way to propagate uncertainty in exposure duration, erosion rate and inherited concentration from concentration-depth data, while preserving the geological constraints needed to make such inversions meaningful (Hidy et al., 2010). Subsequent depth-profile applications and synthetic tests have shown that shallow bedrock profiles can contain substantially more information than surface samples alone, particularly where erosion is limited and inherited signals remain measurable (Andersen et al., 2024). These studies established depth-profile modelling as a useful framework for testing exposure, erosion and inheritance histories, but they were generally developed for specific sample arrangements, data modes and parameterisations.

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Other studies have used external climate, orbital, or ice-volume information to define candidate exposure-burial histories. Climate-based approaches have compared cosmogenic concentrations with glacier histories forced by palaeoclimate records, showing that ^{10}Be and ^{14}C can help distinguish among Holocene glacier configurations where geomorphic evidence is incomplete (Goehring et al., 2011, 2012). Threshold-based models have similarly converted climate or benthic-isotope records into alternating exposure and burial histories, allowing the sensitivity of paired-nuclide data to ice cover, erosion, and inheritance to be evaluated over glacial-interglacial timescales (Andersen et al., 2024; Knudsen et al., 2015; Knudsen and Egholm, 2018). These approaches demonstrate the value of externally defined histories, but they also show that translating a driver record into a local exposure state must be treated as a hypothesis rather than a direct reconstruction.

A parallel modelling lineage has developed around explicit ice-surface histories. Elevation transects and nunatak datasets have been used to infer long-term ice-surface fluctuations, ice-cover frequency, and the compatibility of cosmogenic inventories with externally modelled ice-thickness histories (Andersen et al., 2025; Halberstadt et al., 2023; Jones et al., 2017). More recently, subglacial bedrock-core studies have used in situ ^{14}C, ^{10}Be and ^{26}Al to test whether ice was thinner than present and to reject null hypotheses in which samples remained continuously shielded by thick ice (Balco et al., 2023; Small et al., 2026). These studies demonstrate that cosmogenic data can test specific hypotheses about glacier and ice-sheet history, including reversible thinning and re-thickening beneath modern ice. However, the modelling workflows are commonly tailored to one site, one data mode or one class of history. In summary, the key need is an operational framework that brings existing modelling concepts into a common, reproducible workflow.

1.3 Paper objectives

In this paper, I describe iceHIST v1.0, a Matlab-based model suite for testing hypotheses about glacier and ice-sheet history using in situ cosmogenic ^{10}Be, ^{14}C and/or ^{26}Al. iceHIST forward-models nuclide concentrations for specified histories of exposure, cover, burial, erosion and inheritance, while accounting for sample depth, thickness, elevation or position, density, and shielding. It serves as a

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hypothesis-testing framework rather than a tool for producing unique reconstructions when the data and assumptions do not support uniqueness.

This paper has four aims: 1) define the scope and workflow of iceHIST; 2) describe the OneStage, DynamicPeriods, TimeSeries and IceSurface scenario families; 3) outline the shared forward model, likelihood structure, and inference workflows; and 4) demonstrate the suite using synthetic and example experiments for surface and depth-profile recovery, threshold-derived histories, thinner-than-present lowstands, MC-to-MCMC inference, and ranking of an imported ice-surface ensemble.

2 Model suite overview

2.1 Scope, purpose and workflow

The full iceHIST workflow is summarised in Fig. 1. iceHIST forward-models in situ cosmogenic-nuclide concentrations for hypothesised glacier and ice-sheet histories, then evaluates whether those histories can explain measured inventories. The model treats concentrations as outcomes of explicit exposure, cover, burial, erosion, inheritance, ice-surface or climate-driver scenarios, rather than as direct estimates of a single event.

The suite supports three data modes: core mode for bedrock cores or other forms of depth profiles, transect mode for surface samples distributed across elevation or vertical/horizontal position relative to an ice margin, and core-plus-transect mode for testing one shared history against both data types. These modes can be applied to modern subaerial samples, subglacial samples or mixed datasets.

An iceHIST analysis begins with measured nuclide concentrations and sample metadata, together with optional external inputs such as climate or ice-volume time series, prescribed exposure-burial intervals, or imported ice-surface histories. The user then selects a scenario family, which defines how exposure, cover or ice-surface state varies through time. For each proposed history, the common forward model predicts cosmogenic ^{10}Be, ^{14}C and/or ^{26}Al concentrations by accounting for production, shielding,

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radioactive decay, erosion, inheritance, sample depth, thickness, elevation or position, density and shielding. Model-data fit is then evaluated using Monte Carlo screening, MCMC posterior exploration or likelihood weighting of imported fixed-history ensembles, depending on the scenario family and inference objective.

Standard outputs include predicted concentrations, residuals and likelihoods, accepted or posterior histories, parameter summaries, exposure and burial metrics, lowstand metrics where relevant, diagnostic plots and exported result files. These outputs are intended to support model-data comparison, uncertainty analysis and transparent reporting of compatible histories. They are not intended to provide an automated interpretation of glacier or ice-sheet behaviour without geological judgement and explicit assumptions.

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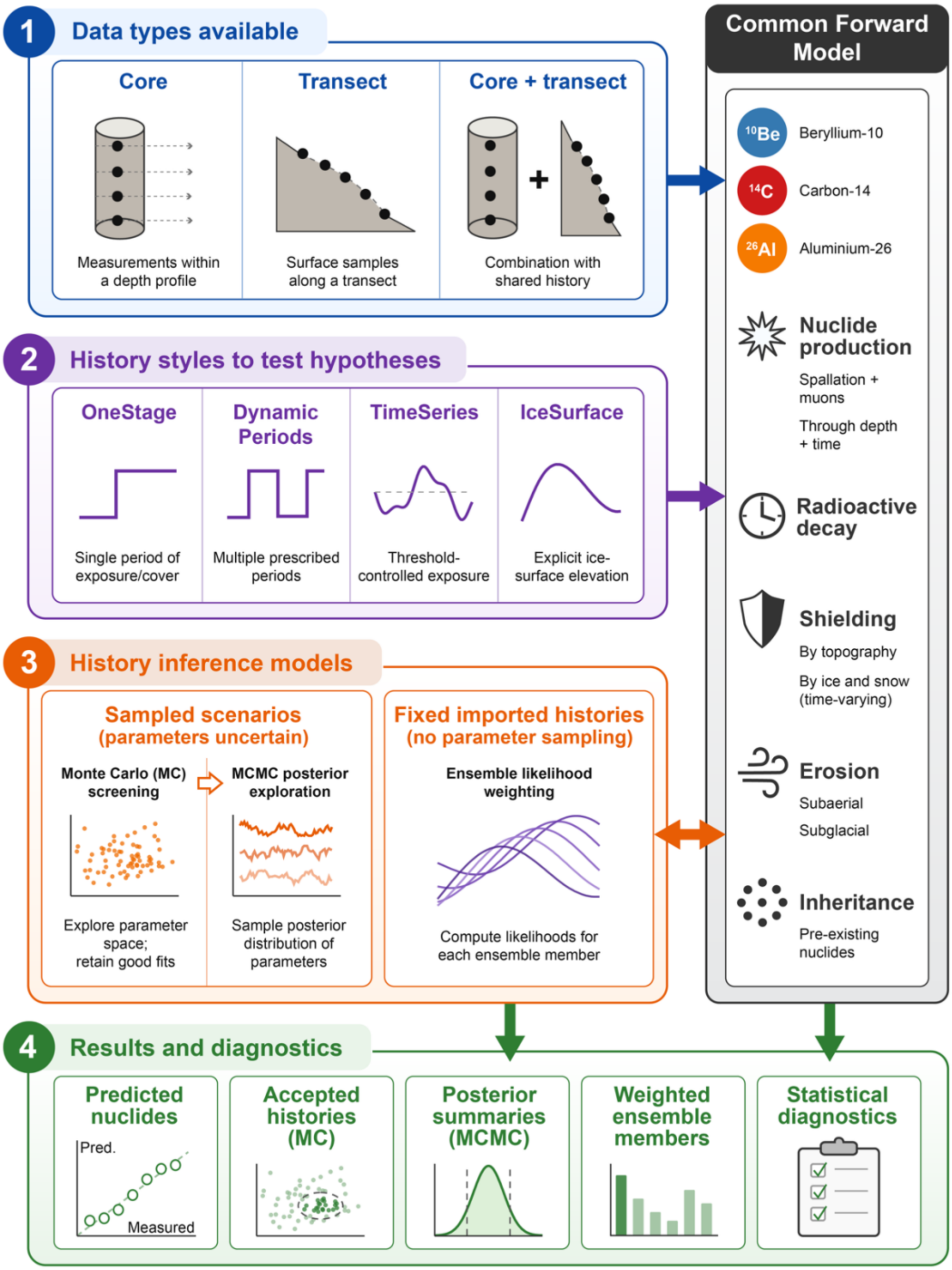

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Figure 1: iceHIST model-suite workflow. A user progresses from stages 1 to 4: 1) data inputs should be provided for a core (or other form of depth profile) and/or a transect of surface samples; 2) a model family representing different ice history styles should then be

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selected based on the hypothesis being tested (see Fig. 2); 3) an inference approach then need to be selected, which for most cases should be MC for parameter exploration before full MCMC posterior distribution assessment (the exception is a likelihood assessment of an imported ice surface ensemble); and 4) the user can then interpret the outputs from the forward model and inference models.

2.2 Model boundaries and design philosophy

iceHIST is a forward-modelling framework with Monte Carlo, MCMC and likelihood-weighting tools for cosmogenic-nuclide scenario inference. It does not invert cosmogenic-nuclide data for an unconstrained glacier or ice-sheet history, and it does not simulate ice dynamics. Instead, it predicts nuclide concentrations for user-defined, sampled, threshold-derived or imported histories, then evaluates which histories or parameter combinations are compatible with the measured data.

The suite is organised around four scenario families of increasing structural complexity. OneStage tests simple exposure, burial or cover histories; DynamicPeriods tests repeated exposure or burial windows with prescribed approximate timing; TimeSeries derives exposure or burial states from an external driver and sampled threshold; and IceSurface calculates sample-specific cover from time-varying ice-surface elevation. This hierarchy is a workflow guide, not a ranking of preferred explanations.

This hierarchy is intended as a modelling workflow rather than a ranking of preferred explanations. Simple scenario families provide useful null models and first-order tests, and more complex histories should only be used when required by the scientific question, sample arrangement, data mode or independent constraints. In practice, a typical analysis begins with broad Monte Carlo screening to identify whether a scenario family and parameter bounds can reproduce the data. MCMC posterior exploration should then be used where continuous parameters require formal uncertainty estimation and the model structure is already plausible. Imported ice-surface histories are treated differently: each history is evaluated as a fixed ensemble member and assigned a likelihood or relative weight, rather than being varied as a random-walk MCMC parameter set.

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This design separates the assumed glacier or ice-sheet history from the cosmogenic forward model and the statistical comparison with measured concentrations. The validity of any interpretation remains conditional on the production scheme, sample information, measurement uncertainties, parameter bounds, prior assumptions and geological plausibility of the tested histories.

2.3 Data modes, sample states and nuclide scope

iceHIST supports three primary data modes. Core mode represents bedrock cores, or other forms of depth profiles, in which samples occupy known top and bottom depths below a rock surface. This mode is designed for questions involving depth-dependent production, inherited nuclide inventories, erosion, burial, cover and lowstand exposure. Transect mode represents surface samples distributed across elevation, height relative to a common datum, or horizontal position (e.g. relative to a present ice margin). This mode is designed for questions involving ice-surface change, ice-cover frequency, thinning histories and spatially variable exposure or shielding. It should be noted that the intended surface samples here are in situ bedrock, as erratic samples (e.g. cobbles, boulders) may have moved during periods of ice cover; the nuclide inventory of a sample that has moved could reflect different nuclide production conditions and ice history, which cannot be reliably accounted for in a model. Core-plus-transect mode evaluates both data types under one shared history, providing a test of whether a single physically interpretable scenario can explain both the vertical concentration structure of a core and the spatial or elevation-dependent structure of a transect.

The meaning of a shared history depends on the scenario family. In OneStage, DynamicPeriods and TimeSeries scenarios, samples generally share an exposure, burial or cover-state history, while their predicted concentrations differ because of sample depth, elevation, shielding, thickness and nuclide-specific production and decay. In IceSurface scenarios, the shared quantity is instead an ice-surface history, from which sample-specific cover depths are calculated according to sample elevation or position. This distinction allows iceHIST to represent both depth-independent histories and geometrically explicit ice-surface histories without changing the common forward-model structure.

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The current sample-state logic covers samples exposed at the modern surface, samples currently buried beneath ice and mixed datasets containing both subaerial and subglacial samples. This distinction is important because modern sample state controls the recent exposure or shielding boundary condition and determines how the present-day exposure or shielding boundary condition is interpreted. In particular, modern subglacial samples can be evaluated without assuming present exposure, allowing iceHIST to test histories in which a surface was exposed during a thinner-than-present ice configuration and later reburied.

iceHIST v1.0 focuses on in situ ^{10}Be, ^{14}C and ^{26}Al in quartz-bearing samples. ^{10}Be records long-lived cumulative exposure and inheritance, ^{26}Al provides paired-nuclide burial information with ^{10}Be, and in situ ^{14}C is most sensitive to recent exposure, thin-cover production and Holocene or latest-Pleistocene burial (Fig. 3). Other cosmogenic systems, including ^{3}He, ^{21}Ne and ^{36}Cl, are treated here as future extensions.

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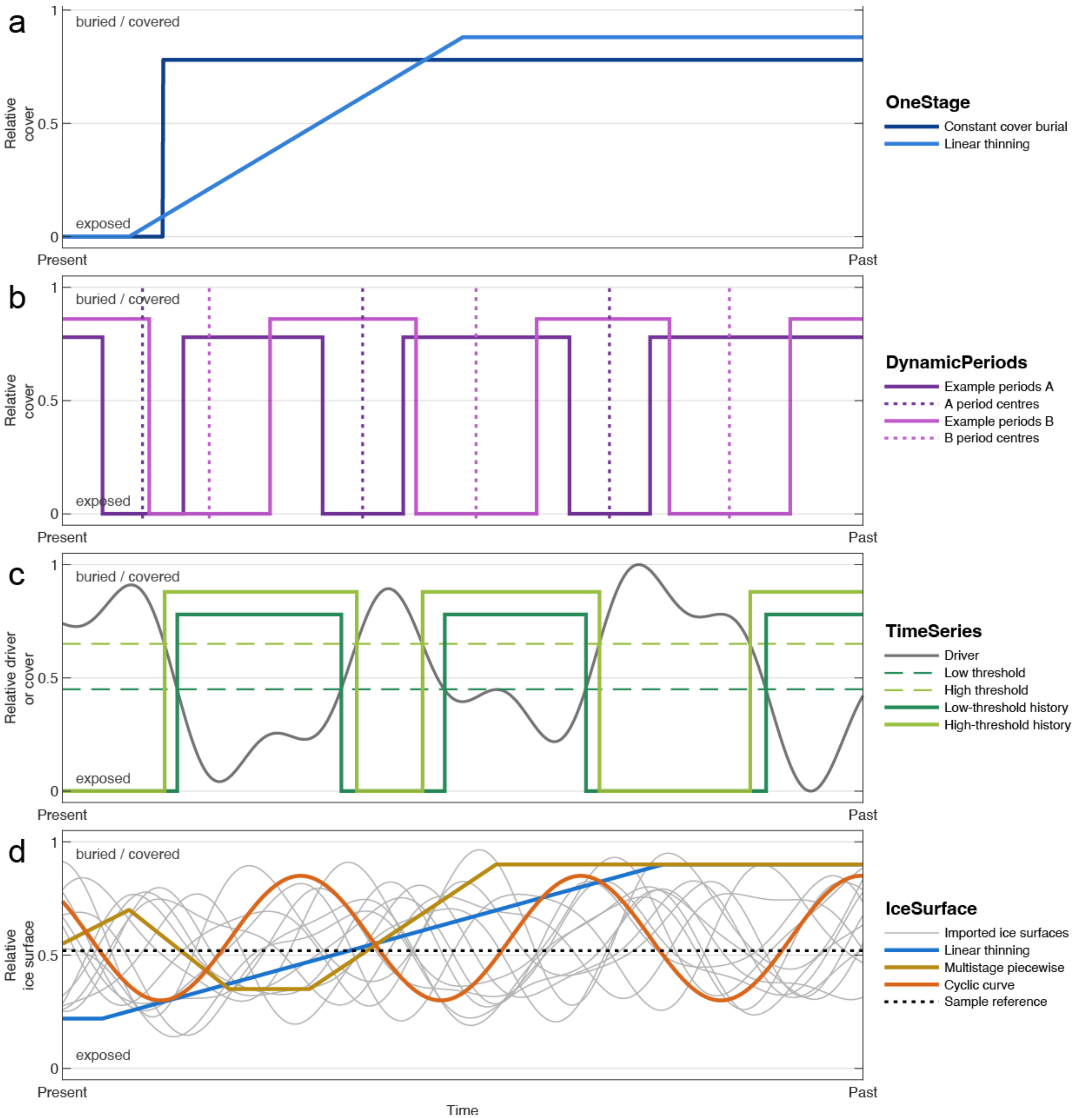

215 **Figure 2: Schematic overview of the model scenario families.** The examples show the forms of ice history available in the model suite. Relative cover or ice-surface index is schematic only, where lower values indicate exposed/no-cover conditions and higher values indicate burial or thicker cover. (a) OneStage scenarios represent simple depth-independent histories, here shown as constant-cover burial followed by exposure, and as linear thinning. (b) DynamicPeriods scenarios represent user-prescribed exposure or burial windows, with period

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durations varied between model iterations. (c) TimeSeries scenarios convert an external driver into exposure/burial histories by applying a threshold. (d) IceSurface scenarios use explicit ice-surface histories, including linear, multi-stage, cyclic and imported-ensemble examples, from which cover depth is calculated from ice-surface elevation relative to sample or site elevation.

3. Scenario families

3.1 Scenario-family hypothesis ladder and shared concepts

iceHIST represents glacier and ice-sheet histories through four scenario families: OneStage, DynamicPeriods, TimeSeries and IceSurface. These families define how exposure, burial, cover or ice-surface position changes through time before the common forward model calculates cosmogenic-nuclide concentrations. They form a hypothesis ladder from simple histories with few parameters to histories based on prescribed periods, external drivers or explicit ice-surface elevation (Fig. 2).

The key distinction is how cover is defined. OneStage, DynamicPeriods and TimeSeries prescribe a shared exposure, burial or cover-state history; samples differ in predicted concentration because of their depth, elevation or position, shielding, thickness, erosion and nuclide-specific production and decay. IceSurface instead calculates cover separately for each sample or site from the difference between ice-surface elevation and sample or site elevation. For bedrock cores, this cover calculation uses the core-top or bedrock-surface elevation, while the depth of each core interval is handled separately in the production calculation.

The hypothesis ladder is a workflow guide, not a rule that more complex models are preferable. Scenario choice should be reported as part of the tested hypothesis, together with parameter bounds, active nuclides, sample states, inference method and assumptions about erosion, inheritance and cover.

3.2 OneStage

OneStage is the minimum-complexity scenario family in iceHIST (Fig. 2a). It is designed to test whether a dataset can be explained by a simple exposure, burial or cover history before introducing

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repeated periods, external drivers or explicit ice-surface geometry. OneStage scenarios are therefore useful as baseline or null hypotheses: they ask whether the measured concentrations require a complex history, or whether they are already compatible with a small number of physically interpretable parameters.

In its constant-cover form, OneStage represents a single transition between exposed and covered conditions. During exposed intervals, samples accumulate cosmogenic nuclides according to their production rates, depths and shielding factors. During covered or buried intervals, production is reduced according to the specified cover thickness, and radioactive nuclides decay. This structure can be used to test simple hypotheses such as continuous exposure after deglaciation, burial after an earlier exposure interval, or a single lowstand followed by renewed cover.

OneStage also includes simple monotonic-cover options, such as linear thinning, where cover depth changes at a prescribed or sampled rate over a defined interval. In this mode, the thinning parameter represents a change in local cover depth rather than a fully resolved ice-surface history. It is therefore appropriate for first-order tests of gradual cover reduction, but not for questions that require sample-specific ice-surface geometry across an elevation transect. Those questions are better represented by the IceSurface family.

The parameters sampled in OneStage depend on the selected option, but can include the start time or transition time of the modelled history, the duration of exposure or burial, cover depth, thinning rate or thinning end time, snow depth, subaerial and subglacial erosion rates, and inherited nuclide inventories. The same scenario can be evaluated against core, transect or core-plus-transect datasets where a shared simple history is appropriate. A good fit should be interpreted as evidence that the data are compatible with the tested simple history, not as proof that the history was unique.

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3.3 DynamicPeriods

DynamicPeriods represents histories in which exposure and burial reoccur through a set of prescribed time windows (Fig. 2b). This family is designed for problems where independent geological, geomorphic or palaeoclimate information indicates the approximate timing of glacier advance, retreat, ice cover or exposure, but where the duration of each interval is uncertain. Rather than sampling a completely arbitrary time series, DynamicPeriods uses a structured history in which period midpoints are specified and interval durations are sampled within user-defined bounds.

A DynamicPeriods scenario is defined by a model start time, a sequence of period midpoints, duration bounds for each period, and the state assigned to those periods. The specified periods can represent exposure windows within an otherwise covered history, or burial windows within an otherwise exposed history, depending on the hypothesis being tested. Between these windows, the model fills the complementary state. This structure allows repeated exposure-burial histories to be tested while retaining a small and interpretable parameter set.

Additional parameters can be included to represent processes that affect nuclide inventories during and between periods. These include constant ice or cover depth during buried intervals, snow depth during exposed intervals where appropriate, subaerial and subglacial erosion rates, inherited nuclide concentrations and the initial state at the start of the modelled history. Because the timing framework is prescribed by the user, the sampled parameters mainly determine how long each exposure or burial window lasts, how strongly samples are shielded during cover, and how erosion or inheritance modifies the resulting concentrations.

In core mode, DynamicPeriods is useful for testing whether a depth profile can recover repeated exposure and burial intervals, and for evaluating trade-offs among exposure duration, erosion and inherited inventory. In transect and core-plus-transect modes, all samples share the same dynamic sequence; differences among predicted concentrations arise from sample elevation, depth, thickness, shielding, erosion and nuclide-specific production and decay, not from sample-specific ice-surface

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geometry. DynamicPeriods therefore provides an intermediate level of complexity between the simple histories in OneStage and the externally driven or geometrically explicit histories in TimeSeries and IceSurface.

A good DynamicPeriods fit indicates compatibility with the prescribed timing framework and sampled durations, not that the chosen period midpoints are uniquely required. DynamicPeriods is therefore most useful where the timing structure is independently motivated.

3.4 TimeSeries

TimeSeries represents histories in which exposure and burial states are derived from an external driver record (Fig. 2c). This family is designed for hypotheses in which local ice cover is assumed to vary systematically with a palaeoclimate, ice-volume or other time-dependent index, but where the threshold separating exposed and covered conditions is uncertain. Rather than prescribing individual exposure or burial windows, the model samples a threshold, start time and polarity, then converts the driver record into a binary exposure-cover history.

A TimeSeries input consists of time before present, driver value, a descriptive name, a short name and units. Potential drivers include benthic oxygen-isotope stacks, Antarctic or global ice-volume reconstructions, sea-surface temperature records, atmospheric temperature proxies or other time series that can be interpreted as a candidate control on local glacier or ice-sheet state. The polarity defines whether higher driver values correspond to exposure or cover. The threshold then determines when the site is treated as exposed and when it is treated as buried or shielded. This structure makes the driver-state relationship explicit and allows alternative thresholds or polarities to be tested as hypotheses.

In TimeSeries scenarios, the exposure-cover sequence is shared across the dataset. Core samples, transect samples and combined datasets therefore experience the same threshold-derived state history, but predicted concentrations differ because of sample depth, elevation or pressure, thickness, shielding, erosion, inheritance and nuclide-specific production and decay. The threshold is not calculated

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separately for each sample, and cover is not derived from an explicit ice-surface elevation. Where sample-specific cover histories are required, the IceSurface family is more appropriate.

The main parameters sampled in TimeSeries typically include the model start time, driver threshold, polarity, cover thickness during buried intervals, snow depth where represented, subaerial and subglacial erosion rates, and inherited nuclide inventories. These parameters allow the user to test whether a proposed relationship between an external driver and local exposure state can explain measured ^{10}Be, ^{14}C and ^{26}Al concentrations. TimeSeries is therefore useful for evaluating climate-threshold or ice-volume-threshold hypotheses, for comparing the information content of core and transect datasets, and for quantifying how strongly cosmogenic data constrain the driver threshold and derived exposure-burial metrics.

A successful TimeSeries fit supports compatibility with the specified driver-threshold hypothesis. It does not show that the external driver uniquely controlled local ice cover without independent support.

3.5 IceSurface

IceSurface represents histories in which cover is calculated from an explicit time-varying ice-surface elevation (Fig. 2d). Unlike OneStage, DynamicPeriods and TimeSeries, which prescribe a shared exposure–cover state, IceSurface converts an ice-surface history into a separate cover history for each sample. For sample i, the instantaneous ice-cover thickness is

$$h_{\mathrm{ice},i}(t) = \max\left[0, H(t) - z_{s,i}\right], \tag{1}$$

where $h_{\mathrm{ice},i}(t)$ is the ice thickness above sample i at time t, $H(t)$ is the modelled ice-surface elevation, and $z_{s,i}$ is the surface elevation associated with sample i. For surface or transect samples, $z_{s,i}$ is the sample elevation. For bedrock-core samples, $z_{s,i}$ is the core-top or bedrock-surface elevation; the depth of each sampled interval below the rock surface is treated separately in the production calculation. This

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distinction prevents overlying ice thickness from being conflated with rock mass depth within a core. All elevations must be expressed relative to the same vertical datum.

Equation (1) defines geometric ice-cover thickness, not an on/off production switch. In the default interpretation, the sample surface is geometrically exposed where $h_i(t) = 0$ and ice-covered where $h_i(t) > 0$; however, non-zero cover still permits attenuated production through the mass-depth term in Eq. (3). Thin ice or thin cover is therefore represented as reduced production rather than zero production.

Samples below the modelled ice surface are shielded by the resulting ice thickness, whereas samples above the ice surface are treated as exposed, subject to any additional snow shielding or erosion parameters. The same cover-depth calculation is used for both simplified IceSurface scenarios, in which $H(t)$ is generated from sampled parameters, and imported ensembles, in which $H(t)$ is supplied by external ice-surface histories. This structure makes IceSurface the most appropriate family for testing thinning, thickening, reburial, lowstand and elevation-transect hypotheses.

3.5.1 Simplified scenarios

Simplified IceSurface scenarios define $H(t)$ through a small number of sampled parameters. These options are intended for tests where cover depends on sample position relative to a changing ice surface, but where the history can be represented by an idealised form. A variety of simplified scenarios can be generated by the model for testing, based on user choices: monotonic thinning or thickening, piecewise linear histories, multistage lowstand histories and cyclic ice-surface fluctuations. In each case, the sampled parameters define the timing, magnitude and duration of changes in ice-surface elevation.

Simplified IceSurface scenarios are particularly useful for testing whether cosmogenic inventories require ice to have been thinner than present, whether a subglacial bedrock surface was exposed during a lowstand and subsequently reburied, or whether an elevation transect is compatible with a specified thinning history. They can be evaluated with Monte Carlo screening or, where appropriate, MCMC

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posterior exploration. As with other scenario families, a good fit indicates compatibility with the tested ice-surface form and parameter bounds; it does not show that the simplified history is unique.

3.5.2 Imported ensembles

Imported IceSurface ensembles supply $H(t)$ from externally generated ice-surface histories. These histories may come from glacier or ice-sheet models, glacier reconstructions or other independent sources. Each imported member should provide a time series of ice-surface elevation, which is interpolated onto the model time grid and converted to sample-specific cover histories using the same elevation geometry as in simplified IceSurface scenarios.

Imported histories are treated as fixed ensemble members; iceHIST cannot optimise or modify the parameters in the glacier or ice-sheet models used to generate these ensemble ice-surface histories, or sample them as MCMC variables. Instead, each member is evaluated deterministically: the forward model predicts ^{10}Be, ^{14}C and ^{26}Al concentrations for the corresponding cover history, and the predicted concentrations are compared with the measured data. The resulting likelihoods can be used to rank ensemble members or to calculate relative weights conditional on the supplied ensemble, uncertainties and error model.

This workflow is useful when the scientific question concerns which externally generated ice-surface histories are most consistent with cosmogenic data. For example, a core-plus-transect dataset can be used to test whether an ice-sheet model ensemble contains histories that reproduce both depth-dependent concentrations in a subglacial core and elevation-dependent concentrations along a transect. Weighted summaries of ice-surface elevation, cover duration, exposure duration or lowstand metrics can then be calculated across the ensemble.

The interpretation of imported-ensemble results is necessarily conditional. High likelihood or high posterior weight indicates that a member fits the cosmogenic data better than other supplied members under the stated assumptions. It does not demonstrate that the ensemble spans all plausible histories, nor

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that the highest-weighted member is a complete reconstruction of past ice-sheet behaviour. Imported-ensemble analyses should therefore report the source and structure of the ensemble, the time and elevation datums, interpolation choices, active nuclides, uncertainty model and any derived metrics used for comparison.

4 Input data, units and preprocessing

4.1 Measured datasets and sample information

iceHIST uses tabular measured datasets (.xlsx or .csv) with one row per sample, sampled interval or measurement group. The format is similar to that required for iceTEA (Jones et al., 2019), but with some different columns. Required metadata include the sample location, depth/thickness, elevation or position, shielding and production setting: sample name, latitude, longitude, elevation, atmospheric pressure where available, relative position, thickness, density, shielding factor, top and bottom depth, and collection year. Exposure age data can also be provided for each nuclide and sample to support interpretation, but is not used by the model. Core and depth-profile samples use top and bottom depths below the rock surface, whereas transect samples use the position field as sample elevation or height relative to a documented datum.

Nuclide measurements are supplied as concentration and one-sigma uncertainty fields for each active nuclide. iceHIST v1.0 supports combinations of in situ ^{10}Be, ^{14}C and ^{26}Al, so samples do not need all three nuclides. Missing measurements should be entered as NaN or omitted where supported, and are excluded from likelihood calculations rather than treated as zero concentrations. For bedrock cores or other forms of depth profile, available mineral mass is often small, and sometimes aliquots of some samples need to be combined to measure a nuclide concentration. Such concentrations are supported here, with sampling averaging following the approach in Schaefer et al. (2016).

For IceSurface and linear-thinning applications, datum consistency is essential because cover depth is calculated from the difference between modelled ice-surface elevation and sample elevation or position.

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For subglacial cores, the core top or bedrock surface, elevation should be reported in the same datum as the ice-surface history; sample depth within the core is treated separately as rock mass depth.

4.2 Time-series and imported ice-surface inputs

TimeSeries scenarios require an external driver file containing time before present and driver value, together with a descriptive name, short name and unit. Driver records may represent climate, ice-volume, isotope, temperature or other palaeo-environmental indices used to define threshold-based exposure or burial hypotheses. User files can be imported from .xlsx, .csv or .txt formats and converted to the Matlab structure used by iceHIST.

IceSurface scenarios can also use externally defined ice-surface histories. Imported histories may be supplied as a single time-elevation file, a column ensemble in one file, or a folder of individual ensemble-member files. Each history must contain time before present and ice-surface elevation. iceHIST interpolates these histories onto the model time grid and converts them to sample-specific cover depths using the sample elevations or positions defined in the measured dataset.

4.3 Quality-control and reporting checks

Before modelling, measured datasets should be checked for consistent units, complete sample-depth, elevation/position and datum fields, correct active-nuclide settings and appropriate handling of missing values. Particular attention should be given to sample depths, densities, shielding factors, atmospheric pressure or elevation, and whether concentration uncertainties are entered as one-sigma values.

Geometry and datum checks are especially important for IceSurface and linear-thinning scenarios. Sample elevations, transect positions, core-top elevations and imported ice-surface histories must use the same vertical datum. Measurement uncertainties should be reported clearly because they control likelihood sharpness, accepted Monte Carlo scenarios, posterior concentration and imported-ensemble weights.

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Model results should be reported with the assumptions that control the forward calculation and likelihood: scaling model, production-rate overrides (see Sect. 5.1) if used, active nuclides, measurement uncertainties, erosion rates or bounds, inherited inventory treatment, shielding and snow or cover assumptions, modern sample state, scenario family, parameter bounds and inference method.

5 Cosmogenic forward model and likelihood

The scenario families define histories of exposure, cover, burial, erosion and inheritance. The common forward model evaluates those histories by integrating nuclide production and decay through time, then comparing predicted and measured concentrations (Fig. 3). Throughout the equations, i represents samples, k represents nuclides, t is time before present, d is depth below the sampled rock surface, Z is mass depth, and $\widehat{N}_{i,k}$ is the predicted concentration.

5.1 Forward-model target, mass depth and production

For a specified scenario and parameter vector θ, iceHIST predicts the concentration of nuclide k in sample i as

$$\widehat{N}_{i,k} = F_k[\mathcal{H}_i(t), \mathcal{G}_i, \theta], \tag{2}$$

where $\mathcal{H}_i(t)$ is the exposure, cover or ice-surface history experienced by the sample, and $\mathcal{G}_i$ represents depth, thickness, density, elevation or position, shielding and site information. The scenario families differ in how $\mathcal{H}_i(t)$ is defined, but all are evaluated through the same production, shielding, erosion and decay framework.

Production is calculated as a function of mass depth. At a present-day depth d, the mass depth through which cosmic rays must pass at time t is

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$$Z_i(d,t) = \rho_r[d + R_i(t)] + 100 \cdot \rho_{\mathrm{ice}} h_i(t) + 100 \cdot \sum_{m=1}^{n_c} \rho_m \, h_{m,i}(t), \tag{3}$$

where ρ_r is rock density, $d$is present-day depth below the sampled rock surface in cm, $R_i(t)$ is the cumulative thickness of rock removed between time t and the present in cm, $h_i(t)$ is ice-cover thickness in m, and $h_{m,i}(t)$ denotes any additional cover material, such as snow, till or sediment, with density ρ_m. The factor of 100 converts metre-scale cover thicknesses to cm, so that all terms have units of g cm^{-2}. For core samples, d describes depth within rock, whereas $h_i(t)$ and $h_{m,i}(t)$ describe material above the rock surface.

The production rate is represented as the sum of spallogenic and muonogenic terms,

$$P_{i,k}(d,t) = P_k^{\mathrm{sp}}[Z_i(d,t), t; \mathcal{S}_i] + P_k^{\mu}[Z_i(d,t), t; \mathcal{S}_i], \tag{4}$$

where $\mathcal{S}_i$ denotes the location, elevation or pressure, shielding, scaling model and production-rate settings for sample i.

iceHIST uses CRONUScalc-style production and scaling functions as the computational framework for site scaling, depth-dependent production and sample-specific production profiles (Marrero et al., 2016). iceHIST assigns the default decay constants and production parameters listed in Table 1. These defaults distinguish between spallogenic reference production rates, which must be paired with the selected scaling framework, and muon-production parameters, which are calculated separately.

For production by spallation, users can choose among St, Lm, LSD and LSDn scaling. St and Lm are the time-independent and time-dependent Lal/Stone frameworks, respectively (Lal, 1991; Stone, 2000), and LSD and LSDn are the generic and nuclide-dependent versions of the time-dependent Lifton–Sato–Dunai physics-based scaling framework (Lifton et al., 2014). The default reference spallogenic production rates are the scaling-specific calibration values of Borchers et al. (2016) (Table 1).

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Production by muons is calculated separately from the spallogenic scaling choice using Balco (2017) Model 1A. Muon production varies with mass depth, atmospheric pressure and nuclide-specific fast- and negative-muon parameters, but it is not recalculated using the selected St, Lm, LSD or LSDn spallogenic scaling framework. This distinction is important for subglacial cores, deep profiles and thick-cover histories, where muon-produced nuclides can form a large or dominant fraction of the predicted concentration at depth (Balco, 2017; Balco et al., 2023).

Users can override the default reference spallogenic production rates, production-rate uncertainty fields, decay constants or muon-production parameters where site-specific, laboratory-specific or project-specific calibration information is available. This is especially recommended for in situ ^{14}C applications, because the ^{14}C production calibration remains less stable than those for ^{10}Be and ^{26}Al. Production-rate choices, scaling model, production-rate overrides and whether time-dependent scaling was used should therefore be reported for all iceHIST applications.

Time-dependent spallogenic scaling is represented through the time dependence of $P_{i,k}(Z,t)$ in Eq. (4). Where this option is used, scaling factors are evaluated on the model time grid used for forward integration. Otherwise, the selected scaling factor is held fixed for the sample during integration. In all cases, the selected scaling model acts on the corresponding reference spallogenic production rate in Table 1, while muon production is calculated separately using the Balco (2017) Model 1A parameterisation.

Table 1. Default decay constants and production parameters used in iceHIST. Mean spallogenic reference production rates $P_{s,k}^{\mathrm{ref}}$ are in atoms g^{-1} yr^{-1} in quartz at the relevant reference condition for the selected scaling framework. Fast-muon cross-section parameters σ_0 are in cm^2. Negative-muon parameters k_{neg} are effective yields in atoms produced per stopped negative muon. Scaling-specific spallogenic rates follow Borchers et al. (2016). For ^{14}C, users are encouraged to supply application-specific production rates where available.

Nuclide	λ_k (yr^{-1})	P_s^{St}	P_s^{Lm}	P_s^{LSD}	P_s^{LSDn}	σ_0 (cm^2)	k_{neg}
^{10}Be	$4.99745624 \times 10^{-7}$	4.01	4.00	4.09	3.92	2.8000×10^{-31}	$2.45800192 \times 10^{-4}$

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^{14}C	$1.20968094 \times 10^{-4}$	12.24	12.22	12.72	12.76	2.3684×10^{-30}	$1.49281792 \times 10^{-2}$
^{26}Al	9.83×10^{-7}	27.93	27.93	28.61	28.54	3.8900×10^{-30}	$2.58214712 \times 10^{-3}$

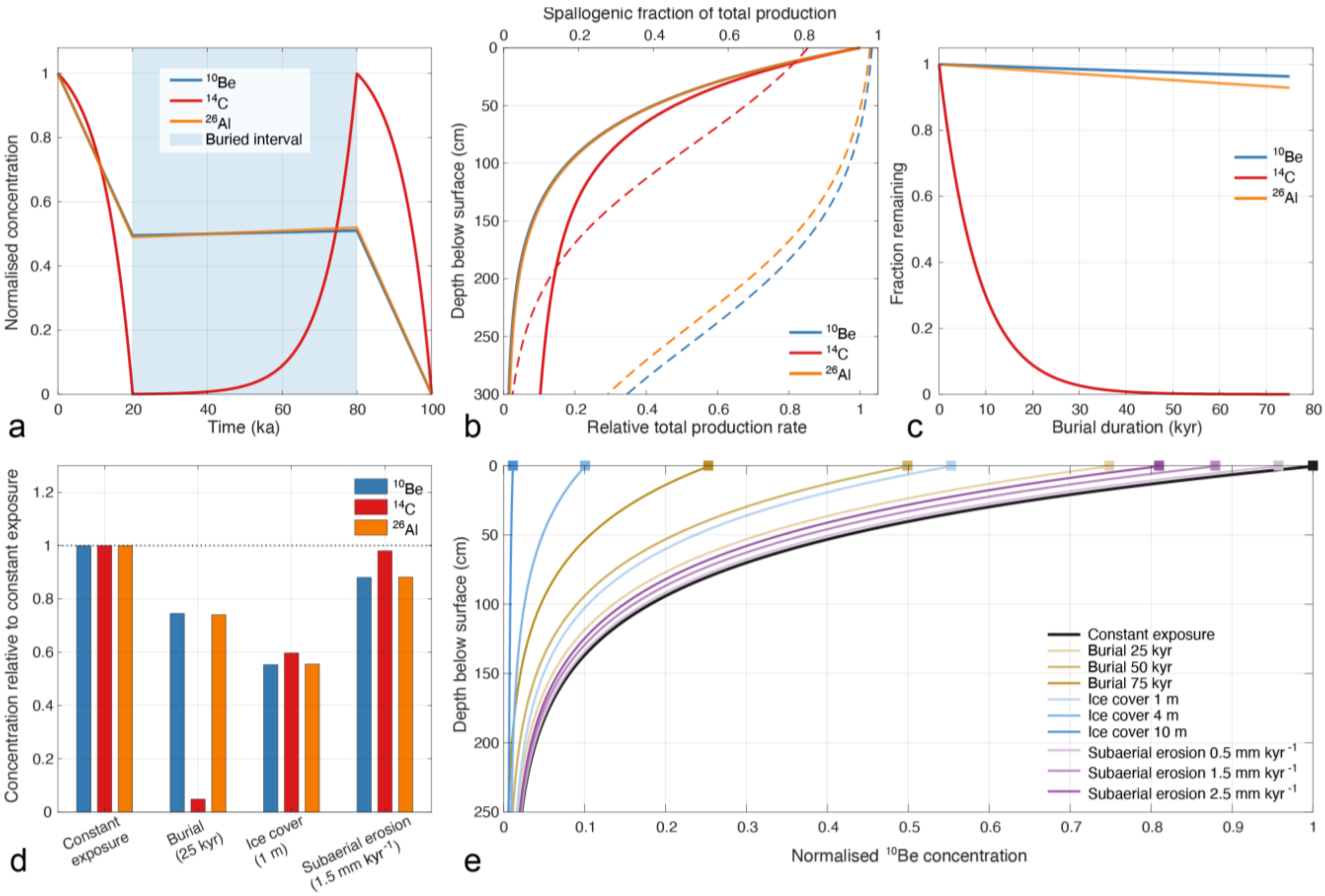

Figure 3. Forward-model calculation and process sensitivity for cosmogenic-nuclide concentrations. (a) Example surface concentrations through an exposure–burial–exposure history, calculated using model-suite production rates and nuclide-specific decay constants; the illustrative history consists of exposure from 100–80 ka, burial from 80–20 ka, and exposure from 20–0 ka. (b) Relative total production rates for ^{10}Be, ^{14}C and ^{26}Al with depth below the rock surface, calculated using the model production functions; dashed curves show the spallogenic fraction of total production for each nuclide. (c) Fraction of each nuclide remaining during burial, highlighting the much shorter effective memory of ^{14}C relative to ^{10}Be and ^{26}Al. (d) Surface-sample sensitivity relative to a 100 kyr constant-exposure baseline for representative burial, ice-cover and subaerial-erosion scenarios. (e) Modelled ^{10}Be depth-profile sensitivity for increasing

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burial duration, ice-cover thickness and subaerial erosion rate. The iceHIST forward-model converts exposure, burial, cover and erosion assumptions into distinct nuclide inventories through time and with depth.

5.2 Nuclide evolution, erosion, inheritance and sample averaging

Scenario histories are defined in time before present, t, but the concentration calculation is most simply written using elapsed model time, τ. For a model that starts at T before present, $\tau = 0$ at the start of the history, $\tau = T$ at the present, and $t = T - \tau$. The concentration at depth d evolves as

$$\frac{dN_{i,k}(d,\tau)}{d\tau} = P_{i,k}[Z_i(d, T-\tau), T-\tau] - \lambda_k N_{i,k}(d,\tau), \quad N_{i,k}(d,0) = N_k^{\text{inh}}, \tag{5}$$

where λ_k is the decay constant. For stable nuclides $\lambda_k = 0$, although iceHIST v1.0 is currently focused on radionuclides ^{10}Be, ^{14}C and ^{26}Al. In the current implementation, an optional inherited inventory is represented as a nuclide-specific scalar initial concentration, N_k^{inh}, applied at the model start to active samples and subsequently modified by production and radioactive decay. It should therefore be interpreted as a simple initial-inventory sensitivity parameter, rather than as a resolved depth-dependent inheritance profile.

Erosion enters through the time-dependent mass depth in Eq. 3. Where subaerial and subglacial erosion are distinguished, the cumulative thickness removed since time t can be written as

$$R_i(t) = \int_0^t \varepsilon_i(s)\,\mathrm{ds}, \quad \varepsilon_i(s) = \begin{cases} \varepsilon_i^{\text{subaerial}}, & \text{exposed state,} \\ \varepsilon_i^{\text{subglacial}}, & \text{ice-covered state.} \end{cases} \tag{6}$$

This expression is schematic: the active scenario family defines the exposure or cover state, and erosion rates may be fixed, sampled or set to zero. The important point is that erosion changes the shielding depth of each present-day sample interval through time, rather than being applied as a correction after concentration has been calculated, which is applied similar to Schaefer et al. (2016).

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Predicted concentrations are averaged over the finite sampled interval. For aliquot or interval a of sample i and nuclide k,

$$\bar{N}_{i,k,a} = \frac{1}{Z_{i,k,a}^{\text{bot}} - Z_{i,k,a}^{\text{top}}} \int_{Z_{i,k,a}^{\text{top}}}^{Z_{i,k,a}^{\text{bot}}} N_{i,k}\,(Z,T)\,dZ, \tag{7a}$$

where $Z_{i,k,a}^{\text{top}}$ and $Z_{i,k,a}^{\text{bot}}$ are the top and bottom mass depths of the interval used for that nuclide, and T denotes the present. Where a measured concentration combines more than one interval or aliquot, the model prediction is the mineral-mass-weighted mean,

$$\widehat{N}_{i,k} = \frac{\sum_{a=1}^{n_{i,k}} W_{i,k,a} \bar{N}_{i,k,a}}{\sum_{a=1}^{n_{i,k}} W_{i,k,a}}, \tag{7b}$$

where $W_{i,k,a}$ is the mineral-mass weight for interval or aliquot a. For a single interval, Eq. (7b) reduces to Eq. (7a). This formulation allows different nuclides from the same sample group to use different sampled intervals or combined mineral masses where required.
For surface samples, the same expression applies over the measured sample thickness; for an idealised zero-thickness sample it reduces to the surface value. This finite-interval averaging is particularly important for bedrock cores and shallow depth profiles, where production changes rapidly with mass depth.

The different decay constants give the active nuclides different memory of the same history. Long-lived ^{10}Be and ^{26}Al retain older exposure and inherited inventories, whereas in situ ^{14}C is more strongly weighted toward recent production, thin-cover intervals and late burial. These differences are what allow multi-nuclide datasets to test exposure-burial histories, but the interpretation remains conditional on the assumed erosion, shielding, production and inheritance terms.

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In the model, user-facing times are specified in ka before present and converted to years before present. Histories are evaluated on a fixed model interval of 10, 100 or 1000 years. Where exposure, cover and erosion are constant over consecutive intervals, adjacent intervals with the same exposure/burial state are collapsed for computational efficiency. Full interval resolution is retained when time-dependent scaling, time-dependent cover or time-dependent erosion is required.

5.3 Misfit, likelihood and joint datasets

Predicted and measured concentrations are compared for each active sample–nuclide pair. Let $N_{i,k}^{\text{obs}}$ be the measured concentration, $\sigma_{i,k}$ its one-sigma uncertainty and $\mathcal{A}$ the set of non-missing active measurements. The normalised residual is

$$r_{i,k}(\theta) = \frac{\hat{N}_{i,k}(\boldsymbol{\theta}) - N_{i,k}^{\text{obs}}}{\sigma_{i,k}}, (i,k) \in \mathcal{A}. \quad (8)$$

Missing nuclides are excluded from $\mathcal{A}$, not treated as zero. For independent Gaussian concentration errors, the log likelihood is

$$\log L(\theta) = -\frac{1}{2} \sum_{(i,k)\in\mathcal{A}} \left[r_{i,k}^2(\theta) + \log\left(2\pi\sigma_{i,k}^2\right)\right]. \quad (9)$$

Equivalently, model fit can be reported using

$$\chi^2(\theta) = \sum_{(i,k)\in\mathcal{A}} r_{i,k}^2(\theta), \quad (10)$$

with the understanding that both χ^2 and $\log L$ are conditional on the selected production model, scaling model, active nuclides, measurement uncertainties, parameter bounds and geological assumptions. For combined core-plus-transect datasets, one scenario is evaluated against both data types. The joint likelihood is therefore the product of component likelihoods, or equivalently the sum of log likelihoods,

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$$\log L_{\mathrm{joint}}(\theta) = \log L_{\mathrm{core}}(\theta) + \log L_{\mathrm{transect}}(\theta). \quad (11)$$

This structure allows core-only, transect-only and combined constraints to be compared using the same residual definition, provided the active data and uncertainty model are stated.

For MCMC runs, the posterior distribution is

$$p(\theta \mid D, M) \propto L(D \mid \theta, M)\, p(\theta \mid M), \quad (12)$$

where D denotes the measured dataset and M the selected scenario family. In Eq. (12), $p(\theta \mid M)$ is the product of the parameter priors defined for the selected MCMC scenario. These priors are bounded by the user-defined or example-defined parameter ranges. Most applications use uniform bounded priors over these ranges, and proposals outside the allowed bounds have zero prior density. Any non-uniform prior choice should be reported with the MCMC settings.

For imported IceSurface ensembles, the histories are fixed members rather than continuous parameter vectors. The relative weight of member j is calculated from its log likelihood as

$$w_j = \frac{\exp(\log L_j - \log L_{\max})}{\sum_m \exp(\log L_m - \log L_{\max})}, \quad (13)$$

where subtracting $\log L_{\max}$ is a numerical stabilisation and does not change the relative weights. These weights express support only within the supplied ensemble and error model; they should not be interpreted as probabilities over all possible ice histories.

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6 Inference workflows and outputs

6.1 Monte Carlo screening

Monte Carlo (MC) screening is the first inference step for most sampled scenario families. It is intended to test whether a scenario family, parameter range and set of geological assumptions can reproduce the measured data before more formal posterior inference is attempted. For each of Q MC iterations, indexed by q, iceHIST samples a parameter vector $\theta^{(q)}$ from the user-defined bounds, calculates predicted concentrations $\widehat{N}_{i,k}^{(q)}$ with the forward model, and evaluates $\chi^2\left(\theta^{(q)}\right)$ or $\log L\left(\theta^{(q)}\right)$ using the framework in Sect. 5.3. Scenarios are then ranked or retained according to the selected fit criterion.

iceHIST provides several formal fit and acceptance criteria for MC screening. These include a sigma-box criterion, in which active predictions must fall within a specified multiple of the reported one-sigma measurement uncertainty; a chi-square criterion using Eq. (10); a reduced chi-square criterion that normalises by the effective number of degrees of freedom; and a likelihood criterion based on Eq. (9), in which acceptance requires the log likelihood to exceed a specified threshold. The selected criterion should be reported because it affects which MC scenarios are labelled compatible. For grouped nuclide fits, the implementation can require all active observations, any active observation, or at least two observations to satisfy the selected criterion.

MC screening is useful for broad hypothesis testing, not only parameter estimation. It can identify incompatible scenario families, reveal trade-offs among erosion, inheritance, cover and exposure duration, and define focused bounds for later MCMC runs. Accepted or high-likelihood MC histories should therefore be reported as compatible screened histories, not as a formal posterior distribution unless the sampling design and weighting are explicitly treated that way.

MC results should be reported with the scenario family, data mode, sampled bounds, number of iterations, active nuclides, fit or acceptance criterion, and the main compatible-history summaries. In the demonstrations below, MC screening is used to evaluate surface-sample and depth-profile recovery,

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thinner-than-present lowstand hypotheses and TimeSeries threshold constraints before any posterior interpretation is attempted.

6.2 Markov chain Monte Carlo posterior inference and diagnostics

MCMC is used to explore posterior distributions for continuous parameters after MC screening has identified a plausible scenario family and parameter range. In each chain, where a chain is one sequential run of the sampler through parameter space, the MCMC model proposes a new parameter vector by random-walk perturbation of the current vector, recalculates predicted concentrations and the log posterior using Eq. 12, and accepts or rejects the proposal according to the sampler rule. Let θ be the current parameter vector, θ' the proposed parameter vector, and

$$\ell(\theta) = \log p(\theta \mid D, M), \tag{14a}$$

the log posterior for dataset D and model family M. For the symmetric random-walk proposals used here, proposal-density terms cancel, so the Metropolis acceptance rule can be written as

$$\log \alpha = \min\{0, \ell(\theta') - \ell(\theta)\}, \quad \theta' \text{ is accepted if } \log u < \log \alpha, \quad u \sim U(0,1). \tag{14b}$$

Accepted proposals replace the current parameter vector in the chain, whereas rejected proposals repeat the current vector. The retained chain therefore samples the posterior distribution defined by Eq. (12), conditional on the selected model family, priors, likelihood and parameter bounds. Multiple chains are used to test whether independent runs converge on the same posterior distribution rather than remaining dependent on their starting values. Note, imported IceSurface ensembles are not treated this way, because their members are fixed histories evaluated by likelihood weighting.

An MCMC run is defined by the scenario family, data mode, active nuclides, prior or bounded parameter ranges, number of chains, number of steps, burn-in period and proposal settings. The workflow records chain histories, log-prior, log-likelihood and log-posterior values, accepted and

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rejected proposals, posterior parameter summaries and model predictions. Diagnostic outputs include acceptance rates, trace plots, posterior histograms, split $\hat{R}$, effective sample size and checks for posterior mass accumulating against imposed bounds. Trace plots show how sampled parameter values change through each chain and are used to identify poor mixing, long-term drift or chains that remain trapped in one part of parameter space. Burn-in is the initial part of each chain that is discarded before posterior summaries are calculated, because the chain may still be moving away from its starting value. Split $\hat{R}$ and effective sample size provide numerical checks on whether chains have converged to a common distribution and whether the retained samples contain enough independent information for stable posterior summaries. The model provides guidance to the user based on the MCMC settings and run result.

Short screening runs are useful for checking setup, acceptance behaviour and trace structure, but they are not final inference. Publication-ready applications require adequate chain length, convergence assessment and sensitivity to parameter bounds or priors. Poor mixing, high $\hat{R}$, low effective sample size or boundary pile-up indicate that the posterior may be controlled by the proposal scheme, parameterisation, bounds or an inadequate model family. Reported outputs should include posterior summaries for sampled parameters and derived quantities, such as exposure duration, burial duration, erosion rate, threshold value, lowstand timing or minimum ice-surface elevation.

6.3 Imported ensemble weighting

Imported IceSurface histories are evaluated as fixed, discrete ensemble members rather than sampled as continuous parameters. For each ensemble member j, iceHIST reads the supplied ice-surface history $H_j(t)$, converts it to sample-specific cover histories using the IceSurface cover-depth calculation in Sect. 3.5, predicts concentrations with the common forward model and calculates $\log L_j$ using the likelihood definition in Sect. 5.3. The member likelihoods are then converted to relative weights using Eq. 13.

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This workflow is intended for comparing externally generated glacier or ice-sheet histories with cosmogenic data. Outputs include ranked ensemble members, relative log likelihoods, posterior weights, weighted ice-surface histories and derived summaries such as exposure duration, burial duration, minimum ice-surface elevation and lowstand duration. For any scalar derived quantity q_j calculated for ensemble member j, such as exposure duration, burial duration, minimum ice-surface elevation or lowstand duration, the likelihood-weighted mean is

$$\bar{q}_w = \sum_{j=1}^{M} w_j \, q_j, \tag{15}$$

where M is the number of imported histories and w_j is the relative weight from Eq. (13). The same operation can be applied to ice-surface elevation $H_j(t)$ at each model time step to calculate a weighted history. Weighted quantiles are obtained by sorting the member values and accumulating their weights, and should be interpreted only within the supplied ensemble. Because the histories are fixed, the workflow is distinct from both MC scenario sampling and random-walk MCMC.

The resulting weights are conditional on the supplied ensemble, as well as measurement uncertainties, production model, scaling model and geological assumptions. A high-weight member is therefore the best-supported member of the supplied ensemble, not necessarily the true or unique ice-surface history. If one member receives nearly all posterior weight, this may indicate strong discrimination by the cosmogenic data, but it may also reflect narrow uncertainties, model mismatch or limited ensemble diversity.

7 Demonstration experiments

The capability of iceHIST can be demonstrated via a series of tests under controlled conditions using the example sample data supplied with the model suite (Figs. 4–7). Known synthetic histories were prescribed, forward-modelled to generate measured-style cosmogenic-nuclide concentrations with

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assigned uncertainties, and then re-analysed using the relevant scenario family. These experiments are recovery tests designed to show how the model responds to known histories, and how accepted or posterior histories should be interpreted.

A DynamicPeriods benchmark experiment tests whether a multi-period exposure–burial history can be recovered from a synthetic core dataset (Fig. 4). The imposed history includes repeated exposure windows, zero inherited inventory and specified subaerial erosion. Accepted MC-compatible histories reproduce the synthetic ^{10}Be, ^{14}C and ^{26}Al concentration–depth structure and recover the main imposed quantities, including model start time, exposure-window duration, total exposure and subaerial erosion. The result illustrates that the model can effectively use depth-dependent, multi-nuclide information as well as fitting a surface concentration.

A TimeSeries experiment tests threshold-based exposure–burial histories generated from multiple external drivers (Fig. 5). For this example, modelled Antarctic ice volume (Pollard and DeConto, 2009), the global benthic δ^{18}O stack (Lisiecki and Raymo, 2005) and ice-core-derived atmospheric temperature (Jouzel et al., 2007) are used. MC modelling of the threshold value recovers the imposed thresholds and the main derived history metrics, including the number of exposure periods, exposure/burial time ratio and mean exposure-period duration. The experiment demonstrates that the TimeSeries family can represent different driver-state hypotheses, and that cosmogenic data can recover the key characteristics of distinct threshold-controlled histories.

An IceSurface experiment tests two thinner-than-present histories with a synthetic subglacial bedrock core (Fig. 6). In both end-member cases, MC-compatible histories recover the timing of the imposed lowstand and reproduce the synthetic nuclide concentrations for a representative core sample. The Late Holocene lowstand (2-4 ka) is expressed most clearly in ^{14}C together with ^{10}Be, whereas the older, Last Interglacial lowstand example (121-125 ka) is mainly retained in the longer-lived ^{10}Be and ^{26}Al inventories. This experiment demonstrates the value of multi-nuclide subglacial core data for distinguishing recent exposure from older thinner-than-present ice histories.

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An MCMC demonstration shows the intended workflow from broad MC screening to focused posterior inference (Fig. 7). Broad MC exploration identifies the part of parameter space capable of matching the synthetic data, and those bounds are then used for random-walk MCMC. The resulting traces and posterior marginal distributions recover the imposed start time, exposure-window duration and subaerial erosion within the diagnostic framework. This example illustrates why MC screening is useful before MCMC, and why posterior summaries should be interpreted together with the diagnostic information described in Sect. 6.2.

An imported-ensemble example demonstrates the distinct workflow for externally supplied IceSurface histories (Fig. 8). A 20-member fixed ice-surface ensemble is evaluated against the example transect-only cosmogenic-nuclide dataset, with each member forward-modelled once and assigned a likelihood and relative weight. The output ranks the supplied histories, calculates a likelihood-weighted median history and identifies the best-supported members. Because the histories are fixed, this is not MC scenario sampling or random-walk MCMC; the weights express relative support only within the supplied ensemble and uncertainty model.

Together, the demonstrations show that iceHIST can recover known synthetic histories, compare the information content of different data types, move from broad screening to posterior inference, and evaluate externally generated ice-surface histories. They also reinforce the central interpretation principle of the suite: model outputs identify histories compatible with cosmogenic-nuclide data and assumptions, rather than unique reconstructions independent of model structure.

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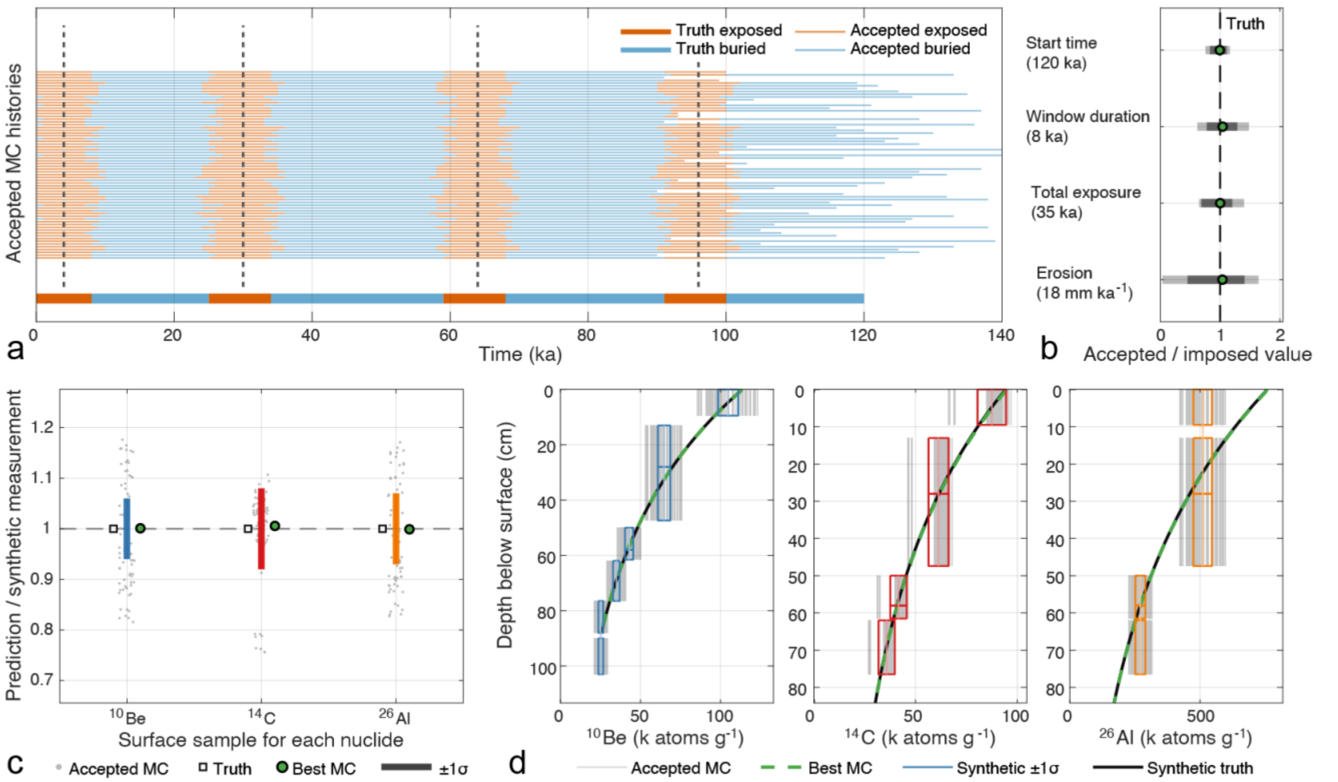

Figure 4. DynamicPeriods surface and depth-profile benchmark using synthetic core data. The example core depths, sample intervals and metadata are taken from the supplied core dataset, but measured concentrations are replaced by synthetic ^{10}Be, in situ ^{14}C and ^{26}Al concentrations generated from a known DynamicPeriods truth. The imposed history has a 120 ka model start, exposure-window midpoints at 4, 30, 64 and 96 ka, an 8 ka exposure-window duration, zero initial inventory, zero subglacial erosion and 18 mm ka^{-1} subaerial erosion. **(a)** Imposed exposure/burial history and accepted MC-compatible histories; orange and blue bars indicate exposed and buried intervals, respectively. **(b)** Accepted MC recovery of imposed quantities, shown as accepted/imposed values for model start time, exposure-window duration, total exposure and subaerial erosion. **(c)** Multi-nuclide fit for a surface sample (the shallowest active core sample for each nuclide), shown as prediction/synthetic measurement; grey points are accepted MC scenarios, the square is the synthetic truth and the circle is the best MC scenario. **(d–f)** Synthetic measured and predicted concentration–depth profiles for ^{10}Be, ^{14}C and ^{26}Al. Synthetic measurements are shown with sample-depth intervals and ±1σ concentration ranges; accepted MC predictions are plotted as sample-depth segments, with the synthetic truth and best MC continuous profiles overlaid.

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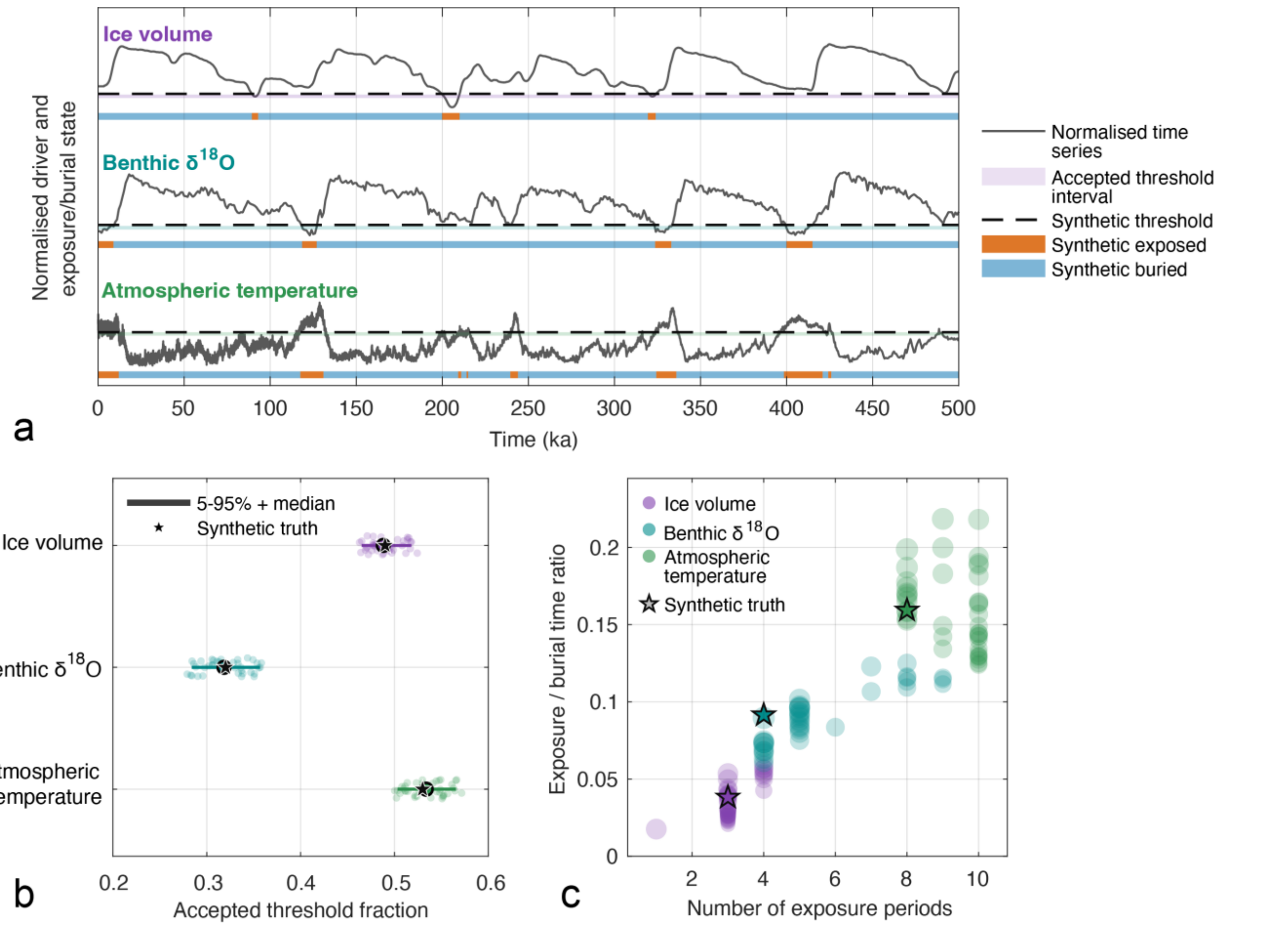

Figure 5. TimeSeries driver flexibility and threshold-based exposure/burial modelling. The TimeSeries model was run for a 500 kyr model interval using three example time-series drivers: ice volume (Pollard and DeConto, 2009), benthic $\delta^{18}O$ (Lisiecki and Raymo, 2005) and atmospheric temperature (Jouzel et al., 2007). For each driver, a synthetic threshold was prescribed, converted into an exposure/burial history, and used to generate synthetic core+transect ^{10}Be, ^{14}C and ^{26}Al concentrations. The synthetic data were then re-modelled using MC sampling of the threshold value. **(a)** Each normalised driver record, the synthetic threshold, the accepted MC threshold interval and the corresponding synthetic exposure/burial history, with orange indicating exposure and blue indicating burial. **(b)** The threshold recovery for each driver as accepted MC values, 5–95 % ranges, medians and synthetic truths. **(c)** Summarised exposure/burial characteristics extracted from the accepted histories, showing the number of exposure periods, exposure/burial time ratio and mean exposure-period duration. The TimeSeries model can use different external driver records to generate distinct threshold-controlled exposure histories and recover their key characteristics from synthetic cosmogenic-nuclide observations.

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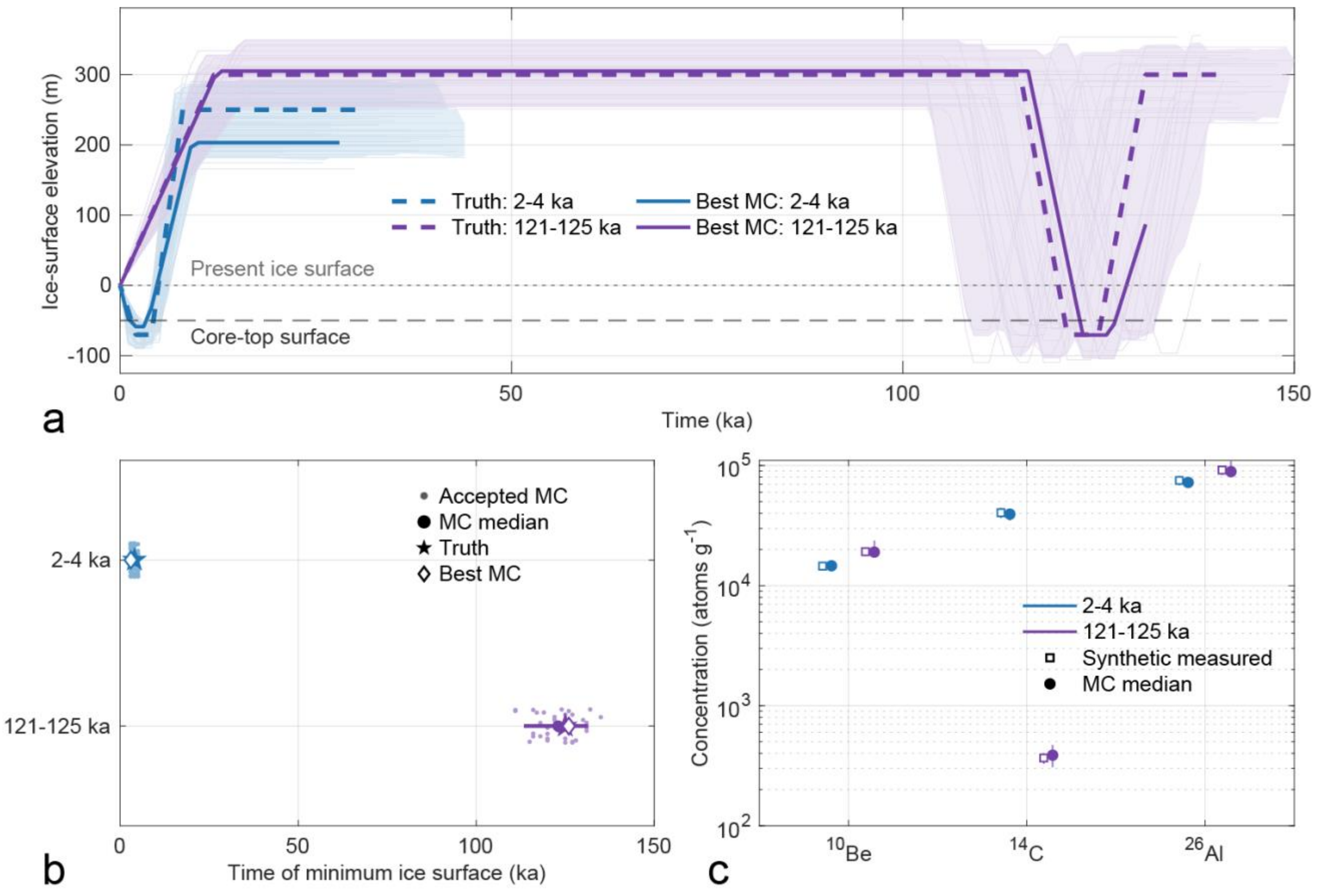

Figure 6. IceSurface test for thinner-than-present ice. The example uses the supplied core geometry and metadata with synthetic measured concentrations, and a present-relative vertical datum where the present ice surface is 0 m and the core top is -50 m. Exposure of the core top is therefore defined as intervals when the modelled ice surface is at or below -50 m. **(a)** Imposed ice-surface histories and accepted MC-compatible histories for two end-member lowstand scenarios: a late-Holocene lowstand at 2–4 ka and an older lowstand at 121–125 ka. Dashed lines show the synthetic truth, thin lines show accepted MC histories, and solid lines show the best-fitting accepted MC history for each case. **(b)** Accepted timing of minimum ice surface for each scenario, with the synthetic truth, MC median and best MC result highlighted. **(c)** Nuclide “fingerprint” for a representative active core sample, comparing synthetic measured concentrations with MC predictions for ^{10}Be, ^{14}C and ^{26}Al; points show the MC median prediction and vertical ranges show the accepted MC interval. The IceSurface core model can recover distinct thinner-than-present histories and that different nuclides provide complementary sensitivity: the 2–4 ka lowstand is most clearly expressed in short-lived ^{14}C with ^{10}Be, whereas the 121–125 ka lowstand is mainly retained in the longer-lived ^{10}Be and ^{26}Al inventories.

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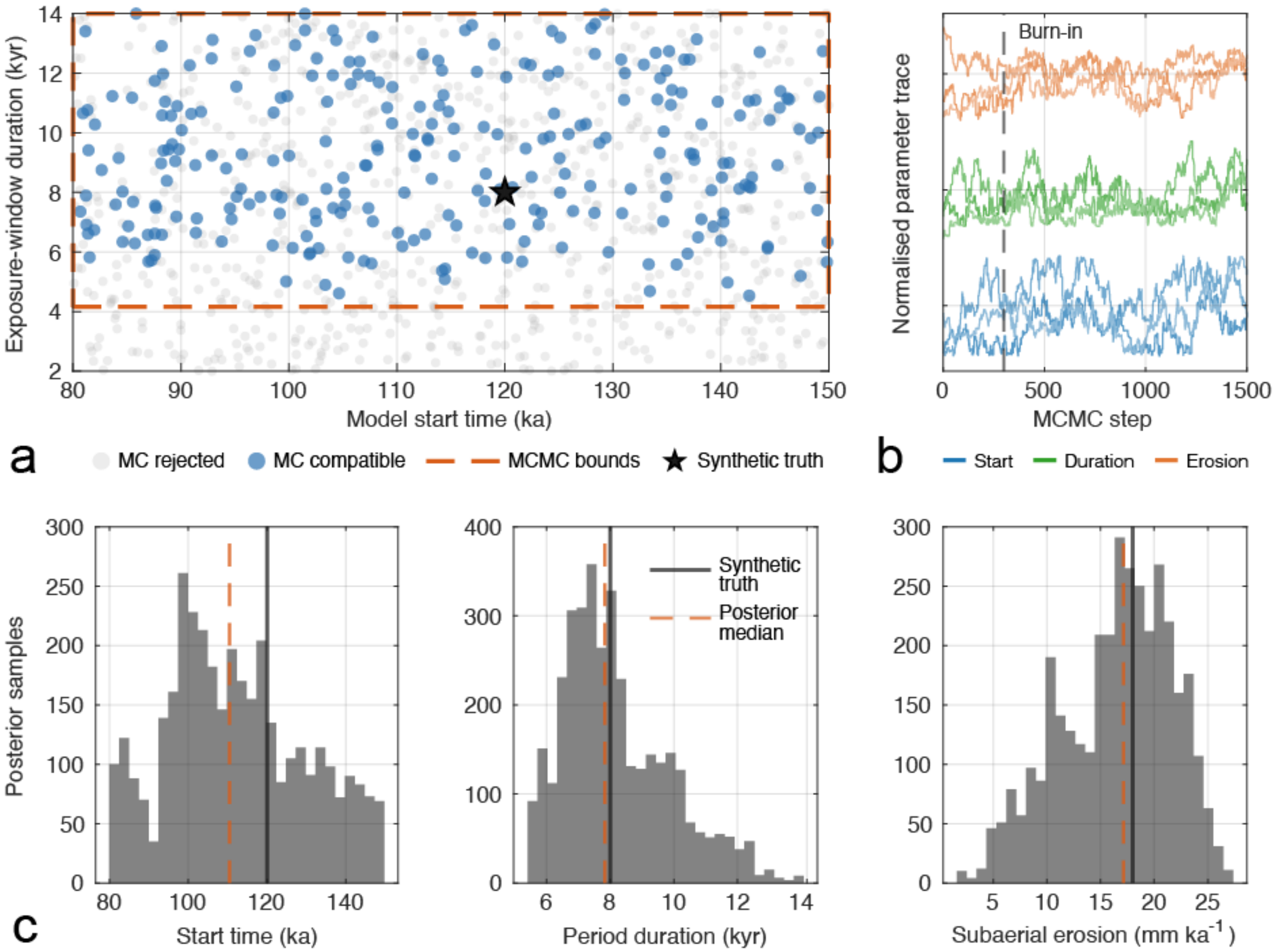

Figure 7. Workflow from broad Monte Carlo screening to focused MCMC inference. The demonstration uses the same DynamicPeriods core logic as the benchmark in Fig. 4, with synthetic ^{10}Be and ^{14}C concentrations generated from a known multi-period exposure/burial history. The imposed truth has a 120 ka start time, exposure-window midpoints at 4, 30, 64 and 96 ka, an 8 ka exposure-window duration and 18 mm ka^{-1} subaerial erosion. **(a)** Broad MC exploration of model start time and exposure-window duration, with rejected or low-ranked scenarios, MC-compatible scenarios, the synthetic truth and the focused MCMC parameter bounds derived from the MC screen. **(b)** Normalised MCMC traces for start time, exposure-window duration and subaerial erosion, with burn-in marked. **(c)** Posterior marginal distributions for the same three parameters, showing the synthetic truth, posterior median and chain diagnostics.

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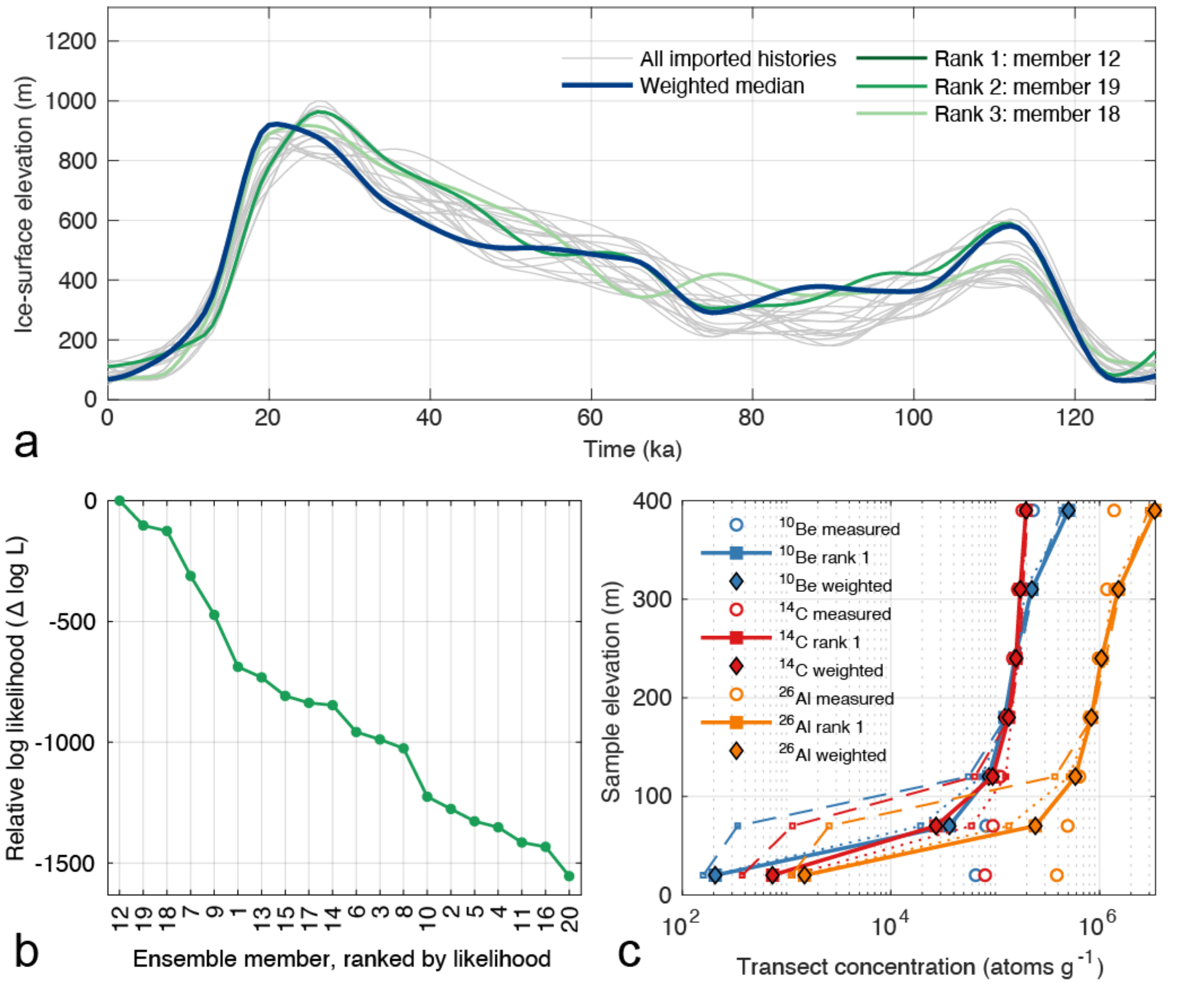

845 **Figure 8. Likelihood weighting of an imported ice-surface ensemble.** The demonstration evaluates a fixed 20-member imported ice-surface ensemble against synthetic transect-only cosmogenic-nuclide observations, using the IceSurface forward model to predict concentrations for each ensemble member and likelihood-weighting the members according to their transect-data misfit. **(a)** Imported ice-surface histories, the likelihood-weighted median history, and the three highest-ranked histories. **(b)** Ensemble members ranked by relative log likelihood, with x-axis labels indicating the original imported member numbers. **(c)** Measured transect concentrations compared with
850 model predictions as a function of sample position/elevation, showing measured concentrations with uncertainty together with the highest-ranked and likelihood-weighted predictions for the active nuclides.

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8 Discussion

8.1 Main contribution of iceHIST

Placed in the context of previous cosmogenic-nuclide modelling, the main contribution of iceHIST is integration. The suite provides a common, accessible and user-friendly framework for converting hypothesised glacier and ice-sheet histories into predicted ^{10}Be, ^{14}C and/or ^{26}Al concentrations, and for comparing those predictions with measured data using consistent misfit, likelihood and diagnostic outputs.

This framework builds on several established modelling approaches. Geologically constrained Monte Carlo depth-profile models showed how concentration–depth data can be used to test exposure, erosion and inheritance histories under explicit bounds (Hidy et al., 2010). Climate-driven and threshold-based approaches showed that external palaeoclimate records can be translated into exposure–burial hypotheses and tested against cosmogenic data (Goehring et al., 2012; Knudsen et al., 2015; Knudsen and Egholm, 2018). More recent depth-profile and transect inversions have demonstrated the value of MCMC, multi-nuclide measurements and combined data arrangements for glaciated bedrock (Andersen et al., 2024, 2025). Subglacial-core studies have shown that ^{14}C, ^{10}Be and ^{26}Al can reject thick-ice or no-lowstand hypotheses and test reversible thinning beneath present ice (Balco et al., 2023; Small et al., 2026). Elevation-transect and ice-sheet model-comparison studies have further shown that cosmogenic data can be used to evaluate ice-surface histories and externally generated model ensembles (Halberstadt et al., 2023; Jones et al., 2017).

iceHIST unifies these approaches by placing multiple scenario families, data modes and inference workflows around one forward-model and likelihood structure. The DynamicPeriods experiment demonstrates continuity with depth-profile and repeated exposure–burial modelling (Fig. 4). The TimeSeries experiment shows how different external drivers can generate threshold-controlled histories within the same workflow (Fig. 5). The IceSurface experiment formalises subglacial-core lowstand testing in terms of explicit ice-surface geometry (Fig. 6), and the MC-to-MCMC example shows how

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exploratory screening can be followed by posterior inference when parameters are continuous and identifiable (Fig. 7). The imported-ensemble workflow extends this same logic to fixed external ice-surface histories, where deterministic likelihood weighting is more appropriate than random-walk MCMC (Fig. 8).

The production and scaling calculations in iceHIST remain grounded in established cosmogenic-nuclide machinery, including CRONUScalc-style production and scaling functions and existing treatments of spallogenic and muonogenic production (Balco, 2017; Marrero et al., 2016; Schaefer et al., 2022). The added value of iceHIST is therefore the history-testing and model–data comparison layer: it links scenario definitions, sample depth and elevation, ice-cover calculations, likelihoods and diagnostics in one workflow.

8.2 Interpreting compatible histories and non-uniqueness

The demonstrations show that iceHIST can recover known histories under controlled synthetic conditions, but they also reinforce a central limitation of cosmogenic-nuclide interpretation: compatible histories are not necessarily unique. Production, shielding, radioactive decay, erosion and inherited inventories can compensate for one another, so similar concentrations may arise from different combinations of exposure duration, burial duration, cover thickness and erosion rate. This non-uniqueness is well established in depth-profile, paired-nuclide and glaciated-landscape applications (Andersen et al., 2024; Balco, 2020; Hidy et al., 2010; Knudsen and Egholm, 2018; Schaefer et al., 2022).

iceHIST treats this ambiguity as an output to be quantified rather than a problem to be hidden. MC screening identifies histories that meet a stated fit criterion. MCMC describes posterior distributions conditional on the selected scenario family, parameter bounds or priors, likelihood and uncertainty model. Imported-ensemble weighting ranks fixed external histories only within the supplied ensemble. These outputs provide different forms of conditional support and should not be reduced to a single best-fitting history without considering the accepted range, posterior spread, residual structure and geological plausibility.

The synthetic experiments illustrate this distinction. The DynamicPeriods and MCMC examples recover the imposed exposure-window and erosion parameters, but the accepted and posterior ranges remain part of the results (Figs. 4 and 7). The TimeSeries experiment shows that threshold-controlled histories can be recovered under different external drivers, but the interpretation remains conditional on the chosen driver, polarity and threshold (Fig. 5). The IceSurface experiment tests explicit thinner-than-present histories and the multi-nuclide information needed to distinguish past lowstands (e.g. Holocene vs Last Interglacial), but real applications may still involve trade-offs among lowstand timing, duration, residual cover, erosion and inheritance (Fig. 6). Imported-ensemble weights similarly indicate which supplied ice-surface histories best match the data, rather than whether the ensemble spans all plausible histories (Fig. 8).

For this reason, iceHIST results should be reported as compatible-history ranges, posterior intervals, or likelihood-weighted summaries, together with the assumptions underlying them. Strong interpretations are most defensible when they explicitly test hypotheses, such as a no-lowstand null model or a specified driver-threshold relationship. They are less defensible when presented as complete reconstructions without independent geological constraints.

8.3 Sampling design, data types and science questions

The usefulness of an iceHIST analysis depends strongly on whether the sampled material can distinguish among the histories being tested. Depth profiles are most informative where concentration gradients remain measurable and erosion has not removed most of the inherited or exposure-related signal, consistent with previous depth-profile modelling studies (Andersen et al., 2024; Hidy et al., 2010). Surface or elevation transects are most useful where samples span the elevation range over which plausible ice-surface histories differ, and where sample elevations can be related to a common datum (Andersen et al., 2025; Halberstadt et al., 2023; Jones et al., 2017).

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Subglacial bedrock cores are particularly valuable for testing whether ice was thinner than present and later re-thickened, but their resolving power depends on cover thickness, core depth, active nuclides and the timing of the lowstand. In situ ^{14}C is highly sensitive to recent or Holocene production, whereas ^{10}Be and ^{26}Al retain longer-lived inventories and can help distinguish recent lowstands from older exposure-burial histories (Balco et al., 2023; Small et al., 2026). Where erosion, snow or till shielding, or inherited inventories are poorly constrained, the most useful additional data are likely to be those that discriminate among competing processes, such as deeper core intervals, complementary nuclides or nearby surface/transect samples, rather than additional shallow replicates alone.

Combined core-plus-transect datasets provide a stricter test because a single shared history must explain both the vertical concentration structure of a core and the elevation-dependent pattern across surface samples (e.g. Balco et al., 2023). This is useful when the scientific question concerns ice-surface change rather than merely local exposure duration. Synthetic modelling can therefore be used to compare candidate sampling strategies before field sampling: which core depths, transect elevations, nuclide combinations, or drill sites would best discriminate among a no-lowstand history, a thin-ice lowstand, full exposure, or an externally modelled ice-sheet history. In this role, iceHIST can support value-of-information tests prior to field sampling or subglacial drilling, thereby complementing model-informed site-selection approaches (Briner et al., 2022).

8.4 Limitations and future development

Several limitations stem directly from the intended scope of iceHIST v1.0. The current implementation focuses on in situ ^{10}Be, ^{14}C and ^{26}Al; other cosmogenic systems, including ^{3}He, ^{21}Ne and ^{36}Cl, require additional production, decay, target-mineral and reporting support before inclusion.

The suite does not simulate glacier or ice-sheet dynamics. However, a range of ice histories can be explored, sampled from scenario-family bounds, derived from external drivers, or imported from external model outputs. Their glaciological plausibility must be assessed independently. In particular,

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the imported ice surface history functionality provides one-way coupling to test glacier and ice-sheet model ensembles, which could be applied to multiple cosmogenic nuclide datasets from around an ice margin.

The forward model inherits the limitations of the underlying production and scaling choices. Production-rate calibration, scaling model selection and muon-production uncertainty can affect inferred histories, especially for deep profiles, subglacial cores, long integrations and samples where most production occurs under thick cover (Balco, 2017; Marrero et al., 2016; Schaefer et al., 2022). Snow, firn, till, sediment, rock cover, erosion and inherited inventories can also mimic or obscure exposure–burial signals. These terms should be measured, constrained, sampled or tested via sensitivity analyses where they are important, rather than treated as incidental corrections.

The three model–data comparison approaches depend on the tested model structure and uncertainty model. MC-compatible histories depend on the sampled bounds and the acceptance criterion. MCMC results require adequate chain length, convergence diagnostics, effective sample-size checks, and sensitivity to priors or bounds before they can support publication-level inference. Imported-ensemble weights depend on the supplied histories and error model, and should not be interpreted as evidence that the ensemble spans all plausible ice-surface histories.

Future development could extend iceHIST in several directions: additional nuclides and minerals; firn density or time-varying cover structure; more flexible erosion and cover histories (e.g. time-dependent subglacial erosion rate); hierarchical or correlated error models; multi-site or regional ensemble weighting; and formal pre-field synthetic sampling-design tools. Detrital subglacial cobbles or sediment grains with unknown source areas and transport histories would require additional source-area and transport models, rather than the deterministic sample-depth and sample-position framework used here (e.g. Corbett et al., 2021).

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9 Conclusions

iceHIST v1.0 is a cosmogenic-nuclide model suite for testing hypotheses about glacier and ice-sheet history using in situ ^{10}Be, ^{14}C and ^{26}Al. The suite forward-models nuclide concentrations for specified histories of exposure, cover (ice, snow), burial, erosion (subaerial, subglacial) and inheritance, and evaluates those histories against measured data from bedrock cores, depth profiles, surface or elevation transects, and combined core-plus-transect datasets.

The four scenario families provide a practical hypothesis ladder. OneStage tests simple exposure, burial or cover histories; DynamicPeriods tests repeated prescribed exposure or burial windows; TimeSeries converts external driver records into threshold-controlled exposure–burial histories; and IceSurface converts explicit ice-surface histories into sample-specific cover histories. These scenario families share a common forward model and likelihood framework and can be evaluated using Monte Carlo screening, MCMC posterior inference or likelihood weighting of imported fixed ice-surface ensembles.

The synthetic demonstrations show that iceHIST can recover known multi-nuclide depth-profile histories, compare threshold-derived histories across different external drivers, test for thinner-than-present lowstands beneath modern ice, move from broad MC screening to focused MCMC inference, and rank imported ice-surface histories by likelihood.

The main value of iceHIST is to make cosmogenic-nuclide history testing explicit, reproducible and comparable across data arrangements and scenario types. Its outputs are best interpreted as compatible histories, posterior summaries, likelihood-weighted rankings and diagnostic trade-offs, all under stated assumptions. Used in this way, iceHIST can help address questions such as how long glaciers were larger or smaller than present, whether ice sheets thinned below present and later re-thickened, and which glacier or ice-sheet simulation is most consistent with cosmogenic-nuclide observations.

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Code and data availability

The model suite has been written in MATLAB (The MathWorks Inc., 2024), and is available at https://doi.org/10.5281/zenodo.21212291, including a user manual (README.md). Generative AI tools were used to assist with model auditing, including code review and functionality checks; all fixes were reviewed and verified by the author.

Author contributions

RSJ designed the model framework, formulated the numerical implementation, ran analyses using the models to demonstrate their capabilities, produced the figures, and wrote the manuscript.

Competing interests

The author declares no conflict of interest.

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References

Andersen, J. L., Knudsen, M. F., Stroeven, A. P., Olsen, J., and Pedersen, V. K.: Ice-sheet burial and erosion inferred from cosmogenic nuclide bedrock depth profiles: Implications for the glaciation history of northeastern Fennoscandia, Quaternary Science Reviews, 344, 109010, https://doi.org/10.1016/j.quascirev.2024.109010, 2024.

Andersen, J. L., Lifton, N. A., Linge, H., Stuart, F., Olsen, J., and Pedersen, V. K.: Ice-burial history and early Holocene thinning of the Scandinavian Ice Sheet at Gaustatoppen, southern Norway, Quaternary Science Reviews, 361, 109409, https://doi.org/10.1016/j.quascirev.2025.109409, 2025.

https://doi.org/10.5194/egusphere-2026-4007
Preprint. Discussion started: 21 July 2026

Balco, G.: Production rate calculations for cosmic-ray-muon-produced 10Be and 26Al benchmarked against geological calibration data, Quaternary Geochronology, 39, 150–173, https://doi.org/10.1016/j.quageo.2017.02.001, 2017.

Balco, G.: Glacier Change and Paleoclimate Applications of Cosmogenic-Nuclide Exposure Dating, Annual Review of Earth and Planetary Sciences, 48, 21–48, https://doi.org/10.1146/annurev-earth-081619-052609, 2020.

Balco, G., Brown, N., Nichols, K., Venturelli, R. A., Adams, J., Braddock, S., Campbell, S., Goehring, B., Johnson, J. S., Rood, D. H., Wilcken, K., Hall, B., and Woodward, J.: Reversible ice sheet thinning in the Amundsen Sea Embayment during the Late Holocene, The Cryosphere, 17, 1787–1801, https://doi.org/10.5194/tc-17-1787-2023, 2023.

Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J., and Stone, J.: Geological calibration of spallation production rates in the CRONUS-Earth project, Quaternary Geochronology, 31, 188–198, https://doi.org/10.1016/j.quageo.2015.01.009, 2016.

Briner, J. P., Walcott, C. K., Schaefer, J. M., Young, N. E., MacGregor, J. A., Poinar, K., Keisling, B. A., Anandakrishnan, S., Albert, M. R., Kuhl, T., and Boeckmann, G.: Drill-site selection for cosmogenic-nuclide exposure dating of the bed of the Greenland Ice Sheet, The Cryosphere, 16, 3933–3948, https://doi.org/10.5194/tc-16-3933-2022, 2022.

Corbett, L. B., Bierman, P. R., Neumann, T. A., Graly, J. A., Shakun, J. D., Goehring, B. M., Hidy, A. J., and Caffee, M. W.: Measuring multiple cosmogenic nuclides in glacial cobbles sheds light on Greenland Ice Sheet processes, Earth and Planetary Science Letters, 554, 116673, https://doi.org/10.1016/j.epsl.2020.116673, 2021.

Goehring, B. M., Schaefer, J. M., Schluechter, C., Lifton, N. A., Finkel, R. C., Jull, A. J. T., Akcar, N., and Alley, R. B.: The Rhone Glacier was smaller than today for most of the Holocene, Geology, 39, 679–682, https://doi.org/10.1130/g32145.1, 2011.

Goehring, B. M., Vacco, D. A., Alley, R. B., and Schaefer, J. M.: Holocene dynamics of the Rhone Glacier, Switzerland, deduced from ice flow models and cosmogenic nuclides, Earth and Planetary Science Letters, 351–352, 27–35, https://doi.org/10.1016/j.epsl.2012.07.027, 2012.

Gosse, J. C. and Phillips, F. M.: Terrestrial in situ cosmogenic nuclides: theory and application, Quaternary Science Reviews, 20, 1475–1560, 2001.

Halberstadt, A. R. W., Balco, G., Buchband, H., and Spector, P.: Cosmogenic-nuclide data from Antarctic nunataks can constrain past ice sheet instabilities, The Cryosphere, 17, 1623–1643, https://doi.org/10.5194/tc-17-1623-2023, 2023.

https://doi.org/10.5194/egusphere-2026-4007
Preprint. Discussion started: 21 July 2026

Heisinger, B., Lal, D., Jull, A. J. T., Kubik, P., Ivy-Ochs, S., Neumaier, S., Knie, K., Lazarev, V., and Nolte, E.: Production of selected cosmogenic radionuclides by muons: 1. Fast muons, Earth and Planetary Science Letters, 200, 345–355, 2002a.

Heisinger, B., Lal, D., Jull, A. J. T., Kubik, P., Ivy-Ochs, S., Knie, K., and Nolte, E.: Production of selected cosmogenic radionuclides by muons: 2. Capture of negative muons, Earth and Planetary Science Letters, 200, 357–369, 2002b.

Hidy, A. J., Gosse, J. C., Pederson, J. L., Mattern, J. P., and Finkel, R. C.: A geologically constrained Monte Carlo approach to modeling exposure ages from profiles of cosmogenic nuclides: An example from Lees Ferry, Arizona, Geochemistry Geophysics Geosystems, 11, https://doi.org/10.1029/2010gc003084, 2010.

Hippe, K.: Constraining processes of landscape change with combined *in situ* cosmogenic 14C-10Be analysis, Quaternary Science Reviews, 173, 1–19, https://doi.org/10.1016/j.quascirev.2017.07.020, 2017.

Jones, R., Norton, K., Mackintosh, A., Anderson, J., Kubik, P., Vockenhuber, C., Wittmann, H., Fink, D., Wilson, G., and Golledge, N.: Cosmogenic nuclides constrain surface fluctuations of an East Antarctic outlet glacier since the Pliocene, Earth and Planetary Science Letters, 480, 75–86, 2017.

Jones, R., Small, D., Cahill, N., Bentley, M., and Whitehouse, P.: iceTEA: Tools for plotting and analysing cosmogenic-nuclide surface-exposure data from former ice margins, Quaternary Geochronology, 51, 72–86, 2019.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J.-M., and Chappellaz, J.: Orbital and millennial Antarctic climate variability over the past 800,000 years, Science, 317, 793–796, https://doi.org/10.1126/science.1141038, 2007.

Knudsen, M. F. and Egholm, D. L.: Constraining Quaternary ice covers and erosion rates using cosmogenic 26Al/10Be nuclide concentrations, Quaternary Science Reviews, 181, 65–75, https://doi.org/10.1016/j.quascirev.2017.12.012, 2018.

Knudsen, M. F., Egholm, D. L., Jacobsen, B. H., Larsen, N. K., Jansen, J. D., Andersen, J. L., and Linge, H. C.: A multi-nuclide approach to constrain landscape evolution and past erosion rates in previously glaciated terrains, Quaternary Geochronology, 30, 100–113, https://doi.org/10.1016/j.quageo.2015.08.004, 2015.

Lal, D.: Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, Earth and Planetary Science Letters, 104, 424–439, 1991.

https://doi.org/10.5194/egusphere-2026-4007
Preprint. Discussion started: 21 July 2026

Lifton, N., Sato, T., and Dunai, T. J.: Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes, Earth and Planetary Science Letters, 386, 149–160, https://doi.org/10.1016/j.epsl.2013.10.052, 2014.

Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records, Paleoceanography, 20, n/a-n/a, https://doi.org/10.1029/2004pa001071, 2005.

Marrero, S. M., Phillips, F. M., Borchers, B., Lifton, N., Aumer, R., and Balco, G.: Cosmogenic nuclide systematics and the CRONUScalc program, Quaternary Geochronology, 31, 160–187, https://doi.org/10.1016/j.quageo.2015.09.005, 2016.

Nishiizumi, K., Kohl, C., Arnold, J., Klein, J., Fink, D., and Middleton, R.: Cosmic ray produced 10Be and 26Al in Antarctic rocks: exposure and erosion history, Earth and Planetary Science Letters, 104, 440–454, 1991.

Pollard, D. and DeConto, R. M.: Modelling West Antarctic ice sheet growth and collapse through the past five million years, Nature, 458, 329–332, 2009.

Schaefer, J. M., Finkel, R. C., Balco, G., Alley, R. B., Caffee, M. W., Briner, J. P., Young, N. E., Gow, A. J., and Schwartz, R.: Greenland was nearly ice-free for extended periods during the Pleistocene, Nature, 540, 252–255, 2016.

Schaefer, J. M., Codilean, A. T., Willenbring, J. K., Lu, Z.-T., Keisling, B., Fülöp, R.-H., and Val, P.: Cosmogenic nuclide techniques, Nat Rev Methods Primers, 2, 18, https://doi.org/10.1038/s43586-022-00096-9, 2022.

Small, D., Fülöp, R.-H., Smedley, R. K., Lees, T., Trabucatti, S., Fabel, D., Miguens-Rodriguez, M., Smith, A. M., and Boeckmann, G. V.: A thinner-than-present West Antarctic Ice Sheet in the southern Weddell Sea Embayment during the Holocene, The Cryosphere, 20, 2035–2052, https://doi.org/10.5194/tc-20-2035-2026, 2026.

Spector, P., Stone, J., Balco, G., Hillebrand, T., Thompson, M., and Black, T.: Miocene to Pleistocene glacial history of West Antarctica inferred from Nunatak geomorphology and cosmogenic-nuclide measurements on bedrock surfaces, American Journal of Science, 320, 637–676, 2020.

Stone, J. O.: Air pressure and cosmogenic isotope production, Journal of Geophysical Research: Solid Earth (1978–2012), 105, 23753–23759, 2000.

The MathWorks Inc.: MATLAB, 2024.