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THE INFLUENCE OF INDEPENDENT GEOLOGICAL CONSTRAINTS ON APATITE FISSION TRACK MODELLING AND INTERPRETATION: SOME PITFALLS ILLUSTRATED USING FORWARD AND INVERSE TECHNIQUES

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INTRODUCTION

We examine some common pitfalls of apatite fission track (AFT) modelling and interpretation using the results of forward and inverse computer programs which generate theoretical fission track ages and track length distributions. These programs are applied here to two samples of widely different ages and burial/exhumation histories: one Tertiary (Oligocene) , and one early Paleozoic (Middle Ordovician). Although forward models may be useful in simple, well-constrained settings, the inherent nonuniqueness of this approach limits its applicability. The inverse approach, which is a generalization of the foward modelling technique, is more objective and gives the user a better appreciation of the variability in thermal histories allowed by the data. Our inverse model is a modified version of a program initially developed by Willett (in press) and modified as discussed by Issler and Willett (1996). As illustrated here, the model-derived thermal histories, for both the forward and inverse approaches, can be influenced dramatically through careful use of independent geological constraints.

FORWARD MODELLING

In forward modelling, which uses published models of AFT annealing (we use here the Crowley et al., 1991, model for Durango apatite, and a modified version of the forward model of Willett, 1992), the user specifies a time-temperature history which is used to calculate an AFT age and a track length distribution for comparison with measured values. The user modifies the trial solution until an acceptable fit is obtained, using available geological data as independent contraints. In the absence of any such contraints, however, a unique solution may not be possible from AFT data alone.

Figure 1 illustrates how the forward modelling approach may suffer from the nonuniqueness problem. Panels a and c show acceptable time-temperature histories that were used to calculate AFT age and track lengths for comparison with measured values (panels b and d). The sample AFT age (66 Ma) is significantly older that its stratigraphic age (~30 Ma), indicating that it preserves a record of cooling prior to deposition during Oligocene time. In both models A and B, the post-30 Ma thermal history as estimated from the known burial history, is identical. However, prior to 30 Ma, model A has a protracted period of cooling from temperatures above the total annealing temperature (approximately 120°C), whereas model B shows moderate heating from surface temperatures to 80°C followed by cooling. Both models produce virtually identical AFT age and length parameters (panels b and d), but have vastly different geological implications.

Model A suggests that the apatite may have been derived from disparate sources which experienced complete AFT annealing, that it cooled during the Late Cretaceous-early Tertiary regional exhumation, and that it was deposited during the Oligocene. Model B suggests a more discrete source such as a volcanic ash which formed at the surface and experienced moderate burial temperatures (80°C) followed by erosion and redeposition. Other geological criteria are needed to choose between these and other possible models.

Figure 3: Inverse AFT Modelling

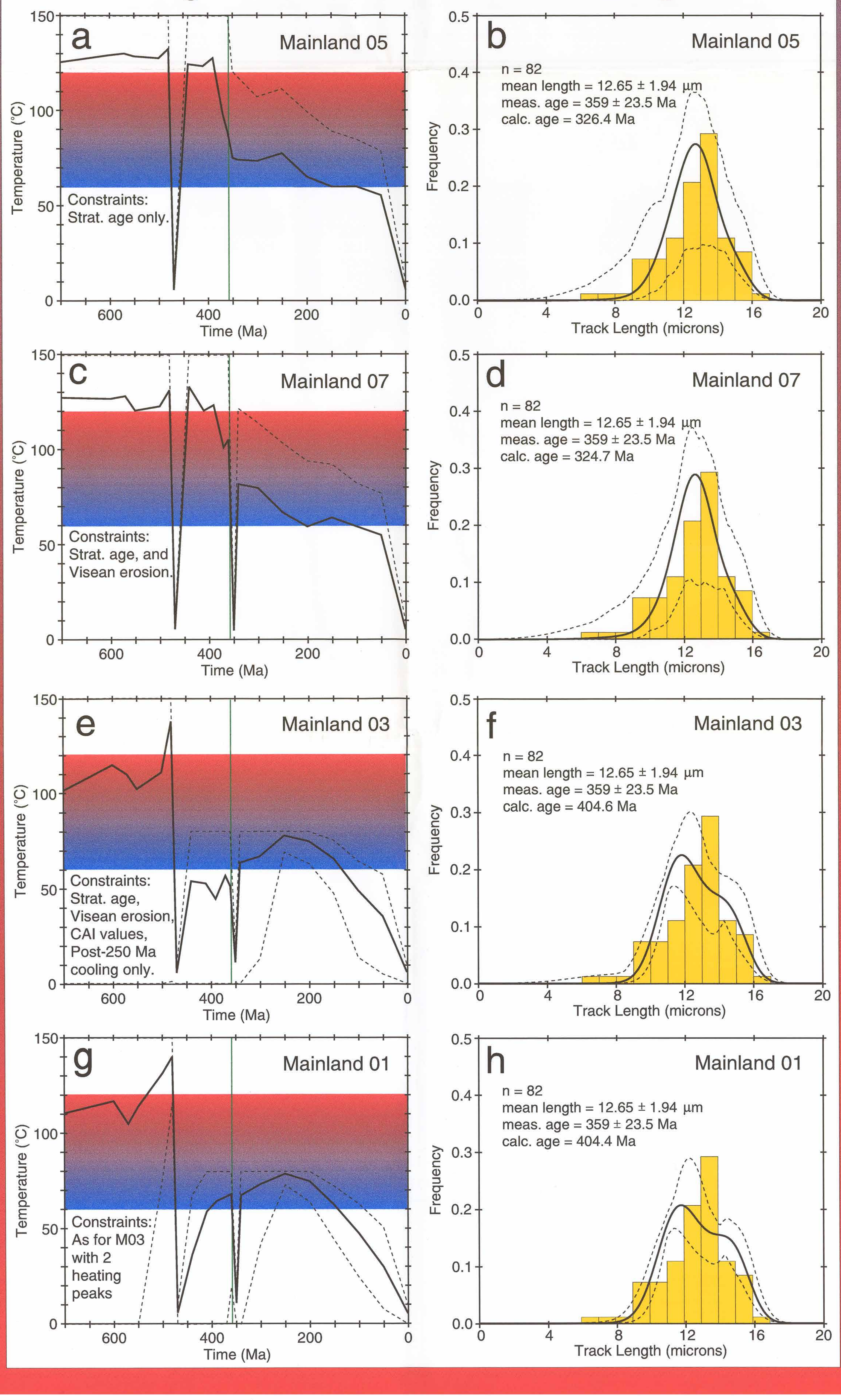
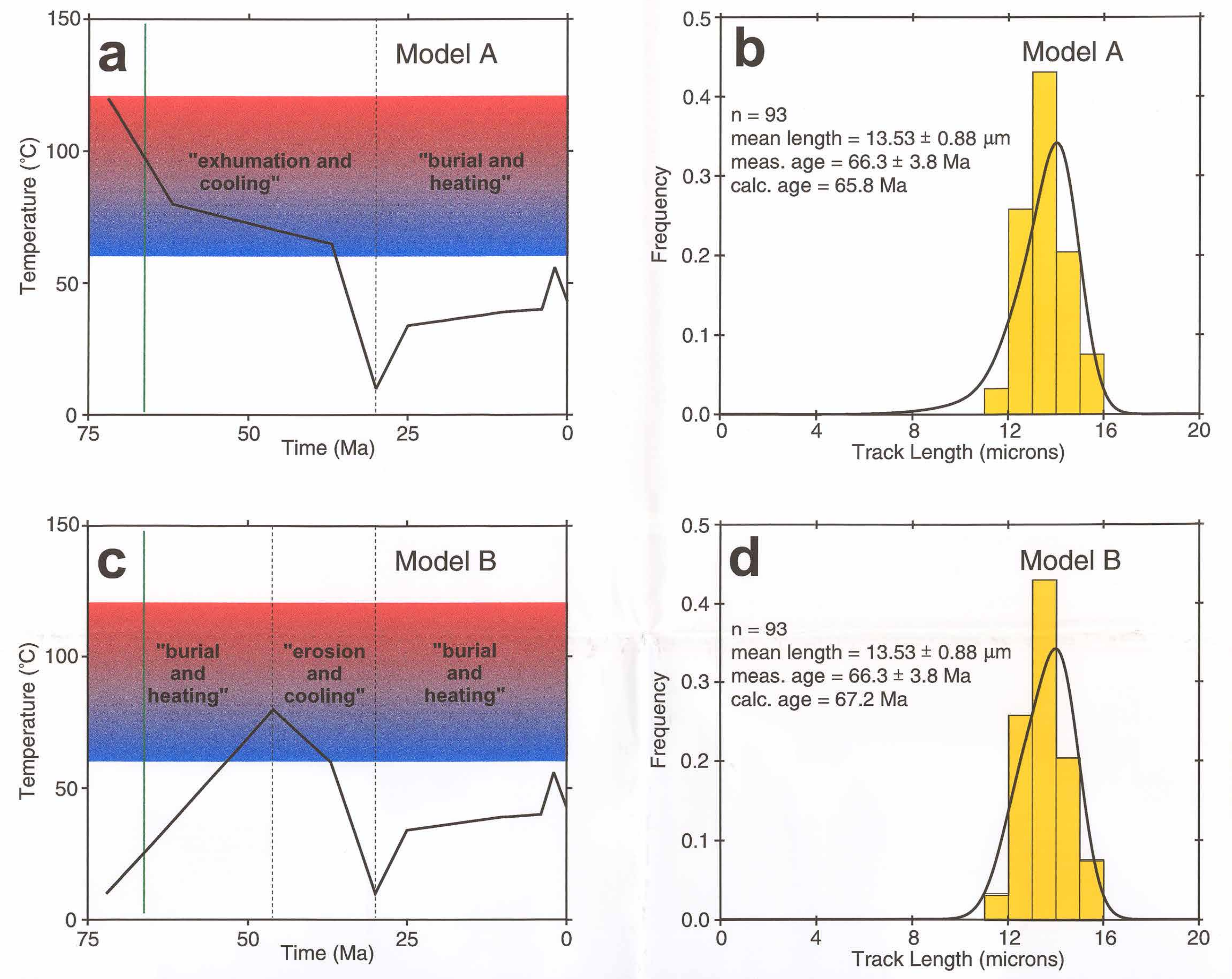


Figure 1: Forward AFT Modelling



INVERSE MODELLING

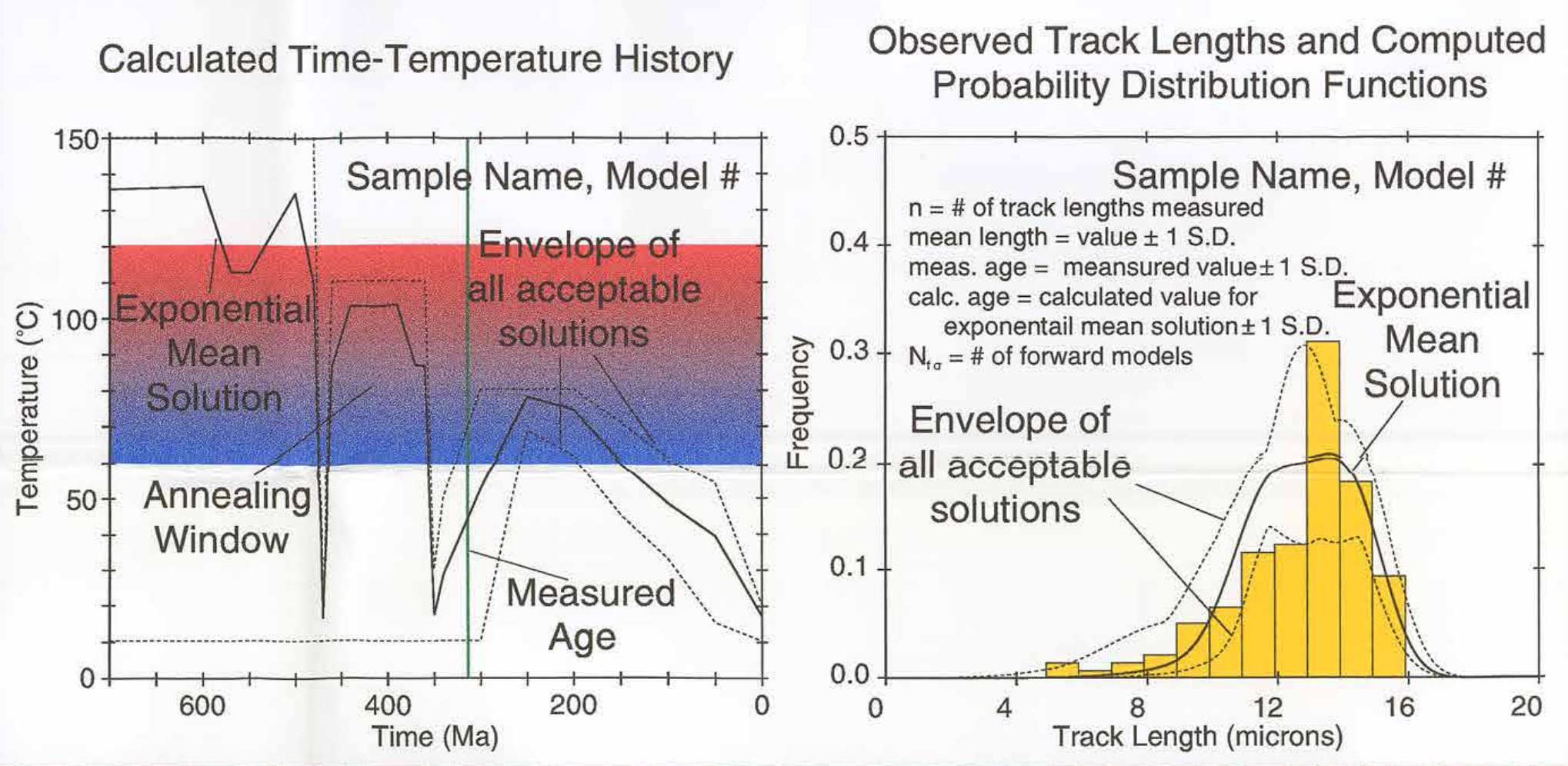
Inverse modelling provides an objective assessment of the variation in thermal histories permitted by a given data set. This approach can also indicate which portions of the thermal history are well resolved by the AFT data and which are poorly constrained. The inverse model used here (see Issler and Willett, 1996, as noted above) runs interactively using a constrained random-search algorithm, to find a set of forward models (any number, specified by the user) which statistically fit the observed fission track age and track length distribution. Figure 2 is a guide to the presentation of the inverse model results.

Figure 2: Presentation Key

Figure 2 explains the presentation of inverse model results. The inversion code used to model observed fission track ages and track lengths generates a set of time-temperature histories which produce ages and track lengths that statistically match observed values.

The first diagram shows the exponential mean thermal history (solid line), and the envelopes on the entire set of solutions (dashed lines); the envelopes are not solutions themselves. The shaded region approximates the partial annealing zone, and the vertical green line marks the measured fission track age.

The second diagram shows the measured track length distribution in histogram form, overlain by the computed distribution function for the exponential mean solution (solid line) and the envelopes on the distribution functions for the entire set of solutions. The stated calculated age is for the exponential mean solution of the entire set of solutions.



The left-hand panel shows: (1) the exponential mean solution for the solution set which statistically fits the measured age and track lengths, (2) envelopes bounding the solution set (the bounds are not solutions themselves), (3) the measured age of the sample (yellow line), and (4) the partial annealing window for AFT (approximately 60°C to 120°C for rates considered here). The right-hand panel shows: (5) statistics indicating the number of observed tracks, mean track length, measured and calculated mean exponential solution ages, and number of forward models required for convergence, (6) a histogram of measured track lengths, (7) the track length probability distribution function for the exponential mean solution, and (8) the envelopes bounding the distribution functions for all solutions.

Figure 3 shows the results of four inverse model runs for a Middle Ordovician sample involved in Appalachian orogenesis and subsequent exhumation, successor basin formation, and re-exhumation. The range of acceptable thermal histories is strongly influenced by the use of additional geological constraints. These include: (1) depositional age of 470 Ma; (2) known proximity to an Early Carboniferous (Visean) erosion surface (modelled as 350 Ma); (3) maximum temperature constraints from Conodont Alteration Index (CAI) values (observed CAI of 1, constraining paleotemperatures to be less than 80°C); and (4) cooling only after 250 Ma (known from regional history of the Carboniferous Maritimes basin). A fifth possible constraint permissible in the inversion program is to place bounds on the maximum geologically reasonable rates for heating and cooling (these would be a function of known environment and history); such bounds are not considered here.

Model 05 for the Mainland Sandstone (Mainland 05, panels a and b, Figure 3), is constrained only by stratigraphic age (constraint (1), above). Model 07 (panels c and d) is constrained by stratigraphic age and proximity to the Visean erosion surface (constraints (1) and (2), above). Model 03 (panels e and f) is constrained by all four constraints considered above. Model 01 (panels g and h) is identical to 03, except that individual acceptable solutions are constrained to have a single heating peak between 470 Ma and 350 Ma, and a second single heating peak between 350 Ma and 0 Ma. The solution sets for models 01, 05, and 07 each include 250 statistically acceptable thermal histories, whereas the solution set for Model 03 includes 1000 thermal histories (a larger number of forward models was required to fill solution space, probably due to the complexity of the imposed constraints).

Models 01 and 03, with identical geological constraints, are very similar, with the mean solution for Model 01 being smoother than that for Model 03 (reflecting the constraint of discrete thermal peaks in Model 01). However, models 01 and 03 are significantly different than models 05 and 07. Imposing independent geological constraints, in the form of maximum temperatures from CAI values, and knowledge regarding the final exhumation history, have sharpened the resolution on the thermal history afforded by the AFT data.

DISCUSSION

These examples underscore the importance of using independent geological constraints in the interpretation of AFT data. "Letting the data speak for themselves" is a useful exercise, but significantly more information can be gleaned by prudent incorporation of other, independent t-T constraints. In the case of the Mainland sample, this additional information has important implications for hydrocarbon exploration in a frontier setting.

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