Introduction to Quaternary Geochronology

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INTRODUCTION

In this day and age an Earth scientist cannot describe Earth's history without numerical age estimates and a geochronologist cannot provide a numerical age in the absence of geological context. Mutual support is thus required, and the best results are achieved when both disciplines understand each other and work together. In this volume we have put Earth scientists and geochronologists together to explain their art of telling time with a wide variety of materials, lifeforms and landforms found on or just beneath the earth's surface. We focus on those parts of the Earth system that have been affected by tectonic activity during the Quaternary period, the last 1.8 million years (Ma). This involves determining the timing and rates of neotectonic activity, the pursuit of a field of study known as paleoseismology. It is commonplace within the field of paleoseismology to obtain rigorously detailed age estimates involving several dating methods. With such a focus the information presented here is entirely useable in nearly all other known applications in Quaternary science. Determining the age of an event is a common pursuit amongst Quaternarists and most will find that dating an earthquake can be much like dating a host of other geologic events. Whereas the age of materials under inspection here fall within the Quaternary, many of the methods, approaches, and applications are relevant to the telling of time in all of Earth history. Thus this volume should be of wide interest and information included herein should be widely applicable.

A variety of geochronologic methods are used in Quaternary science. The status of these methods falls in one of two categories: well-established or experimental. Many dating methods are well established, meaning that they have been widely accepted and applied by the scientific community. In fact some of the methods, such as K-Ar geochronology, were established on much older Earth materials and their range of applicability continues to be extended to ever younger ages. Other methods are new, have not been fully tested or have not yet been widely accepted. These methods are considered experimental. In this volume we review a selection of both the major established methods and promising new or experimental methods. In particular, we describe those methods that offer the greatest potential for constraining the timing and rates of Quaternary tectonic deformation. These methods are described in a series of peer-reviewed papers (chapters) authored by knowledgeable experts, in most cases the researcher is actively involved in the development, application, or refinement of the method described. The geochronology chapters are followed by a section on paleoseismology and case studies that present a variety of current applications of these methods.

Tips to the Reader

It is intended that the reader of this volume gain an overall appreciation and understanding of Quaternary geochronology. Key attributes of the major methods are summarized in chart

Quaternary Geochronology: Methods and Applications
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form in Plate 1, a handy reference that should allow quick comparison and selection of methods, even if one has not read this volume. For each method on this chart we describe what the community considers to be its status, age range and resolution of its applicability, typical reporting error, basis of the method, and applications of the method to dating Earth materials and landforms. See *The Essence of Quaternary Geochronology* below for information that further explains this chart. Our intent is to assist Earth scientists with the selection of appropriate geochronological methods for their specific field setting (context). The information herein also is of use in evaluating and interpreting existing data and interpretations thereof.

Chapters on geochronological methods were written from the same basic outline to make it easier for the reader to find information and compare methods. The parallel organization of topics begins with theory and basis of the method, including principles and assumptions, time range of applicability, and appropriate geologic setting. The "how to" of the method is presented next, including sample collection, preparation and transportation, and analysis in the field and/or laboratory. All important techniques, subsets of the method, are provided for the most part in a "cook book" style. Guidance is provided as to how to analyze the results and assess confidence in the interpretations thereof. Tips are provided for how to present and communicate these results to others. Paleoseismic applications, both known and potential, are discussed. Finally, sections on limitations, maximum utility and future developments in the method should provide the reader with an honest assessment of just how good the method is now and may be in the future. Not all chapters cover all of these topics, and not necessarily in this exact order. For each method has its own peculiarities that preclude such universal treatment of the subject.

Not a Rulebook

Let it be known here that *this volume is not a rulebook.* Thus it should not be read as such. The intent of this volume is provide the reader with a guide to conventions and ways of doing things in assessing the age of Quaternary Earth materials and landforms. The methods, approaches, applications and other information presented here are not unique to the presenting author, but rather are held in common by the community at large. Each author was given the charge to be as fair and balanced as possible in bringing the differing viewpoints, if they exist, to the attention of the reader. We wish the reader a healthy bit of skepticism in reading this volume and creative energy in applying this knowledge, for in this way we will continue to see advances in methodology and applications.

No Black Boxes

Quaternary geochronology can be seen as a collection of strategies or approaches that apply one or more methods in the quest to estimate the age of a material and/or landform. There are no simple "black boxes" in this field. Strategies and methods vary widely in theoretical basis, mode of measurement, applicable geologic settings, resolution, type of result, and community confidence. Some methods employ highly sophisticated instrumentation and analytical methods, whereas others rely on simple field measurements. No one approach or method can provide reliable age estimates in all contexts; thus the researcher must be familiar with as many methods as possible. Because it is not unusual that no method is found to be entirely suitable, the researcher should be prepared to adapt an existing method or develop a new strategy for a specific field problem. Let's now consider the complexity of the types of methods and their results, and then be introduced to one useful means of classifying them. The arrangement of method chapters in this volume follow this classification scheme.

CLASSIFICATIONS OF QUATERNARY GEOCHRONOLOGIC METHODS

Steven M. Colman and Kenneth L. Pierce

Introduction

In the past three decades, considerable progress has been made in estimating the age of Quaternary deposits and surfaces. These efforts use methods that range from traditional geologic analysis, such as stratigraphy and correlation, to high-precision analytical techniques such as those used in isotopic dating. All dating methods, both established ones and new experimental ones, yield results that vary greatly in precision and accuracy. Consequently, terminology for Quaternary dating methods has evolved along lines that describe the types of age information provided by the methods. Unfortunately, this evolution has sometimes led to confusing, inaccurate, or deceptive terminology. Colman and others (1987) suggested a terminology for Quaternary dating methods that is seeing increased use among geologists, and is reproduced with minor modification here. The terminology is derived from two types of classifications, based on type of method, and type of result. These suggestions represent an evolution in our thinking over a period of years (Colman and Pierce, 1977, 1979, 1991; Birkeland and others, 1979; Colman, 1986; Pierce, 1986; Colman and others, 1987). This chapter is adapted from Colman and others (1987). Several summary papers have been recently published on Quaternary dating methods, including Easterbrook (1989), Geyh and Schleicher (1990), Rosholt (1991), Rutter and others (1989), and Beck (1994).

Classification by Method

A practical classification of Quaternary dating methods is one that groups methods that share similar assumptions, mecha-

Table 1. Classification Of Quaternary Geochronologic Methods

Type Of Result

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≡≡≡≡≡≡≡≡ Numerical-Age ≡≡≡≡≡≡≡≡[1]---------------------------------------------------------
                     -----------≡≡≡≡≡≡≡ Calibrated-Age ≡≡≡≡≡≡≡[1]-------------------------
                     -----------≡≡≡≡≡≡≡ Relative-Age ≡≡≡≡≡≡≡≡[1]--------------------------
                                -----------------------------≡≡≡ Correlated-Age ≡≡≡[1]
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Type Of Method

Sidereal	Isotopic	Radiogenic	Chemical and Biologic	Geomorphic	Correlation
Dendrochronology[3] Sclerochronology[3] and annual growth in other organisms (e.g. mollusks) Varve chronology[3] Historical records	Radiocarbon[3] Cosmogenic isotopes[3] ^{36}Cl, ^{10}Be, ^{26}Al, ^{14}C, ^{3}He, and others[2] K-Ar and ^{39}Ar-^{40}Ar[3] Uranium-series[3] ^{210}Pb[3] U-Pb, Th-Pb[3]	Fission track[3] Thermoluminescence[3] Optically stimulated luminescence[3] Infrared stimulated luminescence Electron-spin resonance[3]	Amino-acid racemization[3] Obsidian hydration[3] and tephra hydration Rock-varnish cation ratio[3] Lichenometry[3] Soil chemistry ^{10}Be accumulation in soils	Soil-profile development[3] Rock and mineral weathering[3] Scarp morphology[3] and other progressive landform modification Rock-varnish development[3] Rate of deposition Rate of deformation Geomorphic position Stone coatings ($CaCO_3$)	Stratigraphy Paleomagnetism[3] Tephrochronology[3] Paleontology[3] Archeology Climatic correlation[3] Stable isotopes Astronomical correlation Tectites and microtectites

[1] Triple-dashed line indicates the type of result most commonly produced by the methods below it; single-dashed line indicates the type of result less commonly produced by the methods below it.

[2] Some cosmogenic methods, particularly exposure ages, have some similarities with methods in the "Radiogenic" column (see text).

[3] Methods discussed in detail in this volume.

nisms, or applications. Accordingly, we group dating methods into the following six categories:

1. *Sidereal* (calendar or annual) methods, which determine calendar dates or count annual events.
2. *Isotopic* methods, which measure changes in isotopic composition due to radioactive decay and/or growth.
3. *Radiogenic* methods, which measure cumulative effects of radioactive decay, such as crystal damage and electron energy traps.
4. *Chemical and biological* methods, which measure the results of time-dependent chemical or biological processes; these processes are generally simpler that those whose results are measured under "geomorphic methods."
5. *Geomorphic* methods, which measure the cumulative results of complex, interrelated, physical, chemical, and biologic processes on the landscape.
6. *Correlation* methods, which establish age equivalence using time-independent properties.

These six groups of methods are shown in Table 1 under the lower header "Type of Method." Not all methods fit neatly into one category or the other. For example, weathering and soil development are primarily the result of chemical and biological processes, but they are also geomorphic processes, and their use in estimating ages is more akin to other methods in the geomorphic category. Also, cosmogenic isotopes, used as a measure of surface-exposure age, are quite similar to radiogenic methods, despite measurement techniques and other applications that are typical of isotope-decay methods.

Classification by Result

The most useful classification of dating methods is probably one based on the types of results that they produce. Age estimates, like any other measurement, can be classified by the type of measurement scale according to measurement theory (Stevens 1946; Krumbein and Graybill, 1965, p. 38; Griffiths, 1967, p. 247; Colman 1986). These scales are *nominal* (measurement is a class or group assignment), *ordinal* (measurement is an order or rank), *interval* (measurement is a number whose difference with another is fixed), or *ratio* (measurement is a number whose ratio with another number is fixed). This scheme requires modification for dating methods because (1) most methods that actually measure ages, by definition, contain more information than nominal measurements, and (2) even though many methods, such as isotopic methods, use an arbitrary zero (the present or A.D. 1950) and are thus interval methods, in effect, they can be considered ratio methods (Colman, 1986). Nevertheless, this classification derived from measurement theory is useful for classifying dating methods according to the results that they produce.

The classification listed below is also given at the top of Table 1; it divides dating methods into four categories based on the type of result that they produce: *numerical-age, calibrated-age, relative-age*, and *correlated-age* methods.

1. *Numerical-age* methods are those that produce results on a ratio (or absolute) scale, that is, they produce quantitative estimates of age and uncertainty whose ratios can be compared; results of some of these methods have been called absolute ages, although we object to this usage, as discussed later.

2. *Calibrated-age* methods can provide approximate numerical ages. Many dating methods that measure systematic changes resulting from individual processes or related groups of processes are being developed. The rates of these processes depend on environmental variables, such as climate and lithology, so that the process rates must be calibrated by independent chronologic control; we refer to these increasingly useful methods as calibrated-age methods. Many relative-age methods (see #3), when calibrated by independent chronologic control, become calibrated-age methods, employing a ratio scale. This usage should not be confused with "calibrated" radiocarbon ages.

3. *Relative-age* methods provide an age sequence (an ordinal measurement), and most provide some measure of the magnitude of age differences between members of a sequence. These methods have also been called "relative-dating methods," but the use of "relative-age" is encouraged for consistency.

4. *Correlated-age* methods do not directly measure age; they produce ages only by demonstrating equivalence to independently dated deposits or events, and thus are essentially nominal-scale methods.

Considerable overlap exists in these classes (Table 1). For example, measurements of amino acid racemization may yield results as relative age, calibrated age, correlated age, or numerical age, depending on the degree to which calibration and control of environmental variables constrain the reaction rates. In addition, the grouping by type of result may be considerably different than that by type of method. For example, some isotopic and radiogenic methods routinely produce numerical ages, whereas others are more experimental or empirical and require calibration to produce numerical ages. Such methods commonly serve as calibrated-age methods, but under unfavorable conditions they may produce only relative ages.

Some Terminology

The North American Stratigraphic Code (N. A. Commission on Stratigraphic Nomenclature, 1983) made several recommendations concerning terminology for geochronologic data. The discussion that follows is generally compatible with those recommendations; it includes some additions and amplifications pertinent to Quaternary geochronology.

Strictly defined, a *date* is a specific point in time, whereas an *age* is an interval of time measured back from the present. The use of "date" as a verb to describe the process of producing age estimates is generally accepted. However, in geologic applications, "date," when used as a noun, carries a connotation of calendar years and a degree of accuracy that is seldom appropriate. Most "dates" are better described as "age estimates" or simply "ages." Exceptions include dates derived from historical records, and some ages derived from tree rings, varves, or coral growth bands. Further, the degree of confidence that is associated with an age can be conveyed by expressing ages in terms of the method that was used to generate them, as in "amino-acid ages." In spite of its connotations, we recognize that the use of "date" is firmly entrenched, that alternatives are sometimes awkward, and that the verb or its derivatives are acceptable. Finally, the phrase "age dating" is grossly redundant, and should be abandoned.

With regard to abbreviations used to express ages, the North American Commission on Stratigraphic Nomenclature (1983) made a distinction between (a) *ages* determined by geochronologic methods and (b) *intervals* of time. They recommend the use of the SI-derived abbreviations *ka* and *Ma* (thousand and million years *ago*, respectively, measured from the present) for ages, and informal abbreviations such as *yr, k.y.*, and *m.y.* for time intervals. Time measure from the present is implicit in *ka* and *Ma*; neither "before present" nor "ago" should be added to these abbreviations. Ages of less than 1,000 years may be awkward to express in *ka*, but radiocarbon ages in this range can be expressed in *yr B.P.*, and ages derived from sidereal methods (Table 1) can usually be expressed as calendar dates. In the rare remaining cases, we recommend that ages of less than 1 ka be expressed simply in years or *yr*, despite the lack of distinction in such cases between ages and time intervals.

Radiocarbon dating has established the use of the phrase *yr B.P.* to indicate radiocarbon ages measured from 1950 A.D. Radiocarbon ages depart from true calendar ages due to past variations in the atmospheric production of radiocarbon. To indicate that radiocarbon ages have been calibrated for such atmospheric variations, the designation "cal" should be included, such as *13,500 cal yr B.P.* ("cal" designates calibrated, not calendar.) To avoid confusion, the use of *yr B.P.* should be restricted to radiocarbon ages. Historic calendar ages should be reported as the year A.D. or B.C.

The use of the word "absolute" to describe any dating method, all of which carry inherent uncertainties is not recommended. "Absolute" commonly has been used to describe the results of isotopic dating methods, but variation in estimates of analytical precision, decay constants (e.g., Steiger and Jager, 1977), or half-lives (e.g., Grootes, 1983) invalidates the "absoluteness" of the age estimates derived from these methods. In addition, undetected contamination and geologic uncertainties, such as the delay between a geologic event and the "time zero" used by a dating method, commonly render isotopic ages (indeed, all age estimates) less than absolute. Radiocarbon dating is perhaps the most widely applied isotopic method used for the Quaternary, yet many reports discuss the difficulties in interpreting radiocarbon ages (e.g., Thom, 1973; Goh and others, 1977; Worsley, 1980; Clayton and Moran, 1982; Bloom, 1983). The departure of the radiocarbon time scale from calendar years is well determined for Holocene time (Stuiver and Reimer, 1993) and from 6,000 to 8,000 years ago, radiocarbon ages are 700-1,000 years too young (Stuiver and Pearson, 1993). For pre-Holocene time, the departures are considerably larger, but much less well determined. For example, about 20,000 years ago, apparent radiocarbon ages are about 3,000 years younger than ^{230}Th/^{234}U ages (Bard and others, 1993; see also Mazaud and others, 1991).

Earlier, we recommended that "absolute" be abandoned and the term "numerical" used for age estimates that provide quantitative estimates of age and uncertainty on a ratio (absolute) time scale (Colman and others, 1987). Ample precedent exists for this use of the term "numerical" in the geochronologic literature, especially for pre-Quaternary time (cf. papers in Snelling, 1985). Furthermore, this usage is recommended in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983).

Summary Statements for Classification

We group Quaternary geochronologic methods into four classes based on **type of result** – *numerical-age, calibrated-age, relative-age*, and *correlated-age* – to describe the level of information and the degree of confidence they produced. We further classify Quaternary dating by **type of method** into *sidereal, isotopic, radiogenic, chemical* and *biological, geomorphic*, and *correlation methods*. We recommend that the term "absolute" be replaced by "numerical," and that the use of "dates" be minimized in favor of "ages" or "age estimates." Recommended abbreviations for most ages are *ka* and *Ma*. Calendar dates (A.D. or B.C.) can be used for ages derived from sidereal methods and calibrated radiocarbon ages. Uncalibrated radiocarbon ages are designated by *yr B.P.*

THE ESSENCE OF QUATERNARY GEOCHRONOLOGY

Janet M. Sowers and Jay Stratton Noller

Introduction

Estimating the ages of Quaternary materials and landforms has proved to be a challenge. Some isotopic methods that provide insights into the age of the Earth are inapplicable to materials of Quaternary age. Whereas some isotopic methods that are applicable to the Quaternary have a narrow time range and a limited number of appropriate applications. In fact, no single method has emerged that is applicable throughout the Quaternary to common materials of this age. Thus, with this in mind, we present in this volume a large selection of tools that are presently available to estimate the age of Quaternary geologic materials.

Twenty-two dating methods or groups of methods are described in the following chapters. A summary of these methods is provided in chart form on Plate 1, Methods for Dating Quaternary Surficial Materials. The following general discussion can be used as a guide to this chart. On Plate 1, geochronologic methods are grouped by type of method and expected type of result. Plate 1 also identifies the Earth materials and landforms that are most suitable for each dating method.

The time range of applicability indicated for each method is that considered by the respective author(s) to be typical for each method under optimum conditions where the assumptions of the method are met and samples are of high quality. The range may be extended under especially favorable circumstances. Conversely, the range may be shortened under less than ideal circumstances. Resolution shown is also that which the author(s) believe is typical under optimum conditions, and does not generally include error associated with geologic context, unless otherwise noted. Care must be taken to assess all sources of uncertainty and to add this error to the analytical error, as we discuss later.

The distinction between methods that provide the age of the Earth material and those that provide the age of a geomorphic surface is critical. The age of the Earth material represents the time when the material was deposited (sedimentary materials), manufactured, grew or died (biological materials), cooled from a melt (igneous materials), or ceased metamorphism (metamorphic materials). For example, the radiocarbon age of a peat represents the time since the peat was deposited; the hydration age represents the time since someone made a tool out of obsidian; the luminescence age of an eolian sand represents the time since the sand was last exposed to sunlight, then deposited and buried; and the K-Ar age of a basalt represents the time since the basalt cooled and crystallized shortly after eruption.

The age of a geomorphic surface, however, represents the time interval of exposure of the surface to the atmosphere or hydrosphere (shallow water). For example, a soil-profile development age represents the length of time the surface was exposed to soil-forming processes; a cosmogenic nuclide age represents the length of time the surface was exposed to cosmic radiation; a lichenometry age represents the length of time the exposed surface was suitable for lichen growth; and a marine shoreline age (by correlation with the global sea level curve) represents the time since waves were breaking on it.

In some cases, the age of the deposit and the age of the surface are the same, and a method applicable to the deposit also can estimate the age of the surface and vice versa. For example, the K-Ar age of a lava flow may be the same as the cosmogenic nuclide age of the lava flow surface if the flow in question is presently at the surface and has not been eroded, or buried and exhumed. As a rule, however, the age of a deposit and the age of a surface are different. If a lava flow is overlain by subsequent flows, its age will be much greater than the time interval that this particular flow was exposed at the surface. Similarly, the time of development of a soil-profile on the surface of an alluvial deposit that has not been eroded since deposition will represent fairly well both the time interval of exposure and the age of the deposit. If, however, the soil has formed on an eroded deposit, the age determined by an evaluation of soil-profile development will be younger than the deposit. Soil age will better represent the age of the erosion event. The deposit itself must be assayed by a method that dates the time of deposition, such as luminescence geochronology or tephrochronology.

Sidereal (Calendar or Annual) Methods

Sidereal methods, also known as calendar or annual methods, are those that determine calendar dates or count annual events. Three sidereal methods are presented in this volume: dendrochronology, varve chronology, and sclerochronology. Dendrochronology is based on the tendency of trees to produce one new ring of growth each year. Rings can be counted and patterns of wide and narrow bands correlated. Varve chronology is based on the annual accumulation of winter and summer sediment layers that can also be counted and correlated. Having parallels with dendrochronology, sclerochronology is based on annual growth rings in corals. Other sidereal methods may use growth rings in other organisms such as mollusks. Use of historical records to obtain calendar dates of geologic events (not presented here) also is a sidereal method, based on historical documentation of these events.

All sidereal methods provide a numerical-age result, meaning they estimate age on an absolute scale. A sidereal age estimate is typically expressed as a calendar date to the nearest year. The number for the year may vary depending on local conventions for denoting calendrical time; for example, AD (anno Domini) or CE (common era) are used for the past two millenia in most scientific publications. Resolution may be as little as an hour, as with a well-documented historical event, or as great as a decade or more if the record is poor or if correlations are uncertain.

Isotopic Methods

Isotopic methods are those that measure changes in isotopic composition due to radioactive decay. Radioactive decay is the spontaneous emission of alpha particles, beta particles, or gamma rays and the production of a daughter nuclide by the disintegration of a parent nuclide. This decay occurs at a constant rate without regard to environmental factors. Isotopic methods use the basic decay equation:

$$\text{rate of decay} = \frac{\partial N_p}{\partial t} = -\lambda_p N_p \tag{1}$$

where Np is the number of parent isotope atoms, λp is the decay constant of the parent nuclide.

The half life of the parent nuclide ($t^{1/2}$) is the period of time during which one half of the existing parent atoms decay to daughter atoms. The half-life is equal to the natural log of two divided by the decay constant:

$$t^{½} = \frac{\ln 2}{\lambda_p}. \tag{2}$$

The geologic material can be dated given the initial and current ratios of parent to daughter atoms, and the half-life of the parent nuclide:

$$t = \frac{1}{\lambda_p} \cdot \ln\left[\left(\frac{N_d}{N_p}\right) + 1\right], \tag{3}$$

where t is the time elapsed since the system was closed. This is the simplest case, and each method may require modifications and assumptions to deal with multiple decay constants or more complex systems.

We subdivide the isotopic methods into either: (1) standard isotopic methods, those that are based on the steady of decay of a fixed amount of radioactive material incorporated into the sample at the time of formation; or (2) cosmogenic nuclide methods, which are based on the constant formation and decay of radioactive isotopes in the sample, with additional radiogenic nuclides continually formed from cosmic ray bombardment near the surface.

Standard isotopic methods assume a completely closed system after formation, and no loss or gain of isotopes except through decay. Radioactive isotopes are incorporated into the sample at the time of formation, and ages are calculated based on the relative numbers of parent and daughter isotopes. Standard methods presented in this volume include radiocarbon, potassium-argon, argon-argon, U-series, ^{210}Pb, U-Pb, and Th-Pb. Of these, radiocarbon is by far the most widely used for Quaternary studies. The radiocarbon method is applied to cosmogenic carbon incorporated into living plant and animal tissue, or carbonate, materials common to Quaternary deposits, and is applicable over the Holocene and latest Pleistocene.

Cosmogenic nuclide methods also assume a closed system in that nuclides cannot be gained or lost within the geologic material. The system must be open with respect to cosmic rays, however, and nuclides in the material convert to other nuclides *in situ* from cosmic-ray bombardment. These cosmogenic nuclides then may undergo radioactive decay to daughter nuclides. Cosmogenic methods presented include ^{26}Al, ^{36}Cl, ^{3}He, and ^{14}C.

All cosmogenic nuclide methods provide surface exposure ages; they measure the length of time that the near-surface geologic materials have been exposed to cosmic rays. For example, they have been used to estimate the age of the surface of a lava flow, the age of the surface of a fluvial terrace, or the time a boulder outcrop has been exposed. The occurrence of erosion or deposition during exposure is a complicating factor that introduces error into the result.

Both standard and cosmogenic isotopic methods produce a numerical-age result, expressed in years or thousands of years in the past. Some isotopic methods benefit from calibration with other methods to provide more accurate results.

Radiogenic Methods

Radiogenic methods measure the cumulative non-isotopic effects of natural radioactive decay on minerals. Three methods are presented: fission track, luminescence, and electron-spin resonance. The fission track method measures the accumulation of damage trails (fission tracks) in minerals or glass from the natural fission decay of trace uranium. The luminescence and ESR methods measure the accumulation of electrons in the crystal lattice defects of silicate minerals due to natural radiation. All radiogenic methods must be calibrated for the level of natural radiation. In the case of fission track, the ^{238}U content of the mineral grain is measured. In the case of luminescence and ESR, the environmental dose rate is determined by field or laboratory measurements.

The type of result produced by radiogenic methods is generally considered to be a numerical-age result. The results do not depend on other methods for calibration. However, the confidence in the result can often be improved by calibration to other methods.

Chemical and Biological Methods

Chemical and biological methods are based on time-dependent chemical or biological processes, or both. Chemical methods involve change in chemistry or chemical properties of materials with time, including diagenesis of organic compounds (amino-acid racemization), adsorption of water (obsidian hydration), and leaching (rock-varnish cation-ratio). Biological methods involve the growth of lifeforms that do not provide a sidereal record (e.g., lichenometry). Other methods, not presented in this volume, include progressive changes in soil chemistry, growth of carbonate stone coatings in soils, tephra hydration, and ^{10}Be accumulation in soils.

Chemical and biological methods provide a relative-age result unless they are calibrated to other methods, in which case they provide a calibrated-age result. The rates of these processes may be linear or non-linear, and they vary with both materials and environmental factors. Thus, calibration is best made to similar materials in similar environments and age range. The methods may sometimes provide a correlated-age result if the properties of the material of interest can be compared with, and correlated to, material of known age in a similar environment.

Geomorphic Methods

Geomorphic methods are based on progressive changes of geomorphic features through time, including landscapes and soils. These features are the results of complex, interrelated, time-dependent geomorphic processes, including chemical and biological processes as well as physical surface processes. Presented in this volume are soil-profile development, rock and mineral weathering, and decay of scarp morphology. Both soil-profile development and rock and mineral weathering can also be considered chemical and biologic methods, but typically involve a more complex interaction of processes than other chemical and biologic methods. Conversely, rock varnish development, presented in the chemical-biologic section along with rock varnish cation-ratio, can also be considered a geomorphic method. Scarp morphology measures the progressive rounding of scarp profiles due to surface processes. Other geomorphic methods based on landscape evolution are those that measure rates of downcutting, deposition, or deformation, or that utilize geomorphic position as a relative age indicator.

Geomorphic methods provide a relative-age result, and, under favorable circumstances, a calibrated-age result. Indeed, geomorphic methods, especially rock and mineral weathering techniques, have often been termed relative-age-dating techniques (RAD). Calibrated ages can be determined if an independently dated stratigraphy is available. However, the rates of geomorphic processes are highly dependent on factors other than time, such as climate, lithology, biota, and topography, and rates are typically non-linear through time. This results in typically poor resolution for calibrated ages. The most accurate and precise calibrated ages are those calibrated to a well-dated local stratigraphy where environmental and geologic factors closely match those at the site. Even so, resolution will be below that of most other methods. The benefits of applying geomorphic methods, however, are that they are easily performed and widely applicable to a variety of environments, and that the relative-age results and gross calibrated ages, though approximate, are quite reliable.

Correlation Methods

Correlation methods are those that establish age equivalence using time-independent properties. To obtain an age-estimate, a geologic unit is correlated, using a variety of properties, to another independently dated geologic unit. Methods presented include: (1) paleomagnetism, in which remanent magnetism of the rock or sediment is correlated to a dated magnetic stratigraphy; (2) tephrochronology, in which distinct physical or chemical characteristics allow identification of tephra of a specific eruption; (3) paleontology, in which correlation is made to a dated sequence of fauna or flora; and (4) climatic correlations, in which deposits and landforms, such as glacial deposits, coastal terraces, eolian deposits, fluvial terraces, or lacustrine features, can sometimes be correlated to climatic events, based on models of geomorphic response to climate change and known ages for specific climatic events. Correlation methods not presented include archaeology, astronomical correlations, and tectites and microtectites, in which meteor shower events are correlated.

Correlation methods generally provide a correlated-age result. The age is determined by establishing age-equivalence to an independently dated unit. For example, a tephra may be correlated by its chemistry to an eruption whose associated flows are dated by K-Ar, thus the tephra is assigned the same age as the flow. Some correlation methods, those that show progressive change in the properties through time, can also provide a relative-age result. Paleontology often provides relative ages. For example, the evolution of microtine rodents is progressive such that any group of fossil remains can be placed in relative-age order. Geomorphic features also can provide relative ages by their relative geomorphic position, as seen in a flight of coastal terraces or sequence of nested moraines.

Assessment of Confidence in Result

A date is of little value if the confidence associated with that date is low, unknown, or unassessed. Degree of confidence is critical to any geological interpretations that rely on the geochronological data. Clearly, a date of 10,000 ± 800 years will merit a different sort of interpretation than a date of 10,000 ± 8,000 years. Despite its obvious importance, geochronologic data commonly are published without an adequate assessment of confidence.

Assessment of confidence begins with an inventory of sources of uncertainty. All sources of uncertainty should be accounted for and quantitatively evaluated to the extent possible. Sources of uncertainty will vary with the geologic context, age range, and methods used, but usually include the following categories:

- Analytical error
- Natural variability in sample quality or suitability
- Geologic context errors
- Calibration errors
- Violations of assumptions

Analytical error for the numerical and radiogenic methods commonly is reported by the geochronology laboratory in terms of a mean and standard deviation. For the radiocarbon age 7550 ± 320 yr B. P., the mean of the data is 7550 yr B. P. and the standard deviation (1-σ) is 320 years. If the reported error is 1-σ, then there is 68 percent confidence that the true mean lies within the stated range. If the reported error is 2-σ, then there is 95 percent confidence that the true mean lies within the stated range. Analytical error is usually based on repeated counts, measurements, and comparison with standards of the same sample.

Natural variability is evaluated by analyzing a representative population of suitable material, then determining a mean and standard deviation. If only one sample is analyzed, natural variability cannot be assessed. Unfortunately, error due to natural variability often is ignored if multiple analyses are not run, a common consequence of insufficient funding. A common misperception is that analyzing large numbers of samples increases error. The truth is that, although analyzing one or two samples may produce a small known error, the unknown error due to natural variability could be very large, and will remain unknown until a representative sample is analyzed. Analyzing a larger number of samples allows appropriate quantification of the error associated with natural variability, and will result in greater confidence in the accuracy of result.

Errors in documenting and interpreting geologic context have the potential to be among the largest of errors, and thus are important to evaluate. Geologic context refers to the relationship of the sampled material (ultimately dated) to the surrounding stratigraphy. For example, detrital charcoal washed into a peat bed may yield a much older radiocarbon date than the peat itself, thus the geologic context error is large. Geologic context error also may be quite large when measuring anomalously thick weathering rinds on clasts inherited from an older soil. Geologic context error also is introduced when a paleomagnetic sequence is miscorrelated because the stratigraphic context was improperly interpreted. In some cases geologic context error can be quantified and added to other errors, simply decreasing the precision of the date. In other cases, a geologic context error will be so large or unquantifiable as to result in discarding the data.

Calibration error must be considered when calibrating one method to another to improve the age result, e.g. converting a relative-age result to a numerical-age result. Calibration error is the cumulative error propagated from the original data set and that of the calibrator method. For example, soil-profile development can be calibrated by establishing a sequence of reference soils for which numerical ages have been obtained by other methods. Ages for soils formed under similar conditions are then estimated by comparison to the reference soils. The uncertainty in ages of the reference soils constitute a portion of the calibration error that must be factored into the uncertainties in the soil ages. In another example, radiocarbon ages are calibrated using dendrochronology to compensate for variations in the production rate of atmospheric ^{14}C. Computation and propagation of the errors and uncertainty associated with the calibration must be carefully performed. Routines and even full computer programs on the web are available for radiocarbon (e.g., CALIB, Stuiver and Reimer, 1993) and other methods to perform calibrations.

A critical source of error is any failure to satisfy the assumptions of the method. If such errors are discovered and their effects cannot be quantified, often the data must be discarded. For example, if the luminescence of a sand deposit is not completely reset during deposition, the luminescence date will reflect inherited luminescence, and thus will be too old by an unknown amount. If calcite has not acted as a closed system since its crystallization, uranium may have been leached resulting in a U-series age that is too old. Similarly, if a geomorphic surface has undergone erosion and some cosmogenic isotopes were removed, cosmogenic isotope ages will be too young.

All of these sources of uncertainty must be evaluated when using a dating method to assess the age of a geologic deposit or landform. All uncertainty must be quantified to the extent possible, and the combined magnitude (error) presented along with the age estimate. All uncertainty, whether quantified or not, must be acknowledged and factored into the geologic interpretation of the feature under investigation.

Community Confidence

Confidence of the scientific community in the utility of any given geochronologic method is measured by the barometer we refer to here as "community confidence." This is not to be confused with popularity, for there are other and certainly less objective reasons for the latter. Historically, a geochronological method waxes and wanes in its community confidence. Methods generally go through a process from experimental status and accompanying low community confidence, to established status and accompanying moderate to high community confidence. It is important that both those inside and those outside the community understand this "initiation" of methods, much as other scientific hypotheses are posited, debated, and ultimately rejected or accepted.

Community confidence in a method generally goes through four phases: (1) an early upsweep in confidence due to initial optimism and flurry of testing of the method and its applications; (2) a down-turn in confidence as initial and new-found doubts are amplified and published; (3) a rebound of confidence as test results validate the method and free it from prior criticisms; and finally, (4) a stabilization in confidence (either high or low) as the method becomes accepted by the community, and considered "established," or rejected by the community and discarded. This stabilization is accompanied by a generally agreed upon assessment of the strengths and limitations of the method. Variations on this theme include the case where (A) a method is outright rejected by the community either through scholarly proof of the inviability of the basic principle(s) of the method or through disuse, even though it might be the only means of establishing an age estimate; or (B) a base assumption is later disproved, sending the community confidence into another swing through phases (2), (3) and (4), and (C) refinement of an established method leads to an upswing in confidence, followed by restabilization at a higher level.

It is our hope that this volume contributes towards greater community confidence in the field of Quaternary geochronology.

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