DATING LASSEN COUNTRY ROCKS

Several age-dating methods were used to place age constraints on Lassen Country rocks and surficial deposits. These methods involved a combination of relative and absolute age-dating techniques. Relative age dating techniques are useful for determining the age relationship of rocks and structures relative to other rocks or structures. Relative dating laws—applied in most geologic mapping projects—include horizontality, superposition, cross-cutting relationships, presence of inclusions, and degree of weathering, erosion, and faulting of rocks and deposits. A geologist studying an area can usually get a pretty good feel for the relative ages of rocks and surficial deposits by simply applying the principles above. For example, tills that overlie lava flows are younger than the lavas upon which they rest. However, in order to really calibrate the relative ages, we need to use absolute dating methods.

To determine the absolute age of a rock we need some form of natural clock that runs at a constant rate. Absolute dating techniques include radiometric, dendrochronology (tree-ring), and paleomagnetic dating. **Radiometric** dating relies on the **radioactive decay** of naturally occurring chemical elements. Dendrochronology relies on the observation that trees grow one new ring of wood annually. **Paleomagnetic dating** can sometimes be used to date rocks, but is more often used in conjunction with radiometric dating to help verify radiometric dates.

Geologists most often employ **radiometric dating** to date igneous and metamorphic rocks. Dating of sedimentary rocks and unconsolidated sediments is generally more complicated because they are usually made up of material from different sources and ages. The youngest age for a sedimentary rock is constrained by the age of the youngest material it contains. Commonly, geologists use fossils for the relative age dating of sedimentary rocks if any are available. For unconsolidated Quaternary sediments or any deposits less than about 50,000 years old and containing organic or other carbon-bearing material, radiocarbon dating can be effective. Radiocarbon dating is particularly useful for dating geologic events such as earthquakes or mudflows. Radiometric dating based on exposure to naturally occurring cosmic rays (cosmogenic dating) is also effective on rocks and unconsolidated sediments.

The potassium/argon (K/Ar) dating method used to be the dating method used most often by geochronologists. It is based on the decay of naturally occurring potassium-40 (^{40}K) to stable argon-40 (^{40}Ar). Argon is a gas that is released from lava and rocks at high temperature. When the rock or deposit cools, it has a zero age and accumulation of ^{40}Ar begins. Knowing the amounts of ^{40}K and ^{40}Ar present allows the age of the rock to be determined. Potassium is a relatively abundant chemical constituent in rocks and minerals containing potassium (such as feldspar) are readily available in most rocks. Depending on the amount of potassium generally in the rock, K/Ar dating works well for rocks as young about 50,000–100,000 years, but can be plagued by incomplete degassing of the lava at the time of eruption.

The argon-40/argon-39 (^{40}Ar/^{39}Ar) dating method is a form of K/Ar dating in which potassium-bearing samples are irradiated in a nuclear reactor to convert all the ^{40}Ar in the rock to ^{39}Ar with is then compared to the amount of ^{36}Ar (a stable isotope) in the sample. The ^{40}Ar/^{39}Ar dating method has several advantages over the K/Ar method: 1) greater precision is obtained in the measurements and therefore it can be applied to smaller and younger samples, and the amount of radiogenic argon (^{39}Ar) retained by the sample during cooling can be evaluated. Depending on the amount of potassium generally in the rock, ^{40}Ar/^{39}Ar can be applied to rocks as young about 10,000–20,000 years and even younger potassium-rich minerals or rocks.

Uranium-series disequilibrium dating methods are based on the decay of uranium-238 (^{238}U), uranium-235 (^{235}U), and thorium-232 (^{232}Th) to different isotopes of lead (Pb). These elements decay in a chain that produces a number of intermediate **daughter isotopes**. The decay chain maintains an equilibrium between the amounts of the various daughter isotopes unless some magmatic or chemical process interrupts it. When the magma is erupted or sediment deposited, the decay chain trends back toward equilibrium, and analysis of the amount of disequilibrium remaining dates the time since the geologic event. Uranium-series age dating is used for a variety of situations ranging from marine and lake sediments to volcanic rocks, and can be used for dating rocks and geologic events over time periods ranging from less than a few tens to about 250,000 years.

The radiocarbon method is used for dating volcanic deposits and unconsolidated sediments up to about 50,000 years old. It requires *in situ* carbon-bearing material such as charcoal or carbonate in or enclosing the deposit. This method is based on the decay of carbon-14 (^{14}C) to produce stable nitrogen-14 (^{14}N). Carbon-14 is produced in the upper atmosphere by bombardment of nitrogen-14 by cosmic rays. The radiocarbon atoms combine with oxygen to produce carbon dioxide (CO_2) with is used by plants to build all their living parts during photosynthesis. During their lifetimes plants maintain equilibrium with the amount of ^{14}C in the atmosphere. However, when they die, new ^{14}C is no longer incorporated into the plant, and the existing ^{14}C is depleted by decay back to ^{14}N, and the isotopic clock begins ticking.

Also common is the dendrochronology (**tree-ring dating method)** in which the geologist counts the number of annular rings in a tree. Each year that a tree is alive it produces a concentric annual growth ring that is often preserved long after the tree has died. This method is used for dating recent geologic events such as young volcanic eruptions, landslides, and lahars. Analysis of tree-ring widths and patterns can also yield important insights about past climates. Both ^{14}C and tree-ring dating need to be carefully interpreted. It is required that the relationship between the sample and deposit be well established in order to get an accurate age.

To provide additional constraints on the age of sediments and rocks, geologists rely on **paleomagnetic dating**, which is based on the changes in orientation and intensity in the Earth's magnetic field over time (polar wander). When lava erupts, it is unmagnetized, and as the lava cools magnetic minerals (mostly magnetite) crystallize and align themselves parallel to the local magnetic field lines at the location where it was erupted. Thus, lava flows and hot pyroclastic deposits record the orientation of the Earth's magnetic field at the time they cool. Similarly, the magnetic grains in sediments deposited in the ocean or lakes align themselves with the Earth's local magnetic field as the sediment is compacted. Paleomagnetism itself usually does not provide an exact age of emplacement or deposition and so is more often used as a correlation tool for volcanic deposits than a dating tool, because deposits of similar age will have similar magnetic directions. When calibrated with deposits of known ages, paleomagnetic analysis can provide constraints, for example, a maximum or minimum limit on the age. However, if the history of the orientation of the magnetic field at the location of the deposit is well known and the recorded direction is unique, the age of the rock can often be determined.

The ages of most volcanic and sedimentary rocks and deposits in the Lassen Country were estimated using used relative dating methods. These were facilitated and constrained by dating some rocks and deposits using radiometric dating. Most radiometrically dated rocks in the Lassen Country utilized the potassium-40/argon-40 (K/Ar) and argon-40/argon-39 ($^{40}Ar/^{39}Ar$) methods. Many pyroclastic volcanic deposits were dated with carbon-14 (^{14}C), and a few dendrochronologic and paleomagnetic ages were also determined. Uranium series disequilibrium dating, particularly of zircon (a U-bearing zirconium silicate mineral) was particularly useful in dating magmatic processes in the Lassen Volcanic Center.

Table 1. Absolute-dating techniques used to date Lassen Country rocks and surficial deposits. *Sources: Clynne and Muffler (2010), Klemetti and Clynne (2014).*

Method	Materials
Potassium/argon (K-Ar)	Volcanic rocks and potassium-bearing minerals
Argon/Argon ($^{40}Ar/^{39}Ar$)	Volcanic rocks and potassium-bearing minerals
Uranium Series	Volcanic rocks and some U-bearing minerals, for example, zircon
Radiocarbon (^{14}C)	Geologic events up to about 50,000 years such as tephra fall,

	pyroclastic flows, hydrothermal deposits, landslides and mudflows, glacial deposits, archeological sites, fault offsets
Dendrochronology (tree-ring dating)	Recent geologic events such as tephra fall, pyroclastic flows, landslides and mudflows
Paleomagnetic dating	Constrains maximum and minimum age limits when correlated with strata with polarities of known ages and directions, but can be used to date deposits under certain conditions.

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