5. Chronostratigraphy and Geological Time

Chronostratigraphy is the unifying construct that defines (ideally by international agreement) boundaries for systems, series, and stages. Chronostratigraphy is the study of establishing the time relationship among rock units.

5.1 Geologic time units

Geologic time units: Stratigraphic units defined and delineated on the basis of time.

(1) Chronostratigraphic unit
An isochronous body of rock that serves as the material reference for all rocks formed during the same spans of times. The fundamental chronostratigraphic unit is the **system**, e.g. Tertiary system (第三系).

(2) Geochronologic unit
The interval of time during which a correspondingly ranked chronostratigraphic unit was deposited. The fundamental geochronologic unit is the **period** – the time equivalent of a system, e.g. Tertiary period (第三紀).

(3) Geochronometric unit
Pure time units. Direct divisions of geologic time with arbitrarily chosen age boundaries, e.g. Archean (太古代), Proterozoic(原生代).

Table 18.1 Geologic Time Units

Chronostratigraphic Unit—an isochronous body of rock that serves as the material reference for all rocks formed during the same spans of time; it is always based on a material reference unit, or stratotype, which is a biostratigraphic, lithostratigraphic, or magnetopolarity unit

Eonothem—the highest ranking chronostratigraphic unit; three recognized: **Phanerozoic,** encompassing the Paleozoic, Mesozoic, and Cenozoic erathems, and the **Proterozoic** and **Archean,** which together make up the Precambrian.

Erathems—subdivisions of an eonothem; none in the Precambrian; the Phanerozoic erathems, names originally chosen to reflect major changes in the development of life on Earth, are the: Paleozoic ("old life"), Mesozoic ("intermediate life"), and Cenozoic ("recent life")

System—the primary chronostratigraphic unit of worldwide major rank (e.g., Permian System, Jurassic System); can be subdivided into subsystems or grouped into supersystems but most commonly are divided completely into units of the next lower rank (series)

Series—a subdivision of a system; systems are divided into two to six series (commonly three); generally take their name from the system by adding the appropriate adjective "Lower," "Middle," or "Upper" to the system name (e.g., Lower Jurassic Series, Middle Jurassic Series, Upper Jurassic Series); useful for chronostratigraphic correlation within provinces; many can be recognized world wide

Stage—smaller scope and rank than series; very useful for intraregional and intracontinental classification and correlation; many stages also recognized worldwide; may be subdivided into substages

Chronozone—the smallest chronostratigraphic unit; its boundaries may be independent of those of ranked stratigraphic units

Geochronologic Unit—a division of time distinguished on the basis of the rock record as expressed by chronostratigraphic units; not an actual rock unit, but corresponds to the interval of time during which an established chronostratigraphic unit was deposited or formed; thus, the beginning of a geochronologic unit corresponds to the time of deposition of the bottom of the chronostratigraphic unit upon which it is based and the ending corresponds to the time of deposition of the top of the reference unit; the hierarchy of geochronologic units and their corresponding geochronostratigraphic units are:

Geochronologic Unit	Corresponding Geochronostratigraphic Unit
Eon	Eonothem
Era	Erathem
Period	System
Epoch	Series
Age	Stage
Chron	Chronozone

Geochronometric Units—direct divisions of geologic time with arbitrarily chosen age boundaries; they are not based on the time span of designated chronostratigraphic stratotypes; a geochronometric time scale is commonly used for Precambrian rocks, which cannot be subdivided into globally recognized chronostratigraphic units; ages generally expressed in millions of years before the present (Ma) but may be expressed also in thousands of years (Ka) or billions of years (Ga)

Source: *North American Stratigraphic Code and International Stratigraphic Guide* (Salvador, 1994)

Boggs (2001)

Table 18.2 The Internationally Accepted Geologic Systems of the Phanerozoic and Their Type Localities

System name	Type locality	Name proposed by	Date proposed	Remarks
Quaternary	France	Jules Desnoyers	1829	Defined by lithology, including some unconsolidated sediment
Tertiary	Italy	Giovanni Arduino	1760	Originally defined by lithology; redefined with type section in France on the basis of distinctive fossils
Cretaceous	Paris Basin	Omalius d'Halloy	1822	Defined initially on the basis of strata composed of distinctive chalk beds
Jurassic	Jura Mountains, northern Switzerland	Alexander von Humbolt	1795	Defined originally on the basis of lithology
Triassic	Southern Germany	Frederick von Alberti	1843	Defined lithologically on the basis of a distinctive threefold division of strata; also defined by fossils
Permian	Province of Perm, Russia	Roderick I. Murchison	1841	Identified by distinctive fossils
Pennsylvanian	Pennsylvania, United States	Henry S. Williams	1891	Not used outside the United States
Mississippian	Mississippi Valley, United States	Alexander Winchell	1870	Not used outside the United States
Carboniferous	Central England	William Conybeare and William Phillips	1822	Named for lithologically distinctive, coal-bearing strata but recognizable by distinctive fossils
Devonian	Devonshire, southern England	Roger I. Murchinson and Adam Sedgwick	1840	Boundaries based mainly on fossils
Silurian	Western Wales	Roger I. Murchinson	1835	Defined by lithology and fossils
Ordovician	Western Wales	Charles Lapworth	1879	Set up as an intermediate unit between the Cambrian and Silurian to resolve boundary dispute; boundary defined by fossils
Cambrian	Western Wales	Adam Sedgwick	1835	Defined mainly by lithology

Note: The Precambrian has not yet been divided into internationally accepted systems

Boggs (2001)

Cambrian: Derived from the Roman name for Wales (Cambria)
Ordovician: Named for Ordovices, an ancient Welsh tribe that was the last in Britain to submit to Roman domination.
Silurian: Named for Silures, an ancient tribe that had once inhabited Wales.

5.2 The geologic time scale

Establishing the relative ordering of events in Earth's history is the main contribution that geology makes to our understanding of time.

Development of the geological time scale

Two fundamental stages of development:

1. Establishing local stratigraphic sections (using principle of superposition, fossil controls, and radiometric ages)

2. Establishing a composite international chronostratigaphic scale.

Although the systems are accepted by the international geologic community as the basic reference sections for the geologic time scale, considerable controversy still exists regarding the exact placement of system boundaries and the subdivision of some systems.

Eonothem	Erathem	System and Subsystem		Series	Numerical Age (Ma)
PHANEROZOIC	Cenozoic	Quaternary		Holocene	0.1
				Pleistocene	1.8
		Tertiary	Neogene	Pliocene	
				Miocene	23.8
			Paleogene	Oligocene	
				Eocene	
				Paleocene	65.0
	Mesozoic	Cretaceous		Upper	
				Lower	144.2
		Jurassic		Upper	
				Middle	
				Lower	206
		Triassic		Upper	
				Middle	
				Lower	248
	Paleozoic	Permian		Upper	
				Lower	290
		Carboniferous	Pennsylvanian	Upper	323
			Mississippian	Lower	354
		Devonian		Upper	
				Middle	
				Lower	417
		Silurian		Upper	
				Lower	443
		Ordovician		Upper	
				Middle	
				Lower	490
		Cambrian		Upper	
				Lower	543
PRECAMBRIAN	PROTEROZOIC	Not formally subdivided			2500
	ARCHEAN	Not formally subdivided			

Source of ages: Geological Society of America 1999 Geologic Time Scale

Nomenclature of Phanerozoic (顯生元) chronostratigraphic units

Boggs (2001)

Figure 18.2
Nomenclature of Phanerozoic chronostratigraphic units commonly used throughout the world. Precambrian rocks are divided into the Archean and Proterozoic; however, no scheme for further subdivision of the Precambrian is globally accepted.

INTERNATIONAL STRATIGRAPHIC CHART

ICS

IUGS

International Commission on Stratigraphy

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
Phanerozoic	Cenozoic	Quaternary	Holocene		0.0117
Phanerozoic	Cenozoic	Quaternary	Pleistocene	Upper	0.126
Phanerozoic	Cenozoic	Quaternary	Pleistocene	"Ionian"	0.781
Phanerozoic	Cenozoic	Quaternary	Pleistocene	Calabrian	1.806
Phanerozoic	Cenozoic	Quaternary	Pleistocene	Gelasian	2.588
Phanerozoic	Cenozoic	Neogene	Pliocene	Piacenzian	3.600
Phanerozoic	Cenozoic	Neogene	Pliocene	Zanclean	5.332
Phanerozoic	Cenozoic	Neogene	Miocene	Messinian	7.246
Phanerozoic	Cenozoic	Neogene	Miocene	Tortonian	11.608
Phanerozoic	Cenozoic	Neogene	Miocene	Serravallian	13.82
Phanerozoic	Cenozoic	Neogene	Miocene	Langhian	15.97
Phanerozoic	Cenozoic	Neogene	Miocene	Burdigalian	20.43
Phanerozoic	Cenozoic	Neogene	Miocene	Aquitanian	23.03
Phanerozoic	Cenozoic	Paleogene	Oligocene	Chattian	28.4 ±0.1
Phanerozoic	Cenozoic	Paleogene	Oligocene	Rupelian	33.9 ±0.1
Phanerozoic	Cenozoic	Paleogene	Eocene	Priabonian	37.2 ±0.1
Phanerozoic	Cenozoic	Paleogene	Eocene	Bartonian	40.4 ±0.2
Phanerozoic	Cenozoic	Paleogene	Eocene	Lutetian	48.6 ±0.2
Phanerozoic	Cenozoic	Paleogene	Eocene	Ypresian	55.8 ±0.2
Phanerozoic	Cenozoic	Paleogene	Paleocene	Thanetian	58.7 ±0.2
Phanerozoic	Cenozoic	Paleogene	Paleocene	Selandian	~ 61.1
Phanerozoic	Cenozoic	Paleogene	Paleocene	Danian	65.5 ±0.3
Phanerozoic	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6
Phanerozoic	Mesozoic	Cretaceous	Upper	Campanian	83.5 ±0.7
Phanerozoic	Mesozoic	Cretaceous	Upper	Santonian	85.8 ±0.7
Phanerozoic	Mesozoic	Cretaceous	Upper	Coniacian	~ 88.6
Phanerozoic	Mesozoic	Cretaceous	Upper	Turonian	93.6 ±0.8
Phanerozoic	Mesozoic	Cretaceous	Upper	Cenomanian	99.6 ±0.9
Phanerozoic	Mesozoic	Cretaceous	Lower	Albian	112.0 ±1.0
Phanerozoic	Mesozoic	Cretaceous	Lower	Aptian	125.0 ±1.0
Phanerozoic	Mesozoic	Cretaceous	Lower	Barremian	130.0 ±1.5
Phanerozoic	Mesozoic	Cretaceous	Lower	Hauterivian	~ 133.9
Phanerozoic	Mesozoic	Cretaceous	Lower	Valanginian	140.2 ±3.0
Phanerozoic	Mesozoic	Cretaceous	Lower	Berriasian	145.5 ±4.0

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
					145.5 ±4.0
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	150.8 ±4.0
Phanerozoic	Mesozoic	Jurassic	Upper	Kimmeridgian	~ 155.6
Phanerozoic	Mesozoic	Jurassic	Upper	Oxfordian	161.2 ±4.0
Phanerozoic	Mesozoic	Jurassic	Middle	Callovian	164.7 ±4.0
Phanerozoic	Mesozoic	Jurassic	Middle	Bathonian	167.7 ±3.5
Phanerozoic	Mesozoic	Jurassic	Middle	Bajocian	171.6 ±3.0
Phanerozoic	Mesozoic	Jurassic	Middle	Aalenian	175.6 ±2.0
Phanerozoic	Mesozoic	Jurassic	Lower	Toarcian	183.0 ±1.5
Phanerozoic	Mesozoic	Jurassic	Lower	Pliensbachian	189.6 ±1.5
Phanerozoic	Mesozoic	Jurassic	Lower	Sinemurian	196.5 ±1.0
Phanerozoic	Mesozoic	Jurassic	Lower	Hettangian	199.6 ±0.6
Phanerozoic	Mesozoic	Triassic	Upper	Rhaetian	203.6 ±1.5
Phanerozoic	Mesozoic	Triassic	Upper	Norian	216.5 ±2.0
Phanerozoic	Mesozoic	Triassic	Upper	Carnian	~ 228.7
Phanerozoic	Mesozoic	Triassic	Middle	Ladinian	237.0 ±2.0
Phanerozoic	Mesozoic	Triassic	Middle	Anisian	~ 245.9
Phanerozoic	Mesozoic	Triassic	Lower	Olenekian	~ 249.5
Phanerozoic	Mesozoic	Triassic	Lower	Induan	251.0 ±0.4
Phanerozoic	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ±0.7
Phanerozoic	Paleozoic	Permian	Lopingian	Wuchiapingian	260.4 ±0.7
Phanerozoic	Paleozoic	Permian	Guadalupian	Capitanian	265.8 ±0.7
Phanerozoic	Paleozoic	Permian	Guadalupian	Wordian	268.0 ±0.7
Phanerozoic	Paleozoic	Permian	Guadalupian	Roadian	270.6 ±0.7
Phanerozoic	Paleozoic	Permian	Cisuralian	Kungurian	275.6 ±0.7
Phanerozoic	Paleozoic	Permian	Cisuralian	Artinskian	284.4 ±0.7
Phanerozoic	Paleozoic	Permian	Cisuralian	Sakmarian	294.6 ±0.8
Phanerozoic	Paleozoic	Permian	Cisuralian	Asselian	299.0 ±0.8
Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian Upper	Gzhelian	303.4 ±0.9
Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian Upper	Kasimovian	307.2 ±1.0
Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian Middle	Moscovian	311.7 ±1.1
Phanerozoic	Paleozoic	Carboniferous	Pennsylvanian Lower	Bashkirian	318.1 ±1.3
Phanerozoic	Paleozoic	Carboniferous	Mississippian Upper	Serpukhovian	328.3 ±1.6
Phanerozoic	Paleozoic	Carboniferous	Mississippian Middle	Visean	345.3 ±2.1
Phanerozoic	Paleozoic	Carboniferous	Mississippian Lower	Tournaisian	359.2 ±2.5

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
					359.2 ±2.5
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	374.5 ±2.6
Phanerozoic	Paleozoic	Devonian	Upper	Frasnian	385.3 ±2.6
Phanerozoic	Paleozoic	Devonian	Middle	Givetian	391.8 ±2.7
Phanerozoic	Paleozoic	Devonian	Middle	Eifelian	397.5 ±2.7
Phanerozoic	Paleozoic	Devonian	Lower	Emsian	407.0 ±2.8
Phanerozoic	Paleozoic	Devonian	Lower	Pragian	411.2 ±2.8
Phanerozoic	Paleozoic	Devonian	Lower	Lochkovian	416.0 ±2.8
Phanerozoic	Paleozoic	Silurian	Pridoli		418.7 ±2.7
Phanerozoic	Paleozoic	Silurian	Ludlow	Ludfordian	421.3 ±2.6
Phanerozoic	Paleozoic	Silurian	Ludlow	Gorstian	422.9 ±2.5
Phanerozoic	Paleozoic	Silurian	Wenlock	Homerian	426.2 ±2.4
Phanerozoic	Paleozoic	Silurian	Wenlock	Sheinwoodian	428.2 ±2.3
Phanerozoic	Paleozoic	Silurian	Llandovery	Telychian	436.0 ±1.9
Phanerozoic	Paleozoic	Silurian	Llandovery	Aeronian	439.0 ±1.8
Phanerozoic	Paleozoic	Silurian	Llandovery	Rhuddanian	443.7 ±1.5
Phanerozoic	Paleozoic	Ordovician	Upper	Hirnantian	445.6 ±1.5
Phanerozoic	Paleozoic	Ordovician	Upper	Katian	455.8 ±1.6
Phanerozoic	Paleozoic	Ordovician	Upper	Sandbian	460.9 ±1.6
Phanerozoic	Paleozoic	Ordovician	Middle	Darriwilian	468.1 ±1.6
Phanerozoic	Paleozoic	Ordovician	Middle	Dapingian	471.8 ±1.6
Phanerozoic	Paleozoic	Ordovician	Lower	Floian	478.6 ±1.7
Phanerozoic	Paleozoic	Ordovician	Lower	Tremadocian	488.3 ±1.7
Phanerozoic	Paleozoic	Cambrian	Furongian	*Stage 10*	~ 492 *
Phanerozoic	Paleozoic	Cambrian	Furongian	*Stage 9*	~ 496 *
Phanerozoic	Paleozoic	Cambrian	Furongian	Paibian	~ 499
Phanerozoic	Paleozoic	Cambrian	Series 3	Guzhangian	~ 503
Phanerozoic	Paleozoic	Cambrian	Series 3	Drumian	~ 506.5
Phanerozoic	Paleozoic	Cambrian	Series 3	*Stage 5*	~ 510 *
Phanerozoic	Paleozoic	Cambrian	Series 2	*Stage 4*	~ 515 *
Phanerozoic	Paleozoic	Cambrian	Series 2	*Stage 3*	~ 521 *
Phanerozoic	Paleozoic	Cambrian	Terreneuvian	*Stage 2*	~ 528 *
Phanerozoic	Paleozoic	Cambrian	Terreneuvian	Fortunian	542.0 ±1.0

Eonothem Eon	Erathem Era	System Period	Age Ma	GSSP GSSA
			542	
Precambrian Proterozoic	Neo-proterozoic	Ediacaran	~635	GSSP
Precambrian Proterozoic	Neo-proterozoic	Cryogenian	850	GSSA
Precambrian Proterozoic	Neo-proterozoic	Tonian	1000	GSSA
Precambrian Proterozoic	Meso-proterozoic	Stenian	1200	GSSA
Precambrian Proterozoic	Meso-proterozoic	Ectasian	1400	GSSA
Precambrian Proterozoic	Meso-proterozoic	Calymmian	1600	GSSA
Precambrian Proterozoic	Paleo-proterozoic	Statherian	1800	GSSA
Precambrian Proterozoic	Paleo-proterozoic	Orosirian	2050	GSSA
Precambrian Proterozoic	Paleo-proterozoic	Rhyacian	2300	GSSA
Precambrian Proterozoic	Paleo-proterozoic	Siderian	2500	GSSA
Precambrian Archean	Neoarchean		2800	GSSA
Precambrian Archean	Mesoarchean		3200	GSSA
Precambrian Archean	Paleoarchean		3600	GSSA
Precambrian Archean	Eoarchean		4000	
Hadean (informal)			~4600	

This chart was drafted by Gabi Ogg. Intra Cambrian unit ages with * are informal, and awaiting ratified definitions.

Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic (~542 Ma to Present) and the base of Ediacaran are defined by a basal Global Boundary Stratotype Section and Point (GSSP), whereas Precambrian units are formally subdivided by absolute age (Global Standard Stratigraphic Age, GSSA). Details of each GSSP are posted on the ICS website (*www.stratigraphy.org*).

Numerical ages of the unit boundaries in the Phanerozoic are subject to revision. Some stages within the Cambrian will be formally named upon international agreement on their GSSP limits. Most sub-Series boundaries (e.g., Middle and Upper Aptian) are not formally defined.

Colors are according to the Commission for the Geological Map of the World (*www.cgmw.org*).

The listed numerical ages are from 'A Geologic Time Scale 2004', by F.M. Gradstein, J.G. Ogg, A.G. Smith, et al. (2004; Cambridge University Press) and "The Concise Geologic Time Scale" by J.G. Ogg, G. Ogg and F.M. Gradstein (2008).

August 2009

2009 version

5.3 Calibrating the geological time scale

The major tools for finding ages of sediments to calibrate the geologic time scale are relative-age determinations by use of fossils – biochronology – and absolute age estimates based on isotopic decay – radiochronology.

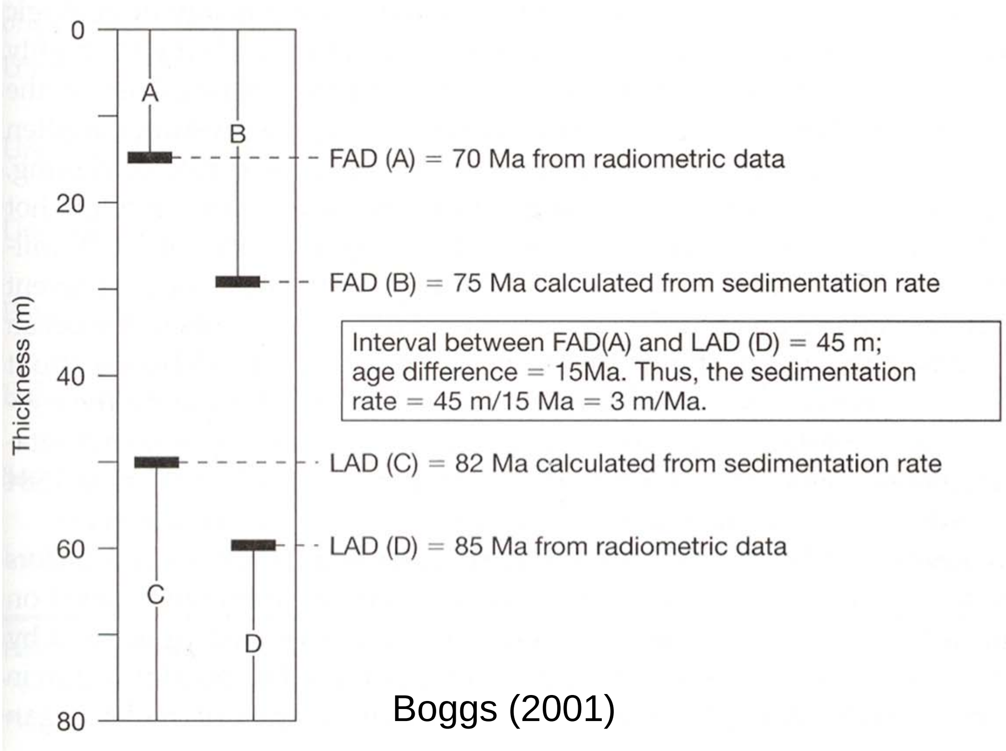
1. Calibrating the geological time scale by fossils: Biochronology

Biochronology is the organization of geologic time according to the irreversible process of evolution in the organic continuum. **FAD**s (first appearance datum) and **LAD**s (last appearance datum) are the most easily utilized and communicated types of fossil information upon which to base biochronology, and they can be used over great distances within the range of the defining taxa.

The duration of the FADs of many planktonic species may be as little as 10,000 years. The error caused by an age discrepancy of this magnitude becomes insignificant when applied to estimation of the ages of rocks that are millions to hundreds of millions of years old. Thus, the FADs and LADs of may fossil species can be considered essentially **synchronous** for the utilitarian purposes of biochronology.

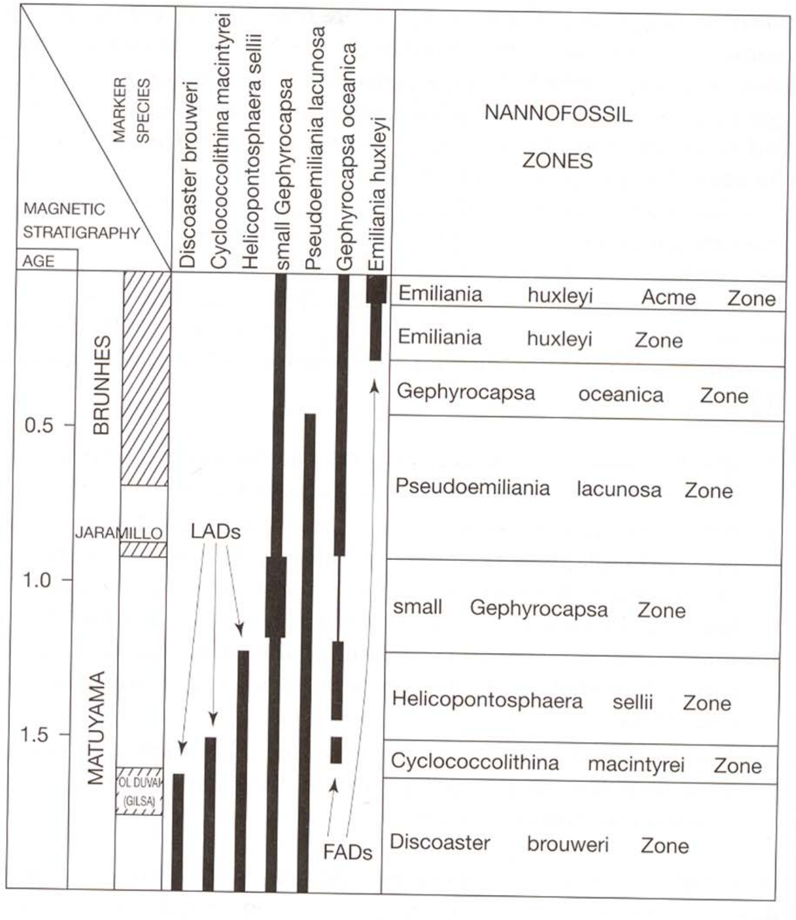
Procedures for establishing the biochronology based on FADs and LADs:

A. Identify wide-spread FADs and LADs
B. Assign ages, if possible, to these events by direct or indirect calibration through radiochronology, magnetostratigraphy or sedimentation rate estimate.



Boggs (2001)

Figure 18.4
Schematic illustration of the application of biochronology to age calibration of a local stratigraphic section. The ages of the FAD for Species A and the LAD for species D are established by radiometric dating of some closely associated physical feature (e.g., an ash bed). The FAD for species B and the LAD for species C cannot be dated radiometrically; however, the ages can be calculated from the sedimentation rate determined between FAD(A) and LAD (D). This rate (3 m/Ma) can then be used to determine the age difference between FAD(A) and FAD(B) (3 m/Ma × 15 m = 5 Ma) and between LAD (D) and LAD)(C) (3 m/Ma × 10 m = 3 Ma).



Boggs (2001)

Figure 18.5
An example of biochronological dating by use of nannofossil datum events correlated with magnetic polarity events. [After Gartner, S., 1977, Calcareous nannofossil biostratigraphy and revised zonation of the Pleistocene: Marine Micropaleontology, v. 2, Fig. 5, reprinted by permission of Elsevier Science Publishers.]

2. Calibrating by absolute ages: Radiochronology

An isotope is defined as one of two or more atoms that have the same atomic number but which contain different numbers of neutrons (e.g., strontium: ^{84}Sr, ^{86}Sr, ^{87}Sr, ^{88}Sr). Some isotopes, known as daughter isotopes, are produced by radioactive decay of another isotope, the parent isotopes, whilst others are totally stable and their abundance does not change through geological time (e.g. ^{87}Sr is the daughter isotope of its parent isotope ^{87}Rb (Rubidium), whilst ^{84}Sr, ^{86}Sr, ^{88}Sr are all stable).

The equation for calculating radiometric age is

$$t = \frac{1}{\lambda} \ln \left[\frac{D - D_o}{N} + 1 \right] \tag{18.1}$$

where N = the number of parent atoms of an element (e.g., uranium) present in any given amount of the element, *ln* is log base *e*, D is the total number of daughter atoms (e.g., lead), D_o is the number of original daughter atoms, and λ is the decay constant, which is calculated from the relationship

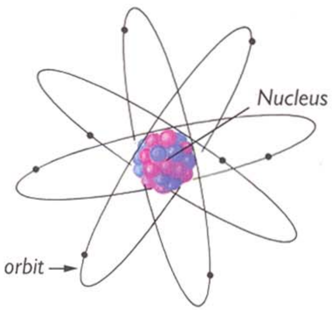
$$\lambda = \frac{0.693}{T_{1/2}} \tag{18.2}$$

where $T_{1/2}$ is the half-life of the radioactive element (Faure, 1986, Chapter 4). N and D are measurable; D_o is a constant whose value is either assumed or calculated from data for cognetic samples of the same age.

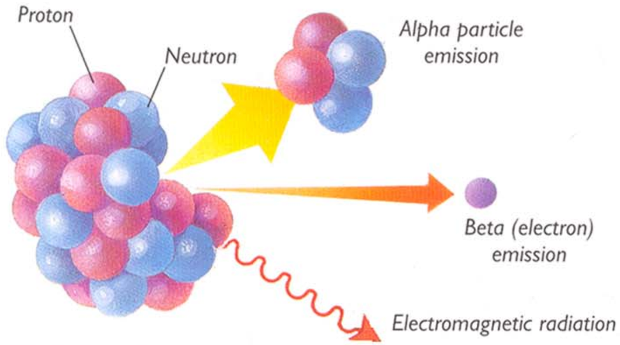
RADIOACTIVE DECAY

Lamb & Sington (1998)

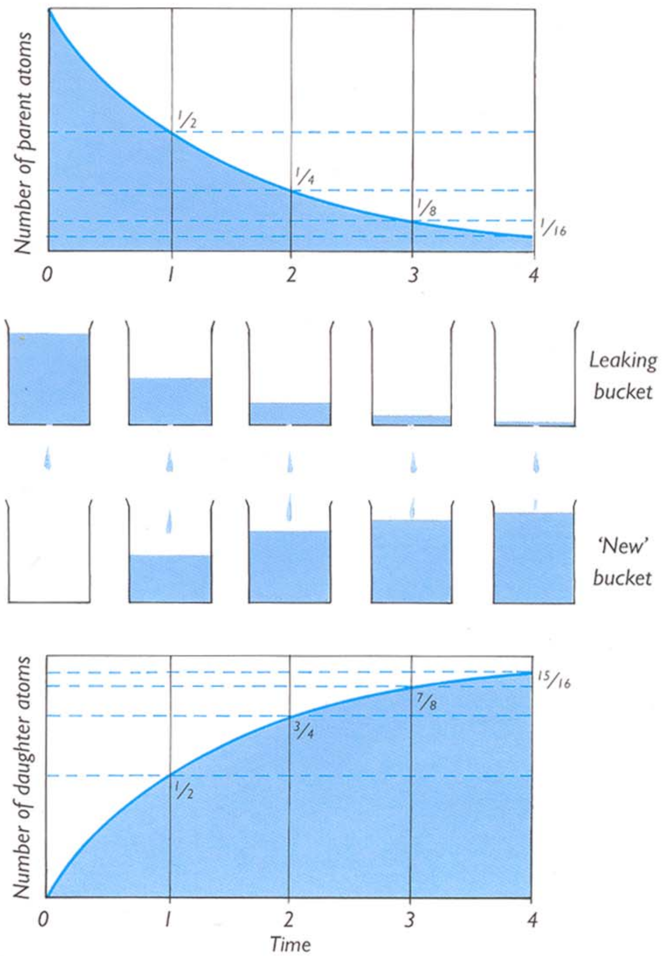
(a) Granite (rock sample)



(b) Atom model



(c) Nucleus (detail)



(d) Radioactive exponential decay

Almost all natural rocks contain atoms of radioactive elements **(a–b)**. The nucleus of any of these atoms spontaneously emits particles (alpha or beta particles) and energy, steadily transforming to a new daughter element **(c)**. Geologists can date rocks by comparing the number of daughter and parent elements in the rock today.

The process of decay is rather like a leaking bucket. The initial full bucket represents the number of radioactive parent elements when the rock first formed. An empty bucket underneath catches the drips – this represents the number of daughter elements **(d)**.

In simple situations, such as when a volcanic rock solidifies, there are no daughter elements to begin with. Gradually, like the water levels in the buckets, the number of daughter elements increases and the number of parent elements decreases. In radioactive decay, the time taken for the number of parent radioactive elements to halve is constant – this is the characteristic half-life of the parent–daughter decay system.

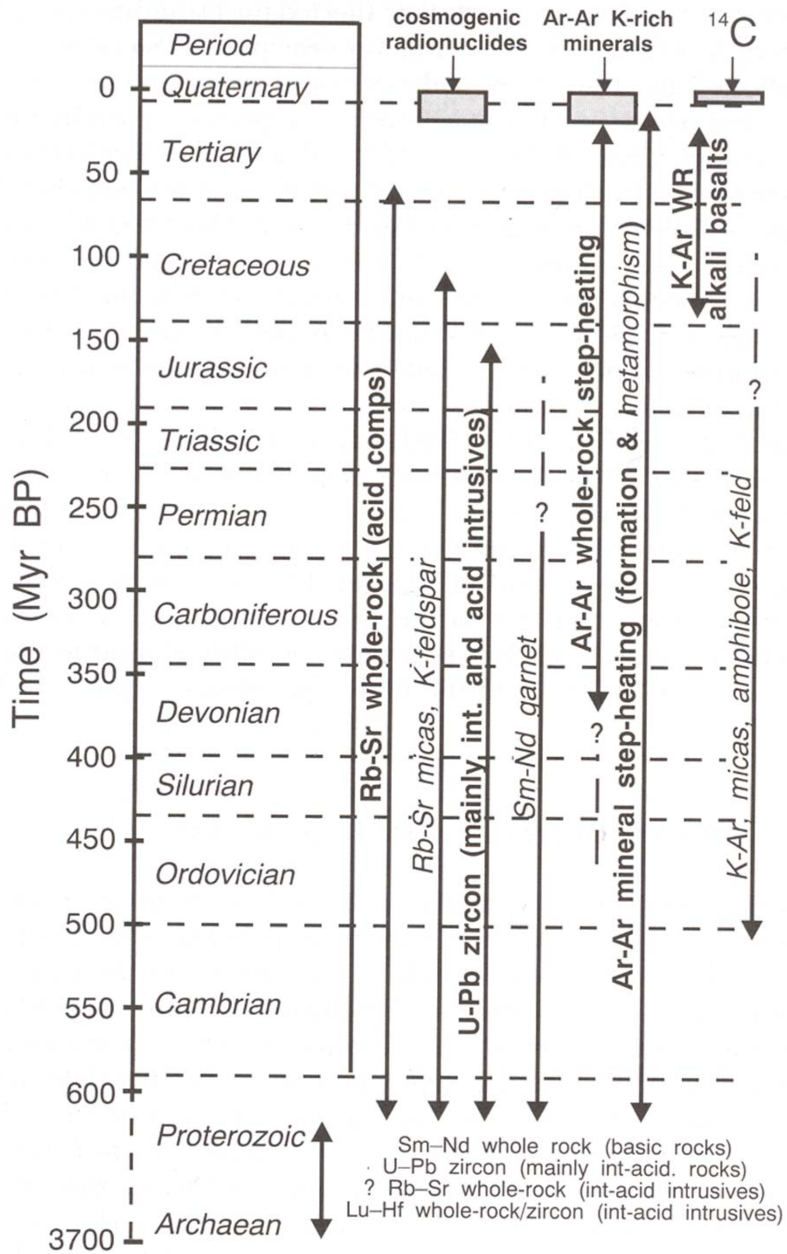


Figure 12.11 *Application of different methods of radiogenic isotope geochronology to different rock types of differing ages. Methods in italics will yield dates that are likely to reflect predominantly metamorphic/uplift events, whereas methods in normal text are more likely to reflect magmatic crystallization*

Doyle & Bennett (1998)

Table 18.3 Decay Schemes for Principal Methods of Radiometric Age Determination

Parent nuclide	Daughter nuclide	Half-life (years)	Approximate useful dating range (years B.P.)	Materials commonly used for dating
Carbon-14	*Nitrogen-14	5730	**<~40,000	Wood, charcoal, $CaCO^3$ shells
Protactinium-231 (daughter nuclide of uranium-235)	*Actinium-227	32,480	<~150,000	Deep-sea sediment, aragonite corals
Thorium—230 (daughter nuclide of uranium 238/234)	*Radium-226	75,200	<~250,000	Deep-sea sediment, aragonite corals
Uranium-238	Lead-206	4500 million	10–>4500 million	Zircon, monazite, sphene, uranium/ thorium minerals
Uranium-238	Spontaneous fission tracks	—	**<~65 million	Volcanic glass, zircon, apatite, sphene, garnet
Uranium-235	Lead-207	710 million	10–>4500 million	Zircon, monazite, sphene uranium/ thorium minerals
Potassium-40	Argon-40	1250 million	1–>4500 million	Muscovite, biotite, feldspars, glauconite, whole volcanic rock
Rubidium-87	Strontium-87	48 billion	10–>4500 million	Micas, K-feldspar, whole metamorphic rock, glauconite
Samarium-147	Neodymium-143	106 billion	>200 million	Pyroxene, plagioclase, garnet, apatite, sphene
Lutium-176	Hafnium-176	35 billion	>200 million	Pyroxene, plagioclase, garnet, apatite, sphene

Half-life data from Bowen (1998)

*Not used in calculating radiometric ages

**Can be used for dating older rocks under favorable circumstances

U238-Th230 method: ~600,000 yrs for Cave carbonate deposits

Boggs (2001)

Radiometric methods

Carbon-14 method (sediments), good for 100 < age < 40,000 years.

Impact of cosmic-ray neutrons on ordinary ^{14}N atoms produces ^{14}C in the atmosphere. ^{14}C atoms in turn decays backs to ^{14}N. ^{14}C is incorporated into carbon dioxide (CO_2), which is assimilated by plants and animals during their life cycles. The age of a sample is determined by measuring the amount of radiocarbon per gram of total carbon in a sample and comparing this with the initial amount at the time the organism died. The age equation is:

$t = 19.053 + 10^3 \log (A_0/A)$ years

where A is the measured activity of the sample at the present moment in disintegrations per minute per gram of carbon and A_0 is the initial activity.

Thorium-230 method (sediments)

^{238}U decays through several intermediate daughter products, including ^{234}U, to thorium-230. ^{230}Th is an unstable isotope and itself decays with a half-life of 75,000 years to still another unstable daughter product, radium (鐳)-226. Owing to this fairly rapid decay of ^{230}Th, cores of sediments taken from ocean floor exhibit a measurable decrease in ^{230}Th content with increasing depth in the cores. Assuming that sedimentation rates and the rates of precipitation of ^{230}Th have remained fairly constant through time, the concentration of ^{230}Th should decrease exponentially with depth. The ages of the sediments at various depths in a core can be calculated by comparing the amount of remaining ^{230}Th at any depth to the amount in the top layer of the core (surface sediments).

Thorium-230/Protactinium (鏷) -231 ratio method (sediments)
^{231}Pa is the unstable daughter product of ^{235}U. Because ^{231}Pa decays about twice as rapidly as ^{230}Th, the $^{231}Pa/^{230}Th$ ratio in the sediments changes with time. The age of sediment with depth can be determined in a similar manner to the above Thorium-230 method.

Potassium-40/Argon-40 (K-Ar) method (igneous and metamorphic rocks or some sedimentary minerals, e.g. glauconite): drawback: argon-40 is a gas that can leak out of a crystal.

Argon-40/Argon-39 (Ar-Ar) method (igneous and metamorphic minerals)
Increasingly used. Advantages: 1. using very small sample, e.g. single mineral crystal; 2. allowing correction for loss of argon by leakage.

Rubidium-87/Strontium-87 (Rb-Sr) method
Less commonly used because ^{87}Rb is very rare.

Uranium/Lead (U-Pb) method

Fission-track dating
Counting fission tracks in minerals such as zircon. Emission of charged particles from decaying nuclei causes disruption of crystal lattices, creating the tracks, which can be seen and counted under a microscope.

☆ Dating sedimentary rocks

Types of rocks useful for geochronologic calibration of the geologic time table

Table 18.4 Categories of Rocks Most Useful for Geochronologic Calibration of the Geologic Time Table

Type of rock	Stratigraphic relationship	Reliability of age data
Volcanic rock (lava flows and ash falls)	Interbedded with "contemporaneous" sedimentary rocks	Give actual ages of sedimentary rocks in close stratigraphic proximity above and below volcanic layers
Plutonic igneous rocks	Intrude (cut across) sedimentary rocks	Give minimum ages for the rocks they intrude
	Lie unconformably beneath sedimentary rocks	Give maximum ages for overlying sedimentary rocks
Metamorphosed sedimentary rocks	Constitute the rocks whose ages are being determined	Give minimum ages for metamorphosed sedimentary rocks
	Lie unconformably beneath nonmetamorphosed sedimentary rocks	Give maximum ages for the overlying nonmetamorphosed sedimentary rocks
Sedimentary rocks containing contemporary organic remains (fossils, wood)		Give actual ages of sedimentary rocks
Sedimentary rocks containing authigenic minerals such as glauconite		Give minimum ages for sedimentary rocks

1. Finding ages of sedimentary rocks by analyzing interbedded “contemporaneous” volcanic rocks

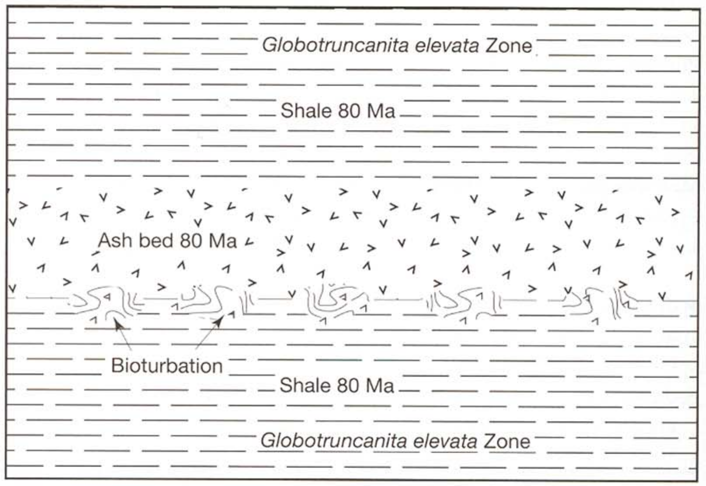


Figure 18.6
Diagram illustrating how the contemporaneity of sedimentary rocks to an associated, datable volcanic layer can be established. The shale beds below and above the volcanic ash bed belong to the same Foraminiferal biozone and the base of the ash bed has been bioturbated, indicating that the underlying sediment was still soft at the time of the ash fall. Therefore, the shale beds are approximately the same age as the ash bed (80 Ma).

2. Bracketed ages from associated igneous or metamorphic rocks.

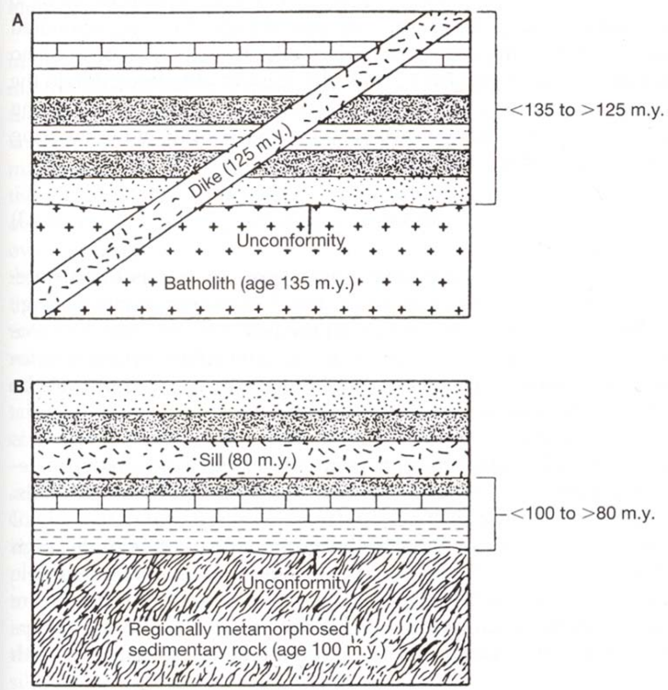
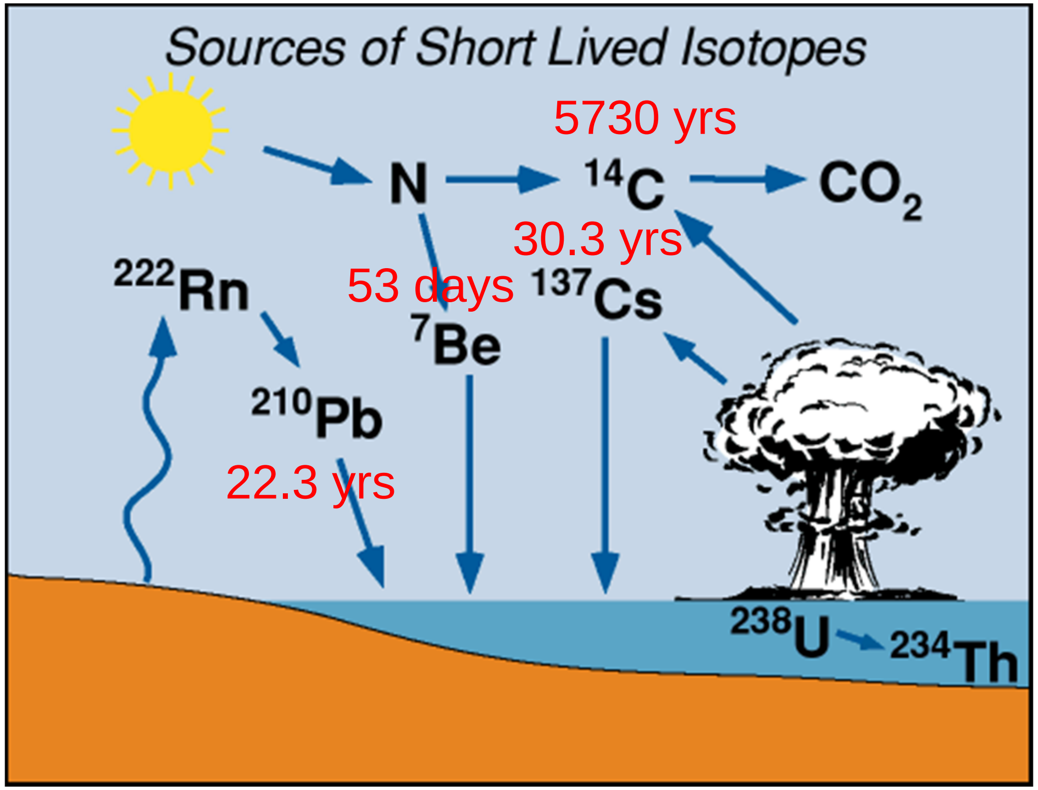
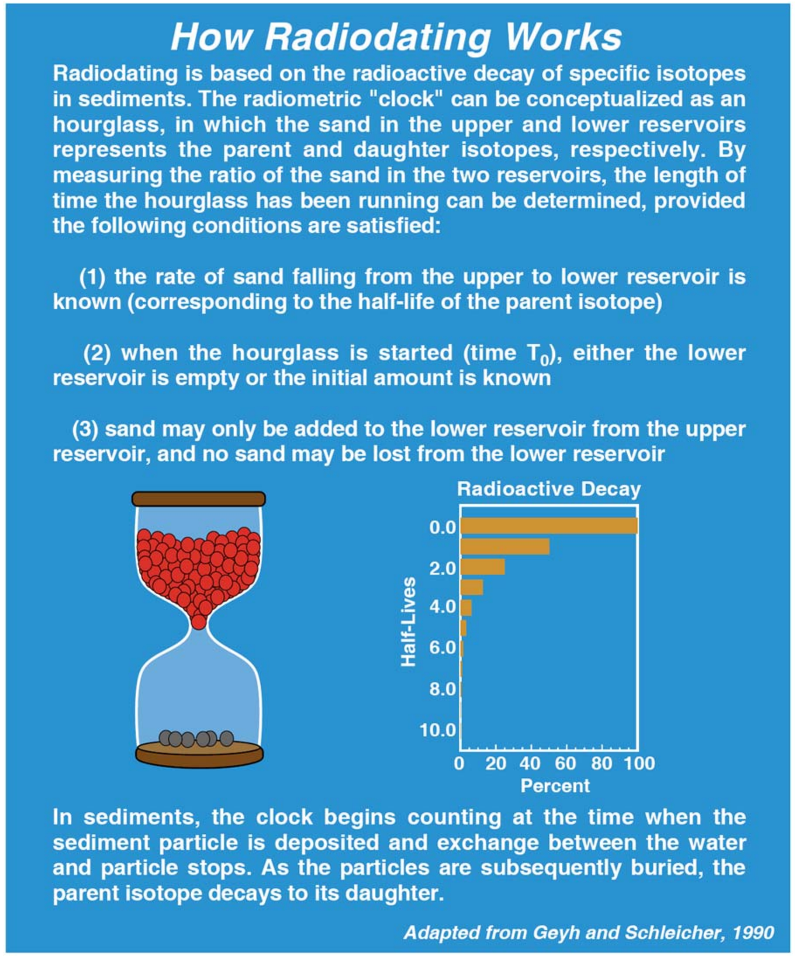


Figure 18.7
Determining the ages of sedimentary rocks indirectly by (A) bracketing between two igneous bodies and (B) bracketing between regionally metamorphosed sedimentary rocks and an intrusive igneous body.

3. Direct radiochronology of sedimentary rocks
   a. Carbon-14 method
   b. Potassium-40/Argon-40 (K-Ar) as well as Rubidium-87/Strontium-87 (Rb-Sr) methods for glauconites.
   c. Thorium-230 method for ocean floor sediments
   d. Thorium-230/Protactinium-231 ratio method for fossils and sediments

Dating for sediments of age less than a few hundred years





After around 7 half-lives most of radioactive elements decay completely

Methods using fallout radionuclides in recent marine sediments

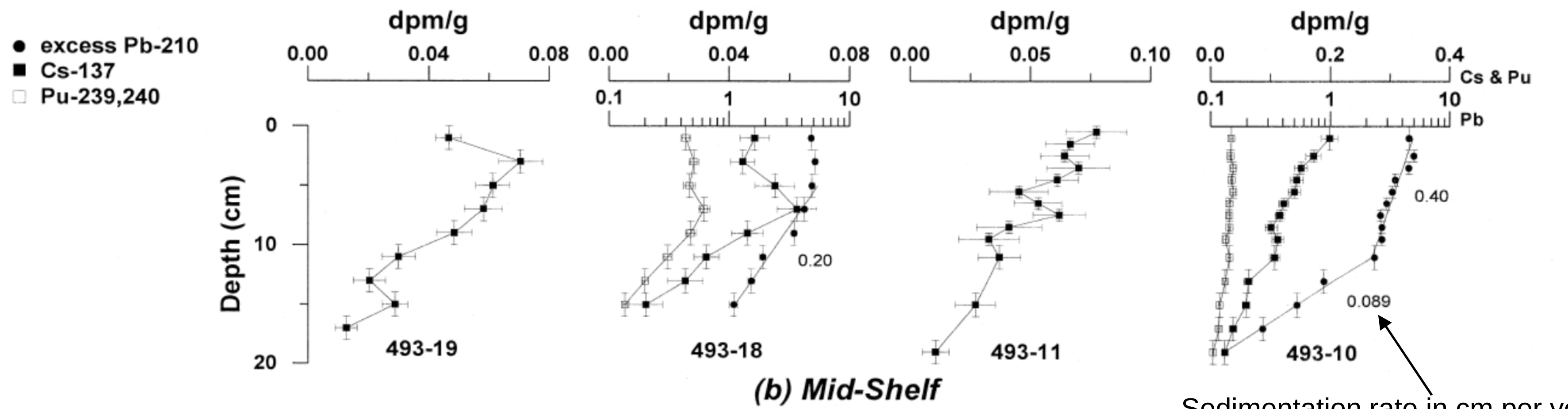
210 Pb, 137Cs and 239,240Pu as tracers.

Pb-210 is a naturally occurring radioactive element that is part of the Uranium-238 Radioactive decay series, and has a half life of 22.3 years. To determine the amount of Pb-210, the alpha radiation emitted by another element, polonium-210 (Po-210), is measured.50

210Pb is the most commonly used chronometer (using 210 Pb profile) for estimating sedimentation rates in near-shore environments.

To constrain 210Pb based sedimentation rates, distributions of 137Cs and Pu are also measured.

An example from the East China Sea



Sedimentation rate in cm per year

From Hu and Su (1999) Marine Geology, 160, 183-196.