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²¹⁰Pb Dating

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Keywords

Geochronology; Radioactivity; Radionuclide; Mass accumulation rates; Sedimentation rates

Synonyms

[Mass accumulation rates](#); [Recent sediment dating](#); [Sedimentation rates](#)

Definition

Method of dating recent sediment deposition and accumulation using down-core profiles of short-lived radioactive ²¹⁰Pb.

History

Roughly 50 years ago, a small group of scientists from Belgium and the USA, trying to better constrain ice sheet accumulation rates, attempted to apply what was then known about environmental lead as a potential geochronometer. Thus Goldberg (1963) developed the first principles of the ²¹⁰Pb dating method, which was soon followed by a paper by Crozaz et al. (1964), who examined accumulation history of Antarctic snow using ²¹⁰Pb. Shortly thereafter, Koide et al. (1972, 1973) adapted this technique to unravel sediment deposition and accumulation records in deep-sea environments. Serendipitously, they chose to work in a deep basin off California, where an independent and robust age model had already been developed. Krishanswami et al. (1971) extended the use of this technique to lacustrine deposits to reconstruct depositional histories of lake sediment and, maybe more importantly, contaminant inputs and burial. Thus, the powerful tool for dating recent (up to about one century old) sediment deposits was established and soon widely adopted. Today almost all oceanographic or limnologic studies that address recent depositional reconstructions employ ²¹⁰Pb as one of several possible geochronometers (Andrews et al. 2009; Gale 2009; Baskaran 2011; Persson and Helms 2011). This entry presents a short overview of the principles of ²¹⁰Pb dating and provides a few examples that illustrate the utility of this tracer in contrasting depositional systems. Potential caveats and uncertainties (Appleby et al. 1986; Binford 1990; Binford et al. 1993; Smith 2001; Hancock et al. 2002) inherent to the use and interpretation of ²¹⁰Pb-derived age models are also introduced. Recommendations as to best practices for most reliable uses and reporting are presented in the summary.

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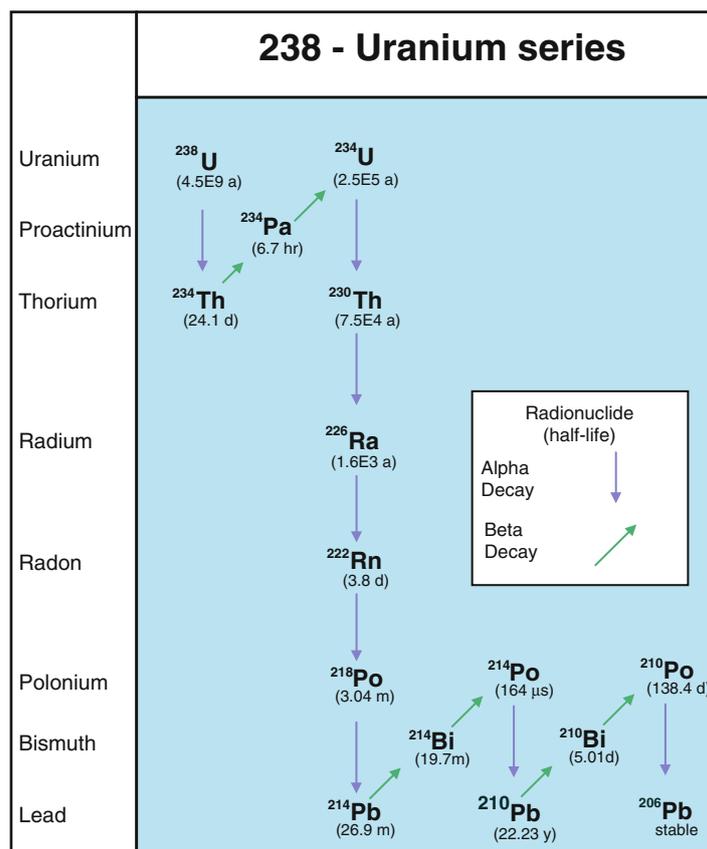


Fig. 1 The ^{238}U decay chain showing ^{226}Ra , ^{222}Rn , ^{210}Pb , and ^{210}Po . Half-lives are shown in parentheses where *a* years, *d* days, *hr* hours, *m* minutes, and μs microseconds

^{210}Pb Dating Principles

Pb-210 is a naturally occurring radionuclide of the ^{238}U radioactive decay chain and has a half-life ($t_{1/2}$) of 22.23 years (Fig. 1). In most environmental systems that have remained “closed” for more than about 120 years (five times the half-life of ^{210}Pb), ^{210}Pb is derived from its parent radionuclide, ^{226}Ra ($t_{1/2} = 1,600$ years), that is present in the material will reach a state of radioactive secular equilibrium. In such settings, ^{210}Pb is not a viable geochronometer. However, in more recently deposited sediment, ^{210}Pb may not be in equilibrium with parent isotope ^{226}Ra and may have an additional source unrelated to ^{226}Ra . First, a fraction of the observed ^{210}Pb is continuously produced by decay of ^{226}Ra and represents “supported” ^{210}Pb , which is considered time independent. The second fraction originates from the decay of atmospheric ^{222}Rn into ^{210}Pb and is called “excess” ^{210}Pb . After wet/dry deposition, rapid scavenging processes remove this radionuclide from the water column (Chanton et al. 1983; Crusius and Anderson 1995) via adsorption onto suspended particulates which may then become incorporated in sediment (Fig. 2). Bottom sediment thus contains a mixture of both supported and excess ^{210}Pb . This excess ^{210}Pb predictably decays with its 22.23 year half-life and can be used to establish recent sediment geochronologies (Goldberg and Bruland 1974; Appleby and Oldfield 1983) under ideal depositional conditions.

If both sediment accumulation and the flux of excess ^{210}Pb to a sediment surface are constant over time, and there are no postdepositional processes that redistribute excess ^{210}Pb present in the sediment, then a down-core profile of excess ^{210}Pb will follow a simple exponential curve that

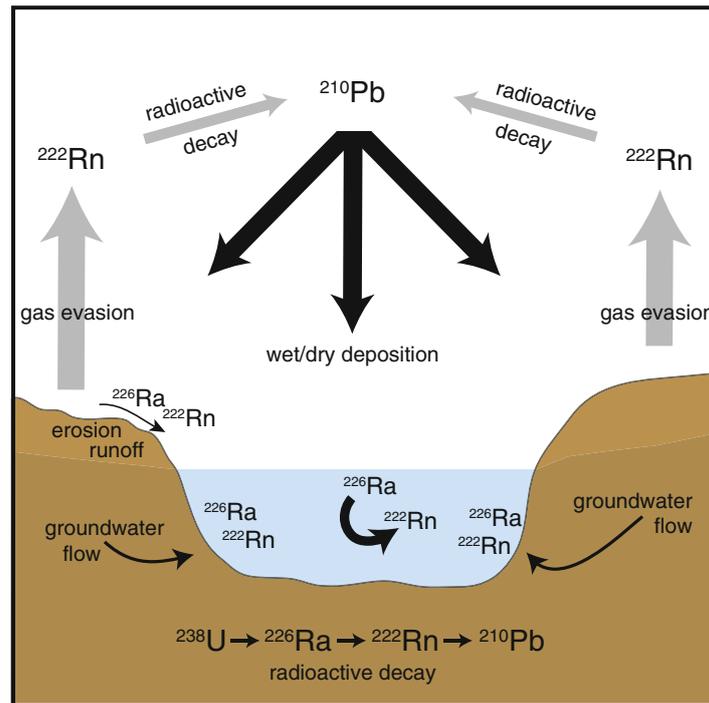


Fig. 2 Conceptual illustration of the dominant sources and transport pathways for ^{210}Pb

tracks its decay. Although these two assumptions are not always observed in natural settings, this simple premise forms the underlying principle for use of ^{210}Pb as a geochronometer. More intricate models have been developed that address nuances in the flux of sediment and ^{210}Pb (Sanchez-Cabeza and Ruiz-Fernandez 2012), as well as the effects of postdepositional mixing (Pourchet et al. 1989), including bioturbation (Benninger et al. 1979; Nittrouer et al. 1983).

Goldberg (1963) first proposed the constant flux model, where the ^{210}Pb flux to sediment is assumed to be constant over time, while the sedimentation rate may vary. This model subsequently became known as the constant rate of supply (CRS) model (Appleby and Oldfield 1978; Benoit and Rozan 2001; Robbins 1978), which is still one of the most often used ^{210}Pb dating models (Sanchez-Cabeza et al. 2000; Persson and Helms 2011). This model assumes that the down-core excess ^{210}Pb activity, vertically integrated to a depth, x , or a cumulative dry mass, m , will equal the flux integrated over the corresponding time interval. Integrating to either x or m ,

$$A(x, m) = A_0 e^{-\lambda t} \quad (1)$$

where $A(x, m)$ is the cumulative residual unsupported or excess ^{210}Pb activity beneath sediment of depth x , or mass m , A_0 is the total unsupported ^{210}Pb activity in the sediment column, λ is the ^{210}Pb decay constant, $0.03114 \text{ year}^{-1}$, and t represents time. The age of sediment at depth x , m is then described by:

$$t = \left(\frac{1}{\lambda} \right) \ln \left[\frac{A_0}{A(x, m)} \right] \quad (2)$$

Unlike the CRS model, in the constant initial concentration (CIC) model, the ^{210}Pb supply varies directly in proportion to the sedimentation rate (Shukla and Joshi 1989). Here the age (t) of a sediment layer is related to the depth (m) by

$$t = m/s \quad (3)$$

where m denotes the mass depth in the core (g cm^{-2}) and s denotes the sedimentation rate ($\text{g cm}^{-2} \text{ year}^{-1}$). The unsupported ^{210}Pb activity ($A(m)$) will thus vary with depth in accordance with the formula:

$$A(m) = A(0)e^{-\lambda m/t} \quad (4)$$

where λ is the decay constant and $A(0)$ is the unsupported activity at the surface of the core. When plotted on a logarithmic scale, the resulting ^{210}Pb activity versus depth profile will appear linear, and the mean sedimentation rate, s , can then be determined using a least squares fit procedure. With these simple equations, ^{210}Pb often can be used as a reliable geochronometer under suitable depositional conditions, although volumes have been written on more elaborate models and their limitations.

Many processes influence the delivery of excess ^{210}Pb to the bottom sediment of a lake or ocean. For example, the atmospheric flux of ^{210}Pb varies by latitude, altitude, and season (Garcia-Orellana et al. 2006; Baskaran and Swarzenski 2007). Catchment size and geology impact scavenging efficiencies and ensuing transport rates of ^{210}Pb (Nittrouer et al. 1983). Water column depth and residence times and suspended particle composition may also affect ^{210}Pb cycling (Turner and Delorme 1996). Based on Appleby (2008), the CRS model will likely produce valid geochronologies if sediment transport rates from the catchment are reasonably constant and produce a minor component of supported ^{210}Pb compared to atmospheric flux rates contributing to excess ^{210}Pb .

^{210}Pb Measurements

Traditionally, the analytical determination of ^{210}Pb was based on either radiochemical separation of ^{210}Pb and measurement of its short-lived beta-emitting daughter, ^{210}Bi ($t_{1/2} = 5.01$ day), or on alpha spectrometry of its indirect decay product ^{210}Po ($t_{1/2} = 138.4$ day) that was assumed to be in secular equilibrium with ^{210}Pb . While both of these methods are laborious, today's alpha-spectrometric systems often consist of sophisticated, integrated sets of multiple detectors so one sediment core can theoretically be counted in just a few days. Advanced planar- or well-type semiconductor detectors enable the gamma-spectrometric analysis of the 46.5 keV decay energy of ^{210}Pb with high relative efficiency (Zaborska et al. 2007). Because gamma analysis of sediment requires only minor (nondestructive) laboratory work, the use of gamma detectors has considerably reduced the effort for most routine ^{210}Pb determinations. In addition, the gamma-spectrometric method provides a concurrent determination of ^{226}Ra , which allows the activities of supported ^{210}Pb to be estimated. Ra-226 activity is determined by quantifying intermediate daughter radionuclides ^{214}Pb (at 295 and 352 keV) and ^{214}Bi (at 609 keV) after establishing their radioactive equilibrium with ^{222}Rn (Kirchner and Ehlers 1998; Swarzenski et al. 2006). Importantly, the gamma-spectrometric method also provides for the determination of ^{137}Cs ($t_{1/2} = 30.17$ year; 661 keV), an independent, nuclear bomb-produced geochronometer.

Based on our own laboratory experience, detection limits for ^{210}Pb are typically less than 10 mBq g^{-1} for well-type HPGe gamma detectors and are likely somewhat lower for planar

detectors that can accommodate much larger sediment sample sizes (~20–50 g). Thus, detection limits for gamma detectors may be considerably higher than those achievable with alpha-spectrometric counting of radiochemically separated ^{210}Po . As a consequence, gamma spectrometry may be of limited use in areas showing small atmospheric deposition rates of ^{210}Pb .

Prior knowledge of the analytical detection limits of the instrumentation as well as the sample size and geometry can affect the decision on how to best section a sediment core for ^{210}Pb analyses (Kirchner 2011). Because of the inverse relationship between particle surface area and particle size, muddy sediment usually contains the highest activities of adsorbed ^{210}Pb (Smith and Walton 1980). Thinner sediment layers expectedly provide a better time resolution of sedimentation rates but may compromise counting statistics if there is not enough excess ^{210}Pb present within a sediment layer. For a given flux of excess ^{210}Pb into the sediment, its activity concentrations are inversely related to the sedimentation rate (Alexander and Lee 2009). Thus, some prior estimate of the expected sedimentation rate is also desirable to guide the core sectioning. An independent estimate of sedimentation rate may be available, for example, from lithological analyses of the core (i.e., varves). Otherwise, the core should be sectioned into thin, consecutive layers and, starting with the youngest sediment, measured layer by layer until excess ^{210}Pb activities approach parent-supported activities. If ^{210}Pb activities approach instrument detection limits, the sediment layers can be combined prior to analysis.

After sectioning, each sediment layer is homogenized and weighed prior to and after drying at 105 C for at least 24 h (Swarzenski et al. 2006). The wet and dry weights provide water content information. The porosity (ϕ) of each sample is calculated as follows:

$$\phi = f_w / [f_w + (1 - f_w)\rho_w / \rho_s] \quad (5)$$

where f_w is the fraction of water in the wet sediment ($=1 - \text{dry wt./wet wt.}$), ρ_w is the density of pore water (assumed to be 1.0 g cm^{-3}), and ρ_s is the density of dry sediment particles (assumed to be 2.5 g cm^{-3}). The cumulative mass depth (M) is calculated as follows:

$$M (\text{mg cm}^{-2}) = \sum [1 - \phi_i] \rho_s x \delta x \quad (6)$$

where ϕ_i is the porosity at depth “ i ” and δx is the thickness of the layer (i.e., 1 cm). The dried sediment layers are pulverized using an agate mortar and pestle and prepared for subsequent analyses.

Three Examples of ^{210}Pb Profiles in Diverse Depositional Settings

Submarine basin – The San Pedro Basin is located in the Southern California Bight, adjacent to Los Angeles, California, USA. This marine basin acts as an efficient trap for both natural and anthropogenic materials. Due to the bathymetry of this deep basin, water circulation is restricted and, as a consequence, water residence times are long. Such a depositional setting is ideal for excess- ^{210}Pb -derived geochronologies. Previous work on sedimentation rates in the San Pedro Basin (Huh et al. 1990; Alexander and Lee 2009) corroborate the excess ^{210}Pb and ^{137}Cs geochronology shown in Fig. 3. Both down-core profiles of ^{137}Cs and excess ^{210}Pb indicate that the sediment has been accumulating at a rate close to 0.09 cm day^{-1} ; although finer scale sectioning would likely show a decline in the sedimentation rates around the turn of the twentieth century, coincident with intensified sediment discharge controls on land.

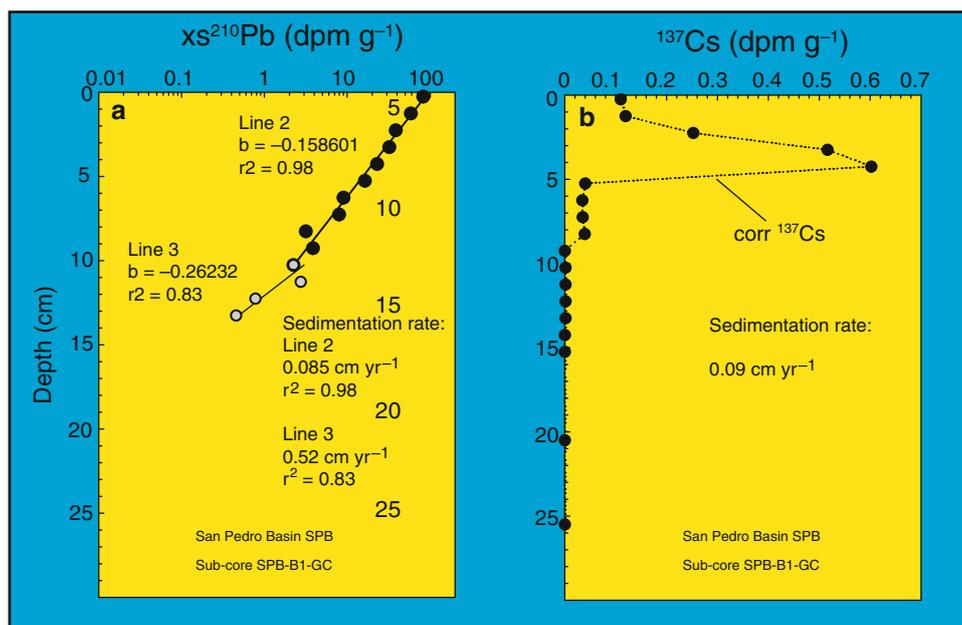


Fig. 3 (a) Excess down-core ^{210}Pb ($x\text{s}^{210}\text{Pb}$) and (b) ^{137}Cs profiles (in disintegrations per minute, dpm) and derived sedimentation rates in a deep submarine basin: San Pedro Basin, California. $60 \text{ dpm} = 1 \text{ Bq} = 27.027 \text{ pCi}$. In (a) *black* and *gray* symbols distinguish unique linear sediment rates. Summary parameters of the linear regression are represented as the slope (b) and r-squared (r^2) value

Alpine lake – Copper Lake is located in the North Cascades National Park, Washington State, less than 10 km from the USA-Canada border (Sheibley et al. 2012). The lake is at an elevation of about 1,600 m above mean sea level and has a surface area of 5.2 ha. The maximum depth of the lake is about 20 m. Figure 4 shows the down-core profiles of excess ^{210}Pb and ^{137}Cs for Copper Lake. The activities of both ^{137}Cs and excess ^{210}Pb are high and indicative of large atmospheric fluxes being delivered into a small basin.

Sinkhole lake – Lake Tulane (40 ha) is located in central Florida at an elevation of 35 m above mean sea level and contains one of the longest climate records for a lake in the USA (Grimm et al. 1993). As a sinkhole lake, Lake Tulane was formed when a limestone deposit catastrophically collapsed due to dissolution by groundwater. Today, the water budget of the lake is balanced by surface and groundwater contributions. Sustained groundwater seepage can also transport radionuclides such as ^{226}Ra . Figure 5 shows the down-core profiles of excess ^{210}Pb and total (supported) ^{210}Pb for Lake Tulane. There is a pronounced mixed layer – ubiquitous in sediment that contains an active biological community – which extends down to ~ 10 cm. Excess ^{210}Pb systematically declines down core to yield two solid sedimentation rates, but at a depth of ~ 40 cm, there is a notable inflection in the total (supported) ^{210}Pb activities. It is likely that this down-core anomaly is produced from ^{226}Ra -rich groundwater seepage (Brenner et al. 2004). Norton et al. (1985) concluded that similar anomalies observed in several high-altitude alpine lakes in Rocky Mountain National Park, Colorado, were the result of groundwater movement that likely impacted the distribution of ^{210}Pb .

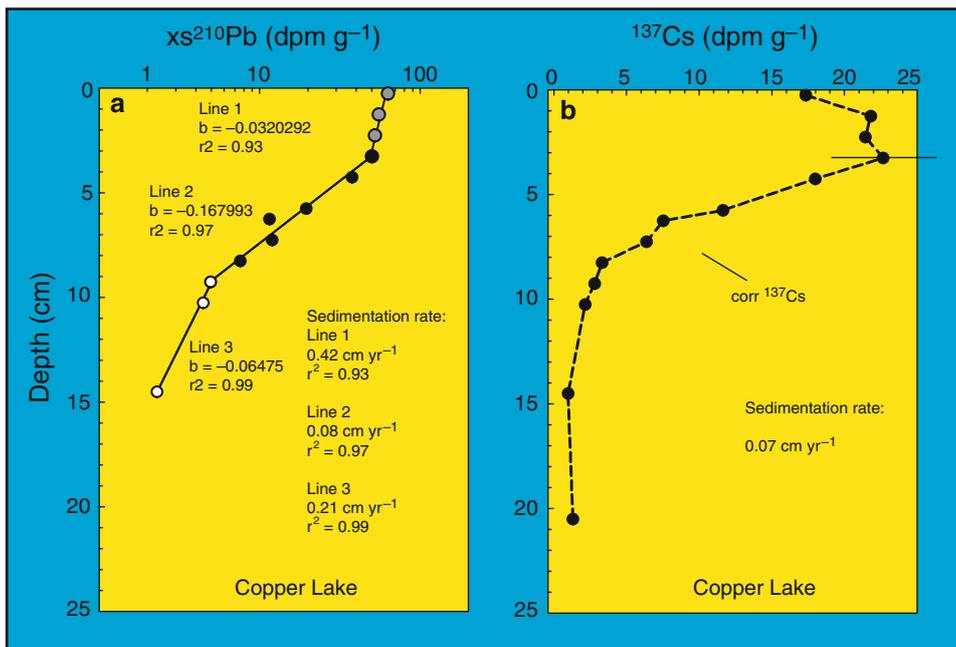


Fig. 4 Excess ^{210}Pb and ^{137}Cs down-core profiles and derived sedimentation rates in an alpine lake: Copper Lake, Washington (Redrawn from Sheibley et al. 2012). In (a) white, black, and gray symbols distinguish unique linear sediment rates. Summary parameters of the linear regression are represented as the slope (b) and r-squared (r^2) value

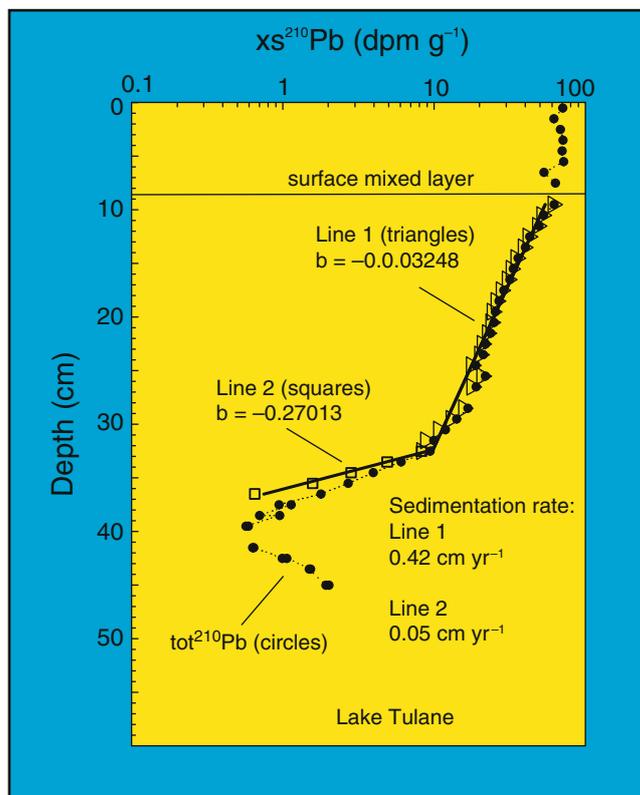


Fig. 5 Excess ^{210}Pb (xs^{210}Pb) and total (supported) ^{210}Pb ($\text{tot}^{210}\text{Pb}$, solid black circles) down-core profiles and derived sedimentation rates in a sinkhole lake: Lake Tulane, Florida. Open triangles (Line 1) and open squares (Line 2) distinguish unique linear sediment rates. Summary parameters of the linear regression are represented as the slope (b)

Summary

During the last decade, there has been an unprecedented push to learn more about how the environment has changed over time. This interest is grounded in trying to better understand differences between natural- and anthropogenic-driven changes and how our environment may respond to such changes in the future. One of the most fundamental steps in establishing a record of environmental change is to first derive an accurate geochronology. The geochronologies generated by ^{210}Pb analysis can resolve the very recent past (last 100–200 years), with total (1σ) uncertainties varying from just under 1 year to around a decade (Baskaran 2011). However, ^{210}Pb geochronologies are not without inherent problems and uncertainties (Robbins and Edgington 1975; von Gunten and Moser 1993). The development of a ^{210}Pb geochronology should never become a routine exercise (Appleby and Oldfield 1992; Appleby 2008). Even some recent studies that employ ^{210}Pb as a geochronometer still fail to meet the minimum requirements identified by Oldfield and Appleby (1984). For example, some of these efforts may fail to adequately evaluate inconsistencies in competing ^{210}Pb models, or they may forego assessing ^{210}Pb model results against independent geochronologies (e.g., other radioisotope systems or varve counting). Lastly, some ^{210}Pb applications may ignore postdepositional mixing (Benninger et al. 1979; Berner 1980; Miguel et al. 2003) that can yield a surprisingly plausible down-core ^{210}Pb profile but which produces a geochronological model that is simply invalid (Kirchner 2011). That said, a carefully developed ^{210}Pb geochronology, and one substantiated in the peer-reviewed literature per recommendations outlined in Smith (2001) and Hancock et al. (2002), is invaluable in any recent environmental reconstruction. Sediment dating using ^{210}Pb methods will continue to be refined with new improvements in analytical and model capabilities.

Cross-References

- ▶ [Alpha Spectroscopy](#)
- ▶ [Lacustrine Varves](#)
- ▶ [Marine Varves](#)
- ▶ [Sediment Mixing Rate, \$^{210}\text{Pb}\$](#)
- ▶ [U-Series Dating](#)
- ▶ [Varve Chronology](#)

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