Summary

Developing an accurate chronological framework for landscape development and processes provides a context of how landforms and depositional environments have responded to variations in external factors such as geomorphic processes and variability in climate. Defining the desired landform or specific event for dating is the first step toward establishing a dating strategy and choosing an appropriate dating technique. As no one dating method can be universally applied to provide an age estimate of landscape evolution, careful consideration of the most appropriate dating method for the specific situations is needed. Numerous factors should be taken into account; such as the type of material that is available for dating, the age of the material being dated (Figure 1), the integrity of the material as an accurate indication of the age of the landform, event, or deposit that is being dated, the resolution required, and the geological setting.

There are numerous dating methods that can be applied to provide an age assessment for a specific event or deposit, and to accurately determine landscape change over a variety of time scales. The types of dating methods that may be used in geomorphic studies; some examples are included to illustrate them.

Types of dating methods can be categorized into the follo wing three types:

1. Relative dating methods
2. Numerical dating methods
3. Correlative dating methods.

1. Relative Dating Methods

Geomorphic surfaces can be dated using a relative order of age by evaluating the degree or intensity of the ring features observed on a particular surface and comparing them to those observed on other surfaces. The physical characteristics of a landform provide clues as to its age, as well as its depositional history, existing level of stability, etc.

2. Numerical Dating Methods

Numerical dating methods are rooted in radiometric dating techniques, such as radiocarbon and cosmogenic nuclide dating, but also include other measurable techniques such as Optically Stimulated Luminescence (OSL). Some scientists prefer the term *absolute* *dating* in this context. Numerical dating methods usually provide specific age estimates from measuring the physical or chemical properties of the materials, including organic material, sand grains, or gravel.

3. Correlative Dating Methods

Correlative dating methods are sometimes referred to as age equivalence dating, and involve correlating physical attributes of a surface or deposit with similar physical attributes that have been constrained with numerical dating methods. The main methods are shortly described here:

3.1 Radiocarbon dating method is probably the single most important dating method in Quaternary science. With a usable age range between 300 and 40,000 years in most applications, and sample types that include most organic material, radiocarbon dating is widely used to date sediments and landforms. Typical analytical uncertainties are 2–5%, although uncertainty typically becomes larger when ages are calibrated into calendar years.

3.2. Cosmogenic-exposure dating (also referred to as *surface exposure dating* and *terrestrial cosmogenic-nuclide dating*) has emerged over the last two decades as the premier chronological tool to date glacial landforms. A family of isotopes is produced in Earth's rocky surface (mostly in the upper few meters) as a result of cosmic-ray bombardment. Many of the resulting "cosmogenic" isotopes are radioactive (e.g.,^{14}C,10Be, ^{26}Al, ^{36}Cl), whereas others are stable (e.g., ^{3}He, ^{21}Ne). Some of the isotopes are produced solely from cosmic ray bombardment (e.g., ^{10}Be), whereas others can be formed by additional means (e.g., ^{36}Cl). The different isotopes have differing target, or parent, minerals. For example, applications of 10Be mainly use quartz-bearing rocks, whereas applications of ^{3}He commonly rely on olivine phenocrysts in igneous rocks. And, some methods use a "whole-rock" approach because there are several parent elements that produce the cosmogenic isotope (e.g., ^{36}Cl). Furthermore, the radioactive cosmogenic isotopes (radionuclides) are used for different applications depending on their varying half-lives.

3.3. *Optically Stimulated Luminescence* method (Stokes, 1999) is a dating technique which indicates the burial time of Quaternary deposits. With the new developments in instrumentation, reducing the sample size to individual grains may provide very accurate numerical dating, with age uncertainties of 5–10%, even for young deposits (<300 years).

3.4. Dendrogeomorphology: The term *dendrogeomorphology* was coined by Alestalo (1971) and stands for the analysis of growth reactions of trees affected by geomorphic processes by *dendrochronological* methods. These methods are based on the principle that trees growing in regions with distinct seasons form annual growth rings. While cells are produced during the growing season, growth ceases during the dormant season. Tree growth and the size of each tree ring is influenced by intrinsic factors (e.g. genetics, age) on one hand and by extrinsic factors including water availability, temperature, light, soil properties and competition on the other hand. Trees growing at the same site therefore normally record the same external influences in their tree-ring series. Apart from these biotic factors common to all trees growing at a site, mechanical impacts such as from torrential activity may cause changes in the growth pattern of individual trees at the location. Such growth changes can be in the form of injuries, tangential rows of traumatic resin ducts, abrupt growth changes (reduction or increase) or the formation of compression wood. The impact and the related growth changes will be recorded in the tree-ring series and allows the later dating of events with yearly and sometimes even monthly precision (Stoffel et al., 2010).

3.5. ***Lichenometry*** is a surface-exposure dating method that uses lichen-growth rates to infer the age of young (few thousand years old or younger) glacial landforms, typically bouldery deposits such as moraines. The technique combines measurements of the size of lichens growing on rocky glacial deposits with independently derived lichen growth rates to derive lichen age, and thus moraine age. Lichen types that grow radially and regularly are used, most commonly the crustose lichen genus Rhizocarpon, where R. geographicum is specifically targeted in most cases, but field identification to the species level is difficult.

We include *historical information* here as a proxy for different proposes. The work in historical documentary sources has a very specific methodological development. Generally, sources with information in historical time may be contained in three different categories: (1) handwritten documents, (2) printed sources, and (3) iconography. Printed and hand written documents include: books, transcription of documentary collections, newspapers, technical & official reports, local historiography; and iconography involves epigraphically records, but also oral history and historical photography, cartography and painting. The information recovered in the documentary sources can be classified and quantitatively defined.

Ice dating:

Ice cores can contain several forms of paleo-proxy data that estimate standard meteorological parameters to help reconstruct past climates. Some of the more common meteorological data that can be reflected in ice include air temperature, atmospheric circulation variations, precipitation amount, atmospheric composition, solar activity, and records of volcanic eruptions. These parameters can be represented by corresponding proxy records including stable isotopes, radioisotopes, dust composition, snow accumulation rate, air bubbles, and volcanic ash or sulfate. All of the modern analytical techniques used to extract these proxy records have been developed and honed over time, and with the assistance of better technology and new ideas more accurate methods of ice core analyses are being developed. Before scientists can begin reconstructing past climates from paleo-proxies derived from ice cores however, the ice must be drilled and analyzed.

since glaciers are known to preserve the precipitation of the past in an unbroken sequence, it might seem that they are especially well suited for the study of the isotopic value of precipitation and its variation with time. This is however, not quite so simple. From the moment the snow has been deposited on the glacier surface, the isotope value of the snow pack begins to change owing to various processes. These processes not only affect the upper-most firn layers but may also affect the entire ice mass. Isotope studies of firn and snow have shown that, in every case, an appreciable isotopic modification is found to take place in glacier surface layers (accumulation) during firnification, i.e. when they undergo changes from snow to glacier ice. Epstein and Sharp (1959a) first showed that, underfavorable conditions, the seasonal δ-variations can survive the firnification processes and are preserved in glacier ice. Such favorable conditions, however, exist mainly in the dry snow zones and occasionally also in the percolation zones, provided the percolation of meltwater is very small. In the percolation zones and especially in the soaked zones the seasonal δ-variations are always more or less smoothed out. Even in the dry snow zone the seasonal δ-variations do not always survive the firnification process. The obliteration of the seasonal δ-variation during firnification in the dry snow zones seems to be inversely related to the accumulation rate, but probably it also depends upon other parameters such as the windiness of the region. It is therefore vital to have a thorough knowledge of the prevailing climate conditions, physical processes and glacier dynamics for the application of stable isotopes in climate reconstruction using ice cores.