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Relative Dating Techniques to Distinguish Late Pleistocene-Holocene Continental Sediments

William J. Wayne
University of Nebraska-Lincoln, wwayne3@unl.edu

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William J. Wayne

Department of Geology, University of Nebraska–Lincoln,
Lincoln, NE 68588-0340, U.S.A.

Abstract
Radiometric dating, particularly with ^{14}C, provides ages for those Late Pleistocene and Holocene sediments that contain datable materials. Standard stratigraphic and morphostratigraphic techniques of superposition, geomorphic position, partial overlap, and offlap provide relative chronology in many situations. The use of multiple relative dating (RD) techniques, developed for the study of glacial deposits, makes use of these techniques where possible, but depends heavily on the additional comparison of the results of surface processes that act continuously and more or less uniformly after accumulation is complete. For sediments at the surface that have not been buried, the most important of these processes are weathering and morphological alteration. Soil profile development is progressive; careful field description plus laboratory analysis provide data to distinguish soils of differing maturity, hence, of different ages. Clasts at the surface and within the soil profile weather continuously, and quantification of the degree of their decay permits recognition of age differences. In mountains adjacent to deserts, a veneer of loess accumulates slowly, and is thicker on older alpine deposits. Quantification of gully development provides still another morphometric approach to dating young sediments. These RD methods have been effective in distinguishing relative ages of continental sediments from 10^2 to 10^7 yr. old in the western U.S.A. mountains and in the Central Andes.

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Introduction

The development of radiocarbon techniques for dating sediments up to a few tens of thousands of years old has revolutionized the chronologies of many sedimentary sequences, but for radiocarbon dating to be useful, appropriate materials must be found in suitable stratigraphic position. Unfortunately, many geologic situations exist in which such samples cannot be found, and investigators working with young continental sediments must depend on the use of relative dating methods for correlation and to estimate ages for the accumulations.

Relative dating (RD) methods depend on the fact that as soon as a deposit becomes exposed, surficial processes, acting continuously, begin to alter it. In a sequence of deposits of different ages, the youngest will be least altered, and progressively older deposits will show greater degrees of modification. RD methods used were developed over nearly a century, principally by students of Pleistocene glacial deposits, but they can be used to advantage on any sediments sufficiently young to retain some of their original constructional morphology. Early efforts were largely descriptive, but increased levels of quantification have made RD methods of dating more effective.

Surficial processes cause several measurable changes to take place on recently deposited—or exposed—sediment. Those changes can be categorized into three groups: (1) changes in morphology, produced by erosion and by deposition; (2) changes resulting from weathering, both surface and subsurface; and (3) plant growth rates. Some of the RD methods have very short time spans over which they are effective; others provide usable data over longer periods. For greatest reliability in estimating the age of a deposit, as many RD methods as possible should be used.

The following discussion covers the RD methods the present author has found useful in the differentiation of glacier, rock glacier, landslide and mud flow deposits in the Ruby Mountains, Nevada, U.S.A., and part of the Rio Blanco drainage basin in the Cordon del Plata, Mendoza, Argentina. Both regions are arid mountain ranges that have been glaciated; the Quaternary succession in each includes two or more Pleistocene tills, associated glaciofluvial and mass wasting sediments, and Neoglacial deposits. In the Ruby Mountains cirque floors range as high as 3100 m above mean sea level, tills of the last major glaciation reach 2100 m and one earlier glacier extended as low as 1830 m (Sharp, 1938; Wayne, 1984). In the Rio Blanco basin cirque floors reach 4500 m, outer moraines of the last major glaciation stand at 2400 m, and at least two earlier ice tongues extended below 2100 m (Wayne, 1981, 1983; Wayne and Corte, 1983).

Relative-Age Dating Methods

Early students of Pleistocene sediments nearly a century ago made use of RD methods. In the Great Lakes region, Chamberlin (1895), Leverett (1899, 1902), Leverett and Taylor (1915), and others distinguished moraines of Wisconsinan age from those of older glaciations by comparison of the degree of topographic alteration. Thornbury (1940) applied depth of leaching of carbonates to better define boundaries of successive glaciations. Matthes (1930) examined both the sharpness of morainal topography and the extent of weathering of glaciated bedrock surfaces in the Sierra Nevada. Blackwelder (1931) compared the number of weathered boulders to unweathered boulders on the surfaces of drifts of three glaciations from the Sierra Nevada to the Rocky Mountains. More recently, Sharp (1938, 1968, 1972), Birkeland (1964, 1973), Birman (1964), Benedict (1967, 1968), Burke and Birkeland (1979), Locke (1979), and others have built on the work of the earlier geologists in order to better define RD methods. Most RD methods are based on field measurements. Considerable operator variation exists, and it is highly unlikely that the measurements made by two or more investigators will be identical. Nevertheless, the data seem to be consistent, in that different investigators will recognize the same major breaks in a sequence of deposits.

Morphology of land forms

Of the several means used to determine ages of surficial sedimentary units relative to each other, perhaps the longest used and most readily understood by most geologists is geomorphic overlap. Advancing ice often overlaps moraines or other deposits laid down earlier, and rock glaciers, landslides, mudflows, dunes and river alluviation partially bury older landforms and sediments. One of the most striking

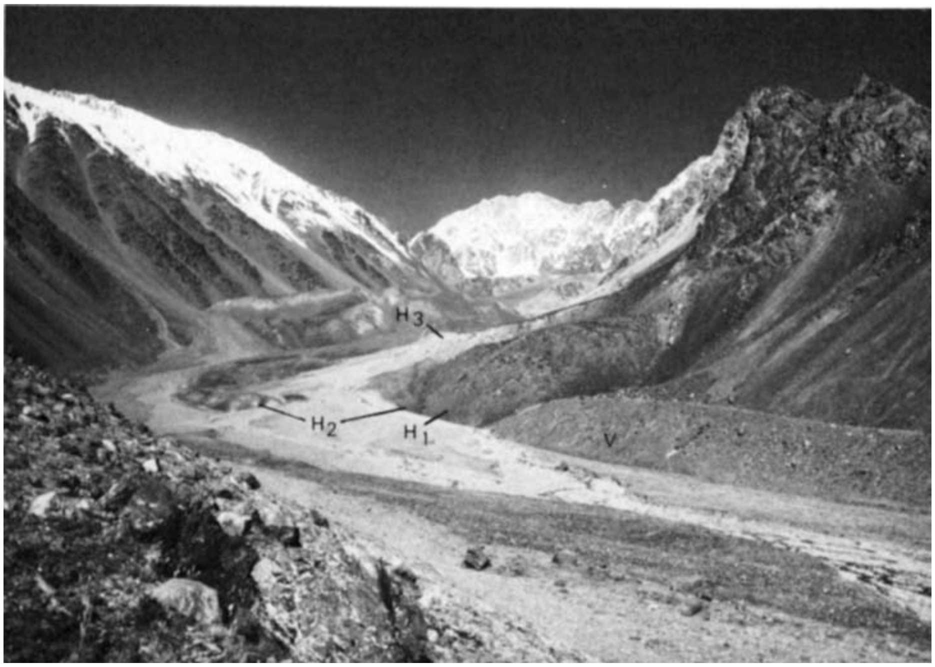

Fig. 1. Overlap of glacial moraines and rock glacier debris in the upper part of Quebrada de los Vallecitos, Mendoza Province, Argentina. Lateral moraine of Vallecitos glaciation *(V)* was overridden by early Holocene *(H_1)* rock glacier, which is in turn overlapped by mid-Holocene *(H_2)* moraine. Active *(H_3)* rock glacier has expanded across the moraine.

examples of a morphostratigraphic sequence can be seen in the late Vallecitos (= Wisconsinan)-Holocene moraines, outwash and rock glaciers in one of the tributaries of Rio Blanco (Fig. 1);

With increasing age, erosional processes have greater time to alter the shape and remove part of the deposits. Freshly deposited moraines, recent landslides, active dunes, and other constructional sedimentary deposits have a sharpness and a ruggedness, that becomes muted with time, and eventually the constructional landform becomes unrecognizable, though some of the deposit may remain. Depth of stream incision and widening of valleys also increase with age.

Streams flowing through Angel Lake (= Pinedale) till in the Ruby Mountains have excavated trenches in the sediment but have made few changes in the bedrock valley floors. Beyond the Angel Lake end moraines, though, the creeks have entrenched themselves well below the bedrock surface on which Lamoille (= Bull Lake?) till was deposited. The bedrock walls of the valleys that were glacially smoothed by Lamoille ice but not reached by Angel Lake glaciers are much more

Fig. 2. Rock surface smoothed by Angel Lake glacial ice *(AL);* more raggedly weathered rock surface immediately downvalley was abraded by Lamoille ice *(L)* but not reached by the younger glacier. Soldier Creek, Ruby Mountains, Nevada, U.S.A.

strongly weathered and eroded than those re-excavated by later ice, which provides an indirect but valid way to identify the deposits within the valley parts (Fig. 2). Angel Lake moraines are hummocky and contain many closed depressions, whereas Lamoille moraines are smooth.

Lateral and end moraines deposited during the most recent glacial advance (Holocene III = "Little Ice Age") in the Mendoza (Argentina) Andes are angular, ice-cored and show few effects of erosion (Fig. 1). Rock-glacier debris retains the steepness and bulk of the still-active forms but the frontal angularity is gone. Progressively older rock glaciers in the valleys have collapsed as the internal ice melted, and they show a progressive decrease in frontal angle. Coupled with this frontal angle change is an increase in silt (loess) cover (Fig. 3). No loessal silt was recognizable on the youngest Holocene deposits but rock glacier and morainal surfaces of Vallecitos (= Wisconsinan) age have a silt cap ~20 cm thick (Wayne, 1981). The loessal veneer provides a more suitable environment for vascular plant growth than does the fresh till or rock glacier debris; thus the older deposits also are characterized

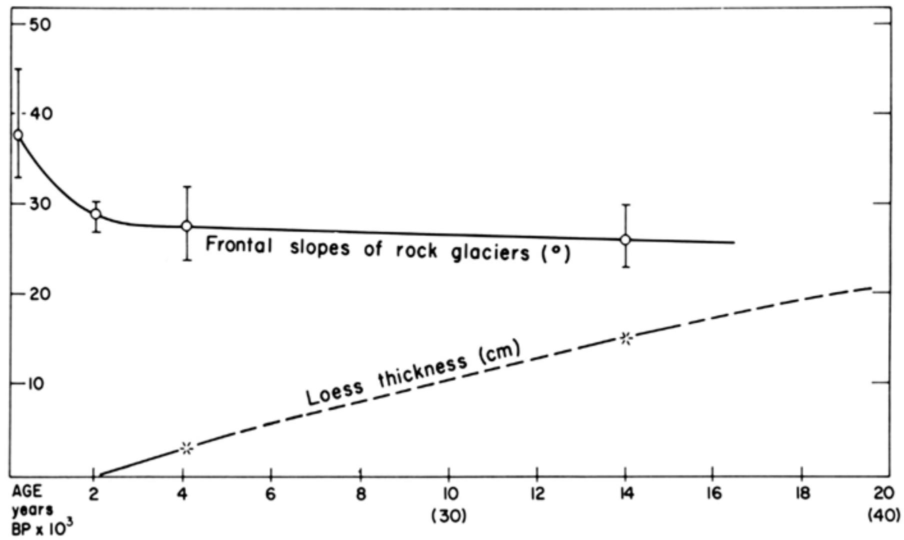

Fig. 3. Graph showing changes in frontal slopes of rock glaciers and accumulation of loess in Rio Blanco basin plotted against age.

by increased vegetation cover as well. The thickening loess cap does not continue on the pre-Wisconsinan deposits; on them much of the accreted silt undoubtedly has been incorporated into the soil profile. Perhaps, too, because most of those older deposits observed are at a lower altitude, a smaller amount of loess accumulated on them.

Boulder weathering

When earth materials are exposed to atmospheric processes, they begin to alter physically and chemically. This alteration is a continuous process, so that those materials exposed longest are altered most. Several kinds of observations can be recorded regarding the weathering of large clasts at and near the surface of any deposit. Coarse-grained igneous rocks undergo granular disintegration and the surface of such a rock that has been exposed will be rough with grains standing about one-half diameter in relief. Such a clast would be called "weathered" or "etched", and the ratio of fresh to weathered along with frequency and depth of weathering pits has been used to subdivide Holocene and Late Pleistocene deposits. The rate of weathering decreases with time, but these measurements permit distinction of deposits more than 10^6 yr. old (Colman, 1981).

Table I. Degree of rounding of quartzite boulders on moraines and rock glaciers, Rio Blanco basin, Mendoza

	Angular	*Subangular*	*Subrounded*	*Rounded*	*Number of sites*
Holocene III	–	–	–	–	–
Holocene II	–	–	–	–	–
Holocene I	52.5	44.0	3.5	0	4
Vallecitos II	15.5	59.2	17.0	8.5	11
Vallecitos I	0	37.7	45.7	16.7	3

Granitoid rocks (granites, granite gneisses, pegmatites) make up 25–40% of the boulders on the moraines in the Ruby Mountains; quartzites dominate the remainder. The pegmatites have weathered rapidly (Wayne, 1984). Pits 10 cm deep are common on surfaces smoothed by Angel Lake (Wisconsinan) ice; pegmatite boulders on Lamoille moraines have bizarre shapes. Surfaces of medium-grained granite boulders on Angel Lake moraines are fully weathered, but few are pitted. Those on Lamoille landforms are broken, rounded, and the pitted surfaces of some show as much as 10-cm relief.

In the Andean Rio Blanco basin granite outcrops are extremely few; hence, granite clasts are rare. Most of the exposed rocks are quartzites and rhyolites. One granite outcrop in Quebrada de la Angostura (Argentina), though, shows clearly the effects of weathering through time. Part of an outcrop that had been exposed since melting of Vallecitos ice, probably ~13,000 yr. ago, is covered with grus, disaggregated grains of quartz and feldspar; an adjacent part that was scoured again by Neoglacial ice (Holocene II, estimated at ~2000 yr. B.P.) has polished and striated surfaces.

Compared to other common lithologies encountered on young sedimentary accumulations, most quartzite boulders weather very slowly. In both the Ruby Mountains and the Cordon del Plata, they show progressive loss of edge and corner angularity from the fresh clasts of latest neoglacial deposits to generally subangular ones on Wisconsinan moraines (Table I). Quartzite boulders on moraines of Lamoille age in the Ruby Mountains are fractured and edges are rounded, although those on a landslide of still greater age have become extensively shattered and pitted. Quartzite boulders now exposed on the oldest glacial sediments observed in the Cordon del Plata are completely rounded (Wayne and Corte, 1983).

Weathering rinds on surface and subsurface clasts have been used to differentiate deposits (Birkeland, 1973; Porter, 1975; Colman and Pierce, 1981). On granitic rocks, weathering rinds sometimes are lost to granular disintegration, but on basic fine-grained clasts, andesites and basalts, they form slowly and steadily for 10^7 yr. or longer (Colman and Pierce, 1981). Weathering rinds form on quartzites, too, and in some areas have proven very useful in relative dating (Anderson and Anderson, 1981; Chinn, 1981). Few of the rocks found in either the Ruby Mountains or the Cordon del Plata show weathering rinds. Those observed were found on surfaces of only a single age, so weathering rind measurements were of little value in these areas.

Soil profile development

Degree of soil profile development has been used for decades as a criterion in the recognition of continental glacial deposits of different ages (Leverett, 1915; Thornbury, 1940). Much of the earlier published work is descriptive only and vague but a few studies described soil profiles in some detail (Leighton and MacClintock, 1930). Profile descriptions, to be useful; need to contain enough detail, including horizon thickness, *Munsell® Color* designation, and structure, to allow the soils to be compared (Birkeland, 1974, pp. 269-273). To obtain maximum value from soil data, some laboratory analyses as well as field descriptions are necessary. Particularly useful are grain-size analyses, clay mineral species and thin-section examination for degree of weathering of mineral grains. Laboratory data on soil profiles in the Ruby Mountains have aided greatly in making interpretations (Fig. 4). Difficulties were encountered, however, in obtaining adequate laboratory analyses for Andean soil profiles, so those interpretations are based solely on field descriptions. Soil profile data are useful in working with sediments as young as a few tens of years to greater than 10^7 yr. old.

Quartz grain surface textures

The surfaces of quartz grains become distinctively marked by some transporting processes, particularly glacial ice and wind. Many of the

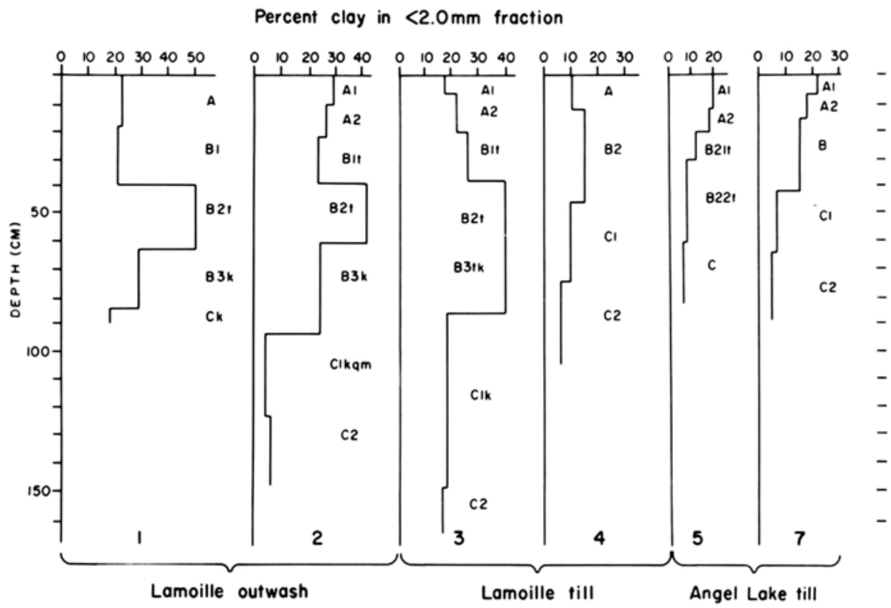

Fig. 4. Percent of clay in soil profiles (horizontal axis) plotted against depth, Ruby Mountains, Nevada. 1, 2 = Lamoille outwash, altitudes 1765 and 1805 m, respec; 3 = Lamoille till, model profile, altitude 1860 m; 4 = Lamoille till, modal profile, altitude 1910 m; 5, 7 = Angel Lake till, altitudes 2135 and 2636 m, respec.

sand grains freshly deposited by a glacier show sharp edges and conchoidal fracture surfaces. After deposition diagenetic alteration takes place so that sand grains may become etched or silica precipitated on once fresh surfaces (Krinsley and Doornkamp, 1973). The rate of diagenetic alteration depends on several factors, one of which is the length of time the grains are in an appropriate environment (Pittman, 1972). It is of no value in the separation of deposits no more than a few tens of thousands of years old, but has had usefulness in comparing deposits of mid to early Pleistocene age (Wayne and Corte, 1983).

Lichens

Lichens begin to grow on rock surfaces exposed to moisture and light soon after the rock becomes exposed. Growth rates differ among species and localities, but one species, *Rhizocarpon geographicum* (s.l.) grows slowly and has been used in many parts of the world to determine an absolute age for some Holocene glacial deposits (Benedict, 1967, 1968). Local conditions, especially moisture, result in vastly different rates of growth of *Rhizocarpon;* thus, it is essential to work out

Table II. Development of age data on landslide in Ruby Mountains, Nevada, from pale-green crustose-foliose lichen measurements

Location	*Estimated total lichen cover (%)*	*Diameter largest thallus (mm)*	*Average diameter 6 largest thalli (mm)*	*Estimated age (yr. B.P.)*
Wheeler Peak:				
Cairn built in 1875	1	8	–	104 (in 1979)
Active rock glacier crest	3	57	51	200
Most distal ridge, *active* part	5	95	75	350
Inactive rock glacier, first ridge	20	105	95	400
First ridge beyond moraine	30	140	126	600+
Most distal rock glacier ridge	30	170	129	600+
Ruby Mountains:				
Landslide scarp	15	72	66	300

a growth-rate curve for each locality if the lichen is to be used for exact age determinations. Most other lichens grow more rapidly and efforts to date sediments with them have been limited. Some do have value, though, in the study of very young sediments (Table II).

Where growth curves for lichen species have not been established, two other measurements of lichen morphology can provide help in relative dating: maximum thallus diameter and percent of lichen cover. The method is limited to sediments of Holocene and very late Wisconsinan age (Fig. 5).

Vascular plants

Where there is a surface-to-plant colonization, vascular plants become established quickly after deposition is complete. Lawrence (1950) described the kinds of data one must obtain in order to date the latest Neoglacial moraines and sediments by the nature of the forest cover and by examining disturbed growth rings of trees established on the surface. Wayne (1981) used density of vascular plant cover as one of several RD techniques in dating moraines and rock-glacier debris in Argentina. Channel migration, hence, ages of floodplain segments, can be dated by examination of the strips of even-aged cottonwood trees along a floodplain (Everett, 1968).

Fossils

Most fossil remains in young sediments either lack distinctiveness that permits their use to identify or correlate or are too rare to be used regularly. Mollusks, however, and particularly snails, frequently are encountered as fossils in sediments deposited in lakes, streams, loess, and intertill silts. Rarely are they found preserved in alpine glacial deposits. Although few land or freshwater mollusks became extinct during the Pleistocene, most species are sufficiently sensitive to climatic and vegetation conditions that they migrated during the climatic fluctuations of the Pleistocene. At any particular site, then, most elements of the faunal assemblages collected may be present in younger or older beds that were deposited under similar climatic conditions although their relative abundance may change. A few species, however, occupied an area only once and will be present in but one of the beds. For example, *Hendersonia occulta* (Say) is a dominant element of the beds that lie directly beneath the basal tills of each of three major glaciations in Indiana and is limited to them. (Wayne, 1963). It is absent from the modern Indiana fauna and from other fossiliferous beds in the Indiana Pleistocene. Its presence in a bed fixes the overlying till as the basal one of a particular glaciation; which glaciation can be determined from the relative proportions of other faunal elements or from the presence or absence of one or two species now extinct.

Discussion and Conclusion

For most young sedimentary deposits, no single relative-age dating method has great enough sensitivity to be applied to all deposits. Some have value in very young materials; others provide little help there but allow one to separate deposits that have greater age (Fig. 5). Where two or more—and preferably more—parameters can be measured, a better estimate of age will develop (Birkeland et al., 1979). Generally, the characteristics examined in the several RD methods have sufficient sensitivity to identify and correlate glacial deposits of stage magnitude but, except for sediments of Holocene age, rarely permit the distinction of substage rank materials. The same holds true for nonglacial sedimentary accumulations. The sensitivity to distinguish units of only slightly differing ages diminishes with time.

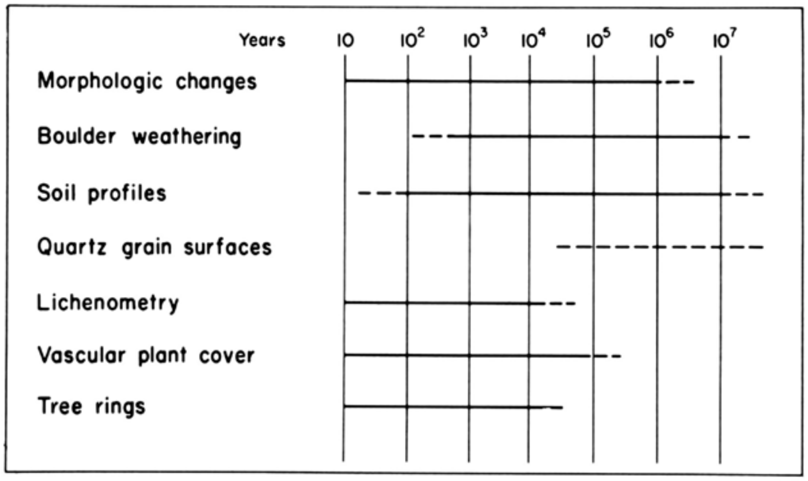

Fig. 5. Estimated ranges of usefulness for seven RD criteria.

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