Contents

Paradise Ice Caves, Washington
Microecosystems in Lehman Cave, Nevada
Information for Contributors
To the Bulletin

Papers in any discipline of speleology are considered for publication in the Bulletin. The upper limit for length is about 10,000 words or approximately 40 pages of manuscript, typed double-spaced. At least one copy but preferably two copies of the manuscript (typed, double-spaced) should be submitted to the Editor, Jerry D. Vineyard, Missouri Geological Survey, Box 250, Rolla, Missouri 65401. Photographs and line drawings, if required, should be submitted with the manuscript. In general, prints and line drawings will be photo-reduced to the size necessary for use in the Bulletin.

For general style, see papers in this Bulletin. Abstracts are required for all papers. Abstracts should be brief and informative. Captions are required for all illustrations, and all unusual symbols used should be explained.

References to the literature should be by author and date, with specific pages where desirable. Literature cited should be listed in an end bibliography with entries arranged alphabetically by author's last names. For books, give total pages; for journal papers, inclusive pages. Consult bibliographies in this Bulletin for general format.

Photographs must be sharp, with high contrast. Because of cost, only photographs essential to the presentation should be included.

All line drawings should be submitted in final form, ready for photographic reproduction. That is, all lettering should be done with lettering instruments, strip printer or other satisfactory means. Typed lettering, unless done with an electric typewriter with carbon ribbon, is not ordinarily satisfactory. Captions will be set in type and added to the illustrations. All drawings must be inked, with India ink or a satisfactory substitute. No drafting services are provided by the Bulletin staff. Because of cost, maps and other drawings should not exceed 24" x 24" except in special cases. Again, consult the Editor in case of doubt.

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The Bulletin is published quarterly in January, April, July and October. Material to be included in a given number must be submitted at least 90 days prior to the first of the month of publication.

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The Paradise Ice Caves, Washington: An Extensive Glacier Cave System

By Charles H. Anderson and William R. Halliday

INTRODUCTION

The existence of caves in glaciers has long been known. The specific cave system discussed in this report has been a tourist attraction for decades (fig. 1). One of us has discussed briefly pseudokarstic surface features of glaciers (Halliday, 1960, p. 112), and these are mentioned in at least one standard text (Cotton, 1945). Further, in deglaciated areas, long sinuous ridges of gravel and silt (eskers) have long been interpreted as deposits in extensive subglacial watercourses; in retrospect it seems surprising that little consideration has been given to their potential speleological implication with
some exceptions (i.e., Russell, 1893). In general, it has been assumed that glacier caves are simple structures of insignificant length and content. It has been believed that these form as small caverns melted annually within glacier snouts, largely or entirely closing in winter as a result of glacial flow.

Recent studies by the Cascade Grotto of the National Speleological Society indicate that this is not true for the Paradise Ice Cave system of Mt. Rainier, Washington.

**PROJECT FORMAT**

The “tourist section” of the Paradise Ice Caves was visited by the Cascade Grotto as early as 1961. Only in preliminary studies during the autumn of 1967, however, did the extent and complexity of the caves become apparent. Participating repeatedly in the project were Charles Anderson, Edith Anderson, Dave Mischke, Eric Nelson, Bill Petty, Ronald Pflum, Rick Rigg and Ken Severa-Jerry Frahm periodically maintained base communications at the Paradise Valley roadhead.

With subglacial torrents stilled by winter, exploration and study were found easier than in summer, once the caves were reached. By midwinter of 1967-68, almost 1½-mile of passage had been mapped. The existence of recurrent seasonal speleothems had been discovered, and new concepts of glaciopelogenesis were fast evolving. Although access was hazardous (Halliday, 1968), the Cascade Grotto did much of its work during that winter. The winter of 1968-69 saw record snow depths, forcing the project to halt temporarily. The longest single passage in the cave is still unmapped because of the volume of streamflow in summer (fig. 2).
Figure 5.
Entrance to the Pillar Passage and Water Passage at the beginning of the tourist season in June, 1967.

Figure 6.
The Paradise Ice Cave system in July, 1967.

Figure 7.
The Paradise Ice Cave system in October, 1967.

LOCATION

The Paradise Ice Caves are in the Paradise-Stevens Glacier on the southeast side of Mt. Rainier, a dormant 14,410-foot volcano in the Cascade Mountains of Washington (fig. 3). The altitude of the caves is approximately 6,500 to 6,900 feet.

A few decades ago, the Paradise and Stevens Glaciers were distinct entities with a common source. The Paradise Glacier has receded rapidly, however, and some consider it to have disappeared entirely so that the caves now should be considered to lie entirely within a southwest lobe of the Stevens Glacier.

The caves are approached from the Paradise Valley visitor center roadhead (fig. 4). The summer route requires no special arrangements if only tourist areas are to be visited, otherwise the chief park ranger should be contacted well in advance, to ascertain current conditions and regulations.

From the Paradise Ranger Station, an excellent trail leads ½-mile eastward to Myrtle Falls. Thence, the Mazama Ridge trail continues across the Paradise River just below Shukskin Falls and up Mazama Ridge to a junction with the Skyline Trail at a point 1 ½-mile from the ranger station. At this junction, visitors proceed left along the Skyline Trail, up Mazama Ridge, for about ½-mile. At this point, a rustic sign “Ice Caves” points right. Beyond this point, the route is informal (fig. 5) and often fogbound. In early summer, flags are emplaced in the snow to mark the route.

The winter route requires special permission and parties must sign in and out at the ranger station. It involves a more direct but much steeper ascent on snow to and across
the Skyline Trail via the "Golden Gate" above Myrtle Falls, thence down the steep wall of Paradise Canyon a few hundred yards from the caves. Travel is routinely by compass in thick fog and blowing snow.

**DESCRIPTION**

As presently known, the Paradise Ice Caves include at least 12,000 feet of passage in a branchwork pattern. Passages totalling about 7,500 feet have been mapped to date, with most of the remainder in the Water Passage (figs. 6, 7 and 8). Collapse has segmented the system during the course of this study (figs. 9 and 10). While some parts of the caves are little more than crawlways, most consist of glorious corridors a dozen or more feet in diameter (fig. 11). Locally, the width and height are much more (fig. 12).

Strong air currents are perceptible in many areas, especially where constricted, but no air flow studies have been made. Rudimentary temperature studies have been made at three points: 100 feet inside the cave in the Water Passage, at the Great Pillar and in Suicide Passage near its confluence with the Water Passage. Recorded air and water temperatures have varied seasonally from 32°F to 36°F, with water temperatures one or two degrees higher than air temperatures except near the entrance on October 7, 1967, when the water and air temperatures respectively were 36°F and 32°F. Only one water temperature reading of 32°F has been obtained.

Streams of various sizes are present in most of the passages in summer (fig. 2). Marked variation of streamflow occurs, with some active freezing within the cave, but at no time has all streamflow been found halted. Atypical eskers-in-development are present in the stream beds; most include large stream...
Figure 11.
Scalloped walls and ceiling in the Pillar Passage.

THE NATIONAL SPELEOLOGICAL SOCIETY
boulders and cobbles in addition to finer sediments (figs. 13 and 14).

Most of the system occurs beneath the glacier but some sections are floored by glacial ice. Although far from homogeneous, the glacier ice is largely glistening white or blue-white. Bedding and some impurities (fig. 15) can be observed. Speleogens and speleothems are well developed. These features and the effects of local illumination through the glacier render the caves entrancingly beautiful. The play of color and light on the scalloped ice walls ranges from delicate green to deep ultramarine. The most prominent speleogens are large scallops or flutes (figs. 1, 2, 11, 12, 13 and 14), often more than a meter in width. Superficially resembling on a grand scale the stream flutes of limestone caverns, they are probably aerogenic. Locally but not universally, their shape and size appear modified by impurities or intraglacial bedding and related features.
Medium-sized flake (right) near complex column in the Big Room. The snow in the foreground drifted into the cave from the lower entrance. Another flake shows in the center distance. A small frozen waterfall can be seen along the surface of the complex column near the left edge of the picture.

Coalescence of scallops in irregular patterns sometimes produces deeply undercut, hanging "flakes" of ice centimeters or meters long (fig. 16), often weighing many tons. Collapse of these flakes is a specific hazard of exploration; some cannot be discerned until one has passed beyond them and relatively minor vibrations sometimes cause them to fall.

Entrances to these caves are located at the snout of the ice lobe and also in the bergschrund (figs. 17, 18 and 19). Three other types of orifices connect the caves and the surface of the glacier. Several of the rounded, domepit-like swallets termed moulins intersect the caves (fig. 20). A crevasse about 4 feet wide and an estimated 500 feet long intersects the Water Passage. As indicated, newly-formed collapse sinks have separated the system into multiple caves during the course of this study; most occurred between August 19 and September 30, 1967.

Large columns of glare ice form seasonally at the base of active moulins, and below...
Figure 19.
Same view as Figure 18, but in early March 1968.

Figure 20.
Looking up a moulin above the Great Pillar. The glacier is about 20 feet thick at this point.

Figure 21.
The Great Pillar in winter, with drifted snow at the base.

Figure 22.
The Great Pillar in late June.
Water dripping through moulin at site of the Great Pillar. A small flake is visible in the foreground. A larger flake barely discernible in the middle distance is about 300 feet long. Tourists are seen in the entrance of the Pillar Passage in the distance.

other drip points to a lesser degree. Most are largely or entirely melted by mid-June of most years (figs. 21, 22, 23, 24). Tapered stalactites are fairly common, and participate in column formation. Tubular stalactites have been observed in the Water Passage. Ribbon draperies form locally but are quite transient. Curious ice helictites are even more evanescent. They have been observed only at the lower entrance of the Water Passage (fig. 25) and on the surface of one column.

GLACIOSPELEOGENESIS

Whether a glacier advances, retreats or remains stationary depends on increases or decreases in snowfall in the area of accumulation, with regional temperature changes also a factor.

Unless virtually all the snow cover melts from the surface of the glacier (in which case the glacier will soon disappear), the weight of compacting snow causes slow plastic flow toward the wastage area. This process eventually delivers all parts of the glacier and its cavities to the glacier's melting snout whether the snout is advancing, retreating or stationary (fig. 26).

The Paradise lobe of the Stevens Glacier is in a state of old age, and is in rapid retreat. Almost all the seasonal snow which mantles it melts annually. The firm limit is almost at the upper end of the glacier. Comparatively little glacial flow thus appears to be present to counteract two forces which enlarge glacier caves: stream action and circulation of warm air.

As in the case of many limestone caves, the size of the cavern passages appears disproportionate to the present streams on their floors, and some are presently stream-free. Some major passages show no evidence of stream action on the ice walls, while others show typical vadose speleogens. Despite
noteworthy fluctuations in streamflow, it seems doubtful that the larger passages could be filled either by present floodwater invasion or by greater past runoff — or by flow when the passage was largely filled with esker. Rather, it appears that each passage was to cause melting which produced most of the present volume of the cave.

Glacial streams may be a significant factor, but tentatively it is felt that most of the heat transfer results from ingress of seasonal air above the freezing point. Photographs of the past few decades indicate that retreat of the glacier has caused loss of considerable length of the cave. Some warming of circulating air by heat transfer from subglacial streams may be a significant factor, but tentatively it is felt that most of the heat transfer results from ingress of seasonal air above the freezing point.

Photographs of the past few decades indicate that retreat of the glacier has caused loss of considerable length of the cave. Plastic flow also probably serves to reduce the size of the caves. Yet direct observation during this study suggests that collapse from over-enlargement is currently more important in destruction of the caves.

Acknowledgments

This study was possible only because of special permission and assistance rendered by the National Park Service and especially the staff of Mt. Rainier National Park. Particular thanks are due to Superintendent John A. Townsley, Chief Park Naturalist Norman Bishop and Chief Ranger Joseph L. Orr. We also wish to express our inestimable obligation to all the members of the National Park Service, Mountain Rescue Council, Cascade Grotto of the National Speleological Society and others who assisted during the 1968 rescue operation near the "Golden Gate."

References


Figure 26. Diagrammatic side view of glacier.
Methods

Careful observations and collections of living material for identification were made at 200 of the existing lights along the trails. Dark areas were also studied. The survey of lights included:

a) light wattage, position, and reflectance
b) algae, mosses, ferns, other plants and their conditions
c) visible evidence of fungi
d) flies, other insects, larvae, spiders, Annelids, mammals (signs)
e) the nature of the substrates i.e., part or all rock, soil, wood, dung
f) the relative moistness of the substratum
g) the minimum and maximum distance from the lights to plant life
h) debris brought in by man.

Data were compiled to show what percentage of the lights had various organisms and conditions. Tentative food chains were diagrammed for the various microecosystems.

Five different representative light positions were studied for microclimate with the lights on and off to better understand the effect of microclimate on the organisms. Air temperatures, relative humidity, the evaporative power of the air, air movement, and light intensity were studied at different distances with lights on and off.

Species and Environment

Of the 200 lights studied, 77.5% had algae, 20.5% had mosses, 75.0% had visible evidence of fungi, 30.5% had Collembola, and 31.5% had various types of dead or live flies (Table 1). A material which I called "flow dust" (fig. 2) appears as rivulets of mud or dust on moist or dry stalagmites. Flow dust on moist lighted sites was composed of diatoms, minerals and organic debris, and was found at 24.0% of the lights. This material is not identical to the vermiculations described by Parenzan (1960) but the original clay deposits may have formed in the same manner as clayish-slimy vermiculations. An oligochaete worm which appears to feed on the diatoms occurred at only 10% of the lights. Many ecological niches are not occupied in the Cave after over 28 years. Ninety-eight percent of the lights had rock as a part of the substrate, while soil occurred at 25.0% and organic debris at 58.0% of the lights. The substrates were graded objectively as wet to moist (48.0%), slightly moist (32.0%) and dry to damp (20.0%).

The Cave was divided into the entrance area which is dry to damp with the least algae, few mosses, no flow dust, and the most old dung; the middle section which has the most moisture and dripping, abundant algae and mosses; and the final section which has less dripping, few mosses or algae, and the least recent animal signs (Table 1, fig. 1).

The entrance area is dry because the inflow of cold, relatively dry air during winter makes part of the entrance a variable temperature zone. The middle section is protected from dry air movement and has the most active dripping and the best development of microecosystems. These first two sections were lighted in 1939-40 and have the healthiest plant life. The last section (Talus Room) was lighted in 1960. The amount of plant life which has become established in eight years is so small that most visitors are not aware that there are any plants there. Collembola are scarce in the Talus Room because they require an area of concentrated dust. Such areas have fungi and no green plants.

Dark areas with dust and lint, support fungi, and occasionally Protozoans. Plant life in the Cave is likely to remain in small areas near lights. In 28 years, the largest plant to invade the Cave and stay is a small fern (Cystopteris fragilis var. fragilis). Limited amounts of soil, low light intensity, and possibly a deficiency of nitrogen and other elements is preventing the establishment of higher plants near lights. The energy level for the Cave ecosystem as a whole is extremely low. This may, in part, explain why the permanent organisms in the Cave are so small. All plants living in the Cave are dispersed by spores probably brought in by water and moved about on the feet of tourists and troglobles. The repeated visits of transient mammals bringing in seeds has not resulted in the establishment of any higher plants possibly because the shortage of food during the spring when young mammals are born causes all usable food to be eaten.

Table 1. Summary of organisms and conditions adjacent to 200 lights and 25 dark areas in Lehman Caves, November, 1968.

<table>
<thead>
<tr>
<th>Sec. No.</th>
<th>Flow Dust</th>
<th>Algae</th>
<th>Moss</th>
<th>Fungi</th>
<th>Collembola</th>
<th>Flies</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.5</td>
<td>25.0</td>
<td>5.0</td>
<td>2.0</td>
<td>0.5</td>
<td>0.1</td>
<td>75.0</td>
</tr>
<tr>
<td>2</td>
<td>56.0</td>
<td>28.0</td>
<td>9.0</td>
<td>5.0</td>
<td>0.5</td>
<td>0.1</td>
<td>65.0</td>
</tr>
<tr>
<td>3</td>
<td>60.0</td>
<td>30.0</td>
<td>10.0</td>
<td>5.0</td>
<td>0.5</td>
<td>0.1</td>
<td>65.0</td>
</tr>
<tr>
<td>4</td>
<td>70.0</td>
<td>25.0</td>
<td>5.0</td>
<td>2.0</td>
<td>0.5</td>
<td>0.1</td>
<td>75.0</td>
</tr>
<tr>
<td>5</td>
<td>80.0</td>
<td>20.0</td>
<td>10.0</td>
<td>5.0</td>
<td>0.5</td>
<td>0.1</td>
<td>70.0</td>
</tr>
</tbody>
</table>

1 Dead and live flies. 2 Moist, moist, no standing water. 3 Dead or slightly damp. 4 Dead or slightly moist. 5 Dead or dry.
A. Producers - Autotrophs synthesizing carbohydrates from CO₂ using light energy.

Algae

Class Myxophyceae - blue green algae
- Anacystis montana (Lightfoot)
- Drouet and Daily form monoma (Drouet and Daily)

Class Chrysophyceae - dinoflagellates
- Schizothrix calcicola (C. Agardh)
- Komont

Class Chlorophyceae - green algae
- Oedogonium Vaucher sp.
- Anabaena Bory sp.
- Coccolitho Sprengel sp.

Class Phaeophyceae - brown algae
- Asplenium
- Amblystegium serpens

B. Producers - Chemotrophs - derive energy from chemical reactions in the absence of light. Leptothrix sp. - iron bacteria.

C. Primary Consumers - utilize plant food for energy

Members of the Phyla Flagellata, Sarco-
dina, Ciliophora, Rotifera, Annelida, and Arthropoda were identified by the Drs. Wheeler, Oribatid mites, Collembola (three species Entomobrya maripinata Tullberg, det. D. L. Wray, USNM; and two others unidentified), three species of flies (Bradyia sp. det. R. J. Gage, USNM; Megasia sp. det. W. W. Wirth USNM; Psychoda sp.), and one beetle were identified. A Psylliopsisidae, Pyddilisicus ramburi Selys-Longchamps (det. E. L. Mockford, Ill.) is from a family of known cave-dwellers which feeds on fungi, pollen and dead insects. Of the larger troglo-
 xenes, only Peromysis monicusculus (deer mouse) and Eutamias sp. (chipmunks) were seen (G. Ralston).

D. Secondary Consumers - eat herbivores

Sixteen species of protozoans were tenta-
vively identified, but many of these are also primary consumers. The pseudoscorpion Microcreagris granis (det. R. R. Bridgeyman) and four species of spiders belong to the carnivores. Of the insects, there were flies (Dolichophyssilidae), bat flies (Streblidae), and Culicoides sp. (det. W. W. Wirth USNM). A moth of the family Tineidae, probably Amydra sp. (det. D. R. Davis, USNM) of uncertain food habit was fairly abundant. Bats were scarce and thought to be mainly insect eaters.

E. Reducers - Large numbers of fungi occur throughout the Cave on moist walls, dead organic matter, dead flies and on stalactites. Bacteria were common in the pools which dry during winter. The slime bacterium Dicyostelium sp. occurs on walls and Ste-
monites sp. the slime mold is common on wood. Chytrids live on dead algae and pollen.

Pack rats were once common in the Caves before the lights were installed. Deposits of pack rat dung over a foot deep remain as evidence of their importance in the Caves in the past. Beetle galleries and frass are com-
mmon under old dung and another type bur-
rrows into the pellets, but no beetles are known to be active in the dung of the Caves today.

During the early solution stage when flowing water was eroding the Caves, plant and animal life may have been transported through the Cave. If fish lived in the Cave at earlier times, no evidence of their past has been found and no fish live there today, probably because the low energy level of the entire system is inadequate to support fish. As the Cave became drier, pack rats, bats and other organisms spent part of their lives there. After the lights were introduced, the slow colonization by plants and micro-
scopic animals from spores began. The pack rats left, and the present troglo-
xenes do not concentrate their dung.

Today there are 12 types of microeco-
systems known to exist in Lehman Cave. These are called "microecosystems" because they are small in areal extent. Some are also "terminal" such as the dung ecosystems since no new dung is being added. Once the dung has no food supply left to support organisms, the dung microecosystems will cease to exist. Others are "pseudo" because they depend on food brought in from the outside and lack any producers to perpetuate food production within the Cave (dung).

Even the true microecosystems are not permanent since two or three weeks with the lights left off or herbicide treatment would damage the green plants and create unsightly brown patches.
"Flow dust," a material composed mostly of diatoms with bits of soil, may be dry and no longer active, brown and moist (dead), or green and alive. Oligochaete worms live within the flow dust and presumably eat diatoms.

The microecosystems of Lehman Caves are:

1. Bare rock, slightly moist, in the dark with fungi, bacteria, living and dead insects, lint, pollen, dust. This is the habitat of Dictyostelium sp.

2. Moist rock in dark with fungi, Prototzoans, bacteria, living on moist dust of dead insects, pollen, lint, bat and mouse dung.

3. "Soda straws," wet, with fungi, bacteria, or in lighted areas there may be algae, some energy may come from organic or inorganic compounds in the water.

4. Moist rock in light with brown (dead) and green (live) flow dust containing minute naviculoid diatoms as the producers and Oligochaete worms as consumers with bacteria and fungi as reducers.

5. Moist rock in light with algae, some diatoms, no flow dust. Collembola, fungi, and bacteria are usually present with mouse or bat dung (small amounts). Rock may have mosses and liverworts.

6. Moist rock in light with 0.1 to 1 cm or more soil, with algae, any of the mosses except the rock forms, Collembola, arachnids, flies, fungi, bacteria, mouse and bat dung.

7. Moist rock in light with soil 1 to many centimeters deep, with algae, mosses and ferns. Collembola, arachnids, flies, fungi, bacteria, dung (recent).

8. Dry dung (moisture under 8%) in dark with fungi and bacteria (beetle galleries and frass may no longer be active), terminal and "pseudo."

9. Moist dung in dark (moisture 12%+), with larvae and Protozoans feeding on fungi, bacteria — terminal and "pseudo," Collembola may be present.

10. Aquatic habitats in the dark with dead flies supporting fungi and chytrids, floating on water surfaces, dead organic matter settles to the bottom and provides food for bacteria, Protozoans, chemotrophic iron bacteria are often present (not terminal as long as organic debris is added).

11. Aquatic habitats (pH 7.0-8.2) in light with algae, dead organic matter such as flies,

THE NATIONAL SPELEOLOGICAL SOCIETY
bats, wood, algae, dung providing food for Protozoans, bacteria, fungi, chytrids. May have iron bacteria.

12. Decaying wood (moist) in dark or light with a variety of Basidiomycetes including Marasmius sp., slime molds (Stemonites sp.), flies, Collembola, bacteria, arachnids. Fruiting bodies have Diptera larvae (terminal).

The positioning and wattage of individual lights strongly influence what lives in the Caves. The most severe microclimate occurs around a light which is boxed on four sides resulting in air temperatures at 0.1 m of 22.5°C after 10 minutes of light (an increase of 11.3°C in 10 minutes), with a loss of 89.9% of surface moisture in four hours or 0.928g/hr. (Table 2). No plant life occurs at this light because of the sudden temperature and humidity fluctuations and the drying power of the air when the lights are turned on. The relative humidity around the boxed light dropped from 98 to 58% in 30 minutes with the light on.

The next most severe habitat occurred at 0.1 m from the light boxed on 3 sides (Table 2). The temperature range there was only 8.2°C, but the drying power at 0.1 m from the reflector nearly equalled that of the light boxed on four sides. The increase in relative humidity occurs when slow air flow and heating allows rapid evaporation.

Arachnids

All other light positions studied had lower temperature ranges, less evaporation and considerable plant life at 0.1 to 2 m distance. The cool temperatures (10.2-11.0°C) produced at the deep reflectored light were ideal for moss growth, while the warmer temperatures (15.1°C) and fast drip rate at the shallow reflectored light favored algae.

The air temperatures around the open light (no reflecting surface close by) fluctuated only 2.9°C in 10 minutes with the lights on. A light over a free water surface caused no change in water temperatures after 30 minutes of continuous light.

Table 2. Microclimates around Lehman Cave lights (100 watt bulbs)

<table>
<thead>
<tr>
<th>Light Type</th>
<th>Distance (m)</th>
<th>10 min. Range</th>
<th>Temperature °C</th>
<th>% Water Res.</th>
<th>Moisture</th>
<th>% Relative Humidity</th>
<th>% Water Loss (cm²)</th>
<th>10 min.</th>
<th>% Water Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>1.0</td>
<td>10.6</td>
<td>13.5</td>
<td>0.7</td>
<td>11.3</td>
<td>10.6</td>
<td>0.7</td>
<td>0.432</td>
<td>0.6</td>
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<td>Moist</td>
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<td>10.6</td>
<td>8.7</td>
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81
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Manuscript received by the editor.
17 February 1969