QUANTITATIVE THERMOCHRONOLOGY

Thermochronology, the study of the thermal history of rocks, provides an important record of the vertical motions of bodies of rock over geological timescales, enabling us to quantify the nature and timing of tectonic processes. Isotopic age data constrain the ages of rocks and minerals, but in many cases they are interpreted without a proper understanding of the relationship between the age measured and the physical processes within the Earth.

Quantitative Thermochronology is a robust review of the fundamental nature of isotopic ages, and presents a range of numerical modelling techniques to allow the full physical implications of these data to be explored. The authors provide analytical, semi-analytical and numerical solutions to the heat-transfer equation in a range of tectonic settings and under varying boundary conditions. The second part of the book illustrates their modelling approach, which is built around a large number of case studies. Various thermochronological techniques are also described in order to help the non-specialist understand the benefits of each method.

Computer programs that provide a means of solving the heat-transport equation in the deforming Earth and allow the prediction of rock ages for comparison with geological and geochronological data are available on an accompanying website (www.cambridge.org/9780521830577). Several short tutorials with hints and solutions are also provided.

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Numerical Methods for the Interpretation of Thermochronological Data

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Preface

The Earth’s surface is continuously reshaped by the interaction of tectonic and surface processes. Where the tectonic forces acting on the lithosphere lead to downward vertical motions or subsidence, the resulting depressions are usually filled with sediments that contain a record of these vertical motions. In actively uplifting regions, however, as well as in passive but formerly uplifted regions of relatively high topography, the surface process response will be mostly erosional and no direct record of past vertical motions exists. In such systems, thermochronology – the study of the thermal history of rocks – provides practically the only record that can be obtained in terms of vertical motions on geological timescales. However, this record is highly non-linear and depends on many parameters that need to be understood in order to interpret thermochronological data meaningfully. In particular, one needs to understand: (1) the relationship between the thermal history of a rock and the accumulation of thermochronological ‘age’, as well as the influences of various physical and chemical parameters on this relationship; and (2) the relationship between advection of rocks towards the surface by the combined effects of tectonics and surface processes, and the thermal structure of the rocks (i.e., the links between the thermal and structural reference frames).

Several outstanding and fundamental problems in the Earth Sciences will rely partly or entirely on the meaningful interpretation of thermochronological datasets for their resolution. To name but one, the debate about the possible interactions between Late Cainozoic climate change and the uplift of some of the Earth’s largest mountain belts has been going on for the last 15 years. Several independent datasets show that sedimentation rates in many of the world’s sedimentary basins have doubled or tripled over the last 2–5 Myr (e.g., Métivier et al., 1999; Zhang et al., 2001; Kuhlemann et al., 2002). This increase is traditionally ascribed to tectonic surface uplift of major mountain belts, which would have led to drawdown of atmospheric CO₂ through increased rates of rock weathering, and ensuing climatic cooling (e.g., Raymo and Rudiman, 1992). However, as Molnar and England (1990) and Zhang et al. (2001) point out, the lack of independent evidence
for surface uplift of mountain ranges during this timespan and the widespread nature of the increase in sediment flux suggest the driving mechanism for this increase to be climatic; thus, the uplift of mountain peaks may be an isostatic response to, rather than a trigger of, increased denudation rates. Such a mechanism requires denudation rates to be highly spatially variable: valley bottoms must eroceed much more rapidly than mountain peaks (i.e., relief must increase) in order for isostatic rebound to be effective in uplifting the peaks (e.g., Montgomery, 1994; Small and Anderson, 1998). The resolution of this debate will thus depend in part on our ability to constrain temporal and spatial variations in exhumation rates within eroding mountain belts effectively.

A related question has arisen out of the realisation that tectonics and erosion are not independently operating processes but must be strongly coupled (e.g., Beaumont et al., 1992; Zeitler et al., 2001). In effect, while tectonics controls erosion rates through the creation of surface relief, erosion in turn also affects tectonic patterns through its role in displacing mass at the surface, thereby influencing the thermal (and hence rheological) stress and potential-energy fields of actively eroding regions. The question is that of whether this coupled system is fundamentally controlled by an internal (tectonic) or external (climatic) driving force. Authors who have attempted to address this question through the comparison of spatial patterns of thermochronological ages with present-day climate (precipitation) data have come to conflicting conclusions (e.g., Burbank et al., 2003; Reiners et al., 2003a; Thiede et al., 2004; Wobus et al., 2003), and its resolution will depend in part on a better comprehension of the significance of spatial variations in thermochronological ages across orogenic systems.

A third and final example may be drawn from the debate about the relative timescales of tectonic versus erosional processes and the significance of the concept of topographic steady state. From a theoretical viewpoint, it is relatively simple to demonstrate that active tectonic systems that are subject to continuous uplift at a constant rate should tend towards flux steady state, where the tectonic influx of material is balanced by the erosional outflux (e.g., Beaumont et al., 1999; Willett et al., 2001). However, it is not clear whether such systems also reach denudational and topographic steady state (where denudation rates and surface topography, respectively, are constant in time). Thermochronological data can be used to test thermal and denudational steady state in mountain belts (Willett and Brandon, 2002), but attempts to demonstrate the existence of denudational steady state in natural settings from such data (e.g., Bernet et al., 2001) have been criticised under the argument that they were inconsistent with other thermochronological datasets (e.g., Carrapa et al., 2003; Cederbom et al., 2004). Again, resolution of this question will depend on our understanding of the significance of spatial and temporal patterns in thermochronological data.
Preface

Technological advance has seen the accuracy and precision of thermochronological techniques rise steadily over the past 15 years. In parallel with this, understanding of the fundamental behaviour of isotopic chronometers on geological timescales has progressed to the point where the thermal sensitivity of key systems can be constrained on a routine basis. These advances have brought progressively greater benefit to quantitative interpretation as a way of adding value to what remain costly analytical techniques.

The purpose of this book is to provide tools to help the Earth scientist undertake such interrogation of thermochronological data in a rigorous and quantitative manner, and, in particular, to extract the information such data contain on the tectonic (i.e., internal deformation) and geomorphic (i.e., surface evolution) history of a given region.

Although working from generally applicable principles, the techniques we develop and describe here are targeted most directly at the interpretation of thermochronological data in environments where (a) tectonic uplift and erosion combine to bring rocks to the Earth’s surface, where they are collected and analysed by the geologist and (b) the amplitude of surface relief is important. We focus in particular on the effect of rock advection and finite-amplitude surface relief on the temperature structure in the Earth’s crust and consider a range of situations from the simplest, where tectonic advection is so slow that the heat is mainly transported by conduction, to the most complex, where rapid vertical advection of heat through a convoluted, cold upper surface produces a complex three-dimensional thermal structure that must be considered. We also consider a range of tectonic settings, ranging from situations where rocks are actively uplifted by ongoing tectonic processes and erosion counteracts the resulting uplift of the surface to situations where, in the absence of any tectonic forcing, rock uplift is solely driven by the isostatic rebound caused by erosional unloading.

The book is built around a progressive increase in complexity both of the tectonic scenarios considered and of the interpretative tools consequently required to interpret thermochronological data. Along the way, a set of Fortran programs developed by the authors is progressively introduced, together with an accompanying series of tutorials designed to assist the reader in understanding how to use these tools to interpret the increasingly complex scenarios. The Fortran programs can be downloaded from the web page; their application will allow the reader to solve the tutorial problems. More importantly, however, the programs are designed to be applied to the interpretation of real thermochronological data in different settings. The Fortran program *Pecube*, which is presented towards the end of the book, is a very general solver of the heat-transport equation that includes conduction, production and advection of heat, as well as the option of varying the geometry of the surface to represent geomorphic processes. It has
been designed for ease of use by any geologist interested in the interpretation of thermochronological datasets. In this context, the book can be regarded as a long, and, we hope, not too painful, introduction to this powerful modelling engine, providing a numerical ‘toolkit’ for a geoscientist looking to interpret such data.

In designing and writing this book, we are aiming at an audience of upper-level undergraduate students and graduate students who are commencing their studies. We have included a set of slides (in PDF format) (see the website) for use during lecturing and tutorials, if one wishes to use this book as a teaching tool. We assume that our audience is acquainted with the basic principles of geochronology, as well as the basics of geodynamics and heat transport in the Earth’s crust. Although we review these basics in early chapters, readers who are unfamiliar with this material may wish to consult textbooks developing these issues in more detail, such as Faure (1986), Turcotte and Schubert (1982) and Fowler (2005). Developments in the field of thermochronology and, more widely, the study of the interaction between tectonics and surface processes are rapid; while we have aimed this book to be up to date as it appears, it is inevitable that we fail to include the most recent studies, however important their implications may be.

The idea for this book was triggered by a short course given by Jean Braun during his appointment as visiting professor at the Université Joseph Fourier in 2002. Most authors who have written a textbook will admit that it has taken them about two to three times as long as they had initially planned. This book is no exception to the rule and we thank the staff at Cambridge University Press for their patience and understanding. Writing of the book was facilitated by mutual visits of the authors; the Research School of Earth Sciences at the Australian National University and the Observatoire des Sciences de l’Univers de Grenoble at the Université Joseph Fourier provided logistical support during these stays. Our thinking on the interpretation of thermochronological datasets was shaped in part through thought-provoking discussions and exchanges with colleagues, collaborators and (former) graduate students. We would like to acknowledge in particular Matthias Bernet, Mark Brandon, Roderick Brown, Jim Dunlap, Kerry Gallagher, Frédéric Herman, Barry Kohn, Erika Labrin, Ian McDougall, Peter Reiners, Xavier Robert, Malcolm Sambridge and Michael Summerfield. Many of the ideas presented in this book were developed during research projects funded by the Australian Research Council (ARC), the Institute of Advanced Studies of the Australian National University, the Institut National des Sciences de l’Univers (INSU) of the Centre National de la Recherche Scientifique (CNRS) in France and the National Environmental Research Council (NERC) in Britain. Finally but definitely not least, we would like to thank our partners Myriam, Gianna and Victoria as well as our families for their support and understanding as we became more and more submerged in this undertaking.