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LETTERS TO THE EDITOR

The Tilted Forest: Glaciological-Geologic Implications of Vegetated Neoglacial Ice at Lituya Bay, Alaska

Porter and Carson (1971) and Heusser (1973) have postulated that stagnant, forest-covered ice persisted as long as 2000 yr after the retreat of late Pleistocene glaciers in Puget Sound, and cite as present examples the still active Malaspina and Martin River Glaciers which have forested margins. Although some trees more than 300 yr in age have been documented on Martin River Glacier, this information does not demonstrate how long the ice may persist once the active glacier has retreated and no longer contributes to the stability of the stagnant mass. A better example of the persistence of isolated glacier ice following the retreat of a large glacier was found in Lituya Bay, Alaska, which was filled by a large glacier until about 350–400 y. a. This area in coastal Alaska presently has a climate, forests, and glaciers quite similar to those existing in western Washington at the time of the retreat of the Cordilleran ice.

Lituya Bay is a glacially scoured inlet extending inland from the northeast shore of the Gulf of Alaska (Fig. 1). The T-shaped bay is 11 km long. Two large tidal glaciers, the Lituya on the northwest and North Crillon on the southeast, descend from the high mountains of the Fairweather Range and discharge small icebergs and large quantities of rock and outwash into the inlets. Enclosing the southwestern part of Lituya Bay is a conspicuous lateral and terminal moraine, "Solomon Railroad," formed when the entire bay was deeply filled with glacier ice (Fig. 1). Goldthwait, McKellar, and Cronk (1963, p. 73) have determined that this moraine is largely Wisconsin in age. As judged by the size of the moraine, representing a vast accumulation of sediment, Wisconsin ice must have filled the bay for a considerable interval of time.

Between about 7100–2200 y. a. the ice retreated and forests flourished along the shores of the bay (Goldthwait, 1966). How far the galciers retreated into the mountains at the head of the bay is unknown. From the nature of the Hypsithermal forest development in most other parts of coastal Alaska, temperatures were warmer than at present (Heusser, 1960). Hypsithermal glaciers were probably much smaller and the inlets forming the head of the bay may have been free of ice. Following this warmer interval, about 3000–2200 y. a., the glaciers readvanced (Goldthwait *et al.*, 1963, p. 72; Goldthwait, 1966). Ice again filled the entire bay, thickening until it reoccupied the Wisconsin lateral moraines.

This Neoglacial advance culminated about 400–600 y. a., as determined by ^{14}C dating of overridden forest remains (Goldthwait *et al.*, 1963, p. 71). Assessment of vegetational and morainal patterns both by direct examination and aerial photography suggests that the Wisconsin terminal moraine was overridden in places and several small lobes were formed outside the moraine. The largest of these lobes extended into the Gulf of Alaska. Huge boulders deposited during this advance are particularly conspicuous along the beaches and outline the limits of the Neoglacial ice. Lateral and terminal moraines, visible on aerial photo-

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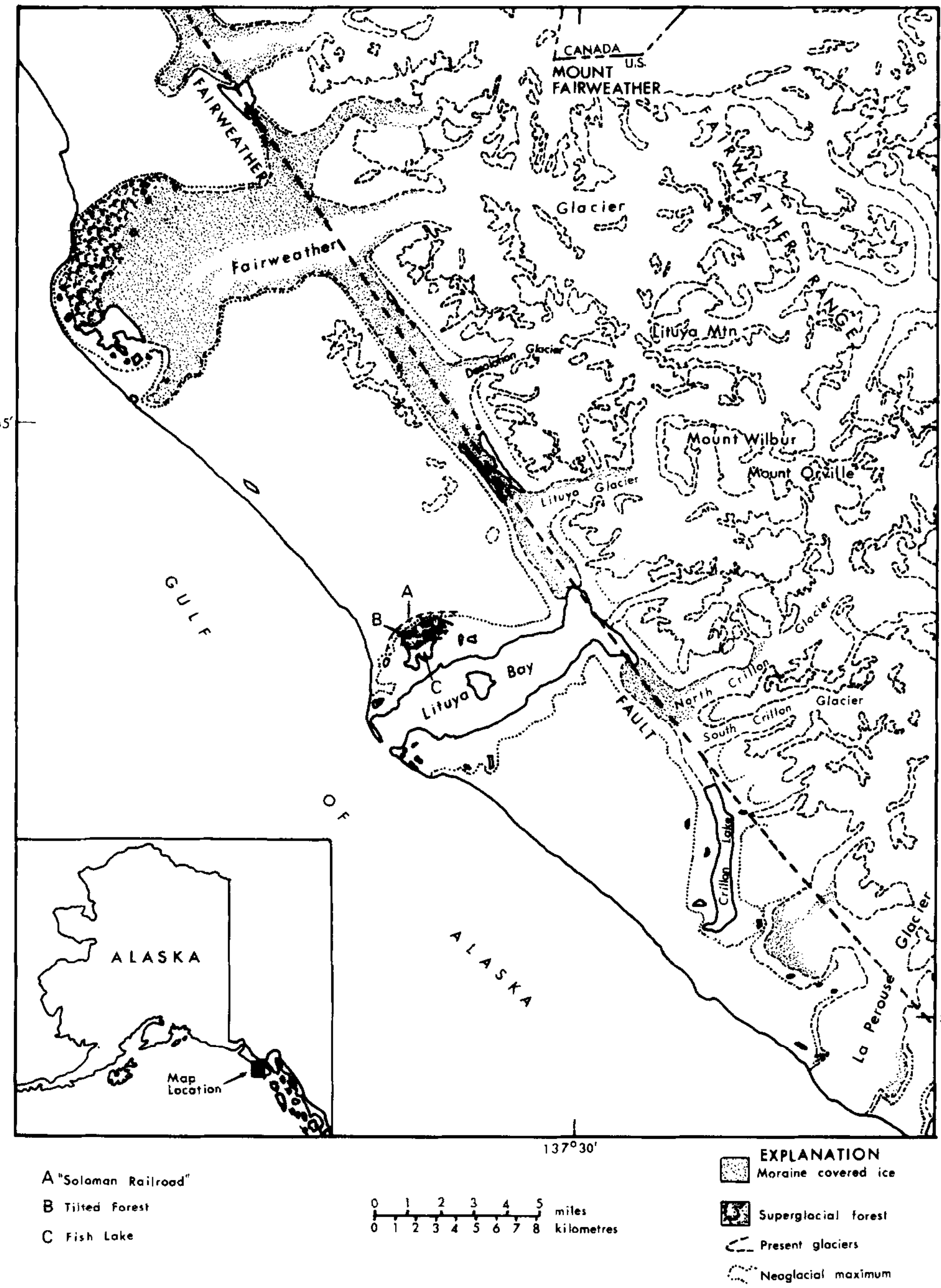

FIG. 1. Regional setting of Lituya Bay, Alaska. The Fairweather Glacier roughly resembles the glacier which formerly filled Lituya Bay.

graphs, disclose the extent of these lobes on land. These moraines are so small in volume that they suggest the glacier maintained this position for a very short interval of time.

When the Lituya Bay glacier first began to retreat, it must have roughly resembled the present Fairweather Glacier both in size and form (Fig. 1). Judging from the record of ice loss of other tidal glaciers observed retreating during the past ecntury, it is probable that only

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about 30–50 yr would be required for the glacier to recede from the Gulf of Alaska to the head of tidewater. The glaciers in Glacier Bay, for example, retreated 100 km between 1786 and 1925, and the Guyot Glacier in Icy Bay near Yakutat retreated 45 km between 1904 and 1972.

The exact time the Lituya Bay glacier retreated is unknown at present, but coniferous forests consisting of large trees were evidently well established about the bay by 1786. In that year the La Pérouse (1799, p. 394) party noted the presence of "lofty pines [actually spruce], which would be fit for masts for our largest ships." In the La Pérouse atlas (1799) illustrations of Indian villages at the mouth of Lituya Bay and within the overridden area also show very large trees. From the time required for these trees to have reached this size it is estimated that the Lituya Bay glacier retreat occurred well over a century before La Pérouse's visit, probably around 1600. The minimum time since the glacier's retreat is thus about 350 yr.

The 1786 chart compiled by La Pérouse

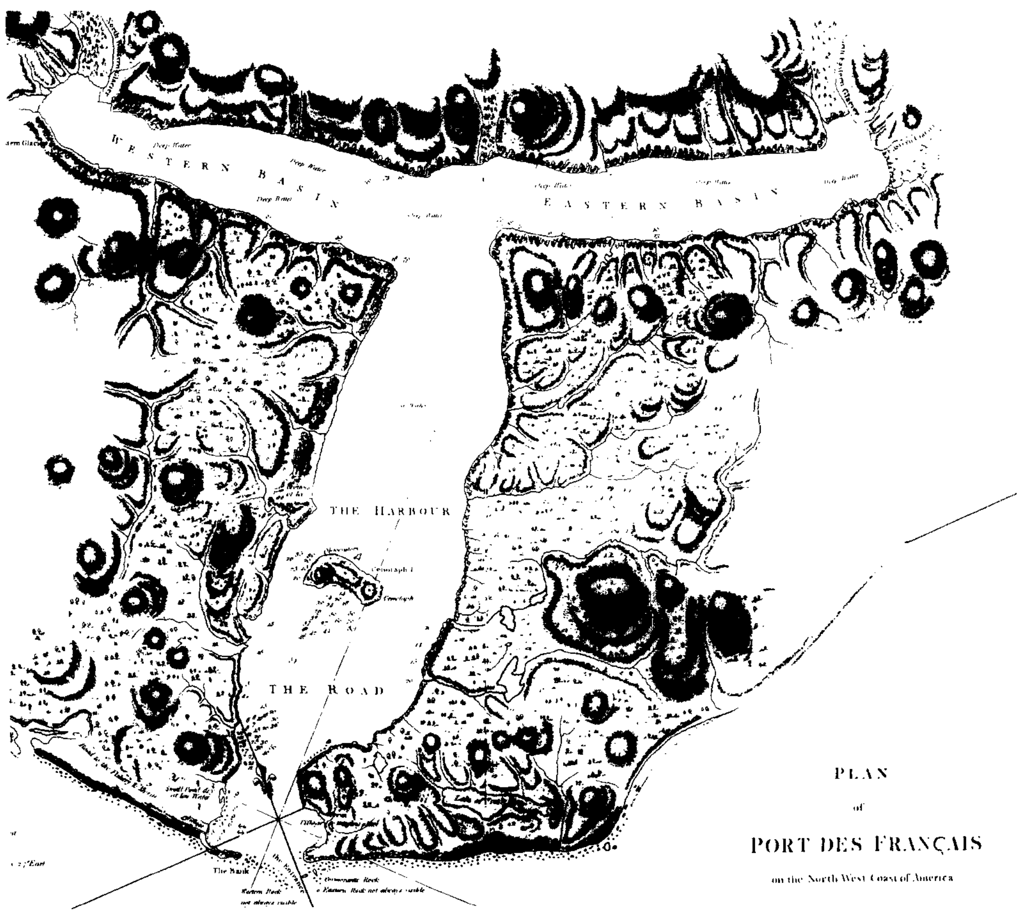

FIG. 2. Plan of "Port Des Francais" now called Lituya Bay, compiled by J. F. G. de la Pérouse (1799) showing 1786 conditions. Long arms extend laterally at the head of the bay in each of which "Western," "Northwestern," "Eastern," and "Northeastern" glaciers terminate. The glaciers in each arm of the bay have since merged and have advanced about 5 km as shown on Fig. 1. The "grottoes of ice" are located on the western shore north of Cenotaph Island. Although most other lakes presently existing are mapped, Fish Lake is absent and it seems likely that this lake was not yet formed in 1786.

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has the note "grottoes of ice" and an indication of cavelike features on the western shore of Lituya Bay (Fig. 2). As practically all of the area within the Neoglacial moraines is shown to have been covered by forest (compare Figs. 1 and 2), there can be little question that forest-covered relic Neoglacial ice was observed by the La Pérouse party.

U.S. Navy vertical aerial photography of Lituya Bay taken in 1948 discloses several curious features. In the area covering about 2.5 km^2 between the west shore of the bay, Fish Lake, and "Solomon Railroad" (Fig. 1), dense forests display evidence of instability. In parts of the area, trees in this tilted forest are leaning in various directions. In a few localities the forest has collapsed into steep-sided depressions, the prostrate trunks forming dense tangles in which brush and youthful trees are taking root. These conditions are rather typical of forest which is growing on debris-covered glacier ice that is slowly melting (Fig. 3).

The possibility of finding buried Neoglacial ice in the area was considered likely enough to be worthy of a day's battle with the dense forest tangle. On the typically showery day of June 23, 1973, the authors, accompanied by Dr. Edward Cushing of the University of Minnesota, traced the western rim of "Solomon Railroad" on foot from the entrance of Lituya Bay to a notch west of the tilted forest (Fig. 1). Immediately after the descent from the moraine crest, evidence of soil creep due to subsidence of underlying deposits was found. Trees of all ages on the slopes of the moraine had extreme curvature in their trunks,

FIG. 3. Scene in the tilted forest, June 1973. Healthy hemlock trees as much as 1 m in diameter are leaning in all directions because of the shifting of the soil covering melting glacier ice below. No uncovered ice could be found in these areas and it is estimated that the soil and debris cover average at least 2 m in thickness.

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occasionally 90° or more. Although in places on the irregular hummocky terrain below the moraine forest trees of Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) were leaning in all directions, in perhaps half of the area little tilting was noted, which would indicate prolonged stability of the underlying deposits. Occasional ponds with no surface drainage, littered with standing and fallen dead trees, gave further evidence that buried ice was present but no exposed ice was immediately found. For the most part, although showing some evidence of subsurface subsidence, the forest was rooted in a massive layer of ablation moraine and organic debris.

A depression floored with forest debris being invaded by vigorous young spruce trees as much as 15 m in height was eventually encountered. At a few points around the perimeter of this basin, in bluffs approximately 8 m high, very recent slumping had taken place. Here soft glacial clay and seeps of muddy water suggested ice close to the surface. A 1-m lateral excavation under an overhanging bank from 2 to 3 m thick, composed of moraine, forest duff, and roots of living plants and trees, exposed clear, slightly bubbly glacier ice.

From the height of the adjacent "Solomon Railroad" lateral moraine which indicates the approximate former level of the ice surface, the maximum ice depth of the Lituya Bay glacier at the present site of the tilted forest is estimated to be at least 200 m. Due to ice flow toward the water prior to stagnation the glacier surface would have been lowered below the moraine crest, reducing the ice surface to about 120 m above sea level by the time the main glacier retreated to the head of Lituya Bay some 300 or more y. a. The present surface of the tilted forest averages about 60 m above sea level. Probably 60 m of buried stagnant ice has melted since the glacier retreat, or an average of about 200 mm/yr.

Although some melting under the forest is demonstrated by leaning trees with curved trunks, rapid melting appears to take place only where the ice became exposed due to slumping of surface debris and forest soil into an adjacent pit. Probably this is most often initiated by the collapse of the roof of a grotto in the ice formed by meltwater. Once bare ice is exposed, the collapse pit is quickly enlarged. Eventually the margins of the pit again become carpeted by debris, which inhibits melting. A new forest meanwhile grows in the collapse area, again insulating the ice. With time new pits form and melting is again accelerated until eventually all the ice is removed. Various stages in this process are illustrated in Fig. 4.

The rate of melting probably decreases with time because of the increase in surface debris and forest duff insulating the ice. For instance, there is a notable difference in appearance between the Lituya tilted forest and the forested part of Fairweather Glacier shown in Fig. 4. The forests on Fairweather Glacier probably represent conditions resembling those on the shores of Lituya Bay at the time of La Pérouse's visit. Forest growth of various ages is vigorous on the debris-covered ice at Fairweather Glacier, but the surface is pockmarked with great pits and slump areas where rapid melting and forest destruction are in progress. By contrast, in only two or three small areas of the Lituya tilted forest do surface conditions indicate that rapid melting is currently taking place.

The thickness of remaining ice under the tilted forest can only be estimated at present but some idea of this can be drawn from the following observations. Adjacent areas known to be ice free are nearly level and only slightly above sea level. The tilted forest rises from approximately 30 m on the south to 90 m

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FIG. 4. Stagnant ice on Fairweather Glacier 23 km northwest of Lituya Bay, September 16, 1966. This shows conditions much as they may have appeared in the vicinity of the tilted forest at the time of the La Pérouse visit. Thick forest veneers moraine-covered ice, but melting has formed large collapse pits in which parts of the forest have been destroyed. Lakes littered with dead trees occupy low areas; brush and forest are being reestablished where the ground is again becoming stable.

on the north. From this it is judged that a considerable part of the remaining ice is 60 m or more thick. At the average rate of melting previously computed it would require at least another 300 or more yr for the remaining ice to disappear.

Stagnant ice masses remaining from lobes of Pleistocene glaciers, which had much greater known ice thickness and vast areas thickly mantled with forest-covered debris, could thus survive much longer in a mild marine climate after the retreat of the main ice sheets. This supports the conclusions of Porter and Carson (1971) and Heusser (1973) regarding the insulating effects of forested debris cover in accounting for the differing ages of various Pleistocene glacial deposits.

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