Radiometric dating/techniques

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Figure 1. The Mississippi River just north of the Atchafalaya River undergoes avulsions frequently, where the relative sequence of events can be seen in the satellite image. The most precise dating technique, of assigning calendar ages required precise record keeping (Fisk 1944) (http://lmvmapping.erdc.usace.army.mil/index.htm). Image source: http://earthobservatory.nasa.gov/IOTD/view.php?id=6887
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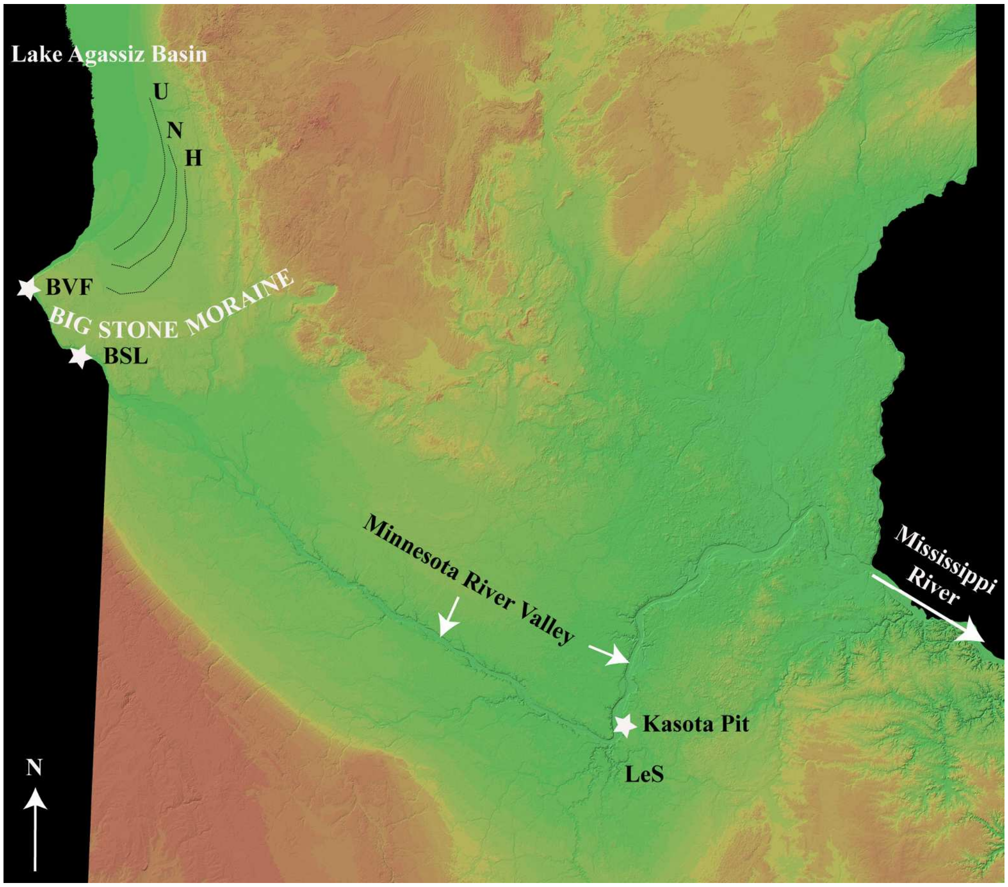

Figure 2. Shaded relief map of southern Minnesota highlighting the Minnesota River Valley and important geographic locations discussed in the case study. U - Upham, N – Norcross, and H-Herman represent the three highest shorelines (from low to high) of Lake Agassiz described by Fisher (2005) and Lepper et al. (2007). BVF – Brown Valley Fan and BSL – Big Stone Lake represent the locations of the two core sites dated by Fisher (2003). LeS represents the approximate location of the LeSueur River which was the focus of Gran et al.'s research (2009; 2013). Kasota Pit is the location of Johnson et al.'s (1998) sedimentologic analysis of a terrace fill within the Minnesota River Valley.
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Radiometric dating/techniques

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Abstract

Earth's natural surface formed from a mosaic of different geomorphic events over time. Thus, documenting the timing of different processes is a critical part of geomorphology. Accordingly, the last sixty years has seen a revolution in techniques used to date landforms. Geographers and other scientists have developed and refined dozens of different dating techniques. This entry presents some of the most common dating methods used by geographers and illustrates the use of these techniques in two case studies: understanding the drainage of proglacial Lake Agassiz of North America and the sequence of glacial events in the Sierra Nevada of eastern California.

Main Text

Geographers both develop and utilize four general types of techniques to determine ages of Earth's deposits and features: calendar ages; relative ages; numerical ages; and correlative ages (Colman et al. 1987). The most precise and accurate techniques assign **calendar ages** to events through historical record keeping (**Figure 1**), the use of annual tree rings (dendrogeomorphology) (Butler et al. 1987; Butler and Sawyer 2008) or counting annual layers (varve chronology) in lake sediment (Tylmann et al. 2013). The least precise dating method simply orders events in a relative sequence from oldest to youngest (Shiraiwa and Watanabe 1991), such as soil development over time or a sequence of superimposed river changes (avulsions) (**Figure 1**). Although no specific age is assigned, **relative ages** are often used to detect problems with more precise techniques when results contradict a relative sequence. **Numerical ages** are assigned most often using radiometric techniques, such as radiocarbon dating, and typically have ± uncertainties based on measurement errors. **Correlative ages** derive from techniques that match an event that has a prior numerical age, such as tephrochronology (Beget 1984) that correlates the mineralogy and geochemistry of a particular volcanic eruption deposit to a volcanic ash deposit that already has a numerical age. Table 1.1 presents just a few of the dating methods used in physical geography.

The selection of the right dating technique for any particular project will usually hinge on a series of questions:

- What chronometric information do I need to answer the question?
- What material is available for dating?
- What method(s) are the most appropriate?
- What does the age represent?
- How does the precision, accuracy and inherent uncertainties influence the ability of the age result to answer the research question?
- How much will the dating research cost?

Since it is not possible to review the entirety of the dating methods presented in Table 1.1, we instead illustrate two uniquely different case studies of landscapes where these key questions are being asked, and a variety of dating methods have been (and are being) employed. One case study involves how geomorphologists are establishing ages of glacial and alluvial landforms to understand the Quaternary history of the Minnesota River Valley and it's genetic relationship to proglacial Lake Agassiz. The other case study involves ongoing efforts to understand the glacial chronology of the Sierra Nevada of California.

Lake Agassiz Case Study. Episodic meltwater discharges from proglacial Lake Agassiz are a possible trigger for periods of abrupt Quaternary climatic change (Johnson and McClure 1976; Licciardi et al. 1999; Teller et al. 2002; Teller et al. 2005). Understanding the evolution of this ancient lake, the timing of spillway activation, and the processes associated with each spillway's discharge event(s) has prompted several decades of research within and bordering the Lake Agassiz basin (Fisher 2004). Dating methods have played a crucial role in developing our understanding of the timing and location of these episodic events – although uncertainty still exists (Fisher 2004; Teller et al. 2005).

For much of the last century the maximum age of lake formation was unknown (Lepper et al. 2007). The southern boundary of the Lake Agassiz basin is marked by the Des Moines Lobe's recessional Big Stone Moraine (BSM; **Figure 2**). Initial age estimates of BSM were largely based on indirect correlations (Clayton and Moran 1982) and thus the age of the lake remained uncertain. Leeper et al. (2007) applied ^{14}C and OSL dating techniques and concluded Lake Agassiz began forming as the Des Moines Lobe retreated out of Minnesota prior to ~12,000 ^{14}C yr B.P. (13,950 calendar years before present, cal yr B.P.). Organic material found in four sediment cores from "lakes, bogs and channels…" were taken from locations inset into and neighboring the moraine to establish this limiting age. OSL samples were collected from Lake Agassiz shorelines below and bordering the moraine. The Herman, Norcross and Upham shorelines (Upham 1895; **Figure 2**) were sampled at locations of road-cuts and gravel pits (Leeper et al., 2007: 667). While the ^{14}C ages dictate that the BSM was no longer an active moraine ca. 13,950 cal yr., OSL results reveal a rapidly lowering lake from 14,200 to 12,600 cal yr. Both ages are consistent with research suggesting an increase in melt water reaching the Gulf of Mexico at this time (Aharon 2003; Broecker et al. 1989).

The initial outlet of Lake Agassiz was to the south through the BSM and Glacial River Warren - ultimately draining into the Mississippi River and Gulf of Mexico

(Upham 1895; Fisher 2003; 2004). The underfit nature and boulder strewn headwaters of the modern Minnesota River Valley (MNRV) reflects the catastrophic nature of the River Warren floods (Fisher 2004). In order to establish when the MNRV spillway was active, Fisher (2003) applied ^{14}C dates from wood and seed fragments in two core locations in Big Stone Lake and the Browns Valley fan in the headwaters of the MNRV (**Figure 2**). He concluded that there were two major episodes of outflow here – the first ending ~10,800 ^{14}C yr B.P. (12,740 cal yr B.P.) and the second ending ~9,400 ^{14}C yr B.P. These periods of active flooding were separated by lacustrine deposits in the cores dating from 12,500 – 12,340 cal yr B.P., which reveal an approximate window of abandonment of the MNRV spillway. The initial abandonment of the MNRV spillway coincides with a period when the Agassiz outlet is thought to have shifted to lower elevations and likely emptied eastward into the great lakes via Lake Superior (Licciardi et al. 1999) – although some controversy exists about this hypothesis (Teller et al. 2005).

The resulting post River Warren landscape of the MNRV has been a dynamic tale of erosion and fluvial response to catastrophic flooding that induced ~65m of base level lowering. These floods carved out most of the modern MNRV. Archeological studies conducted through the Minnesota Department of Transportation collected ^{14}C ages from organic materials in MNRV bottom alluvial fans and fluvial sediments beneath the fans. These measurements suggest that much of the MNRV incised close to its present depth by 10,400 ^{14}C yr B.P. (Hudak and Hajic 2002a, b; Fisher 2003).

Surprisingly, very little is known about the geomorphic history of the MNRV outside of a few studies (Johnson et al. 1998; Hudak and Hajic 2002b). Johnson et al. (1998) is the only modern study that attempted to analyze the morphology and sedimentology of fluvial terraces within the MNRV in order to reconstruct the valley's history. They hypothesized a relative chronology where a major incision event linked to the initial catastrophic flood event from Lake Agassiz was followed by 22m of infilling based on sand and gravel deposits with forset bedding up to 15m in height (**Figure 2**). This period of aggradation was then followed by a brief "more stable" braided stream period and then another significant flood pulse resulting in incision. They concluded that terrace correlation would be impossible without "high-resolution dates" and further sedimentologic work on other terrace locationsin the MNRV.

Several small tributaries of the Minnesota River are far better understood than the MNRV itself. Gran et al (2009; 2013) used the Le Sueur River (**Figure 2**) as a case study to address the assertion that geomorphologist know very little about transient response in the fluvial system (Whipple 2004). The LeSueur River is a transient system responding to ~65m of base level lowering caused by MNRV incision. In order to address the river's incision history and to compare with numerical modeling, OSL and ^{14}C dating determined the age of fluvial terraces along the stream reach. Overbank alluvium was sampled for OSL dating while freshwater mollusks and gastropods were collected from terrace fills for ^{14}C dating. The results of the study revealed that the Le Sueur River is a detachment-limited system where downstream bedload coarsening inhibits incision and transposes the knickpoint over a larger distance in the longitudinal profile.

Sierra Nevada Glaciation Case Study. The Sierra Nevada Mountains in California remains a classic range for the study of glaciations starting with the use of topographic position to establish relative ages (Russell 1889; Matthes 1929; Blackwelder 1931). The current state-of-understanding starts with ^{40}Ar/^{39}Ar ages of basalts atop the range that record a pre-glacial plateau topography prior to 3.3 million years ago (Phillips et al. 2011). K-Ar and $^{40}Ar/^{39}Ar$ dating of the Bishop Tuff (Sharp 1968; Sarna-Wojcicki et al. 2000) provided a minimum age for the most extensive glacial event, the Sherwin glacial till that rests under the 760,000-year-old supervolcano Bishop Tuff deposit.

As for glacial events younger than the Bishop Tuff, for many decades at the end of the last century, only relative dating techniques were available to order a host of different glacial moraines (Burke and Birkeland 1979; Sharp 1969; Sharp and Birman 1963). Then, calibrated strategies provided rough ages for moraines (Dorn et al. 1987). However, it was not until the development and use of cosmogenic nuclide surface exposure dating that researchers began to get a handle on the true complexity of glacial sequences (Phillips et al. 1996, 1988; Poreda et al. 1996; James et al. 2002; Phillips et al. 2009; Rood et al. 2011). In spite of decades of grouping together moraines into broad age classes called “Tioga” and “Tahoe”, the precision and accuracy of cosmogenic methods continues to reveal that Sierra Nevada moraines reflect the complexity of millennial scale climatic changes. Whereas all last glacial maxima moraines were once all grouped as Tioga, they can now be differentiated into multiple age groupings throughout Marine Isotope Stage 2, from 28 to 14 ka.

The timing of Holocene glaciation in the Sierra Nevada has been more difficult to understand. The chitin of insects has been preserved in sufficient quantity for ^{14}C measurements along Bishop Creek in the central Sierra Nevada to establish at least four distinct glacial events at ~2700 cal yr B.P., ~1300 cal yr B.P., ~600 cal yr B.P., and ~150 cal yr B.P. (Dorn 1996). Later, sediment cores along the nearby North Fork Big Pine Creek revealed a continuous record of sedimentation dated through ^{14}C analyses of macrofossils. This research found similar glacial maxima at ~ 2800 cal yr B.P., ~700 cal yr B.P., and 250-270 cal yr B.P., in addition to other maxima at 2200 and 1600 cal yr B.P. (Bowerman and Clark 2011). Thus, ongoing research into understanding the ages of glacial moraines in the Sierra Nevada mirrors and lags behind our understanding paleoclimatology in general – that millennial scale high magnitude changes in climate can imprint itself throughout the geomorphic record globally (Dorn 2009; Thomas 2004; Thomas and Thorp 1995), but the detection of these imprints is limited by the accuracy and precision of the techniques used to date landforms.

Table 1.1 and these two case studies illustrate that a great number of options exist for today’s geomorphologists. In both research contexts, the type of dating technique employed reflects a combination of the type of material available for dating and the expertise of the researchers investigating the problem. What remains true, however, is the ongoing need for chronometric information to advance our understanding of Earth’s landforms.

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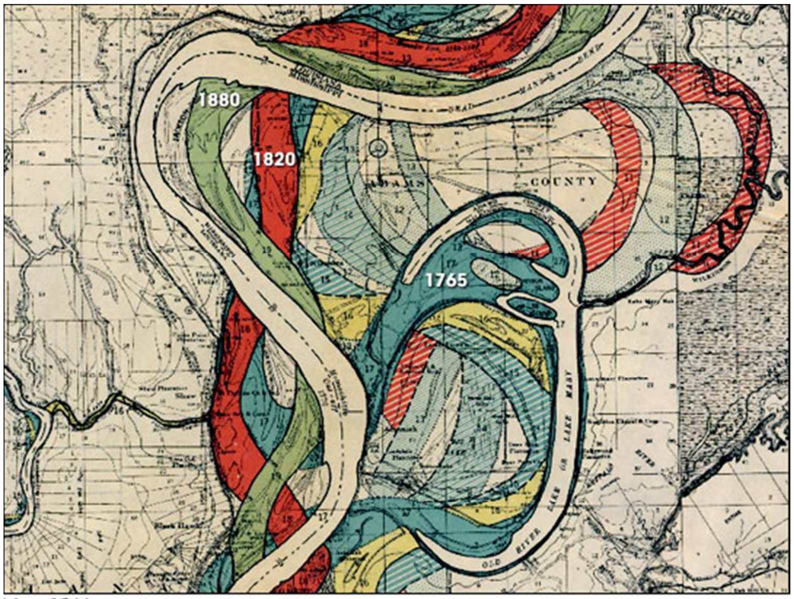
Table 1.1. Selected examples of dating methods used in physical geography

Type of Age	Method
Calendar	**Dendrogeomorphology** employs annual growth rings in trees to place a minimum age on the underlying landform. Its great accuracy facilitates use in analyzing erosion rates and alpine hazards such as avalanches on time scales of 10^0 to 10^3 years (Butler and Sawyer 2008; Stoffel et al. 2013).
Calendar	**Sclerochronology** studies changes in the accumulating tissues of such organisms as corals and mollusks. The annual growth rings in corals offer a powerful tool in climatic change and coastal geomorphic research on time scales of 10^0 to 10^4 years (Halfar et al. 2008).
Numerical	**Radiocarbon** measures the abundance of ^{14}C in samples such as charcoal, wood, peat, shells, and carbon-containing minerals such as oxalate and calcite. The method assumes that the carbon-containing material stopped exchanging $^{14}CO_2$ with the atmosphere upon death or deposition. Radiocarbon has been used in almost every geomorphic setting including fluvial, colluvial, coastal, glacial, eolian materials deposited during the last 40,000 years. Radiocarbon ages are typically translated into calendar ages through the use of calibrations (Hua 2009).
Numerical	**Optically stimulated luminescence (OSL)** measures when sediments were last exposed to sunlight (e.g. transported and then buried). A light-sensitive signal is "trapped" over time in crystal defects that is released upon irradiation (Halfar et al. 2008). This technique has seen an explosion of use, because of its utility in establishing ages on time scales of 10^0 to 10^5 years for non-carbonate deposits such as eolian, fluvial, coastal, glacial, and colluval settings.
Numerical	**Cosmogenic surface exposure dating** relies on cosmic rays interacting with rocks to create new nuclides over time. These include stable nuclides that just build up (^3He, ^{21}Ne) and radionuclides that both build up and also decay at different half lives (^{10}Be, ^{26}Al, ^{36}Cl). Through careful sampling and keeping track of the variables that alter build-up rates (e.g. altitude, latitude, burial history, surrounding topography), outputs include a combination of erosion rates and exposure ages (Cockburn and Summerfield 2004; Heimsath et al. 2010). Different combinations of nuclides can date surfaces on the time scale of 10^2 to 10^6 years
Numerical	**Cosmogenic burial dating** relies on the build up of cosmogenic nuclides in rocks prior to deposition. After deposition, these nuclides decay at different rates, allowing the calculation a burial age (Granger and Muzikar 2001) on the time scale of 10^3 to 10^6 years. This technique can estimate the ages of marine terrace, fluvial terrace, and even cave deposits

	previously undatable due to a lack of suitable materials.
Numerical	**Uranium-series (U-series) dating** typically uses a number of different decay pathways, but typically the ^{238}U-^{234}U-^{230}Th-^{226}Ra system with half-lives of 245,000, 76,000 kyr and 1600, respectively. Coral and speleothem deposits can yield very precise ages, but other materials are often not in truly closed systems typically applied to carbonates with time scales of 10^0 to 10^5 years (van Calsteren and Thomas 2006; Zhao et al. 2009).
Numerical	**K-Ar dating** and the more precise **^{40}Ar/^{39}Ar dating** method measures when liquid magma solidified through the decay of radioactive ^{40}K into stable ^{40}Ar. Thie method can determine the ages of lava flows and tephra on times scales of 10^3 to 10^8 years (Renne et al. 1998).
Correlated	**Lichenometry** compares the growth of lichens (often the maximum diameter of particular species) on surfaces of known age (e.g. cemetery stones) to develop a growth curve for an area. That growth curve then allows age estimates for such features as glacial moraines, debris avalanches, and other features cold dry climates over times scales of 10^1 to 10^5 years (Benedict 2009; Armstrong and Bradwell 2010)
Correlated	**Amino acid racemization (AAR)** uses the protein residues in fossil carbonate that degrade through time-dependent reactions. While alive, organisms form L-configured amino acids (levorotatory) that reequilibrate via the raceimization reaction to the D-configuration (dextrorotatory). Although factors other than time (e.g. temperature, moisture, species) can also influence the D/L ratio, calibration via independent dating techniques and modeling the racemization factors makes it a powerful tool in understanding landforms on timescales of on time scales of 10^0 to 10^7 years (Penkman 2010).
Correlated	**Tephrochronology** "fingerprints" the unique mineralogical and geochemical signature of volcanic ashes (tephra) – allowing the correlation of events over broad areas impacted by an ancient eruption. Since many ashes have precise radiometric ages, tephra events can be used to assign maximum ages for sediment deposited on tephra and minimum ages for the sirface underneath the ash (Lowe 2011).
Correlated	**Varnish microlaminations (VML)** correlates layers found within rock varnish to paleoclimatic events. Calibrated by radiocarbon, K-Ar, and cosmogenic ages, varnish microlaminations deliver millennial-scale minimum ages for the exposure of the underlying rock (Liu and Broecker 2008; 2013). This technique is limited to warm deserts, where rock varnish is biogeochemically stable. It can provide minimum ages for such landforms as alluvial fans, debris flows, and bare rock surfaces and petroglyphs on time scales of 10^2 to 10^5 years.

Relative	**Topographic position** provides physical geographers important guidance in understanding a relative sequence of events. Examples include: superimposition of a younger glacial moraine over an older moraine; a younger river course cutting off the meander scar of an older channel; lower/younger river (fluvial) terraces inset inside older terraces; younger marine terraces lower than older marine terraces; or a younger sand sheet burying a lower older dune deposit. Such relative sequences provide great power in checking the outcomes of correlated and numerical methods that can yield far more precise results – but if done incorrectly can generate inaccurate data.



Map, 1944

Satellite Image, September 22, 1999

Figure 1. The Mississippi River just north of the Atchafalaya River undergoes avulsions frequently, where the relative sequence of events can be seen in the satellite image. The most precise dating technique, of assigning calendar ages required precise record keeping (Fisk 1944) (http://lmvmapping.erdc.usace.army.mil/index.htm). Image source: http://earthobservatory.nasa.gov/IOTD/view.php?id=6887

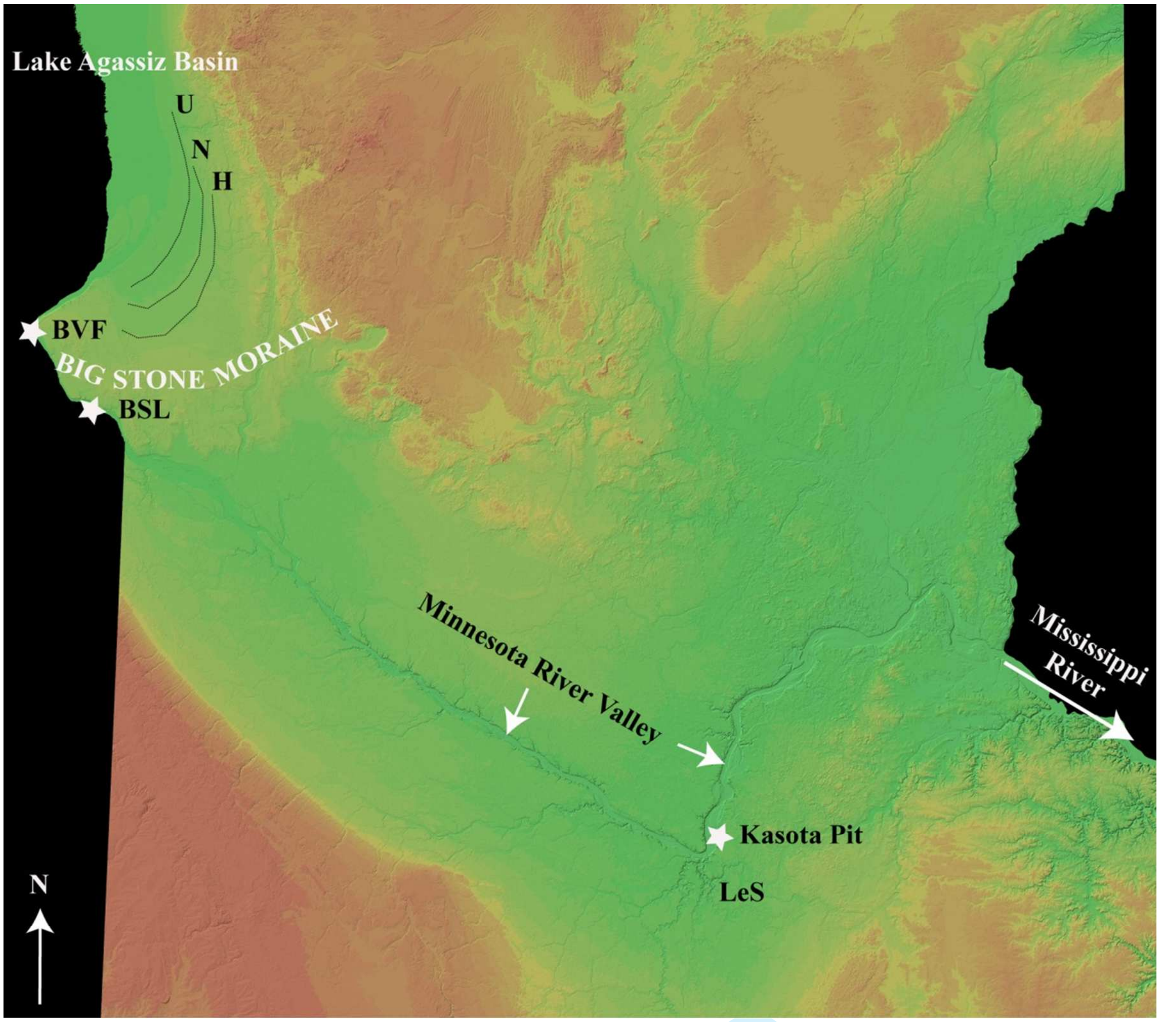


Figure 2. Shaded relief map of southern Minnesota highlighting the Minnesota River Valley and important geographic locations discussed in the case study. U - Upham, N – Norcross, and H-Herman represent the three highest shorelines (from low to high) of Lake Agassiz described by Fisher (2005) and Lepper et al. (2007). BVF – Brown Valley Fan and BSL – Big Stone Lake represent the locations of the two core sites dated by Fisher (2003). LeS represents the approximate location of the LeSueur River which was the focus of Gran et al.'s research (2009; 2013). Kasota Pit is the location of Johnson et al.'s (1998) sedimentologic analysis of a terrace fill within the Minnesota River Valley.