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# Devils Hole, Nevada—A Primer

*This fact sheet summarizes the multifaceted research of the U.S. Geological Survey—published in diverse outlets—that focuses on the subaqueous cavern Devils Hole in Nevada.*

## What is Devils Hole?

Devils Hole is a subaqueous cavern in south-central Nevada within a geographically detached unit of Death Valley National Park (fig. 1). The cavern is tectonic in origin and has developed in Cambrian carbonate rocks bordering the Ash Meadows oasis (Carr, 1988). The open fault zone comprising the cave extends to a depth of at least 130 meters below the water table, which is about 15 meters below land surface (Riggs and others, 1994). The primary source of groundwater flowing through Devils Hole, and discharging from the major springs within the oasis, is precipitation on the Spring Mountains to the east of the cavern. The Spring Mountains are the highest mountain range in southern Nevada (altitude 3,630 meters) (Winograd and Thordarson, 1975; Winograd and others, 1998).

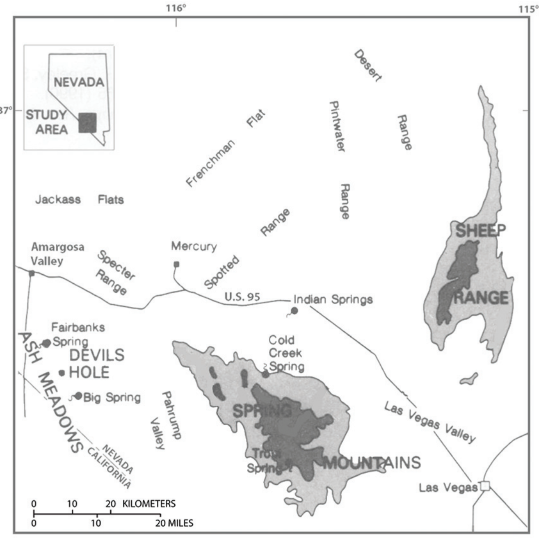


**Figure 1.** Index map of south-central Great Basin showing the locations of Devils Hole, significant springs, and the major mountains, which are shaded as follows: heavy shading denotes altitudes of 2,400 to 3,600 meters; light shading denotes altitudes of 1,800 to 2,400 meters; and ridges less than 1,800 meters are designated by name only.

## Why is Devils Hole of interest to paleoclimatologists?

The importance of Devils Hole to paleoclimatologists is twofold. Below the water table, the near-vertical walls of Devils Hole are coated with up to 40 centimeters of vein calcite that precipitated from groundwater moving through the cavern (fig. 2). The calcite can be accurately and precisely dated with radiometric methods, such that the depth-varying sequences of oxygen and carbon stable isotopes in the calcite provide a record of climatic variations spanning more than 500,000 years (Winograd and others, 1988, 1992, 2006). Additionally, subhorizontal cave deposits, called folia, record variations of the water table during the past 120,000 years (Szabo and others, 1994).

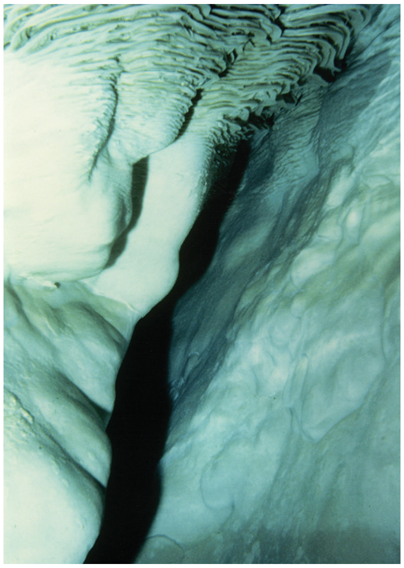

**Figure 2.** Photograph taken just below the water table (at top of photo) in Brown's Room, a remote portion of the Devils Hole cavern. Vein calcite coats the walls of the open fault zone that comprises Devils Hole. The rippling horizontal deposits called folia (in the upper fifth of the photo) mark paleo-water-table levels as much as a meter below the modern water level. (Photograph taken in 1986 by Ray Hoffman, USGS, retired.)

## How was the isotopic record from the Devils Hole vein calcite dated?

Since 1992, vein calcite samples have been uranium-series dated using thermal ionization mass spectrometric (TIMS) methodology (Ludwig and others, 1992). In 1997, the Devils Hole thorium-230 ages were independently confirmed by non-U.S. Geological Survey (USGS) investigators using protactinium-231 (Edwards and others, 1997).

## What paleoclimate phenomena are recorded by the Devils Hole stable isotopic time series?

The Devils Hole oxygen-18 ($\delta^{18}O$) time series (fig. 3) is primarily a proxy indicator of paleotemperatures. Unlike oxygen isotopes in deep-sea cores, it is not a record of past global ice accumulation in terrestrial systems. Rather, the time series appears to correspond, both in timing and relative magnitude, to variations in paleo-sea-surface temperature (SST) recorded in Pacific Ocean sediments off the west coast of North America, from Oregon to California, and as far south as the equatorial eastern Pacific (fig. 4) (Winograd and others, 1996, 1997, 2006; Lea and others, 2000; Herbert and others, 2001; Winograd, 2002). The Devils Hole $\delta^{18}O$ record is also highly correlated with major variations in paleotemperatures recorded in the Vostok ice core from the East Antarctic Plateau (Landwehr and Winograd, 2001; Landwehr, 2002). The Devils Hole carbon-13 ($\delta^{13}C$) time series is thought to reflect changes in global variations in the ratio of stable carbon isotopes of atmospheric carbon dioxide ($CO_2$) and (or) changes in the density of vegetation in the groundwater-recharge areas tributary to Devils Hole (Coplen and others, 1994).

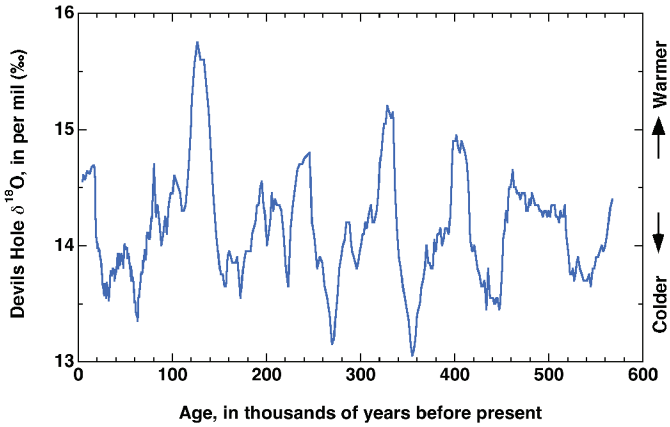


**Figure 3 (top right).** The Devils Hole $\delta^{18}O$ time series from 4,500 to 567,700 years before present, with data as given in Landwehr and others (2011).

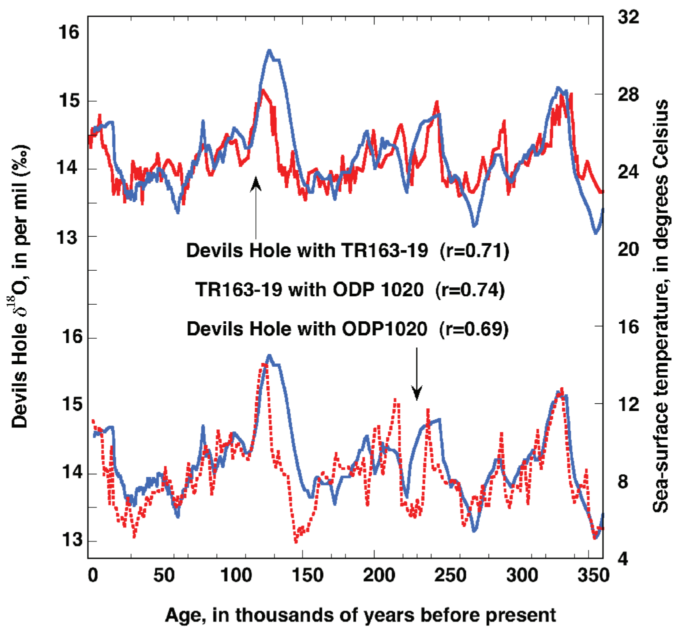


**Figure 4 (right).** The Devils Hole $\delta^{18}O$ (in blue) and sea-surface temperature (in red) time series from marine cores TR163-19 retrieved in the east equatorial Pacific at 2°N and 91°W (Lea and others, 2000) and ODP1020 retrieved off the Oregon-California border at 41°N and 126°W (Herbert and others, 2001). The linear correlation coefficient “r” between records is shown for the period from 4,500 to 360,000 years before present (Winograd and others, 2006).

## Where can one find the isotopic records?

The $\delta^{18}O$ and $\delta^{13}C$ time series from ~560,000 to 60,000 years before present are provided in USGS Open-File Report 97–792 [*http://pubs.usgs.gov/of/1997/ofr97-792/*] (Landwehr and others, 1997). The $\delta^{18}O$ record for Devils Hole was extended into the mid-Holocene (up to ~4,500 years before present) and is provided in USGS Open-File Report 2011–1082 [*http://pubs.usgs.gov/of/2011/1082/* ] (Landwehr and others, 2011).

## What contributions has Devils Hole research made to the fields of paleoclimatology, paleohydrology, and geochemistry?

Publication of the half-million-year-long Devils Hole $\delta^{18}O$ time series in 1992 initiated a decades-long discussion regarding the capability of the Milankovitch hypothesis (also referred to as orbital or astronomical theory) to predict the onset and duration of Pleistocene ice ages, a discussion that continues to this day (Wunsch, 2004; Henderson and others, 2006; Lourens and others, 2010). The radiometrically dated Devils Hole time series indicates an atmospheric warming beginning more than 10,000 years earlier than the timing of the penultimate major deglaciation (also referred to as Termination II) as predicted on the basis of the Milankovitch hypothesis. This has been considered to be a direct challenge to the validity of orbital theory (Broecker, 1992; Karner and Muller, 2000). This challenge was dismissed by some on the grounds that if the question of early warming was ignored, the Devils Hole records might be interpreted as supporting the Milankovitch hypothesis (Emiliani, 1993; Imbrie and others, 1993) but contradicted by others who claimed that early warming, though real, reflected only regional, not global, climate (Herbert and others, 2001). However, the original challenge posed by the early warming recorded in the Devils Hole $\delta^{18}O$ time series continues: it has been reinforced by a variety of studies, not only of interhemispheric paleo-SST warming, but also of sea-level high stands (a direct proxy for global ice volume conditions) that have been directly dated as occurring thousands of years prior to orbitally predicted global deglaciations (Winograd and Landwehr, 1993; Landwehr and others, 1994; Henderson and Slowey, 2000; Henderson and others, 2001, 2006; Gallup and others, 2002; Muhs and others, 2002; Winograd, 2002; Winograd and others, 2006).

Prior to publication of the Devils Hole $\delta^{18}O$ time series, the duration of Pleistocene interglacial intervals was thought to be on the order of 12,000 years, as determined from orbitally tuned chronologies based on marine sediment records (Imbrie and others, 1984). However, an examination of the Devils Hole record published in 1997 revealed that the warmest portion alone of the past four interglaciations lasted on the order of 10,000 to 15,000 years, whereas the entire duration of the warm intervals (interglacials) persisted in excess of 20,000 years, a finding supported by both Antarctic ice core data and sea level data (Winograd and others, 1997; Muhs and others, 2002). An additional continuing challenge to the Milankovitch hypothesis has been the occurrence of a high-intensity and long-duration interglacial from ~420,000 to ~395,000 years before present at a time of minimal variation in insolation, as recorded not only in marine isotopic records but also in the Devils Hole record (Winograd and others, 1992). The high correlation between the Devils Hole record and the ice core record at Vostok on the East Antarctic Plateau indicates a consistent interhemispheric timing of Pleistocene ice ages, which also is not consistent with the Milankovitch hypothesis (Landwehr and Winograd, 2001).

More recent work has corroborated these insights derived from Devils Hole, and it is widely acknowledged today that astronomical forcing alone cannot explain the duration, intensity, or diversity of the past four interglacials. More independently dated proxy records from both hemispheres would be required to achieve such an understanding (Tzedakis and others, 2009). In addition, it is now widely acknowledged that variations in atmospheric greenhouse gases, notably $CO_2$, have played a major role in the glacial-interglacial climatic shifts of the Pleistocene, though major questions persist regarding the origin of the "ice ages" (Raymo and Huybers, 2008).

In addition to the near-vertical vein calcites that precipitated from groundwater below the water table and today line the walls of the steeply dipping open fault, Devils Hole cave also contains subhorizontal wall deposits, called folia, that mark the stands of the paleo-water table in the cavern (fig. 2) (Szabo and others, 1994; Kolesar and Riggs, 2004). The folia are porous deposits that owe their origin to outgassing at the water table of $CO_2$ from the slightly supersaturated groundwater flowing through Devils Hole (Plummer and others, 2000). In Brown's Room, a remote portion of Devils Hole cave, the folia were sampled up to about 9 meters above the modern water table. The folia visible in the upper fifth of figure 2 indicate that the water table was once about a meter lower than its modern level. Uranium-series dating of these folia has enabled the development of a 120,000-year hydrograph of water-table fluctuation in the cavern, which indicates a prominent decline during the past 20,000 years (Szabo and others, 1994).

An unexpected consequence of the ability to carry out precise uranium-series dating of the Devils Hole cave calcite has been a renewed interest in other cave carbonate deposits, notably speleothems and flowstones (Kolesar, 2004), as archives of Quaternary paleoclimate. Speleothems now comprise a major archive of continental paleoclimatic data (Ludwig and others, 1992; Quade, 2004; Lachniet, 2009).

A comparison of the $\delta^{18}O$ measured in the vein calcite relative to that in Devils Hole groundwater has led to a new and significantly different estimate of the oxygen isotopic fractionation between calcite and water in a natural (non-laboratory) environment. This important contribution to aqueous geochemistry was possible because the physical and chemical constancy of environmental conditions at Devils Hole at depths greater than several meters below the water table—a constancy believed to have prevailed for at least 10 millennia—permits measurement of this fractionation in an environment at or near thermodynamic equilibrium (Coplen, 2007). Additionally, the high purity of the dense vein calcite allowed the development and testing of a new method with which to determine the $\delta^{13}C$ and $\delta^{18}O$ isotopic composition of $CaCO_3$ using smaller mass than previously possible (Revesz and Landwehr, 2002).

## What does Devils Hole reveal about how long we can expect the present interglaciation to last?

No one knows for sure how long the present interglacial will last. Any estimate depends on several factors: the paleoclimatic archive and proxy record(s) utilized; the degree to which these records reflect global conditions; the theory invoked; and current potential climatic influences, such as anthropogenically generated greenhouse gases. The Devils Hole $\delta^{18}O$ record indicates that the last four interglaciations each lasted over ~20,000 years, with the warmest portion being a relatively stable period of 10,000 to 15,000 years duration (Winograd and others, 1997). The most recent portion of the Devils Hole record suggests—as do SST records off California—that the warmest portion of the current interglaciation began by 17,000 years before present (Winograd and others, 2006). From these data one might infer that in the absence of any mitigating conditions, such as anthropogenically induced climate warming, the onset of a period of global cooling is imminent or even overdue on a geologic time scale (Ruddiman, 2007). However, some researchers have suggested that the current interglaciation might continue for tens of thousands of years (Berger and Loutre, 2002).

## What are some practical applications of the Devils Hole findings?

In addition to providing information about the possible duration of our present interglacial climate (discussed above), research in Devils Hole has been a source of valuable information for water managers. Devils Hole cave provides hydrologists with direct access for making hydraulic measurements and collecting chemical samples of the regional carbonate-rock aquifer underlying much of south-central Nevada and which supplies the groundwater that is discharging within the Ash Meadows oasis. Meaningful estimates of the sustainable use of this aquifer hinge on knowing the age of the groundwater. Estimates of the groundwater age inferred from carbon-14 dating of dissolved inorganic carbon in the groundwater have yielded an age in the range of 13,000 to 25,000 years (Anderson, 2002), whereas carbon-14 dating of dissolved organic carbon has yielded ages on the order of 3,000 to 7,000 years (Thomas, 1996; Morse, 2002). However, several lines of evidence derived from Devils Hole indicate a groundwater age of 2,000 years or less (as discussed in appendix A in Winograd and others, 2006). The evaluation of Yucca Mountain, which is about 45 kilometers north-northwest of Devils Hole, for the geologic disposal of spent nuclear fuel has required estimation of past and future climates over time frames of hundreds of thousands of years. The paleoclimatologic and paleohydrologic information gleaned from Devils Hole has provided the foundation for such estimates (Forester and others, 1999; Sharpe, 2007; Paces and others, 2010).

## Why is Devils Hole of interest to zoologists?

The endangered species of pupfish *Cyprinodon diabolis* is endemic to Devils Hole, with a habitat dependent on stable groundwater-table levels (Dudley and Larson, 1976). Concern for the protection of this unique species' habitat provided the first test of the Endangered Species Act and resulted in the unanimous affirmative landmark decision by the U.S. Supreme Court in 1976 (*Cappaert v. United States,* 426 U.S. 128). This pupfish species has been studied by zoologists for decades, not only because of its unusual habitat, but also because of speciation-process debates concerning the length of its isolation from other members of its genus (Riggs and Deacon, 2004). Estimates of the length of its isolation range from tens of thousands of years (Riggs, 1991) to perhaps hundreds of thousands of years (Winograd, 1991; based on data in Winograd and Szabo, 1988).

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