THE FORMATION OF FJORDS

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Many explanations of the origin of fjords are to be found in works on geography and geology as well as in guide books, but none of them seems fully to meet the case.

Fjords are the natural result of the laws which govern the movement of glaciers; they are formed by erosion of the beds of glaciers as they flow into the sea and in the course of centuries become displaced inland. For a further account the reader is referred to my two papers on the theory of glacier mechanism.*†

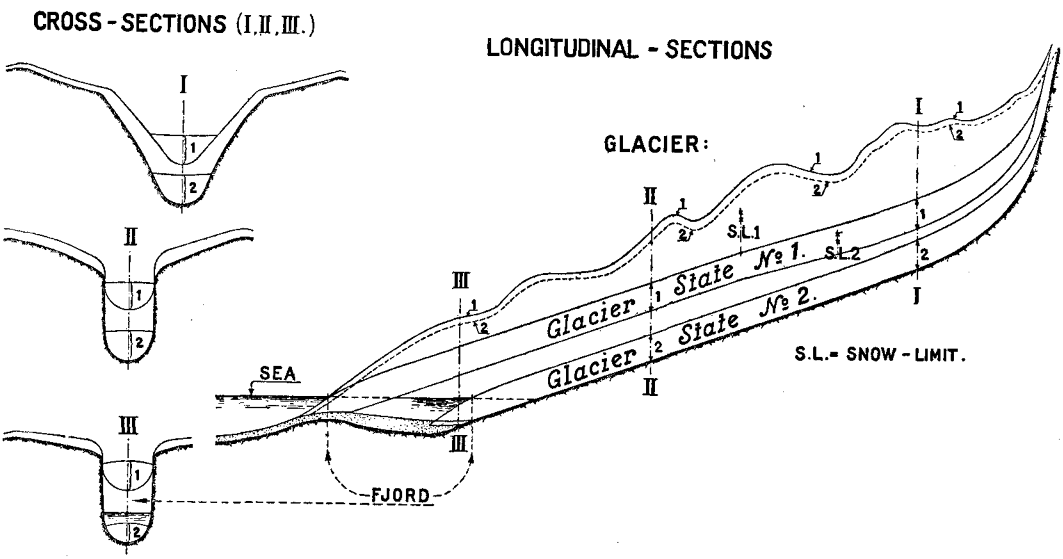

Fig. 1

The Laws of Glacier Movement. Just as liquid precipitation in temperate countries follows its course to the ocean under the impulse of gravity, so does the solid precipitation transformed by compression into ice in Polar regions make its way seawards, eroding its bed as it flows and excavating a rock channel. The erosion is slight in the accumulation areas, but increases greatly at lower levels where I have calculated that it is of the order of 1 cm. a year, as opposed to no more than 0·2 to 1·0 mm. a year for the whole glacier system; the latter figures have been established by the measurement of the amount of solid material found in the streams issuing from glaciers.

Erosion takes place uniformly throughout the bed of the ice stream, so that the glacier gradually sinks into the ground parallel to the surface. At the same time it cuts its way headward (see Fig. 1).

* Koechlin, René. *Mécanisme de l'Eau.* Paris: Librairie Polytechnique, 15 Rue des St. Pères, 1924, Chapters 11, 12 and 13.

† Koechlin, René. *Les Glaciers et leur Mécanisme.* Lausanne: Librairie Rouge & Cie, 1944.

The erosive power is supplied by the detritus which the glacier pushes along its bed; this detritus, too, is almost uniform throughout the lower part of the ice stream, so that the bed also shifts headward parallel to the surface, leaving a nearly vertical rock wall on either side.

In its displacement inland the glacier leaves at its seaward end a channel which becomes the fjord. Its breadth corresponds with that of the glacier and decreases slightly uphill, being a function of the mass of the glacier and the detritus it transports.

The glacier entering the water erodes the rock until a depth is reached at which its erosive power is reduced to nil by the melting of the ice. It will be realized that so long as the erosive power of a glacier remains constant the depth of a fjord in a rock of homogeneous texture will also remain constant. Nevertheless the erosive power and the depth must diminish as the glacier enters the sea, for under the influence of the salt water the ice will melt more rapidly than in the fresher water of the fjord fed by the glacial streams. In this way is formed the rocky threshold so commonly present at the seaward ends of fjords.

The depth of the fjord depends on the erosive power of the glacier that formed it. Thus a glacier of outstanding size will give rise to a fjord of equal importance. Sediments and rocky debris transported by the glacier are deposited on the bottoms of fjords and break up the regularity of their beds. Nevertheless glacial lakes are often present in the higher reaches of a glacier system and contain great quantities of water; from time to time these burst their barriers and produce immensely powerful floods. It is conceivable that, under favourable conditions, these might wash the bed clean and transport the sediments out to sea.

As the glacier excavates its way into the ground it leaves its two walls, which may retain their vertical cross-section or may by degrees, according to the nature of the rock, become less steep by weathering.

I have shown in my theory of glacier formation that there is a relationship on the one hand between the breadth of a glacier and its depth and on the other between its normal depth and its mean slope—a relationship varying, of course, with the nature of the rock. In this way I have set forth the relationship between the slope, depth and width of glaciers varying with varying degrees of roughness (*coefficients de rugosité*) of the rock.

The diagram in my book (1944) gives the observations made in a large number of glaciers and shows that they are in good accord with the formula R.K. given there (p. 111).

If we apply these data to the largest of the Norwegian fjords—the Sogne Fjord—we find that the time it has taken to form, based on an annual wastage of 1 cm., has been 250,000 to 450,000 years, a figure which admittedly aims only at giving the order of magnitude of time.

The calculations are accurate especially for glaciers which only carry small quantities of detritus. To meet these conditions their courses must be relatively short and their rock beds resistant, conditions which are to be found on the coast of Norway. On the Swedish coasts, on the other hand, as in Switzerland, the glaciers have excavated a series of lakes, which, however, develop in accordance with the same laws that govern fjord formation.

The more important prehistoric glaciers flowing into the sea with gentle slopes and much morainic material, such as those which fashioned the great river-beds flowing into the Arctic Ocean in northern Asia, have almost entirely filled up the fjords with alluvium, but the forms of these rivers still betray their origin as glaciers and fjords.

In the Swiss glacial valleys, cut in homogeneous rock, the glaciers usually cut back their beds in a straight line in a manner analogous with that which gives rise to fjords. Thus one often finds in the Alps valleys with vertical sides and even sometimes, in their upper sectors, the remnants of a glacier whose width corresponds with the gorge it has cut in the course of centuries. Examples of this are to found in many places, notably in the Lauterbrunnen valley in the Bernese Oberland and the Blindenthal in the Valais.

AIRCRAFT ICING

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Ice formation on aircraft in flight is still a considerable hazard. Much progress has been made in countering this danger, and we now know how to protect aircraft against the majority of atmospheric icing conditions likely to be encountered by a reasonably cautious pilot. But the best defence is to avoid serious icing conditions by flying over or round regions where icing is likely to occur. The prediction of such regions is a regular feature of the meteorological service, and skilled use of meteorological forecasts enables the pilot to vary his route and time-table so as to avoid areas where serious icing is likely to be encountered.

But this can only be accepted as a stop-gap measure. Civil air transport, in common with all other means of transport, must strive to achieve all-weather regularity throughout the year. This cannot be done so long as route and schedule are liable to be changed in order to take account of transient meteorological conditions.

For long-range flights the best policy is to fly "above the weather." At 30,000 ft. there is little likelihood of icing troubles. But this is not the complete answer. It is clearly impracticable to climb to Everest height on short flights, and there is always the chance that icing regions may have to be traversed on the ascent or descent. Hence aircraft must, so far as possible, be made immune to icing.

Ice can give trouble in many ways. It can stop the engines by blocking up the air intakes or carburettors; it can stick to the propeller, thereby reducing its efficiency and putting it out of balance; it can stop up the pitot head and static vent of the airspeed indicators and blind-flying instruments; it can penetrate into and jam the hinge gaps of ailerons, elevators and rudders; it can build up on wings and tail, thereby impairing their lifting properties and very considerably increasing the air drag; it can fasten on to the radio mast and radio aerials, causing them to break; and it can cause a multitude of other mishaps, such as obscuring the windscreen and jamming the retractable undercarriage.

There are many ways in which these troubles can be overcome. The most obvious is to heat any surface to which ice might adhere. Another method is to dislodge the ice by applying alcohol or other freezing-point depressant to the surface. This has been extensively used for clearing the windscreen. Yet another method is to break off the ice by deforming the surface to which it adheres. This is used in the well-known Goodrich method of wing de-icing. Something can be done by designing certain parts, for instances flying control surfaces and aerial insulators, so that they are protected from the impact of freezing water.

All these methods involve adding to the tare weight of the aeroplane. On a forty-seater aeroplane the weight equivalent of at least two passengers can easily be used up in de-icing