High Stand and Catastrophic Draining of Intracaldera Surprise Lake, Aniakchak Volcano, Alaska

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ABSTRACT

Wave-cut terraces and multiple exposures of lacustrine sediment indicate a former, more extensive stand of intracaldera Surprise Lake in the crater of Aniakchak volcano. The lake once covered nearly half of the caldera floor and had an estimated volume of about 3.7×10^9 m^3. A terrace that marks the high stand of the lake is traceable along the north caldera wall to a break in slope near the top of a v-shaped notch (The Gates) in the caldera rim. Downstream from The Gates, the Aniakchak River flows through a broad, terraced, and boulder-strewn valley. Results from our preliminary investigations suggest that Surprise Lake may have been at its high stand during the explosive destruction of an intracaldera stratocone sometime after 464 yr B.P. Stratigraphic relations suggest that the lake may have drained during this eruptive episode. We speculate that the eruptive activity caused water in the lake to overtop the caldera rim at The Gates, initiating failure of the caldera-rim dam and subsequent catastrophic drainage of Surprise Lake.

INTRODUCTION

Because of their basin-like shape, calderas on many Alaskan volcanoes are geomorphic repositories for water, ice, and snow. The heat flux associated with these volcanoes enhances melting of ice and snow, and caldera lakes commonly result. The caldera rim is a type of natural dam that may impound a substantial amount of water depending on the size of the caldera and the integrity of the bedrock that forms the rim. Failure of a caldera dam and subsequent catastrophic drainage of the intracaldera lake can pose a serious hazard to life and property situated in the flood path (Bolt and others, 1977, p. 94–95). In this report of our preliminary observations, we present geomorphic and stratigraphic evidence for (1) a former extensive intracaldera lake at Aniakchak volcano, (2) catastrophic drainage of this lake by failure of the caldera rim dam, and (3) possible linkages between dam failure and the recent eruptive history of the volcano.

SETTING

Aniakchak volcano is a late Holocene caldera located 670 km southwest of Anchorage on the Alaska Peninsula in Aniakchak National Monument and Preserve (fig. 1). Surprise Lake covers 2.75 km^2 of the northeast floor of the caldera (Cameron and Larson, 1992).

First reported by Smith (1925), the caldera is 10 km wide, about 1 km deep, and circular in plan-view (figs. 2, 3). It formed about 3,400 yr B.P. during a cataclysmic eruption that produced more than 50 km^3 (bulk volume) of pyroclastic material (Miller and Smith, 1987; Beget and others, 1992). An extensive ashflow sheet, originally covering an area of about 2,500 km^2, extends up to 80 km beyond the caldera rim and fills glacial valleys of the pre-caldera stratovolcano to a depth of up to 75 m (Miller and Smith, 1987; Miller and Smith, 1977).

The highest point in the crater is Vent Mountain, a prominent 670-m-high stratocone, located in the southern half of the caldera (figs. 2, 3). Vent Mountain has been active repeatedly since the caldera formed and may be one of the oldest features in the caldera (C.A. Neal and R.G. McGimsey, unpublished field data).

Along the west wall of the caldera is a spectacularly exposed cross section of a young intracaldera stratocone called Half Cone (fig. 3). Our work indicates that this was the site of the most voluminous and explosive post-caldera eruptive activity. Half Cone was destroyed during a violent eruption that produced massive intracaldera pyroclastic-flow and pyroclastic-surge deposits. These deposits extend about *5* km eastward from the vent across the northern floor of the caldera. A wide-spread pumice-fall deposit, of stratigraphic significance to this study, also originated from Half Cone. Field relations indicate that this deposit, informally referred to as the "pink pumice," was formed just prior to

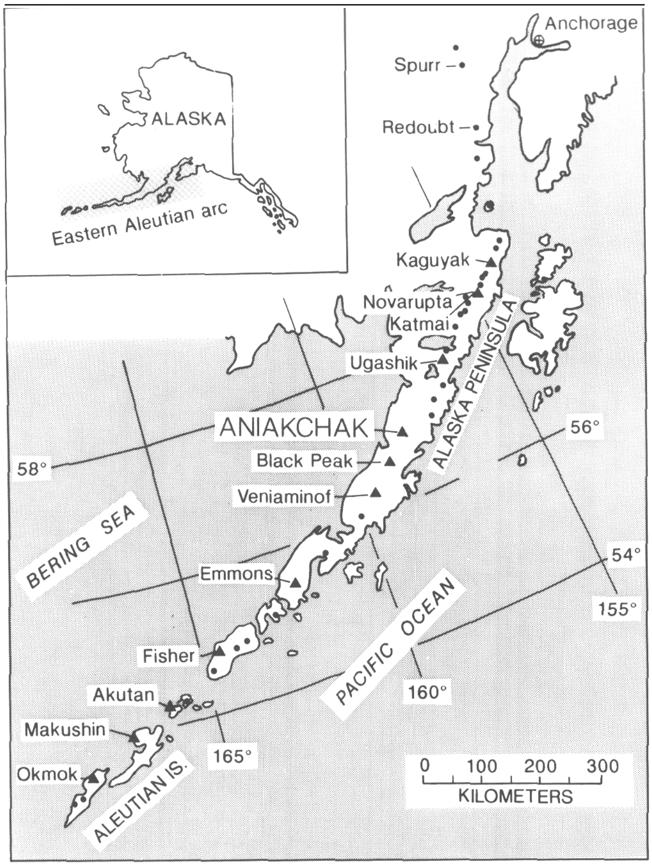


Figure 1. Location of Aniakchak caldera and other major Holocene volcanoes of the eastern Aleutian arc. Triangles denote calderas and circles denote stratovolcanoes. From Miller and Smith, **1987.**

Figure 2. Aerial oblique view from west of Aniakchak caldera. Surprise Lake is located adjacent to northeast rim of caldera. The Gates is prominent notch in east caldera wall in center of view. Vent Mountain is snow-covered cone in south half of caldera, and 1931 vent is circular crater at bottom center of photograph. Photograph by M. Woodbridge Williams, National Park Service, **1986.**

the eruptive cycle that destroyed Half Cone. Organic matter immediately beneath this deposit yielded a radiocarbon age of about **464** yr B.P. (table 1; fig. 3, point D); this is the only post-caldera tephra unit that has been dated. The deposit is exposed along much of the caldera rim where it is up to 1 m thick, and it is also exposed at Half Cone, the flanks of Vent Mountain, and on the tops of Surprise cone and other tuff cones north and east of Vent Mountain **(fig.** 3). In low areas in the northern half of the caldera, the deposit is unusually discontinuous and poorly preserved.

Surprise cone is the westernmost of at least three clustered tuff cones that pre-date Half Cone (fig. 3). Surprise cone is about 150 m high and the entire western half of the cone has been removed by erosion, exposing the eastern inner wall and limbs (fig. 3). The topography of all three tuff cones is rounded and subdued.

Aniakchak volcano last erupted in 1931 (Hubbard, 1931; Jagger, 1932). The 1931 eruption produced a tephra cone along the west caldera wall about **4** km northwest of Vent Mountain and 2.5 **km** south of Half Cone **(fig.** 3).

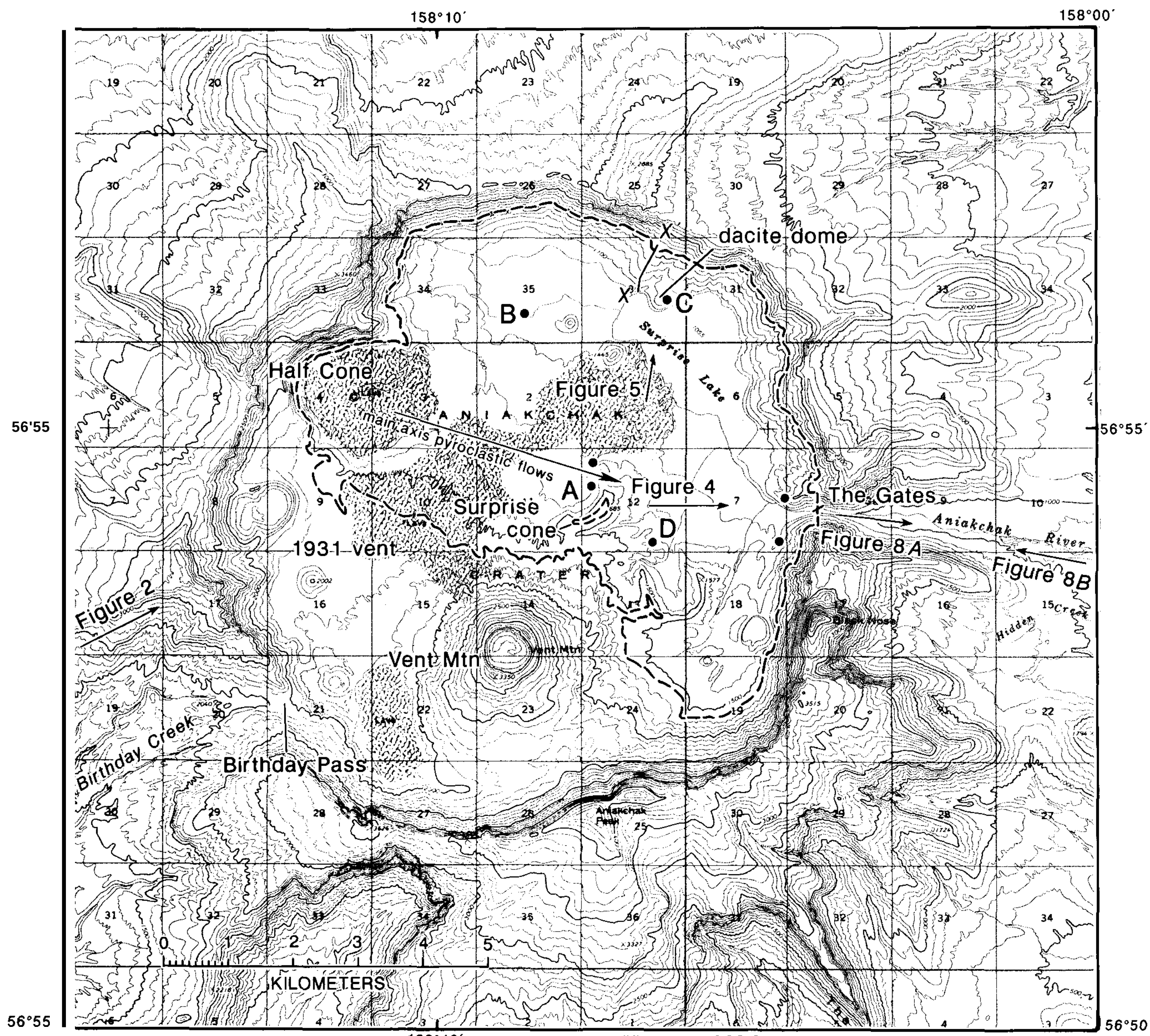


Figure 3. Topographic map of Aniakchak Crater. Large arrow shows main emplacement direction of pyroclastic-flow deposits produced during explosive destruction of Half Cone. Small arrows show direction of view in other figures. Solid circles are locations of lake sediments discussed in text, and points A-C mark specific outcrops referred to in text. Point D is location for radiocarbon-dated organic material underlying Half Cone pumice-fall deposit, which predates destruction of Half Cone. Line *X*-*X*′ marks location of traverse across wave-cut terraces on north caldera wall. Heavy dashed line depicts the maximum area that would be covered by the proposed last high stand of the lake (38 km^2).

This eruption deposited tens of meters of tephra adjacent to the vent, and spread ash over much of southwestern Alaska (Jaggar, 1932).

Table 1. Radiocarbon age of organic sediment underlying prominent pumice-fall deposit from Half Cone (sample location on figure 3).

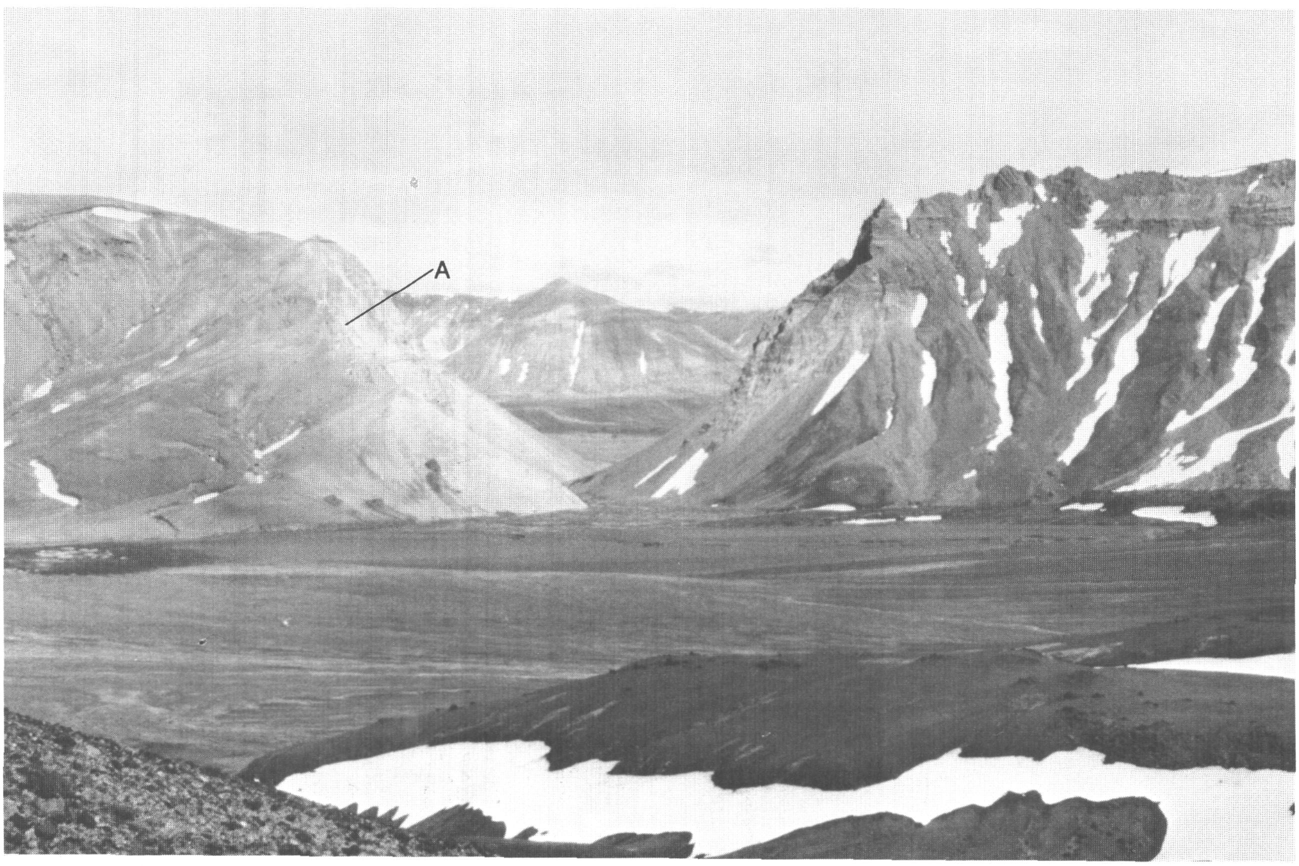
Sample number and material dated	Reported age (^{14}C years B.P.)[1]	Calibrated age[2]	
		Year B.P.	Year AD
CAMS-9851 **organic matter**	390±60	510, 464, 319	1440, 1486, 1631

[1]Age reported in years before present (B.P.) with respect to year AD 1950

[2]Ages calibrated using method of Stuiver and Reimer (1993); reported as: -1σ, age, $+1\sigma$.

GEOMORPHIC RELATIONS NEAR THE GATES

The elevation of the caldera rim'ranges from 1,341 m at Aniakchak Peak to 320 m at the bottom of The Gates **(fig.** 3). The caldera floor is highest (700 m) between Vent Mountain and the south wall and generally slopes northward toward Surprise Lake (321 m). A prominent v-shaped notch in the east wall of the caldera, The Gates, is the only drainage outlet from the caldera (fig. 4A). The maximum width of The Gates is about 700 m and the depth is about 600 m. The caldera rim on either side of The Gates is one of the two lowest points on the entire rim (excluding the bottom of The Gates); the other is Birthday Pass on the south rim. Exposed in the south wall of The Gates is an undisturbed sequence of pre-caldera lava flows and pyroclastic deposits that overlie light- to medium-gray and greenish-yellow basement rocks of Jurassic, Cretaceous, and Tertiary age (Detterman and others, 1981). From a distance, the north wall of The Gates appears to contain reddish-orange basement rocks that are fractured, faulted, and webbed with whitish-gray veins. The alteration



A

Figure 4. ***A***, View east of The Gates from within caldera. Point **A** marks altitude of the highest of several lake terraces above Surprise Lake. *B*, Large slump blocks in north wall of The Gates. Point **A** marks altitude **of** the highest **of** several lake terraces.

of these rocks likely has a hydrothermal origin. This altered zone extends for perhaps 0.5 km along the east wall north of The Gates. On the inside wall of the caldera adjacent to the north wall of The Gates is a chaotic assemblage of tilted slump blocks composed of the same altered bedrock as that in the north wall of The Gates, as well as pre-caldera lava flows and volcaniclastic rocks (fig. 4B). The contact between the inner caldera wall and the first slump block forms a small notch (point A, fig. 3). The crest of this and an adjacent slump block form a ridge that extends down toward the caldera floor. The lower several hundred meters of the ridge is truncated by a horizontal erosion surface (fig. 4*B*). Other parts of the caldera wall have veins, dikes, and landslide debris at the base; however, alteration and veining are particularly pervasive and numerous only along the caldera wall that encompasses The Gates.

HIGH STAND OF SURPRISE LAKE

Most geological studies at Aniakchak volcano to date have focused on the caldera-forming eruption and post-caldera eruptive activity (Smith, 1925; Hubbard, 1931; Miller and Smith, 1977, Miller and Smith, 1987; Neal and others, 1992). However, the history of Surprise Lake and a possible relation between the lake and the latest Holocene eruptive history of the volcano has not been addressed. Smith (1925, p. 142) conjectured that "Surprise Lake may have formerly covered a much larger area..but terraces or high-water marks could not be detected on the wall at the few places examined." Subsequent workers (T.P. Miller, oral commun., 1992) noted possible evidence of a higher stand of the lake such as the ~4-km^2 flat, featureless caldera floor that extends west of the lake, and an erosion surface that truncates the top of a pumiceous dacite dome about 52 m above present lake level (fig. 3).

During field investigations in 1993, we discovered lake sediments at several localities on the caldera floor and lower walls of the caldera above Surprise Lake (fig. 3). Where best exposed, the lake sediments are laminated, clayey silt with sandy intervals. Exposures are located in stream banks on the caldera floor, in gullies on the caldera wall, and in the breach of Surprise cone. All exposures of the lake sediments are overlain by pumiceous pyroclastic deposits from Half Cone. At localities where a complete sequence of lacustrine sediment was exposed, the deposits

B

Figure 4.—Continued.

are about 0.5 m thick and overlie poorly sorted, sandy to pebbly, reworked volcaniclastic material. At the other localities, the lacustrine sediments were frozen below about 40 cm, and we could not determine the thickness of these deposits. One of the 0.5-m-thick sequences of lacustrine sediment occurs on the lowest of three prominent wave-cut terraces (point C, fig. **3).**

We identified at least three wave-cut terraces on the northeast wall of the caldera above Surprise Lake (fig. *5).* The terraces are present along the lower half of the northeast wall of the caldera, which generally has a more gentle slope than the rest of the inner wall of the caldera (fig. **6).** About **1** meter of primary and reworked tephra, principally from the eruption of Half Cone, mantles the lower slopes, including the terraces. The topography along this northeast section of the caldera wall appears more rounded and subdued in contrast to the remainder of the caldera wall (fig. **6).**

Starting at the northwest end of Surprise Lake, we measured the altitude of the terraces using a Jacob Staff and Abney Level (fig. **3).** The lowest terrace is approximately 52 m above the lake and is accordant with an erosion surface on the top of a pumiceous dacite dome (figs. **5, 6).** The second terrace is located about **82** m above the lake, and is at the same level as the top of one of the slump blocks adjacent to The Gates. The top of this slump block also appears truncated by an erosion surface. The highest terrace is **166** m above the lake (elevation 488 m). Although none of these terraces can be traced continuously along the northeast caldera wall, matching segments are preserved intermittently along the wall from our measuring point southeastward to The Gates. A search for lake sediments on the highest terrace was abandoned when we encountered frozen ground at about 40-cm depth. Other terrace segments along the wall were not examined.

Lacustrine terraces typically form during prolonged, stable stands of a lake when there is sufficient time for storm waves to batter the coastline. Although wave-cut terraces can form when the lake is either rising or falling, lacustrine deposits on top of the lowest terrace above Surprise Lake indicate that this terrace probably formed during the filling cycle of the lake. Because we found no evidence to the contrary, we have made the assumption that all of the terraces on the northeast wall of Aniakchak caldera formed **as** the lake rose. Assuming otherwise—that the terraces formed as lake level fell—is inconsistent with a single, catastrophic draining of the lake. Future examination of the other terrace segments on the northeast caldera wall should help **us** determine whether our assumption is correct.

From the highest terrace, prominent geographic points within the caldera at the same altitude were located by hand leveling to determine areas that were submerged when the lake was at **this** position. Among the points that would have been at or below the highest stand of the lake were a break in slope above one of the slump blocks adjacent to the north

Figure 5. Northeast caldera wall and remnants of 3 wave-cut terraces formed during higher stands of Surprise Lake.

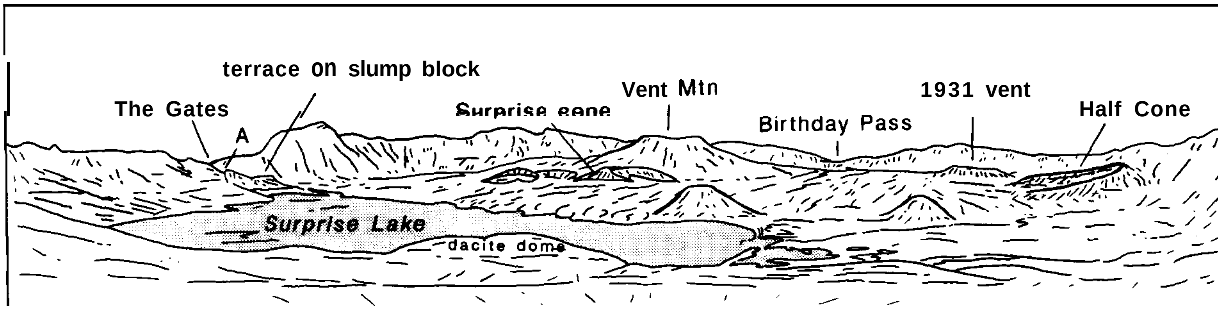


Figure 6. Panoramic view south of Aniakchak caldera from highest lake terrace on north wall above Surprise Lake (*X'*, fig. 3). Surprise cone in center view is breached on the west, facing Half Cone.

wall of The Gates (point A on fig. 4*A*, *B*), and the summit of Surprise cone (fig. 3). At this stand, the lake would have covered about 38 km^2—more than half of the caldera floor (fig.3)—and would have had an average depth of about 98 m and a volume of about 3.7×10^9 m^3.

NATURAL DAM FAILURE AT THE GATES

At the high stand of the lake, we estimate from topography and hand leveling that the low point on the caldera rim was within the area now occupied by The Gates. In its present configuration, formation of The Gates must post-date the existence of the lake because the bottom of the breach would have been 400 to 600 m below the lake surface.

The geometry of The Gates is indicative of erosion by water because the breach is v-shaped and narrow (700 m wide, 600 m deep) and has a low width-depth ratio (about 1.2). In contrast, Birthday Creek valley, the next lowest point on the rim (fig. 3), was formed by pre-caldera glacial erosion and has a width-depth ratio of 12. Thus, it is unlikely that The Gates were formed by glacial erosion. Incision of The Gates could not have happened by slow spillover of water from the lake because the boundary shear stress at the low point on the caldera rim would be so small that erosion of bedrock could not occur. Erosion of bedrock by flowing water is governed by the shear stress at the rock-water boundary. The boundary shear stress (τ) is a function of the depth of water (D), the specific weight of water (y), and the energy slope (S; approximately equal to the water surface slope), as indicated by the following relation (Baker and Costa, 1987):

$$\tau = \gamma DS \qquad (1)$$

If water begins to flow over the low point in the caldera rim because of excess inflow, such as an overflowing bathtub, both D and S and the resulting τ are so small that erosion cannot occur. Thus, formation of The Gates by fluvial erosion requires a significant increase in flow depth and energy slope. In contrast, if the caldera rim failed, both flow depth and energy slope would increase, almost instantaneously, resulting in a flow with significant erosive capacity. Erosion of the caldera rim will commence when τ exceeds the resistance of the boundary. In bedrock fluvial systems not subject to rapid tectonic uplift, large-scale erosion of bedrock is nearly always the result of catastrophic water floods where bedrock is entrained by plucking or cavitation (Baker and Komar, 1987).

We surmise that water was, by some mechanism, discharged rapidly from the intracaldera lake, causing fluvial erosion of the caldera rim to produce The Gates. Furthermore, we suggest that incision of the breach was initiated by failure of the caldera rim at The Gates because this part of the caldera rim appears to be structurally weak. If we consider the catastrophic outflow from the intracaldera lake to be the result of a natural dam failure, we can estimate the peak discharge at The Gates using the method of Costa and Schuster (1988). For earth and rockfill dams, the empirical expression used to predict peak discharge from dimensions of the reservoir and dam is:

$$Q = 0.0184(E_v)^{0.42} \qquad (2)$$

where Q is the peak discharge in meters per second, and E_v is the potential energy of the lake behind the dam in joules (Costa and Schuster, 1988). Potential energy is determined from the relation:

$$E_v = (h)(v)(g) \qquad (3)$$

where h is the dam height in meters, v is the volume of the lake, and g is the specific weight of water in newtons per cubic meter. For h=183 m, v=3.7×10^9 m^3, and g=9,800 N/m^3 the resulting peak discharge is about 81,000 cubic meters per second. The regression equation used to develop the relation between peak discharge and potential energy has a standard error of 91 percent (Costa and Schuster, 1988). This large standard error results from uncertainties in the indirect estimates of peak discharge from dam failures used to develop the relation (Costa, 1985; Costa and Schuster, 1988).

A context for the postulated Aniakchak caldera flood is established by comparing the potential energy and peak discharge of this flood with other dam-break floods (fig. 7). This plot indicates that even with the large standard error, the Aniakchak caldera flood would be a significant event, exceeded by few known dam-break floods. If our hypothesis of a catastrophic caldera rim dam failure is correct, telltale flood evidence should exist outside the caldera.

DOWNSTREAM OBSERVATIONS

We have not yet directly examined the area downstream from The Gates, and the following observations and interpretations are based on brief aerial reconnaissance, analysis of air photographs and topographic maps, and photographs taken by Smith (1925) and during the 1931 Hubbard expedition to Aniakchak (Hubbard, 1931).

Downstream from The Gates, the Aniakchak River flows in a broad valley about 1 km wide and is flanked by at least two terraces (Smith, 1925, plate XLIII-C) that stand an estimated 50 meters above the valley floor and extend downvalley for several kilometers (figs. 8, 9). A cursory air-photo survey of other rivers and streams in the area revealed that none had similar terraces. River terraces can form in response to a wide range of fluvial, sedimentologic, and tectonic conditions, one of which is catastrophic flooding (Bull, 1990). At present, we do not know if the terraces along the Aniakchak River are fluvial terraces; however, incision of the Aniakchak River valley to form these features would be a likely consequence of a catastrophic flood. The apparent absence of similar-scale terraces on other local rivers and streams suggests that the terraces along the Aniakchak River have a unique origin. Also, it seems unlikely that the present Aniakchak River could have incised such a broad and deep valley since the time of caldera formation.

Large boulders (estimated from Hubbard photographs to be up to about 5 m across) of a distinctive volcanic rock-type are strewn about the valley floor outside The Gates and for several kilometers downstream (fig. 8). The same, or similar rocks are exposed in the caldera wall and rim immediately adjacent to the north wall of The Gates. The blocks seemingly are evidence of vigorous sediment transport from the caldera. We interpret the boulders as representing flood deposits; however, without additional field data, other explanations for the origin of the large boulders are possible. For example, an alternative hypothesis is that the blocks were excavated from the deposit in which the valley is cut and were too large to be carried downstream by the Aniakchak River.

About 20 kilometers downstream from The Gates, the Aniakchak River flows out of a rolling upland area onto a low-relief alluvial plain. A large fan-shaped feature is present along the Aniakchak River in the zone where the river debouches from the upland onto the alluvial plain (fig. 9). The feature is topographically identical to alluvial and outwash fans elsewhere in Alaska and the Western United States. Streams crossing the "fan," including the Aniakchak River, are too small to have formed it. This suggests that the fan could be the product of a larger, more competent Aniakchak River. Where the Aniakchak River

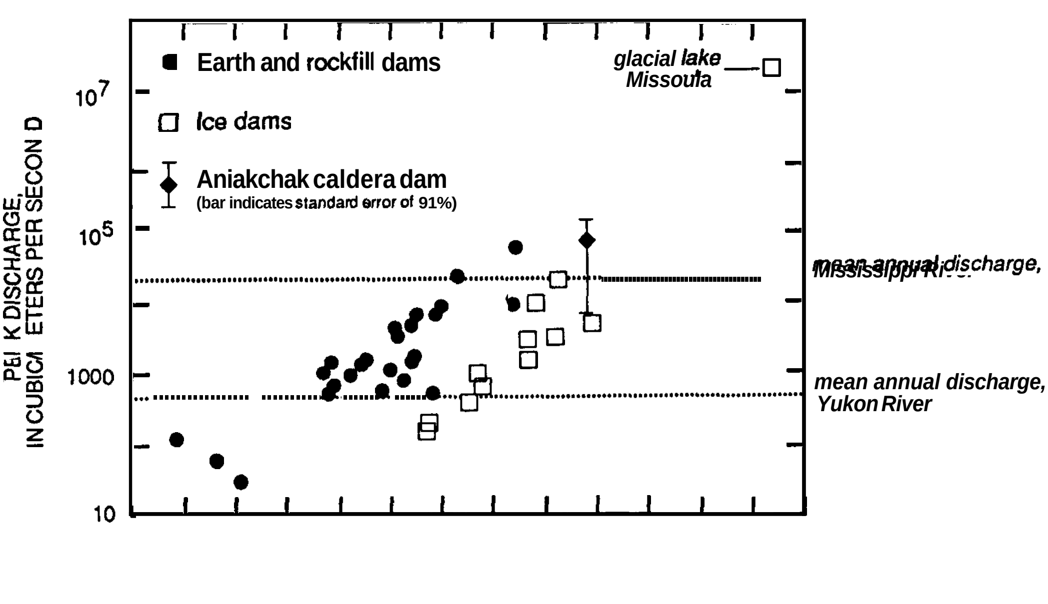


Figure 7. Potential energy of lake water versus peak discharge for natural dam failures, including Aniakchak caldera (data from Costa, 1985, and Costa and Schuster, 1988). Mean annual discharge for the Mississippi and Yukon Rivers shown for comparison.

crosses the fan, the channel is braided and straight. The braided pattern and straight channel of the river indicate, in part, that the channel is formed in coarse, noncohesive sedimentary deposits. Based on its geometry, location, and probable sediment type, and with consideration of the terraces and boulders upstream, our preliminary interpretation is that the fan also is a flood deposit.

TIMING AND CAUSE OF PROPOSED CATASTROPHIC FLOOD

If Surprise Lake drained catastrophically, what mechanism or circumstances might have triggered the event? Eruptive activity has been documented as one method of evacuating water from an intracaldera lake (Bolt and others, 1977; Major and Newhall, 1989). Another possibility is structural failure of the caldera-rim dam, perhaps unrelated to eruptive activity. Either scenario might apply to the draining of Surprise Lake. Based on our preliminary studies we have developed the working hypothesis that Half Cone erupted during the high stand of the lake, that the eruptive activity in some way initiated the catastrophic draining of the lake and concurrent formation of The Gates, and that the eruption continued after the lake level was lowered to near its present position. This hypothesis is founded primarily on three lines of evidence: (1) isolated exposures of pyroclastic surge deposits on the summit of Surprise cone, (2) poorly preserved and laterally discontinuous occurrence of the Half Cone pink pumice deposit in the northern half of the caldera, and (3) the stratigraphic relation of pyroclastic deposits and lake sediments at the base of Surprise cone and on the north floor of the caldera.

Exposed for about 300 m along the summit rim of Surprise cone (ranging vertically over 25 m) is a 2-m-thick section of pyroclastic-surge deposits overlain by less

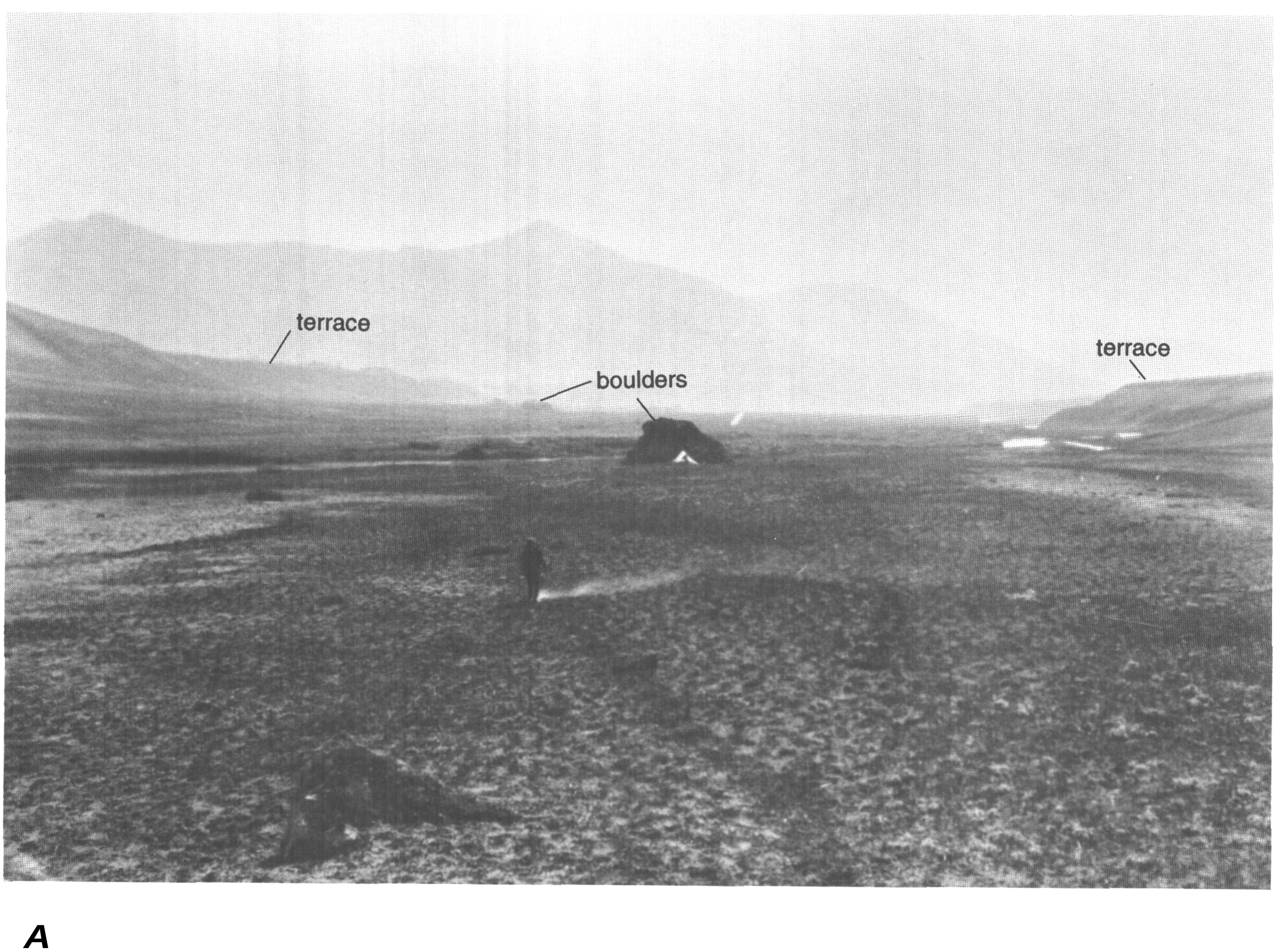


Figure 8. Large (up to 5-m-diameter) boulders in terraced valley immediately outside The Gates may be evidence of catastrophic draining of Surprise Lake. *A*, View downvalley from The Gates, showing large boulders strewn about valley bottom between paired terraces that flank the valley. *E*, View toward The Gates from top of terrace on south side of Aniakchak River. Note large boulders in valley bottom. Photographs from the Bernard R. Hubbard S.J. Collection, Santa Clara University Archives.

than a meter of pumiceous fallout deposits originating from Half Cone. In contrast, massive pyroclastic-flow debris and bombs from Half Cone occur on the flanks of Surprise cone. The eroded west flank of Surprise cone faces Half Cone, about 4.5 km to the northwest. The horizontally laminated, clayey lake sediments we discovered at the northwest base of Surprise cone (fig. 3), about 115 m below the summit and about 75 m above present lake level (point **A,** fig. **3),** are overlain by massive pyroclastic-flow deposits derived from Half Cone.

The distribution, bedforms, and geomorphology of Half Cone pyroclastic-flow deposits indicate that the main flow direction of pyroclastic flows and surges was toward The Gates (fig. **3).** However, pyroclastic-flow deposits also extend radially from Half Cone across the caldera floor. On the flat floor of the caldera, 1.5 km west of Surprise Lake (point B, **fig.** 3), yellowish, clayey lake sediments are present only a few meters above Surprise Lake. In one exposure, the sediments have been invaded and upended by at least one tongue of Half Cone pyroclastic-flow deposits that are at least several meters thick (fig. 10). The imbrication direction of the upended lake sediments indicates that the pyroclastic flow was directed from the southwest, which is consistent with an origin from Half Cone. The lake sediments in contact with the pyroclastic-flow deposits are orange-colored and oxidized, consistent with thermal alteration. Fossil fumaroles, with oxidized alteration halos, occur on the surface of Half Cone pyroclastic-flow deposits a few kilometers south and about ***60*** m above these lake sediments (fig. **3).** Pyroclastic-surge deposits are located near the fossil fumaroles on the caldera floor. In summary, we observed isolated pyroclastic surge deposits on the summit of Surprise cone, Half Cone pyroclastic flow debris overlying lake sediments at the base of Surprise cone and invasively disturbing fake sediments lower on the caldera floor, and fossil fumaroles and pyroclastic surge deposits located on the caldera floor between Surprise cone and Half Cone.

We suggest that pyroclastic surge deposits on the summit of Surprise cone are discontinuous with other surge deposits because the final eruption of Half Cone occurred during the high stand of the lake when only the

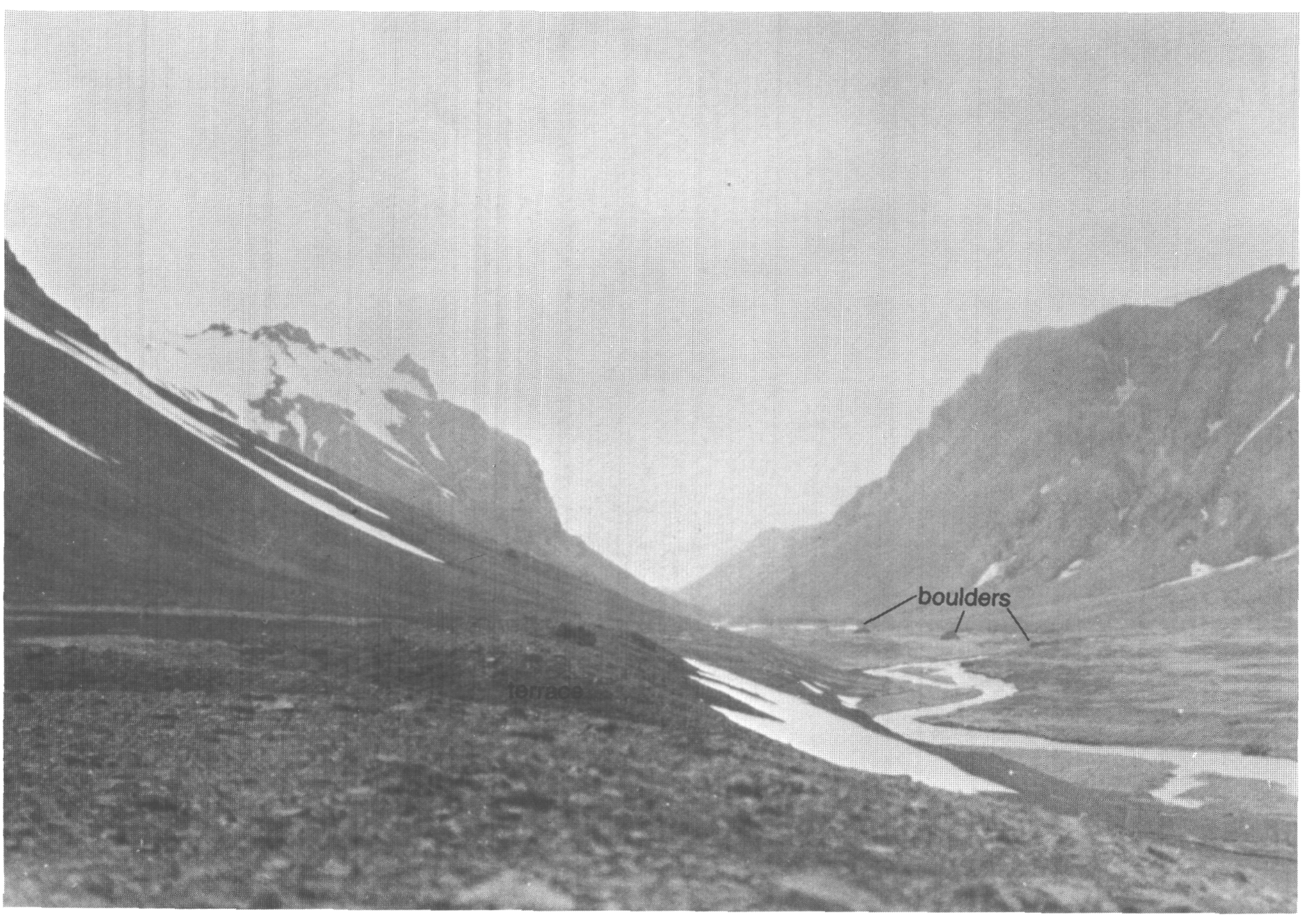


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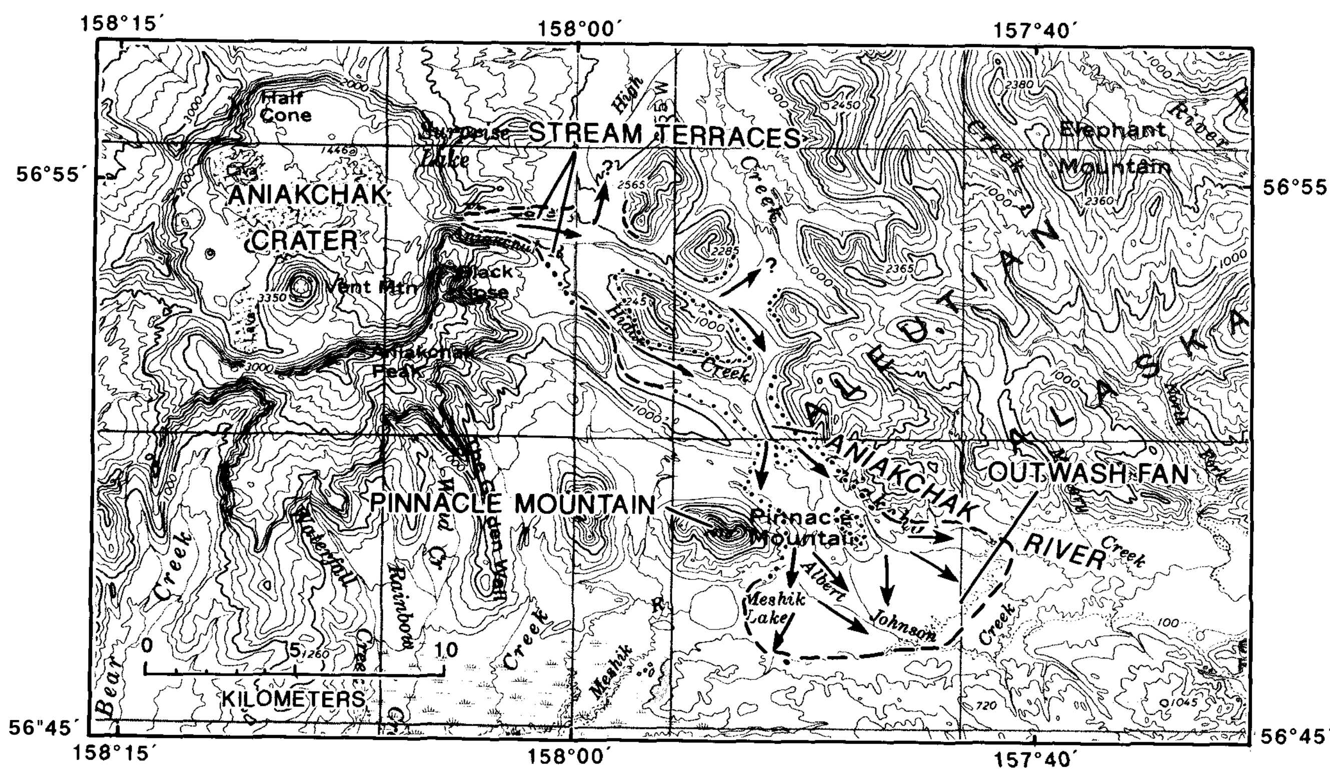
Figure 8.—Continued.

summit of Surprise cone was aerially exposed. According to Cas and Wright (1987, p. 283) when a subaerially erupted pumice flow enters water, an ash-cloud surge continues over the water surface. If an ash cloud of this type encountered an "island" and surge deposits formed, these would later appear, when lake level dropped, as isolated deposits, similar to those observed on Surprise cone. In this model, the pyroclastic-flow and pyroclastic-surge deposits on the floor of the caldera would have been emplaced subaerially after the lake level had dropped during the eruption.

An alternative explanation for the surge deposits on the summit of Surprise cone is that they are not related to lake level, but are instead a spatially limited primary deposit, or an exposure isolated by erosion. This explanation requires (1) Surprise Lake be near its present level during the final eruption of Half Cone (this accounts for Half Cone pyroclastic-flow deposits on the lower floor of the caldera), and (2) a pyroclastic flow, or flows, advanced across the caldera floor from Half Cone, up the 150-m-high eroded face of Surprise cone to deposit about 2 meters of surge deposits. This interpretation also requires the lake sediments, located at the base of Surprise cone and conformably overlain by Half Cone pyroclastic-flow deposits, to have been subaerially exposed during the eruption. We found no evidence for subaerial exposure of these lake sediments (mudcracks, soil development, erosional unconformity).

The foregoing alternative explanation is consistent with many of our observations. However, the discontinuous, poorly preserved character of the ca. 464-yr-B.P. pink pumice deposit in the northern half of the caldera—the same area that would have been submerged during high stand of the lake—is difficult to explain in the absence of a higher lake. We suggest that in the northern half of the caldera the limited distribution and poor preservation of this deposit, which is so uniform and continuously exposed elsewhere in the caldera and along the rim, is a result of reworking by water and deposition through a water column. Thus, a higher stand of Surprise Lake could account for the observed character of the pink pumice.

Accepting the foregoing arguments for a high stand of Surprise Lake during the final eruption of Half Cone, we interpret the Half Cone pyroclastic-flow deposits that immediately overlie the lake sediments at the base of Surprise cone and on the caldera floor west of Surprise Lake to indicate that the lake drained to near its present level during that eruption. The orange-colored, oxidized condition of the invaded lake sediments in contact with Half Cone pyroclastic deposits indicates that the pyroclastic material was probably hot when emplaced, causing alteration of the lake sediments.



Base from USGS Chignik and Sutwik Island quadrangles, 1963, 1:250000

Figure *9.* Course of the Aniakchak River eastward from caldera. Large, south-facing alluvial fan is delineated by topography southeast of Pinnacle Mountain. We suggest this fan formed during catastrophic draining of Surprise Lake in Aniakchak caldera. Arrows indicate possible routes for floodwaters, and dashed and dotted lines delineate probable extent of floodwaters.

If this interpretation **is** correct, the lake could not have been more than a few meters deep, because it is unlikely that pyroclastic flows can maintain their heat and physical integrity upon entering water (Cas and Wright, 1987). However, the behavior of subaqueously emplaced pyroclastic flows is controversial (Cas and Wright, 1987). Fossil fumaroles and alteration halos observed in Half Cone pyroclastic-flow deposits on the caldera floor are similar to those in the 1912 ashflow sheet in the Valley of Ten Thousand Smokes near Mt. Katmai, Alaska, which were emplaced subaerially, and some of which still retain heat. Thus, rapid draining of the lake, just prior to the cessation of eruptive activity, could account for the pyroclastic-flow deposits with fossil fumaroles, and would allow for the lake sediments on the low north floor of the caldera to be disrupted and overlain by hot pyroclastic-flow deposits.

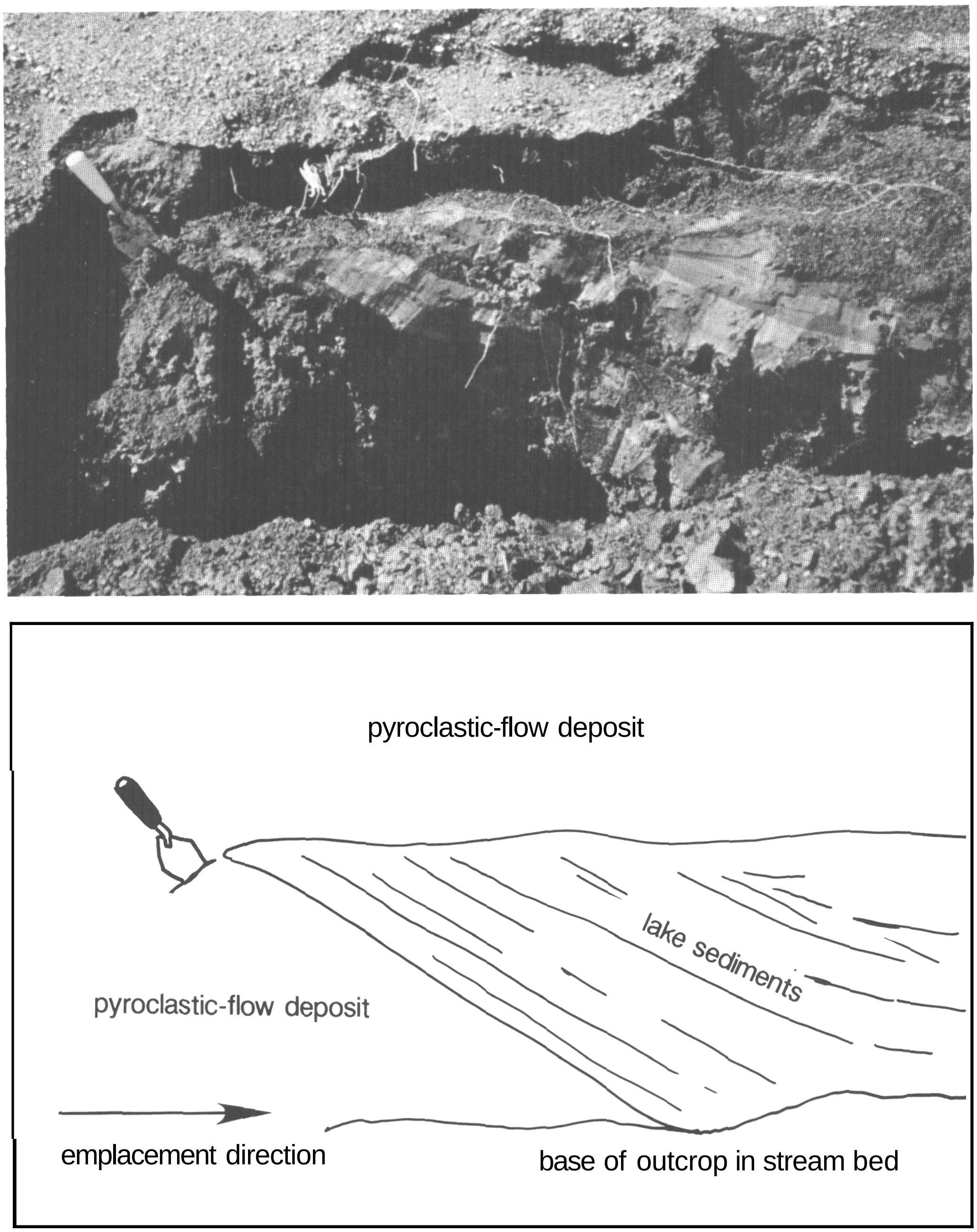


Figure 10. Lake sediments that are displaced and overlain by Half Cone pyroclastic-flow deposits (point **B, fig. 3).** Tongue of pyroclastic-flow deposits bulldozed into and beneath soft lake sediments, thereby upturning, truncating, and baking the beds.

Eruption of Half Cone during the high stand of Surprise Lake also provides a plausible mechanism for initiating the catastrophic drainage of the lake. If the lake was at its high stand when Half Cone explosively erupted, pyroclastic flows and debris avalanches(?) entering and displacing water in the lake likely would generate large waves (Latter, 1981). Additionally, strong seismicity that is typically associated with eruptive activity might also generate waves in the lake. Assuming that the low point on the caldera rim was at or near water level, we suggest that waves could have produced a rush of water over the low point of the rim, initiating dam failure, subsequent erosion of The Gates, and catastrophic drainage of the lake.

The timing of the destruction of Half Cone, and the subsequent catastrophic draining of Surprise Lake, is in part constrained by the 464-yr-B.P. age of the distinctive pink pumice, that was deposited just prior to the final eruption of Half Cone.

During field studies planned for 1994, we will test the catastrophic flood hypothesis by investigating possible flood deposits identified on topographic maps and aerial photographs and by collecting additional samples for radiocarbon dating to better constrain the timing of events.

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