IN-SITU COSMOGENIC NUCLIDES*: THEIR ROLE IN STUDYING THE AGE AND EVOLUTION OF LANDSCAPES, OR WHAT "AS OLD AS THE HILLS" REALLY MEANS

by Lorraine A. Manz

Introduction

The concept of using radioisotopes to determine the chronologies of petrologic events is an old one. Since its inception in 1905 when B.B. Boltwood, a chemist at Yale University, showed that the radioactive decay of uranium-238 to lead-206 could be used as a means of dating minerals in rocks, several parent/daughter nuclide pairs have been identified that have been successfully applied to the dating of geologic materials. Some of the more useful ones are shown in Table 1. In all these methods (except carbon-14), ages are calculated by measuring the ratio of the parent nuclide to its daughter element in the material of interest. The end result is an estimation of the time elapsed since the rock or mineral was formed, or the organism (plant or animal) died.

Determining the ages of landforms is another matter altogether. How landscapes develop and change provides valuable insights into the geologic, environmental, and climatic processes that shape them. Landforms of known age allow these processes to be placed within an absolute temporal framework, which in turn facilitates the reconstruction of past environments and aids in understanding the conditions under which they evolved and continue to evolve.

Landforms are difficult to date because they are made of preexisting materials; so whereas the dating methods described above will give the ages of the rocks and minerals of which they are made, they are of little use in dating the landforms themselves. Other techniques must therefore be employed, of which carbon-14 dating is probably the best known. However, this method is limited in its application for two reasons. Firstly it requires the presence, on or within the landform to be dated, of carbon associated with things that were once living such as wood, charcoal, bone, or the shells of aquatic organisms. Secondly, because of its relatively short half-life (5,730 years), carbon-14 is only useful for dating objects that are very young in geologic terms. Anything older than about 40,000 years is beyond its capability.

Carbon-14 (^{14}C) is a member of a group of very rare isotopes called cosmogenic nuclides, which are produced by the interaction of cosmic rays on the nuclei of atoms in the Earth's atmosphere and in rocks and minerals at the Earth's surface. In recent years, techniques have been developed that use several of these nuclides as a means of determining the ages and exposure histories of certain types of landforms. Unlike conventional ^{14}C dating, which works with geochemically closed systems, these new methods of surface-exposure dating are based on the principle that the

Table 1. Methods of radiometric isotope dating of geologic materials (adapted from Boggs, 1995)

Parent nuclide	Daughter nuclide	Half-life (years)	Approximate useful dating range (years before present)	Materials commonly dated
Carbon-14	Nitrogen-14**	5,730	$<\sim 40{,}000$	Wood, peat, $CaCO_3$ shells, bone, charcoal
Uranium-238	Lead-206	4,510 million	>5 million	Monazite, zircon, uraninite, pitchblende
Potassium-40	Argon-40	1,300 million	$>\sim 100{,}000$	Muscovite, biotite, hornblende, glauconite, sanidine, whole volcanic rock
Rubidium-87	Strontium-87	47,000 million	>5 million	Muscovite, biotite, lepidolite, microcline, glauconite, whole metamorphic rock

** The $^{14}C/^{12}C$ ratio is used to determine age.

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* Variously known as "terrestrial in-situ cosmogenic nuclides" or TCN (Gosse and Phillips, 2001), "in-situ cosmogenic isotopes" (Cerling and Craig, 1994) as well as by a host of less specific, but contextually correct terms such as "cosmogenic nuclides" and "cosmogenic radioisotopes".

rate of in-situ accumulation of cosmogenic nuclides in a geologic material is proportional to its exposure time at the Earth's surface. Therefore, the concentration of cosmogenic nuclides is a measure of the age of the landform on which they reside. These techniques have greatly expanded the number and type of geomorphic features that can be assigned an absolute chronology and have proven to be an invaluable asset to the study of landscape evolution.

Principles of Surface-Exposure Dating with Cosmogenic Nuclides

Most of what follows is derived from several publications on cosmogenic radionuclides that have appeared in various technical journals since 1986. All of these articles are cited in two excellent reviews on the subject by Cerling and Craig (1994), and Gosse and Phillips (2001). The two stable cosmogenic nuclides helium-3 and neon-21 have been deliberately omitted from the discussion to keep the size of this article within manageable limits. For those who are interested, both of the above-mentioned reviews include descriptions of the application of these nuclides to surface exposure dating.

Despite a veritable explosion in activity in the field of surface-exposure dating during the past fifteen years or so, almost half a century has passed since the potential of in-situ (terrestrial) cosmogenic nuclides (hereafter referred to as ICNs) as geochronometers was first recognized. That the earth science community was so slow to embrace the concept was not so much a lack of interest as the inability of the instrumentation available up to the late 1970s to measure the infinitesimally small concentrations of these nuclides. Their production rates are imperceptibly slow – only a few atoms per gram of rock per year, which means that even after a period of many tens or hundreds of thousands of years their concentrations may not have amounted to more than about 100 parts per quintillion*, or 0.00000000000001%. It was not until the introduction of accelerator mass spectrometry (AMS) in 1977 that the measurement of atomic species at such low abundances was finally made possible.

ICNs are formed in geologic materials by the interaction of cosmic rays with the nuclei of certain target atoms within their mineral lattices. Reactions typically involve neutron capture, high-energy spallations (the emission of nuclear fragments such as alpha-particles, protons and neutrons) and muon-induced nuclear decompositions (Figure 1). ICNs only accumulate at depths of less than 1 to 2 meters, because cosmic rays do not penetrate below the shallow subsurface. Consequently, for rocks that have been buried below the surface and then subjected to rapid exposure by glacial activity for example, the build up of cosmogenic nuclides is a function of exposure time, and hence the age of the landform or surface feature of which the rocks are a part.

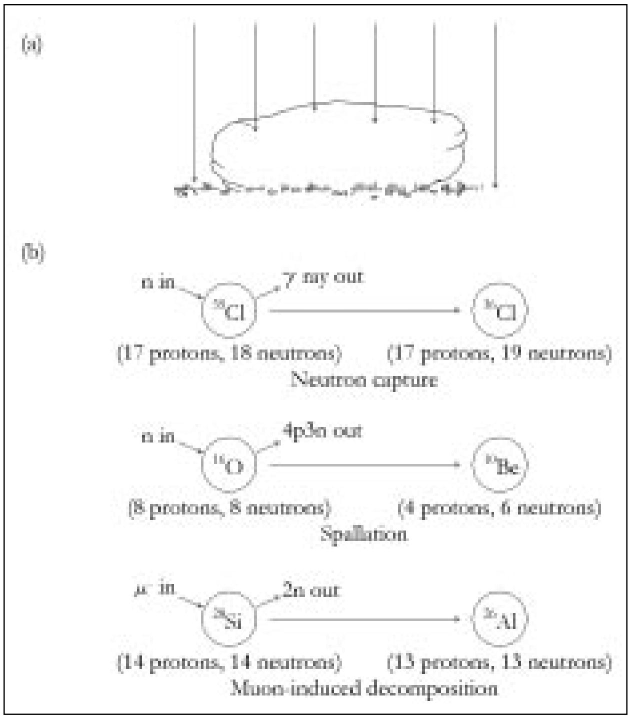

Figure 1(a) Cosmic rays consisting of neutrons, protons, and subatomic particles such as muons ($\mu^{\pm}$) strike and penetrate rocks at the Earth's surface. **(b)** Atoms such as chlorine in chlorite and silicon and oxygen in quartz and feldspars interact with the cosmic rays and by various mechanisms produce in situ cosmogenic nuclides.

Of the large number of nuclides that may be formed cosmogenically, only a few are suitable candidates for surface-exposure dating. Many are already naturally abundant and their cosmogenic component is difficult to determine. Some of the radioisotopes have half-lives that are much too short to be of any use. For example, sodium-24 has a half-life of only 15 hours, and so in geologic terms disappears the instant it is formed. Others, particularly those with atomic weights greater than 56, are often produced in such small amounts that they are below the detection limits of current instrumentation. Table 2 lists the properties of four ICNs, which are frequently used in surface-exposure dating. Note that all four of these nuclides are radioactive, a (non-essential) characteristic that enhances their rarity in terms of abundance, but not to the extent that they cannot be detected against a background of their common isotopes. Furthermore, their half-lives are on the same orders of magnitude (millennia) as the timescales of many geomorphic processes. This means that, in addition to dating landforms, they can also be applied to the study of their development, across a time span ranging from a few thousand to about 2.5 million years.

Although the basic principles of surface-exposure dating with ICNs are fairly straightforward, many factors affect the rate at which cosmogenic nuclides accumulate in geologic materials. All of these must be taken into account to obtain

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* In the U.S. a quintillion is a million million million, or 1 x 10^{18}. The U.K. designation is a trillion.

Table 2. In-situ cosmogenic nuclides commonly used in surface exposure dating

Nuclide	Target nuclides	Half-life (years)	Approximate useful dating range (years before present)	Materials commonly dated
Beryllium-10*	Oxygen-16 Silicon-28 Beryllium-7 Beryllium-9 Boron-10 Carbon-13	1.6 million	< 5 million	Quartz, olivine, magnetite, (plagioclase)
Carbon-14**	Oxygen-16 Oxygen-17 Silicon-28 Nitrogen-14 Boron-11	5,730	<20,000	Quartz
Aluminum-26*	Silicon-28 Sodium-23	705,000	< 5 million	Quartz
Chlorine-36	Calcium-40 Potassium-39 Chlorine-35	301,000	< 1 million	Potassium-feldspar, plagioclase, calcite, chlorite, fluid inclusions in quartz

* Usually measured as the ^{26}Al/^{10}Be pair

** In-situ cosmogenic carbon-14 produced in rocks should not be confused with the cosmogenic carbon-14 shown in Table 1, which is meteoric (formed in the earth's atmosphere, mostly from ^{14}N). The dating methods using these two types of carbon-14 are not the same. A dating method using in-situ cosmogenic carbon-14 has only recently been optimized, and only a few examples of its successful application have been published. Unless otherwise stated, all references to carbon-14 dating in this article refer to the traditional method shown in Table 1.

accurate, meaningful ages. The production rates of ICNs are dependent on the concentrations of the target nuclides, elevation, geomagnetic latitude (the last two of which affect the intensity of the incident cosmic radiation), and surface orientation, whereas rates of accumulation are a function of production rate and the rate of erosion of the rock itself and/or overlying material. Some of these nuclides are also nucleogenic, that is, they are produced by the radioactive decay of elements such as uranium and thorium, common constituents of granites and other crystalline rocks.

The relation between any one of these factors and cosmogenic nuclide build-up is not always simple, nor is it necessarily fully understood or refined. Many of the above-mentioned factors are themselves dependent on other factors. Geomagnetic latitude for example, varies over time as the earth's magnetic field fluctuates, and erosion rates are functions of climate and the nature of the geomorphic processes that are or were active in the study area. The magnitudes of the nucleogenic components are, of course, dependent on the concentrations of their parent radionuclides. The mathematical formulae that are used to calculate exposure ages take all of these factors into consideration as far as the state of the art will allow. Nevertheless, there is considerable scope for improvement in both the models and the understanding of the physical and geologic parameters upon which they are based.

Many of the uncertainties associated with ICN studies may be reduced or avoided completely by the adoption of rigorous sampling procedures. Obviously, the material selected for sampling should represent, as closely as possible, the exposure history of its host landform. Therefore, what is required is a large, flat surface that has remained fully exposed and undisturbed since emplacement and contains no cosmogenic nuclides inherited from previous exposure episodes. Identification of such surfaces may often be difficult, but the application of certain guidelines, careful observation, and a little common sense will improve the odds considerably.

Applications

Since their development in the mid-1980s, ICN-dating techniques have been applied to a wide range of geologic problems, and whereas the uncertainties discussed earlier have led to minor inconsistencies in results, overall the methods have proved to be remarkably accurate. This, together with their utilization of common lithologies and mineralogies (see Table 2), their applicability to a wide range of geomorphic processes under nearly any climatic regime, and their eminently useful time frame explains their enormous potential. The following discussion comments on some of the types of surfaces that have been dated using ICN methods and touches on a few of the possible scenarios that the data

Figure 2. Glacial erratics are prime candidates for ICN dating. They have yielded valuable information about the glacial history of the Pleistocene epoch.

imply. For more complete descriptions, the reader is once again referred to the two reviews (Cerling and Craig (1994), and Gosse and Phillips (2001)) cited earlier.

Many published studies describe how ^{36}Cl and ^{10}Be/^{26}Al have been used to date Quaternary landforms, particularly those associated with Pleistocene glaciation (Figure 2). Determination of the ages of moraine complexes and glacially eroded surfaces has been instrumental in reconstructing the cycles of advance and retreat of both continental and mountain glaciers, with the added bonuses of an unprecedented degree of precision and resolution. An example is the identification of evidence by ^{10}Be dating, of the geologically brief 1,300-year period of global cooling known as the Younger Dryas, among morainal deposits in the Wind River Mountains, Wyoming. Several studies have concentrated on the Pleistocene glaciation of the Rocky Mountains. For example, the Foothills erratics train in Alberta, Canada, is a string of mostly quartzite blocks that runs for more than 360 miles along the eastern edge of the Rocky Mountains and marks part of the line of contact between the Wisconsinan Stage Cordilleran and Laurentide ice sheets. Chlorine-36 dating of these erratics revealed a time of emplacement that coincides with the last glacial maximum, which occurred during the Late Wisconsinan substage about 18,000 years ago. The date is consistent with other evidence of Late Wisconsinan coalescence of montane and continental ice in northwestern North America. Elsewhere, ICNs have been used to investigate the histories of the Fennoscandian and Antarctic ice sheets, the glaciation of the Swiss Alps and the Southern Alps of New Zealand, and the rates of glacial retreat in the Canadian Arctic and Greenland. Closer to home, ^{10}Be/^{26}Al studies in southern Minnesota are helping to reconstruct the glacial chronology of the upper Midwest and northern Great Plains (Bierman et al., 1999).

Recent meteor impact craters, such as Barringer Crater in northern Arizona, are good candidates for ICN dating. They are a source of material that fulfills one of the basic requirements of ICN dating: that of deep burial followed by rapid subaerial exposure, in the form of rock fragments ejected from the crater site at the time of impact. This prerequisite is also met by lava flows, cinder cones and other landforms of volcanic origin, although they fall primarily within the realms of ^{3}He, ^{40}K/^{40}Ar, and other dating methods. Determination of the ages of postglacial landslides on the Isle of Skye in Scotland, fluctuations in lake levels, rates of tectonic uplift and slip along active faults, and characterization of the Yucca Mountain nuclear waste facility in Nevada are just a few more examples of the ever-increasing diversity of applications of ICN-dating methods. Even in the field of archaeology ICNs are proving to be useful. In Portugal, ^{36}Cl was used to settle a dispute over the ages of a set of Paleolithic petroglyphs, and is now promising to finally solve the ancient riddle of Egypt's enigmatic Sphinx.

The dependence of the concentration of ICNs on subsurface depth and erosional processes makes them very useful tools in the study of landscape evolution. ICNs have been used to determine rates of stream incision and soil development, as well as local and regional weathering rates in places as climatically diverse as Antarctica, the Ajo Mountains in southern Arizona, and South Africa's Drakensberg Escarpment. Some erosional histories are obtained from ICN measurements in bedrock, but many more are derived from depositional features such as alluvial fans, fluvial terraces, and beach sediments. In addition to determining landform age, the application of ICN dating to sediments shows great promise as a means of studying geomorphic processes and investigating, for example, the relation between soil development and landscape morphology, and the rates of landscape erosion versus deposition. In terms of surface dating, the principles are similar to those for bedrock, but a growing number of studies are using concentration-depth profiles to evaluate exposure and depositional histories as a function of ICN *depletion*. Burial dating is a relatively recent application of ICNs that is essentially the reverse of exposure dating. Not surprisingly, burial dating measures burial age. It works best on sediments that have enjoyed a long, uninterrupted subaerial exposure history followed by rapid burial at depths beyond the reach of cosmic rays. The method has been used to date cave sediments in Virginia and Kentucky, as a way of measuring stream incision rates, and may also be applicable to lake and marine sediments. Other possible candidates for burial dating include basin sediments, buried paleosols (fossil soils) and surfaces that lie beneath volcanic, glacial or landslide deposits.

And Finally….

What has any of this to do with North Dakota? Most of the state's surface geology is glacial and dates from the last ice age, which ended about 10,000 years ago. During the preceding 1.6 million years or so, ice sheets advanced and receded across North Dakota many times, each cycle leaving its calling card in the form of glacial till and other sediments.

Figure 3. Early/Pre – Wisconsinan glacial erratics in Dunn County. Chlorine-36 dating will reveal how long they have been there.

The ages of most of these deposits have been determined using the ^{14}C dating method and have been found to correspond to the last major ice advance, which began some 26,000 years ago during the glacial stage known as the Late Wisconsinan. Southwest of the Missouri River however, there are other glacial deposits that are much older, but because they are beyond the range of ^{14}C dating their actual ages remain unknown (Figure 3). Yet the answers are there, locked inside the isolated boulders, or erratics, that the glaciers carried here from Canada and left scattered across the countryside when they departed. And ^{36}Cl holds the key. A project is underway to place these remnants of ancient glacial activity within an absolute time frame, by sampling these boulders and measuring the ^{36}Cl they contain. The results of these studies will provide us with a better understanding of the Quaternary climatic cycles of the central and northern Great Plains, and will also provide a means of correlating these early glacial advances with others of known age in North America and other parts of the world.

References

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