History of ice at Candelaria Ice Cave, New Mexico

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Introduction

Unlike deep cores from continental (Dansgaard et al., 1993) and mountain ice sheets (Thompson et al., 1995), which have yielded a spectacular history of global climate variations during the last few hundred thousand years, cave ice has been virtually ignored as a climate proxy. This is in spite of the fact that cave ice has a global distribution, primarily in high-elevation or high-latitude lava tubes (Henderson, 1933), and tends to be layered, suggesting annual resolution. Ice caves are restricted to areas that have sub-zero winter temperatures, but not necessarily a mean annual temperature below zero (Henderson, 1933; Blach, 1970). Conceivably, some of these caves could contain Pleistocene ice; cave ice was dated to 3000 yrs B.P. (years Before Present) in Romania's Ghetarul de la Scarisvara (Bogli, 1980, p. 227).

There has been little quantitative research to explain the physics of ice formation and accumulation in caves, which probably varies with cave morphology and degree of air circulation (Kovarick, 1898; Wigley and Brown, 1971, 1976, pp. 340–343). Wigley and Brown (1971, 1976) derived a model based on Equations of Continuity to define distributions of temperature and humidity throughout a cave. In general, perpetual ice develops because cold, dense winter air sinks into the cave and density stratification between this cool air and lighter summer air keeps the warmer air from entering the cave (Martin and Quinn, 1990). The cold, winter air freezes any existing water and cools the surrounding rock. The latent heat released by freezing the ice warms the cave, which strengthens the exchange (Ohata et al., 1994a). Cooling also may be enhanced by evaporation of surface water and removal of the latent heat by slight turbulence (Harrington, 1934). However, there are disagreements about the importance of evaporation and turbulence in maintaining ice in caves with limited air circulation (Harrington, 1934 vs. Halliday, 1954). Also, little is known about the surface conditions that control rates of ice accumulation and ablation. In northern California lava tubes, perennial ice may have a negative balance during prolonged surface drought conditions (Swartzlow, 1935). In Fuji Ice Cave, Japan, Ohata et al. (1994a, 1994b) found alternating periods of positive and negative ice accumulation. The net accumulation of a given year was highly correlated with deviations from average winter air temperature during the previous four years. This indicates that such cave systems have a high heat capacity, and that the ice bodies they harbor may be highly sensitive to long-term temperature trends at the surface.

As a pilot project to explore the paleoclimatic potential of cave ice in North America, we have been studying Candelaria Ice Cave, west-central New Mexico, a tourist attraction and one of the better-known ice caves in North America. The paleoclimatic potential of layered ice at Candelaria Ice Cave was first indicated by Willis T. Lee (1926, p. 59), a U.S. Geological Survey geologist, who noted, "Each layer may represent a year's accumulation or it may represent a climatic cycle... It is not impossible that the climatic changes recorded in the ice might supplement the chronology obtained by studying the growth of trees." This chapter reconstructs the history of cave ice at Candelaria Ice Cave based on rephotography of images taken by Lee et al. during this century. A paper in progress uses this "chronology" to interpret variations in physical and chemical attributes of ice cores taken on the ice cliff (pre-1900) and ice pond (post-1900).

In June 1990 three ice cores were drilled at Candelaria Ice Cave using an ice-core hand auger. These cores are currently being analyzed for microparticle concentrations, oxygen and hydrogen isotopes, and anion chemistry at the Byrd Polar Research Center, Ohio State University. To obtain the age of the oldest ice exposed in the very back of the cave, we sampled ice, plant, feathers, and insect fragments embedded in the ice and submitted these samples for Tandem Mass Accelerator (TAMS) dating. An attempt was also made to directly date the CO_2 in the older ice using a sublimation procedure and TAMS dating. In June 1996 we mapped the ice body at Candelaria Ice Cave with an Electronic Distance Meter (EDM) Total Station. We also measured temperature and humidity every 6 seconds for 41 hours on June 11, 12, and 13, using a Cole Parmer, Smart Reader, continuous-data logger. The resolution is 0.6°C for the internal thermistor and 0.4% for the relative humidity sensor. The logger was suspended 1.5 m above the ice-pond surface. Ablation and accumulation observations have never been conducted for Candelaria Ice Cave, so we were forced to rely on core measurements and historical photographs. Photographs dating from the 1920s to the 1970s were matched from the same vantage point in May 1991 and June 1996. Photographs were scanned into a Power Macintosh G100/60AV using Ofoto (Version 2) and a Macintosh Color OneScanner. Adobe Photoshop version 2.5 for Macintosh was used to crop and adjust contrast and brightness of the images. The TIFF files were then imported into CorelDRAW! version 3.0 and adjusted to equal scale.

Physical setting

Candelaria Ice Cave (34°59'30" N, 108°05'00" W, 2393 m elevation) is part of a collapsed lava tube at the base of Bandera Crater, directly east of the Zuni Mountains and approximately 25 km southwest of

Grants, Cibola County, New Mexico. The Zuni–Bandera field (also referred to here as El Malpais) resulted from extensive basaltic volcanism during the last million years along the central portion of the Jemez lineament in west-central New Mexico (Maxwell, 1986; Laughlin et al., 1993a). The Bandera flow formed 10,000 yrs B.P., according to radiocarbon dating of charcoal in buried soil and cosmogenic dating (Laughlin et al., 1993b, 1994, this volume). This places an early Holocene upper-age limit to Candelaria Ice Cave and other ice bodies in the Bandera flow. It also indicates that disjunct distributions of arthropods, algae, and cryptogams in the lava-tube caves of the Bandera flow, thought to be Pleistocene relicts (Peck, 1982; Lindsey, 1951), actually represent Holocene dispersals from older flows nearby.

The relatively open woodland in the immediate area of the cave is dominated by ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), Colorado piñon (*Pinus edulis*), Rocky Mountain juniper (*Juniperus scopulorum*), quaking aspen (*Populus tremuloides*), and Gambel oak (*Quercus gambelii*) (Lindsey, 1951). Shallow soils and relatively slow growth rates have produced ideal conditions for development of millennia-long climate reconstructions from tree rings in conifers growing on the Bandera flow and other local basalts (Grissino-Mayer, 1995, 1996, this volume). These tree-ring reconstructions serve as a control for interpreting climatic effects on the history of the ice body at Candelaria Ice Cave.

Based on the period 1948–1994, mean annual temperature at El Morro National Monument, 30 km west of Candelaria Ice Cave, is 8.8°C, and mean annual precipitation is 347 mm, with 33% occurring as monsoonal rains in July and August. Interannual and interdecadal variability in regional precipitation is modulated in part by the Southern Oscillation, the flip flop in sea surface pressure patterns across the equatorial Pacific that marks alternation between El Niño (warm Pacific) and La Niña (cold Pacific) states. In the region of Candelaria Ice Cave, El Niño conditions are associated with stormier winters and springs (Andrade and Sellers, 1988) and its drier summers (Harrington et al., 1992); the opposite is considered true for La Niña years. Twentieth-century climatic trends stemming from interdecadal behavior of the tropical Pacific include wet winters in the early part of the century, a mid-century dry period, and wet winters and erratic summers since 1976. The late 1940s and 1950s constitute the most extreme event of recurrent widespread drought in the southwestern U.S. during the past 300 years (Meko et al., 1993; Betancourt et al., 1993; Grissino-Meyer, 1995, 1996). Ice accumulation at Candelaria Ice Cave should be related positively with low average winter air temperatures and increased annual precipitation. Ablation should be correlated with high summer temperatures and prolonged drought.

Candelaria Ice Cave is one of 100 lava caves and crevices containing perennial ice in the El Malpais, including Navajo, Brewers, La Marchantia, and Lichen Caves (Goar and Mosch, 1994; Hatheway, 1971; Lindsey, 1951). Candelaria Cave is located at kilometer 1.7 along a 26 km long lava-tube system emanating from Bandera Crater.

Candelaria Ice Cave is made up of an upper chamber and a lower chamber (Fig. 1). The upper chamber is approximately 15 m below the surface of the lava and contains perennial ice (Figs. 2–4). The lower chamber is dry and devoid of ice. The ice is composed of two distinct ice accumulations. The first part was deposited as flat layers filling the cave to probably more than 4.5 m above the floor. The front of this older ice body has retreated as a vertical wall through ablation, leaving a vertical to overhanging, semicircular ice "cliff." In its place a new ice body has accumulated as an ice "pond" dammed at the entrance by the steep rock talus and at the back by the ice cliff. The vertical bank has distinctive layering reminiscent of more imposing ice cliffs at the receding edge of ice caps in the Andes and Himalayas. At Candelaria Ice Cave, clear ice alternates with thinner layers of white porous ice; blue–green algae (*Stichococcus subtilis* and *S. bacillaris*) tend to cover the ice more thickly on the latter, imparting a distinct, banded arrangement to the ice. During summer the ice pond becomes slushy or covered by a thin layer of water, and is colonized by the rare green cryoscopic alga *Sphaerella lacustris* (Lindsey, 1951). Unlike ice sheets, the layers in cave ice do not always represent annual increments. It is possible that some layers are semiannual while others are biennial. Along the back of the ice cliff, we counted approximately 85 layers from top to bottom. If the layers are annual or even biennial, then the 4.5 m deep ice cliff should represent no more than 170 years.

The general air circulation in the cave is different in summer and winter as seen in Figure 5 (Harrington, 1934; Blach, 1970; Denbo, 1981). In winter, cold, dense air displaces warmer, lighter air, thus freezing all surface water. This process is referred to as "passive settling of heavier cold air" by Harrington (1934). The latent heat released by the freezing of water, and thus warming the air, is replaced by cold air from outside the cave. This continues until all water is frozen and the surrounding rock is cooled to below freezing. A computer model by Denbo (1981) has shown that in summer warm air can only penetrate a cave as deep as the entrance is wide. Subtle changes in circulation may be caused by sunlight entering the cave, but these changes are negligible. Heat losses are not compensated for during summer and thus ice accumulates. In June 11–13 temperature remained constant between –1.8 and –2.7°C and relative humidity stayed at 100%. This demonstrates that there is no daily cycle in the cave, and it rules out the exchange of outside air during summer. Most of the water in Candelaria Ice Cave probably collects as runoff from the bowl created by collapse of the lava tube, with minor contributions by infiltration and seepage from above the cave. Ablation of the ice cliff probably is an additional internal source of water for current accumulation in the ice pond. This latter process recycles and mixes waters of different isotopic, chemical and microparticle composition, clouding paleoclimatic inferences. Hypothetically, discharge from the basin immediately above Candelaria

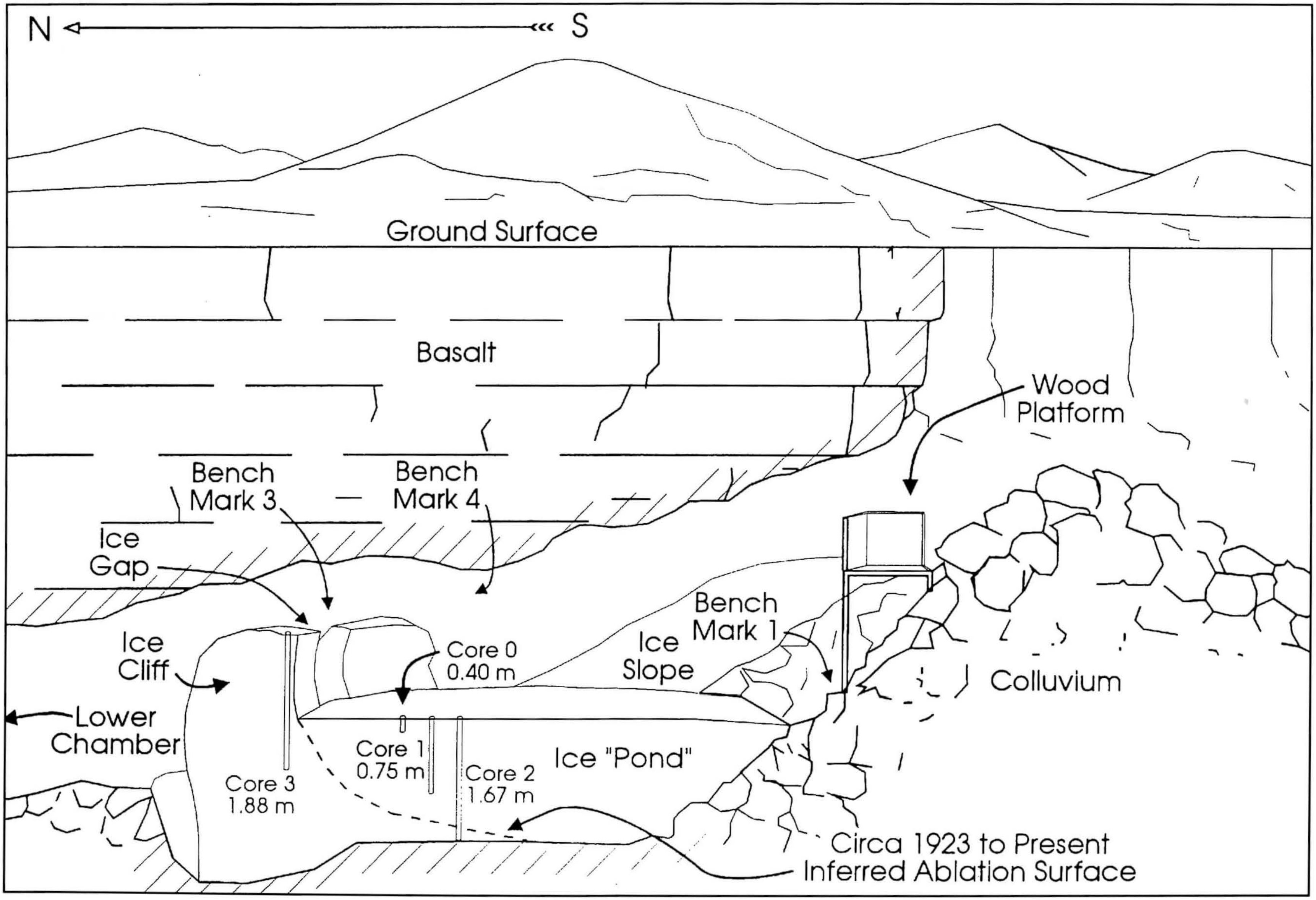

FIGURE 1—Schematic cross section of the upper chamber of Candelaria Ice Cave.

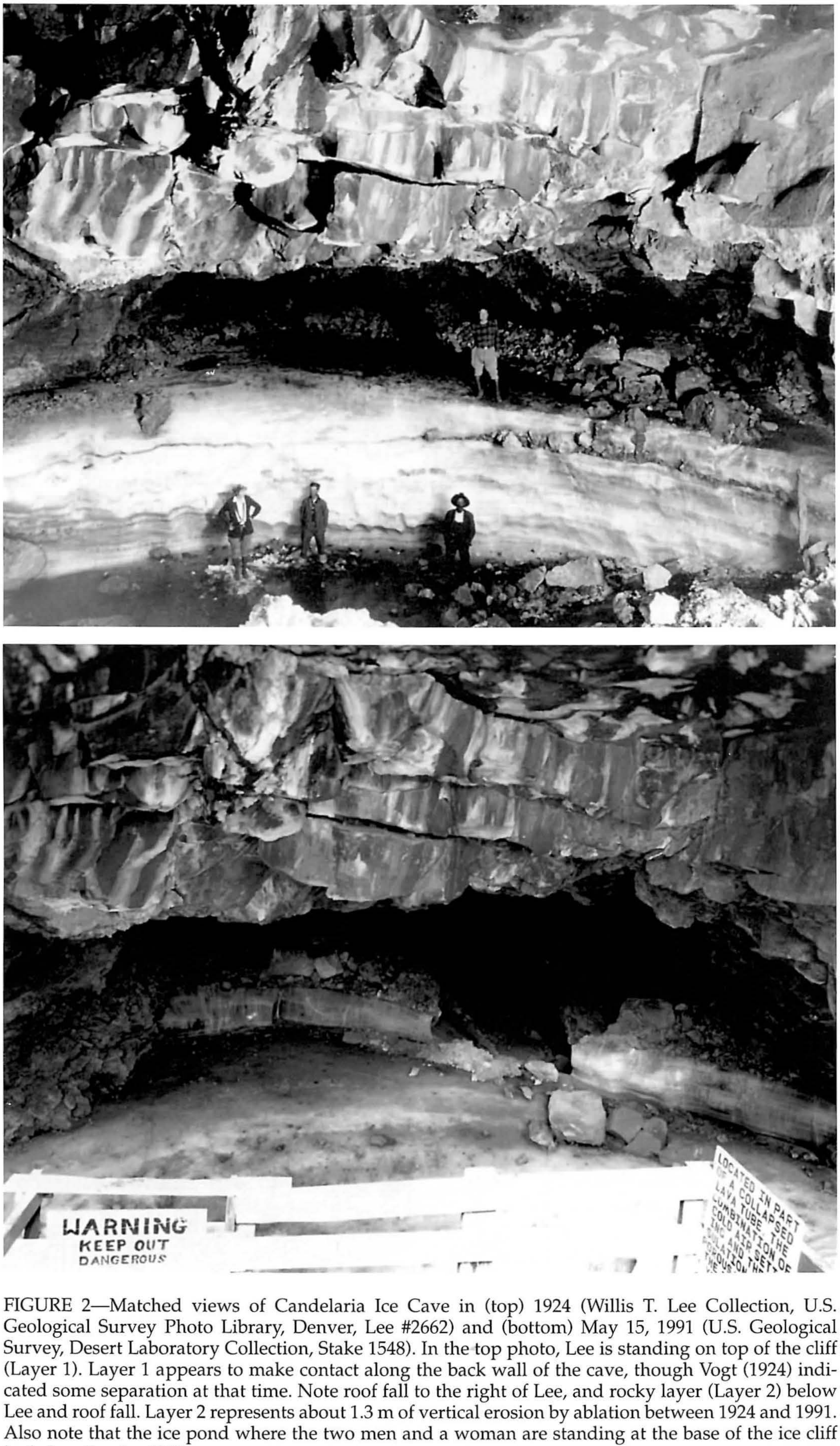

FIGURE 2—Matched views of Candelaria Ice Cave in (top) 1924 (Willis T. Lee Collection, U.S. Geological Survey Photo Library, Denver, Lee #2662) and (bottom) May 15, 1991 (U.S. Geological Survey, Desert Laboratory Collection, Stake 1548). In the top photo, Lee is standing on top of the cliff (Layer 1). Layer 1 appears to make contact along the back wall of the cave, though Vogt (1924) indicated some separation at that time. Note roof fall to the right of Lee, and rocky layer (Layer 2) below Lee and roof fall. Layer 2 represents about 1.3 m of vertical erosion by ablation between 1924 and 1991. Also note that the ice pond where the two men and a woman are standing at the base of the ice cliff had risen 2 m by 1991.

FIGURE 3 —Matched views of Candelaria Ice Cave in (top) 1924 (Willis T. Lee Collection, U.S. Geological Survey Photo Library, Denver, Lee #2663), and (bottom) June 12, 1996 (U.S. Geological Survey, Desert Laboratory Collection, Stake 1546). A scale was developed using Lee's estimate of 4.3 m height of the ice cliff (Lee, 1926).

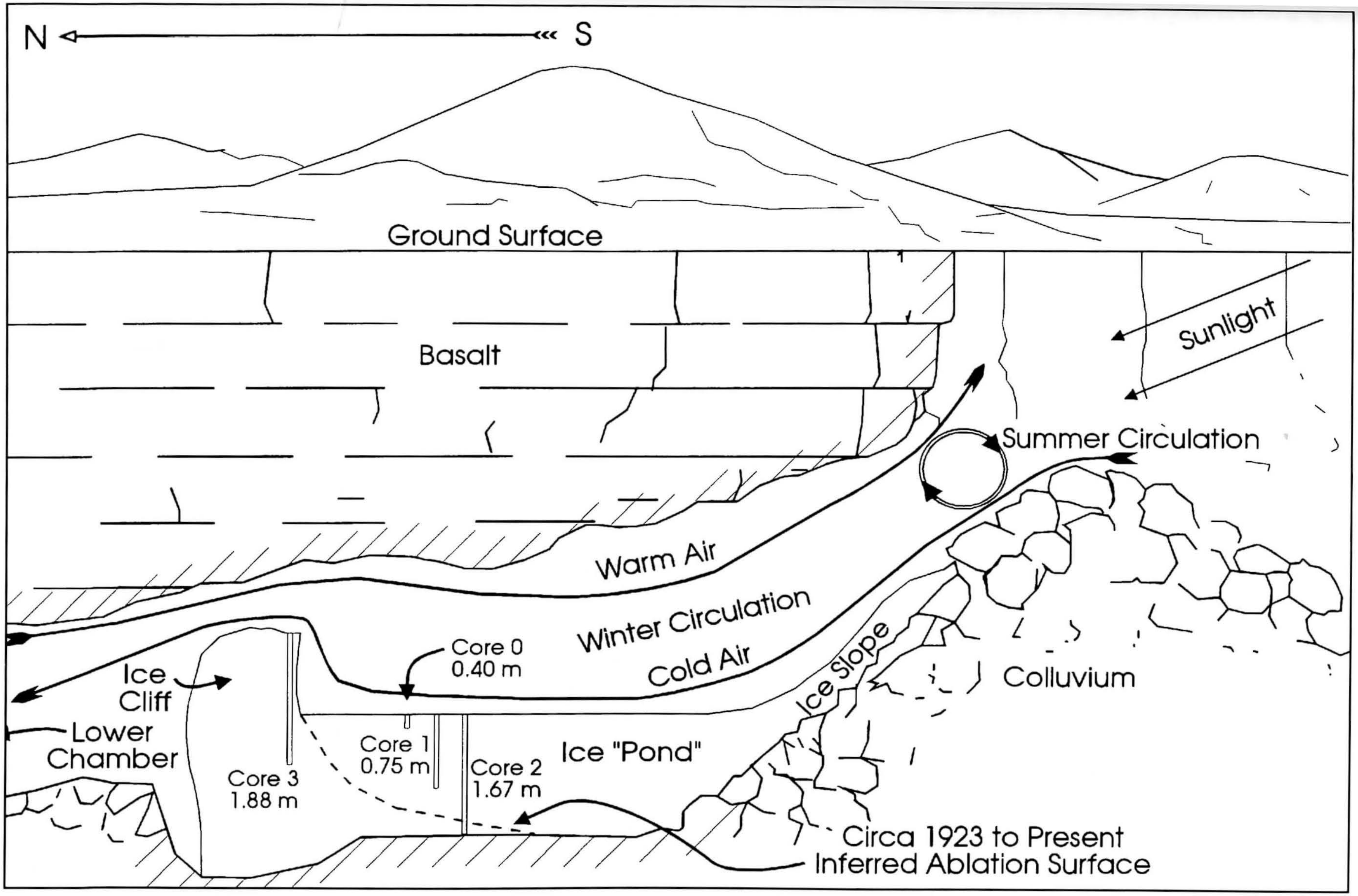

FIGURE 5 —Schematic cross section indicating circulation of air in summer vs. winter.

Ice Cave has to exceed losses from summer ablation to yield ice accumulation in any given year.

Cultural setting

Little is known about Native American use of Candelaria Ice Cave prior to European settlement. Soldiers from nearby Fort Wingate often entered the lava flows near Candelaria Ice Cave (Meketa, 1986). Hearsay has it that soldiers may have mined the ice in the late 1800s. In the 1880s Benito Baca homesteaded land 3 km from the cave (Mangum, 1990) and also may have mined the ice. Sylvestre Mirabal purchased the land containing the ice cave in 1920. In the early 1900s a wooden stairway was built to provide access from the edge of the collapsed lava tube down to the cave's entrance. This stairway was struck by lightning and burned in the 1920s (David Candelaria, pers. comm.). In the 1920s the cave became known to locals as the Perpetual Ice Cave (Vogt, 1924). In the 1930s, a marked trail from the State Highway (present NM–53) led to the cave; still, access was limited and two women lost their way to the cave and were not found for three days. This near-tragedy prompted locals to improve access and take measures to protect the ice cave from vandals (Magnum, 1990). In 1938 Sylvestre Mirabal arranged a lease agreement with Cecil Moore, a local homesteader, to oversee the property. Moore built a saloon and dance hall using the ice from the cave as a means of keeping the beer cold. This establishment served the local homesteaders, lumberjacks, and miners. Cecil also showed the cave and improved the trail and stairway. During this period ice mining slowed but continued until 1946, when Prudencia Mirabal Caldelaria inherited the property and her son David took over management. Dave Candelaria closed the saloon and concentrated on promoting tourism, establishing the Ice Caves Trading Post (Alford, pers. comm.). Candelaria's business picked up with the addition of electricity in 1955 and paving of NM–53 from Grants to the Ice Cave in 1966; improvements were made to the stairway in 1963 (Mangum, 1990). During its early development as a New Mexico tourist stop, Candelaria Ice Cave also attracted considerable scientific interest (Vogt, 1924; Lee, 1926; Yeo, 1930; Harrington, 1934; Lindsey, 1951).

Results

Tandem Mass Accelerator radiocarbon ^{14}C dates were obtained from a moth, two twigs, one feather, and CO_2 gas from four ice samples summarized in Tables 1 and 2. The material was taken from different depths along the back wall of the ice cliff, on both sides of a large gap that first opened in 1976 (depths are from the top surface of the ice cliff, referred to here as layer 2; east and west segments refer to direction from the gap). CO_2 gas from ice samples was extracted by placing the sample of ice core in a glass vacuum system, where it is allowed to sublime at low temperature. The water vapor, CO_2, and other gases produced in the sublimation process are collected in appropriate cold traps, and the CO_2 gas can be dated directly using accelerator mass spectrometry. Though we report these dates in Table 2, all of the CO_2 gas dates from the Candelaria Ice Cave ice samples can be challenged on the basis of carbon isotope ratios ranging from −17.2 to −38 per mil. Carbon isotopic values in the CO_2 gas from the ice should be from −6.5 per mil in preindustrial times to −8.0 per mil in modern samples, or the same isotopic composition as atmospheric CO_2. Fractionation of from −10.7 to −31.5 per mil for the prehistoric dates and −14 per mil for modern samples suggest contamination by diffusion or some other process. Here we rely only on the dates from organic remains. Note, however, that such organic remains have long residence times and can recirculate in caves such as Candelaria Ice Cave.

The radiocarbon dates suggest that the bottom one meter of the ice cliff (3.4–4.5 m) could be as old as

TABLE 1—Tandem Mass Accelerator ^{14}C dates in Candelaria Ice Cave.

Sample description	Sample material	Sample number	δ^{13}C ‰	Radiocarbon age, years B.P.
Core 3, 1.5 m depth in west segment	Moth	AA-20595	1.0	243 ± 55
2.5 m depth in west segment	Feather	AA-6022		27 ± 73
3.4 m depth in back of west segment	Unidentified twig	GX-15920	−24.6	3,116 ± 77
4.0 m depth in back of east segments	Unidentified twig	GX-15919	−20.3	1,810 ± 100

TABLE 2—Tandem Mass Accelerator ^{14}C dates on CO_2 gas from ice samples in Candelaria Ice Cave.

Sample description	Sample material	Sample number	δ^{13}C ‰	Radiocarbon age, years B.P.
0.30 m depth in west segment	Ice sample B	AA-6024	Too small	24 ± 94
2.5 m depth in west segment	Ice sample D	AA-6022	−22.0	55 ± 60
4.3 m depth in east segment	Ice sample A	AA-6021	−17.2	1,857 ± 56
4.5 m depth in east segment	Ice sample E	AA-4915	−38	1,780 ± 60

1800–3000 yr B.P., and that there is a 1500–2000 yr hiatus between this older ice and the upper 3 m of ice, which yielded modern to historic dates. This apparent hiatus may have resulted from similar catastrophic loss of ice that happened in the 20th century. The upper 3 m of the ice cliff probably represent no more than 250–300 years before about A.D. 1850–1880, when the ice cliff apparently formed at the front of the cave and began to retreat. If the 85 layers in the 4.5 m tall ice cliff are annual or even biennial, they did not accumulate continuously. Erosion of layers through ablation probably has happened as frequently as accumulation. This is particularly evident in the discontinuities and unconformities observed in the layering in the bottom part of the ice cliff.

Because Candelaria Cave is accessible and easily photographed from a well-lit overlook, it has a rich photographic history dating back to the 1920s. The earliest photographs were taken by Willis T. Lee of the U. S. Geological Survey, most likely in 1924 (Figs. 2–4; Lee, 1926). The Lee images are undated, but the lady in the three photographs appears in a 1925 Lee photograph of Mammoth Caves, Kentucky; she appears to be wearing the same hat. Also, another Lee photo of nearby Inscription Rock (El Morro National Monument) has a 1920s roadster in the foreground. Alton A. Lindsey photographed the cave in 1947 and again in 1981 (Lindsey, pers. comm.). Another series of photographs, mostly from Dave Candelaria's files, date from the late 1930s/early 1940s to the 1980s. The latest photographs were taken in May 1991 and June 1996 from the same vantage point as earlier photographs to measure rates of ice-cliff retreat and accumulation in the ice pond.

The most distinctive feature of Candelaria Ice Cave is the photogenic ice cliff at the back of the cave (Figs. 2–4, 6–15). Lee (1926) estimated the ice cliff at 4.3 m high in 1924, compared to Yeo's (1930) estimate of 2.3 m. The latter number is probably an eyeball estimate and in gross error; Lindsey (unpublished notes) estimated a height of 2.7 m for the ice cliff in 1947. Lee (1926) stated that the upper surface of the ice cliff was level for about 9 m from the face, gradually sloping towards the back of the cave. Evon Vogt, superintendent of nearby El Morro National Monument, accompanied Lee's party in their visit to Candelaria Ice Cave (Vogt, 1924). In 1924 the ice had separated from the back wall: "With a miner's lamp or trustworthy flash light, one may descend into this hole which opens into a tunnel. It winds below and around a part of the ice..." (Vogt, 1924, p. 38).

Distinctive layers (1–3) in the semicircular ice cliff in the back of the cave can be identified across most of the photographs (Figs. 2–4) and are labeled in Figure 3. We developed a scale from Lee's photo in 1924 (Figs. 2–4) by using Lee's estimate of 4.3 m for the ice cliff. This allowed us to measure the depth between layers 1–3. The same scale was exported to other photographs, which were reduced or enlarged to equalize the depth between layers 1 and 3. Our estimate of 2.70 m in 1947 agrees with Lindsey's measurement. The uppermost Layer 1 was recognized in all the pre-1950 images. Layer 1 is missing in the more recent photographs, indicating ablation at the top of the ice cliff down to the level of Layer 2 between 1924 and the early 1950s. Layer 3 is a dark layer in between a thick upper and a thin lower white layers ca 0.85 m below Layer 2.

Poor dating of the photographs probably yields the largest error in ablation and accumulation. Few of the photographs are dated to the year. We made estimates based on the current ages of individuals in the photographs, styles of clothing worn, and the height of the ice cliff relative to those photographs for which we knew the exact date. Error bars were assigned to each image based on the earliest and latest possible dates. To minimize this error, only the images with the most precise dates were used. We further reduced the effect of poor dating by estimating ablation and accumulation over the longest time intervals possible.

Vertical ablation (from the top down) is evident throughout the photographic record. This ablation has been countered by accumulation of the ice pond at the base of the ice cliff, giving the illusion of more vertical ablation than actually occurred. The ice appears to have ablated vertically from Layer 1 to Layer 2 from 1924 to the early 1950s (Figs. 6–13). Between these layers the ice first ablated down to Layer 2 along the east wall and later ablated on the west side. Layer 2 is a very dirty layer, representing a prolonged lull in ice growth and accumulation of roof fall on the ice surface, and/or concentration of debris from several layers of ablated ice. No measurable vertical mass loss occurred after 1950. Today, remnants of layered ice up to 0.23 m thick, representing the interval between Layer 1 and 2, are patchy across the top surface of the ice cliff. In the debris on top of Layer 2, small amounts of unlayered ice may be seen as high as 0.62 m in the interstices between the rocks.

Horizontal ablation (recession of the ice cliff from the front to the back of the cave) is more difficult to reconstruct from photography. The ice contact with the west wall is only seen in Figures 4, 6, and 13 Top where the ice retreated over 4.5 m since 1924. The retreat along the east wall was less dramatic (Fig. 3), with only about 2 m of ice loss. Between these points, it appears the ice curves gently back. As the ice cliff ablated horizontally, debris sloughed off the top of the ice cliff to the ice pond, continuously changing basin topography (Figs. 6–16). We estimated ice-cliff retreat and measured the area lost using the 1996 survey (Fig. 17, Table 3).

Table 4 summarizes ice-pond accumulation and ice cliff height reconstructed from the photographic record. In 1924 the ice cliff was approximately 2.7 m in front of its current position, and there appeared to be little to no ice in the pond in front of it (Fig. 5). In 1990 an ice core drilled from the ice pond "bottomed-out" at 1.67 m depth, in rocky debris assumed to be debris sloughed off the ice cliff as it retreated past that point. A piece of dimensional lumber encountered at 1.67 m depth could help constrain rates of ice accumulation in the ice pond. This lumber could represent scrap from stairway construction and repairs done in 1963, indicating that the ice-pond core represents the period 1963–1991. Figures 9–15 confirms this conclusion. We

FIGURE 6 —Photograph of Candelaria Ice Cave probably taken between 1933 and 1940. Note series of layers between two dark bands at head level.

FIGURE 7—Ice cliff between 1947 and 1950. Note abundant debris at base of cliff, suggesting rapid ablation of the ice cliff during the mid 1940s.

FIGURE 8 —Woman posing in front of the ice cliff between 1950 and 1955. Note that ice between Layers 1 and 2 has completely ablated.

relied primarily on the photographic record to estimate interdecadal variation in rates of accumulation. We did not take into account the fact that basin size has gradually changed with retreat of the ice cliff since 1924.

The average yearly accumulation in the ice pond is summarized in Table 5. Accumulation was moderate from the late 1920s to ca 1936. The ice rapidly decreased from ca 1936 to 1947. The ice resumed moderate accumulation until 1956–1976, when ice accumulation slowed. Ice-accumulation rates began to increase from the early 1970s to 1981 and reached the highest rates from 1981 to 1991, when the ice pond attained its current height. Photographs in 1996 show ca 0.13 m of ablation since 1991 (Fig. 4). In 1976 a hole developed in the middle of the ice cliff (Dave Candelaria, oral comm.), leaving a bridge of ice approximately 0.70 m deep (Fig. 14). By 1981 the hole had grown to about four times its size in 1976 (Fig. 15, top). By ca 1985 the ice bridge collapsed under the weight of the overlying debris (Fig. 15, bottom). Today all remnants of the fallen ice are buried beneath the ice pond and the ice cliff continues to recede gradually toward the back of the cave.

Discussion

Radiocarbon dates from different depths in the 4.5 m tall ice cliff at Candelaria Ice Cave indicate that the bottom ice could be as old as 1800–3000 yrs, but the upper 2.5–3 m probably encompass some portion of the period between A.D. 1650–1850. Admittedly, there are large uncertainties in these age estimates. However, the lack of ice older than 3000 yrs B.P., as well as the apparent discontinuities in ice buildup, suggest that ice bodies in Candelaria Ice Cave have accumulated and ablated several times during the Holocene, most likely tracking century to decadal and century-scale variability in climate.

The ice cliff at Candelaria Ice Cave could have been initiated several different ways. All explanations assume that the top of the ice cliff in 1924 represents the level to which ice filled the cave, and that ablation began vertically at the entrance and progressed towards the back. The ice cliff could have been initiated by seepage of runoff and/or meltwater along the contact between the ice and the talus that slopes down into the cave (Yeo, 1930). This assumes that seepage can travel below the ice without freezing, which is unlikely in this setting. A second explanation is analogous to the way moats form around the contact of a nunatak, an island of rock surrounded by glacier ice. During an extended warm and dry period, ice at the front of the cave begins to retreat from the rocks near the entrance. Once a "nickpoint" forms, the lack of runoff and warm surface temperatures could accelerate recession though horizontal ablation. Yet another explanation involves collapse of a key overhang exposing the front of the ice body to direct sunlight (Yeo, 1930). The most likely cause of "nickpoint" initiation is extraction of ice by Ft. Wingate soldiers and nearby settlers in the late 1800s. Yeo (1930, p. 22) observed that, "On the day of the examination some

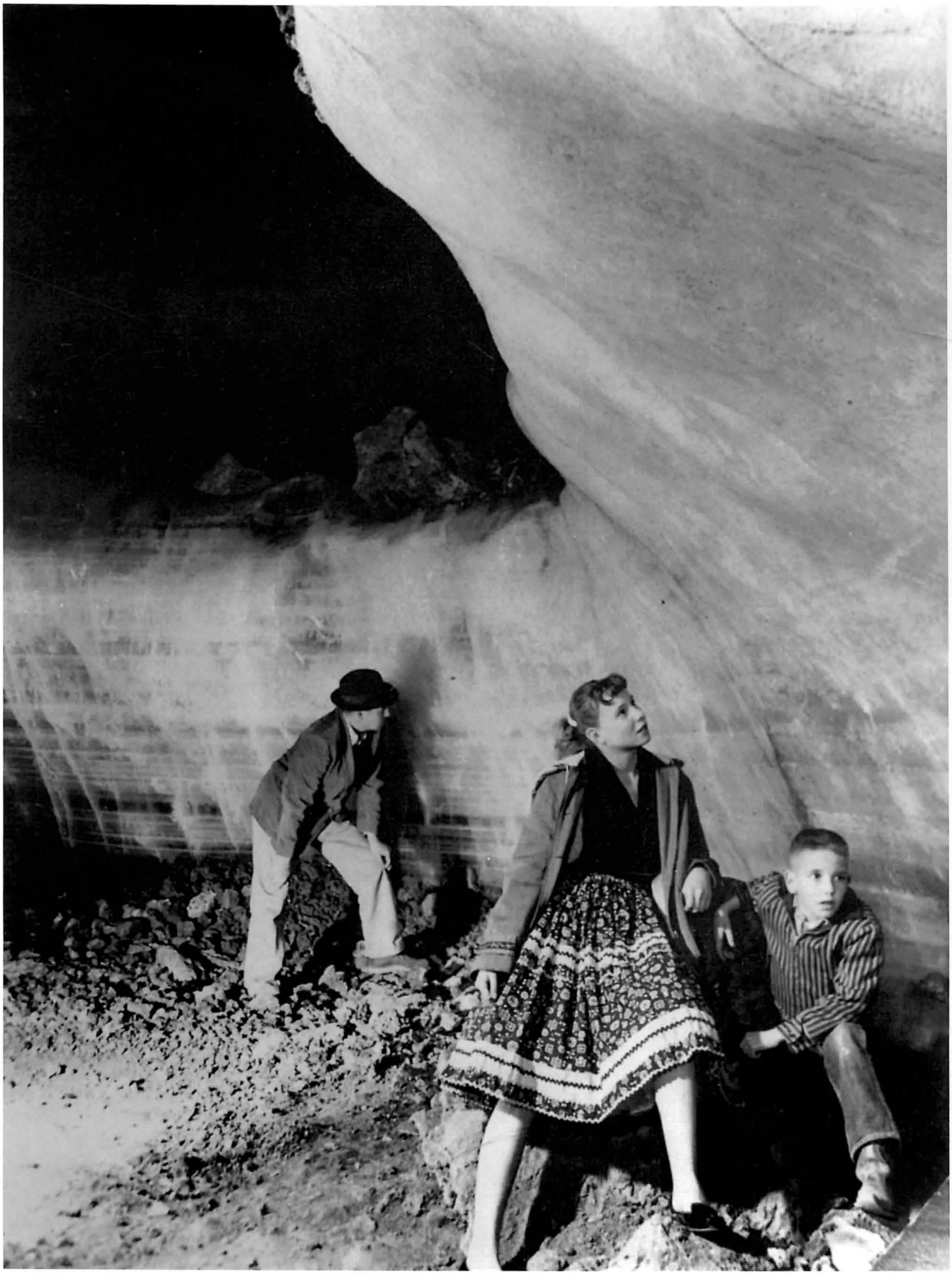

FIGURE 9—Dave Candelaria and his children in front of the ice cliff in 1956.

vandal had taken an axe with a large blade and loosened about a half bushel of ice from the main face, and it was lying at the bottom of the cave. When any warm air or summer comes in contact with this it will melt readily." It is not inconceivable that large volumes of ice were removed from Candelaria Ice Cave, and that ablation of the exposed vertical faces of the excavated pits outpaced refilling of the pits with ice. In 1934 Evon Vogt, the superintendent of nearby El Morro National Monument, wrote a letter to the director of the National Park Service expressing concern over the summertime extraction of hundreds of pounds of ice by nearby homesteaders (Mangum, 1990, p. 81). The mining of ice probably decreased when Cecil Moore began to develop Candelaria Ice Cave as a tourist attraction in 1938, and soon after mining of ice probably ceased. Finally, we cannot rule out possible negative effects that excessive runoff might have on ice accumulation, specifically late in the warm season. In September 1996, heavy rains flooded the pond and the ice floor buckled and cracked towards the front of the cave. The same heavy summer and fall rains that might have been responsible for arroyo-cutting in New Mexico during the 1880s (Leopold, 1951; Tuan, 1966) could have accelerated the erosion initiated by mining of the ice at about the same time.

With few exceptions, accumulation rates in the ice pond that formed in front of the ice cliff generally covary with precipitation and temperature trends in the twentieth century. Climate and tree-ring records (Grissino-Meyer, 1995, 1996, this volume), the latter being most sensitive to cool-season precipitation, indicate that a significant drought with warm summers in 1895–1904 was succeeded by highly variable but generally wet conditions between 1905 and 1943, with particularly wet years in 1905, 1907, 1914–1916, 1919, 1931, and 1941 (Fig. 18). The slow accumulation in the ice pond during at least the early part of this period could be due to ice removal exceeding the rate of accumulation. Also, we know that the cave floor was exposed in the 1920s, which may have enhanced seepage and retarded ponding for an undetermined period of time. Little ice is evident in the pond during the late 1940s and 1950s. This period corresponds with one of the worst droughts in the last 2,219 years (Grissino-Mayer 1995, 1996). Most of the ice in the present pond accumulated since the early 1960s, a period that was consistently wetter than any other time during the last 100 years (Fig. 18). Although the period from 1960 to 1975 was cooler than normal, the period since 1975 has been warmer during both seasons. Apparently net accumulation was negative from 1968 to 1977, and again in 1980–1981. Note the extreme rainfall in late summer and early fall of 1972 (Fig. 18), which could have had a negative effect similar to fall of 1996. The greatest accumulation rates, between 1981 and 1991, coincide with above-normal winter rainfall and temperatures. The greatest accumulation rates, between 1986 and 1991, coincide with the greatest rainfall reconstructed from the 2000 yr tree ring record. Photographs indicate some ablation between 1991 and 1996. This period is marked by drought during a strong La Niña event.

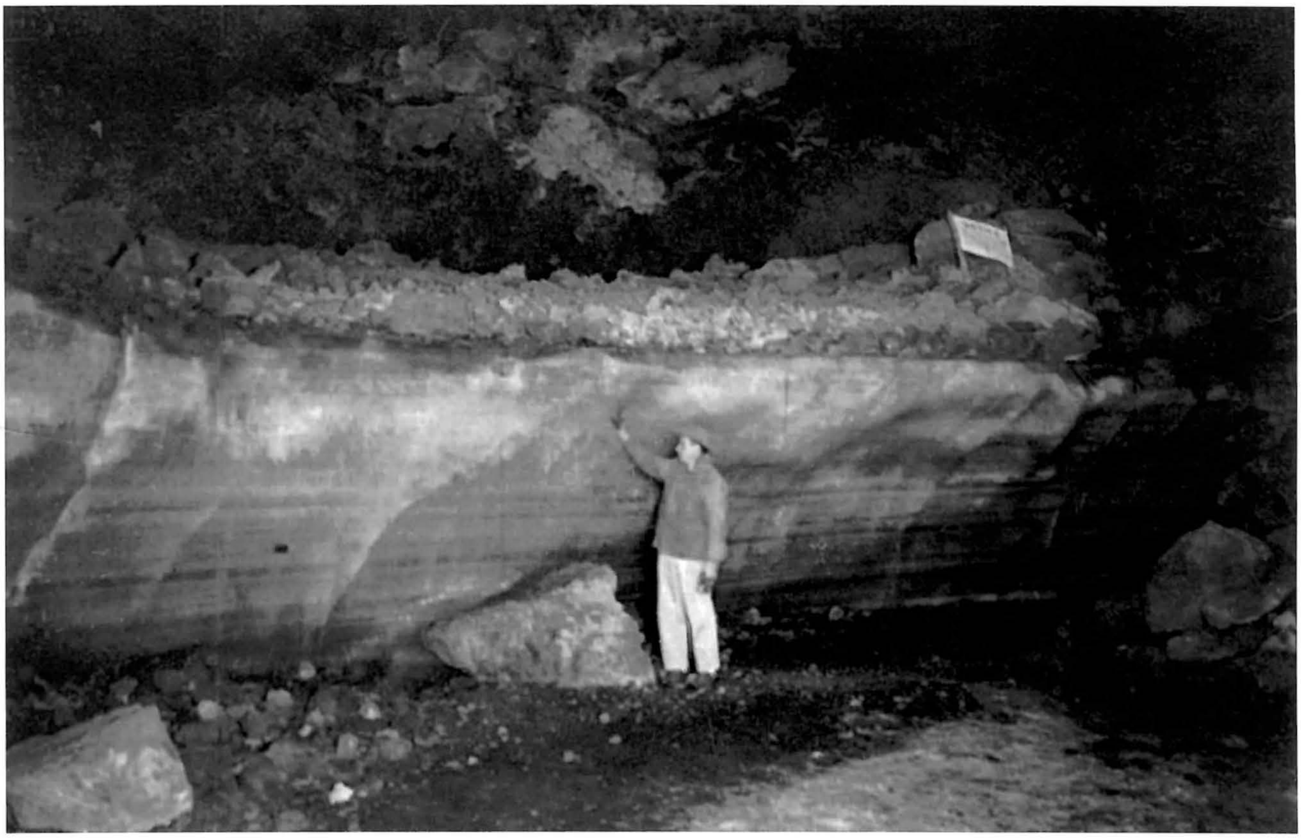

FIGURE 10—Man posing in front of the ice cliff between 1950 and 1970.

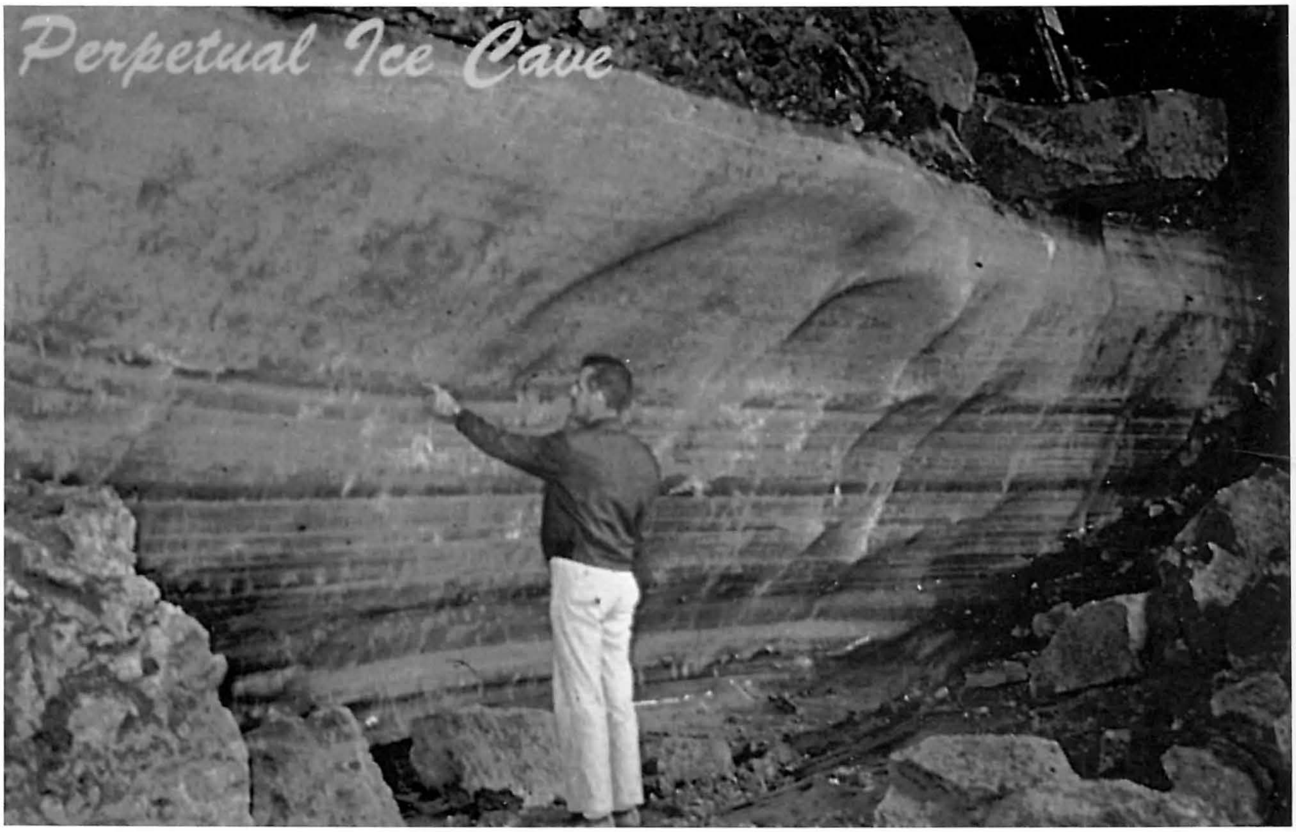

FIGURE 11—Ice cliff between 1950 and 1970. Man is standing at base of ice slope. Large rock in lower left corner of photograph is the same as in center of Figs. 9, 10.

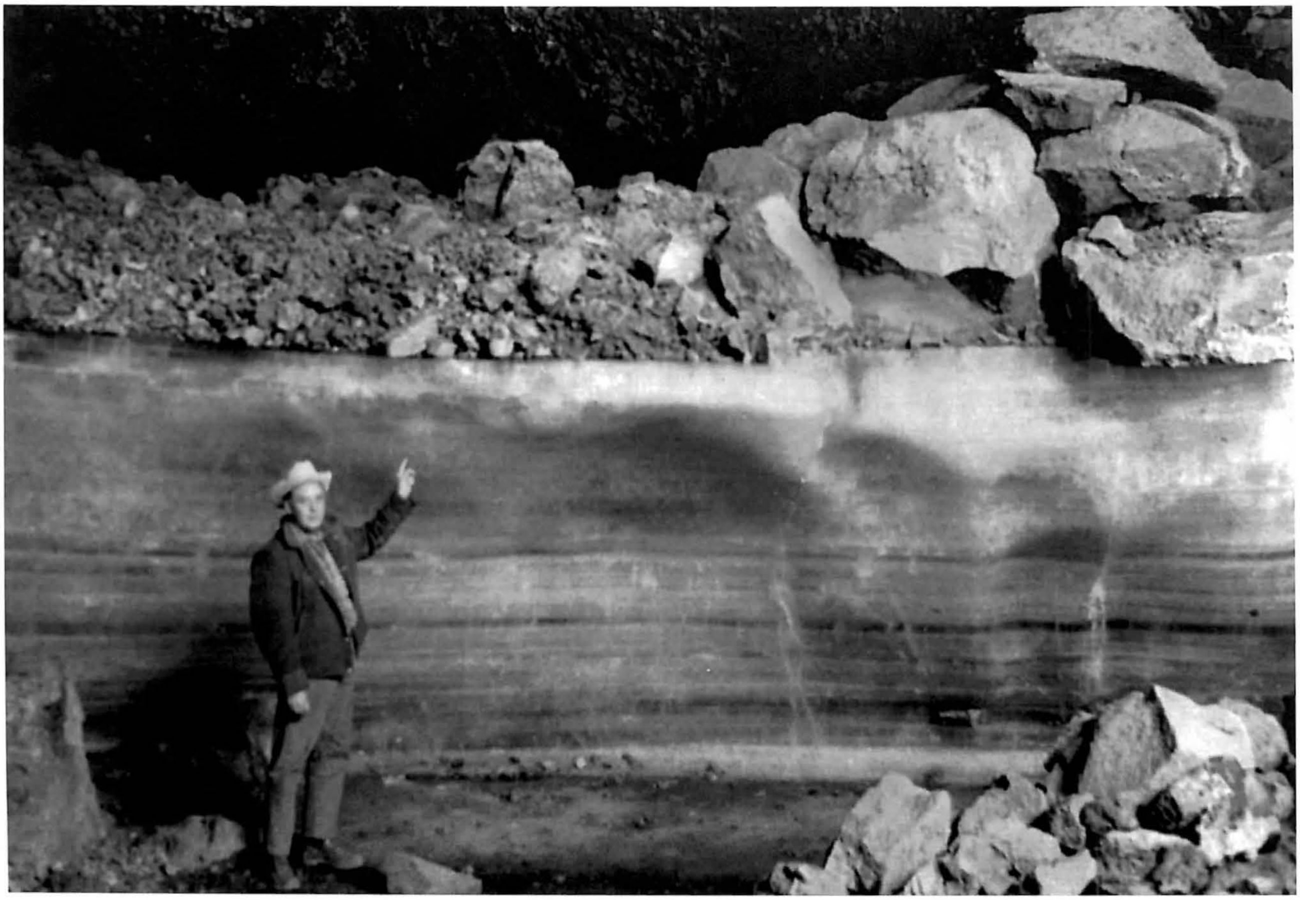

FIGURE 12—Dave Candelaria at base of ice cliff between 1950 and 1970. Compare overhanging rock on top of ice cliff at right-center of photograph with Fig. 11.

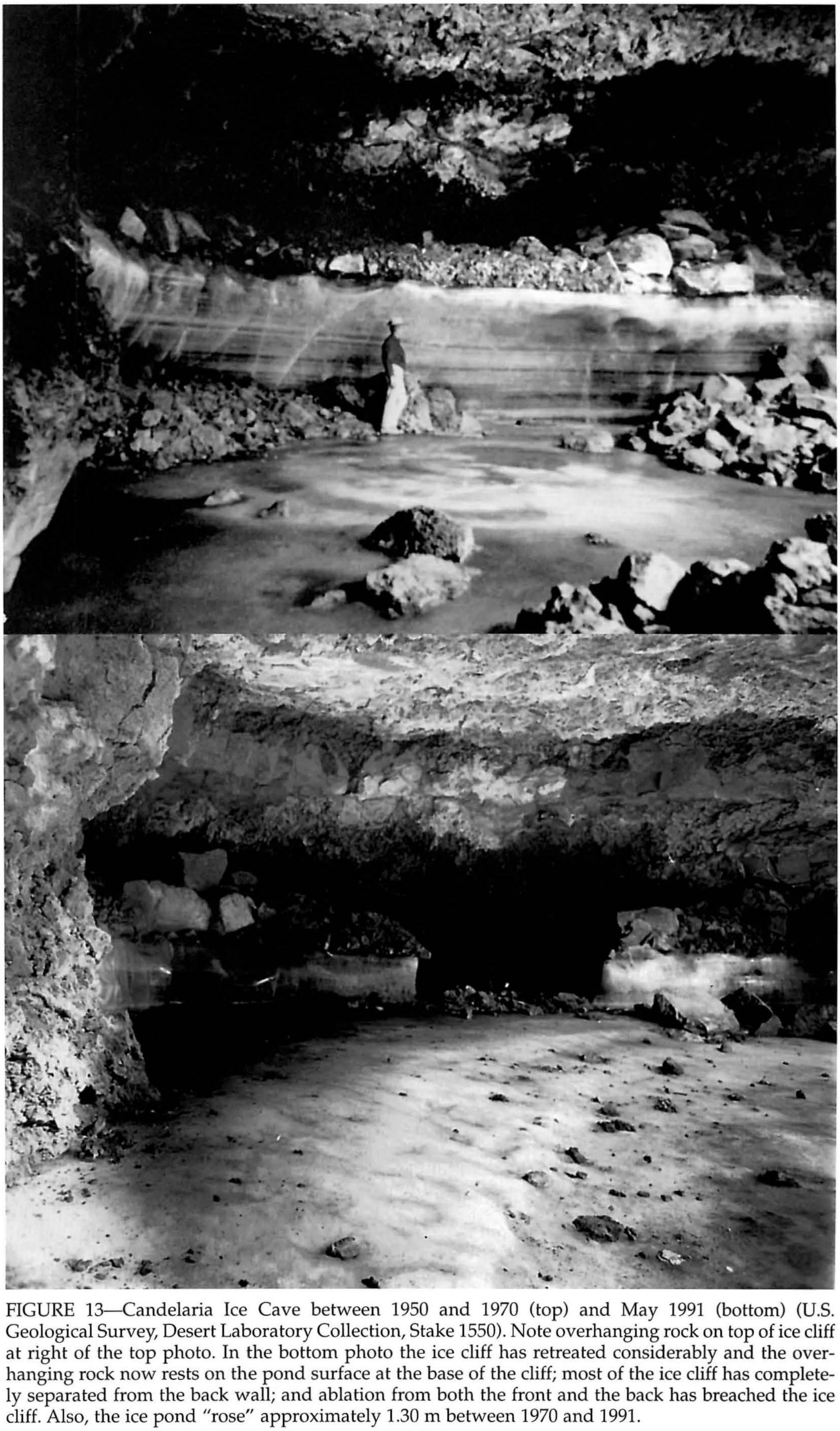

FIGURE 13—Candelaria Ice Cave between 1950 and 1970 (top) and May 1991 (bottom) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1550). Note overhanging rock on top of ice cliff at right of the top photo. In the bottom photo the ice cliff has retreated considerably and the overhanging rock now rests on the pond surface at the base of the cliff; most of the ice cliff has completely separated from the back wall; and ablation from both the front and the back has breached the ice cliff. Also, the ice pond "rose" approximately 1.30 m between 1970 and 1991.

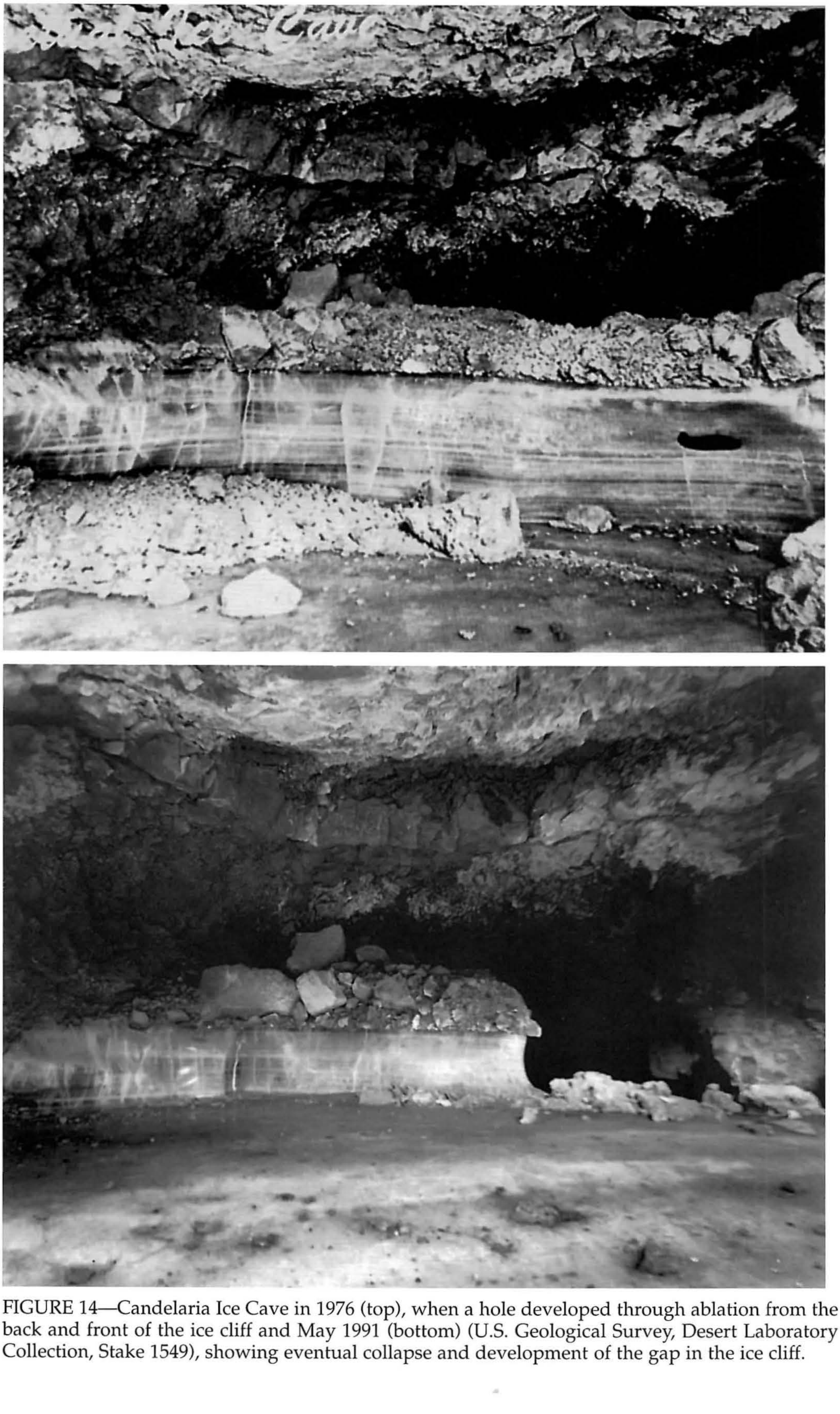

FIGURE 14—Candelaria Ice Cave in 1976 (top), when a hole developed through ablation from the back and front of the ice cliff and May 1991 (bottom) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1549), showing eventual collapse and development of the gap in the ice cliff.

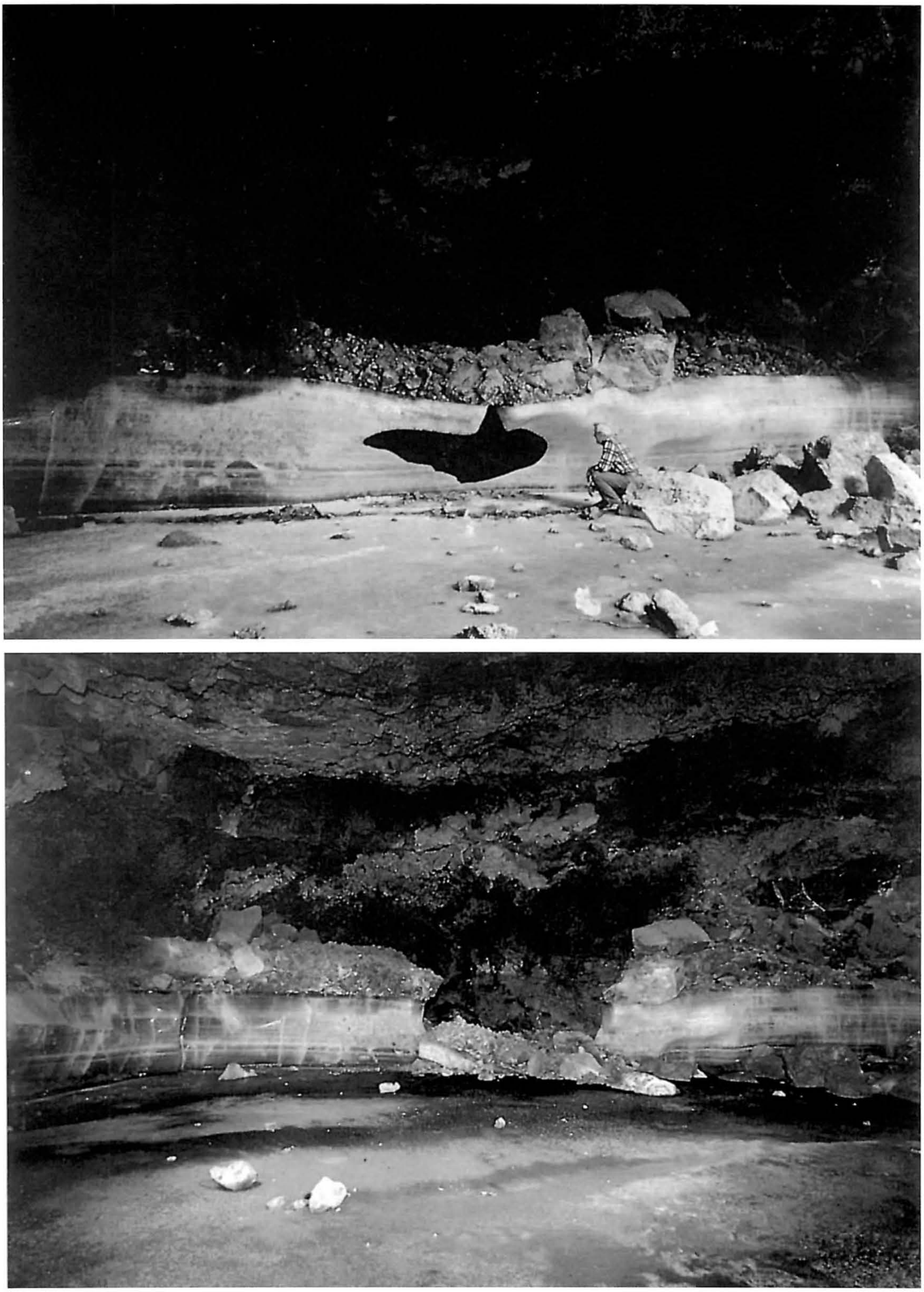

FIGURE 15—Candelaria Ice Cave in 1981 (top) showing widening of hole in ice cliff and collapse of the resulting bridge in 1991 (bottom).

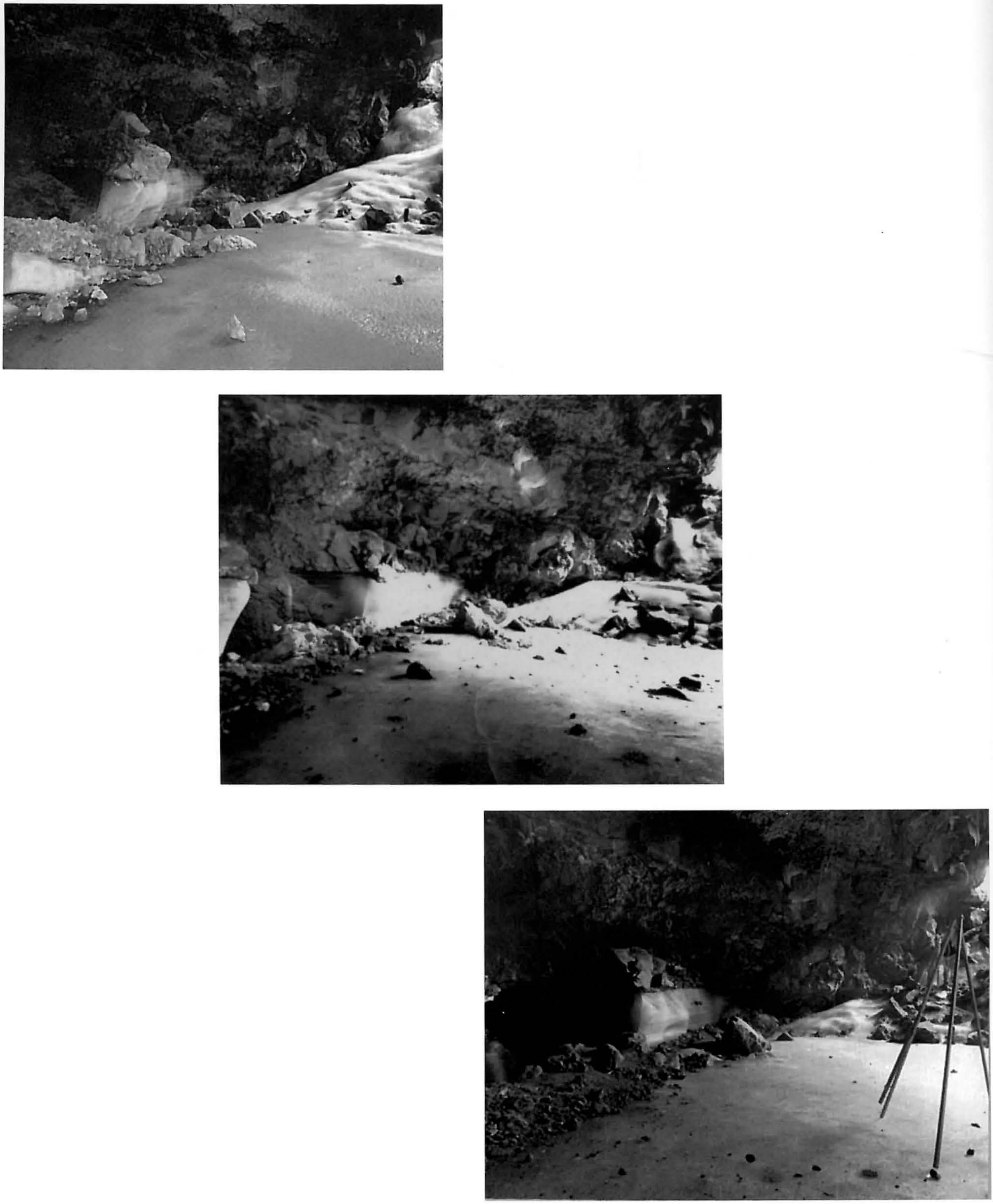

FIGURE 16—Candelaria Ice Cave, showing ice slope from runoff into the cave in 1980s (top), May 1991 (center) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1551), and June 1996 (bottom) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1551). Note sequential emergence of rocks in ice slope from 1980s to 1996.

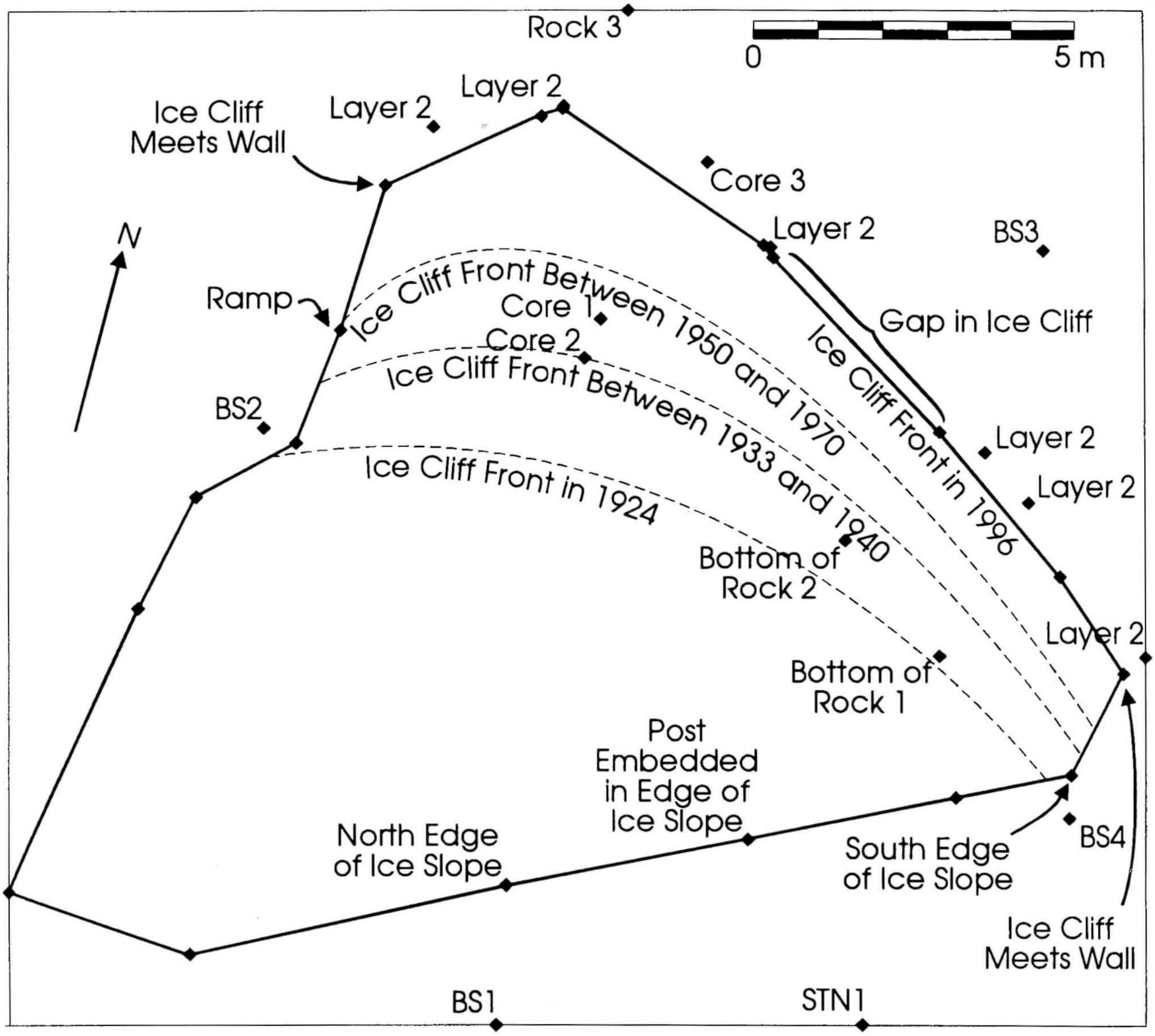

FIGURE 17—Survey of Candelaria Ice Cave showing important features in the cave, the area of the ice pond, and estimated position of the ice-cliff front in 1924, between 1933 and 1940, and between 1950 and 1970.

Conclusions

Cave ice has a global distribution and may have utility as a proxy for past climates. The reconstructed history of cave ice at Candelaria Ice Cave suggests that, in some cave systems, this application may be hindered by frequent discontinuities in ice accumulation and large uncertainties in age estimates. Candelaria Ice Cave may be less than ideal as a paleoclimate proxy because it is hypersensitive to climate variability—prolonged conditions unfavorable for ice accumulation encourage ablation and loss of the ice record. Human impact in this easily accessible cave also confounds attempts to calibrate climate and ice accumulation during the period of instrumental record (the last hundred years or so). Conditions that may be ideal for developing paleoclimate proxies from cave ice include inaccessibility to humans, larger basins for ice accumulation, protected and shaded entrances due to intact lava-tube roofs (Martin and Quinn, 1990), and dominance of inflow from slow infiltration/seepage during snowmelt versus direct runoff. Such ideal conditions may be met elsewhere at El Malpais National Monument and other large basalt flows at higher latitudes and/or altitudes in North America (e.g. the Snake River Plains in Idaho).

Acknowledgments

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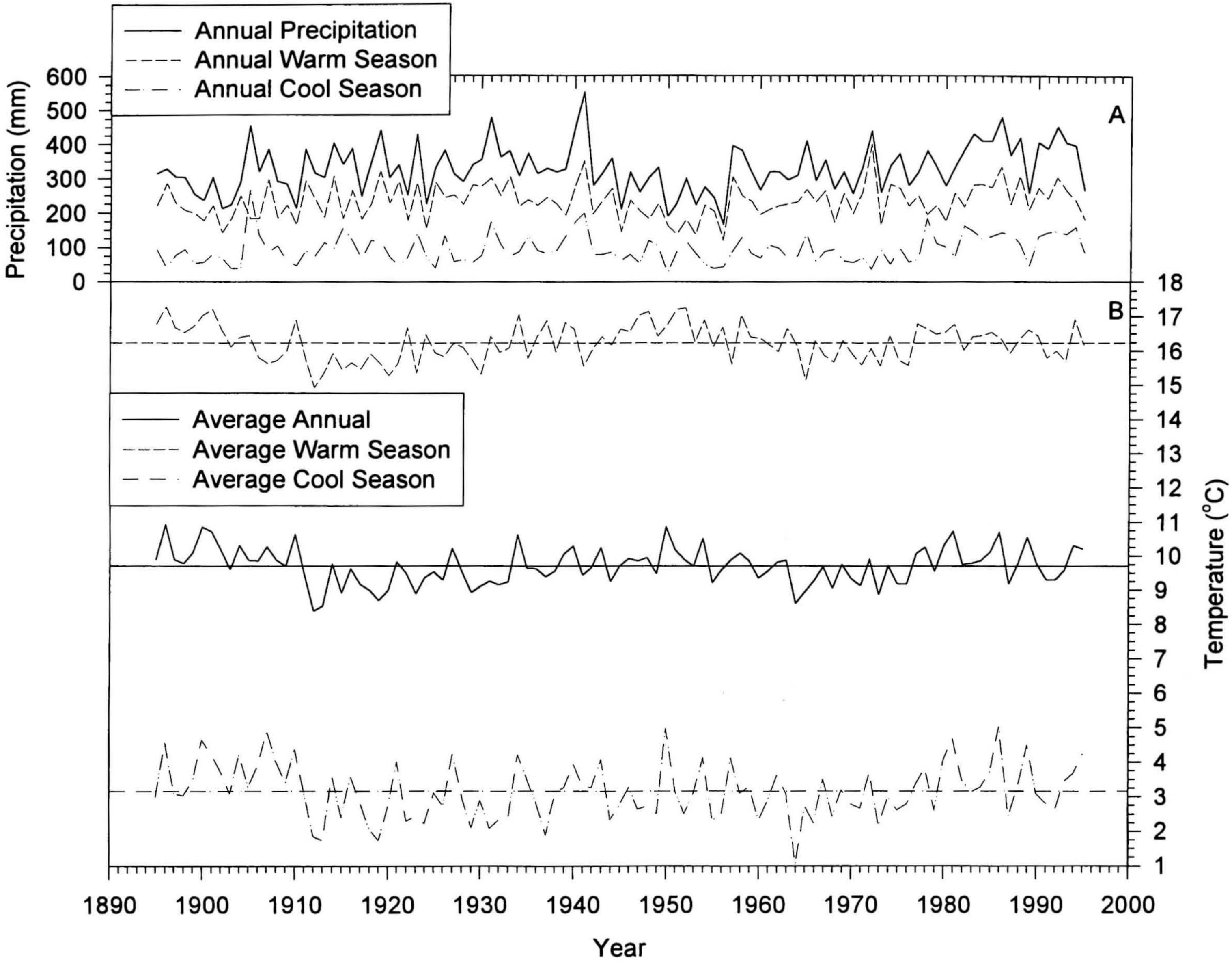

FIGURE 18 —Yearly warm and cool season averages for both temperature (A) and precipitation (B) for NOAA Climate Subdivision Four, South-Central Mountains. Note that annual precipitation is the total of the monthly averages and average temperature is derived from the monthly averages for all the sites in this subdivision.

TABLE 3—Ice cliff ablation history in Candelaria Ice Cave.

Date	Vertical ablation of the ice cliff	Dimensions of ice gap	Horizontal ablation of the ice cliff
1924		—	
1933–1940	–0.95 ± 0.20 m	—	13 ± 3 m²
June 20, 1947	Most ice has ablated down to Layer 2, 1.30 ± 0.35 m on east side of ice cliff	—	
1947–1953	At least 0.80 ± 0.40 m of ice remains above Layer 2 on west side of ice cliff	—	
1950–1955	Most ice has ablated to Layer 2 along the hole length of the ice cliff	—	
1956		—	
1976		A hole opens in the ice cliff to the back of the cave 0.70 ± 0.10 m below the debris 0.22 ± 0.05 m tall and 0.95 ± 0.23 m long	
May 26, 1981		The ice hole has opened through to the overlying debris 2.80 ± 0.75 m long	
1983–1988		The ice hole collapses and is 3.21 ± 0.75 m long	
May 15, 1991		3.30 ± 0.70 m long	32 ± 3 m² since 1933–1940
June 12, 1996		4.10 ± 0.05 m long	

TABLE 4—Estimated ice-pond accumulation and ice-cliff height history in Candelaria Ice Cave.

Date	Total ice-pond accumulation (m)	Ice cliff, total height above ice pond (m)
1924	Little to no ice	4.30 ± 0.80
1933–1940	0.60 ± 0.12	3.35 ± 0.70
June 20, 1947	0.30 ± 0.04	2.70 ± 0.50
1947–1953	1.10 ± 0.25	2.60 ± 0.80
1950–1955	0.50 ± 0.12	2.05 ± 0.50
1956	0.70 ± 0.24	2.30 ± 0.80
1976	0.90 ± 0.21	2.10 ± 0.50
May 26, 1981	1.25 ± 0.25	1.75 ± 0.35
1983–1988	1.60 ± 0.35	1.40 ± 0.30
May 15, 1991	2.00 ± 0.40	1.00 ± 0.20
June 12, 1996	1.87 ± 0.05	1.13 ± 0.05

TABLE 5—Average yearly accumulation in the ice pond of Candelaria Ice Cave for the available time intervals.

Years	Interval (yrs)	Average yearly accumulation (m/yr)
1924–1947	23	0.008 ± 0.005
1924–1936 ± 4	12 ± 4	0.050 ± 0.040
1936±4–1947	11 ± 4	-0.036 ± 0.024
1947–1950 ± 3	3 ± 3	0.300 ± 0.300
1950 ± 3–1956	3 ± 3	0.067 ± 0.067
1947–1956	9	0.050 ± 0.0301
1956–1968	12	0.058 ± 0.020
1968–1977	9	-0.044 ± 0.014
1977–1980	3	0.167 ± 0.047
1980–1981	1	-0.250 ± 0.078
1981–1986	5	0.060 ± 0.012
1986–1991	5	0.090 ± 0.019
1991–1996	5	-0.026 ± 0.005

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