Bulletin of Glacier Research 4 (1987) *107 – 117*

Moraine formation at Soler Glacier, Patagonia

Masamu Aniya
Institute of Geoscience, University of Tsukuba, Ibaraki 305 Japan

(Received December 18, 1986 ; Revised manuscript received January 23, 1987)

Abstract

One of the most prominent characteristics of the moraine field in the proglacial area of Soler Glacier, Northern Patagonia Icefield, is that most gravel and boulders are well-rounded. Angular ones can be found only in the northern part of the field. Secondly, some hillocks show reverse grading of gravel. Thirdly, there are blocks of stratified sediments on top of the ice-cored moraines located in front of the clean ice snout area.

By the austral summer of 1985-86, a belt of ice-cored moraines has been formed on the debris-covered ice near the snout, where it was flat in 1983-84. Subsequently, few ice-cored moraines were found also on the clean ice snout area. These ice-cored moraines are generally covered with round gravel and sand thick enough to insulate the ice underneath. The emergence of these and subsequent investigation of their formation shed some lights on the characteristics of the moraine field. The majority of these new ice-cored moraines are formed by overthrusting. The ice mass near the snout has become stagnant, and ice moving behind overrode the stagnant part, bringing round gravel and sand of subglacial origin up to the glacier surface. These debris protected the ice from ablation, forming ice-cored moraines. Once brought to the surface, large round gravel and boulders tend to roll down to a nearby depression and a thicker deposition with larger gravel ensues near the bottom of the depression. After ice melted, topographic inversion occurred with reverse grading. Blocks of stratified sediments are probably deposited in englacial pools and/or streams and brought to the surface by surface melting and up-flow of the glacier. Some ice-cored moraines have originated in this way by insulation of englacial sediment cover, without thrusting.

1. Introduction

The terrain classification map of the proglacial area was produced in a previous report (Aniya, 1985) ; however, detailed field work during the 1985-86 season and a new set of vertical aerial photographs of larger scale (1 : 5,300) and better resolution have necessitated slight modifications of the map. The new map is presented in Fig. 1. The major landforms recognized include 1) lateral and terminal moraines, 2) glacial bench, 3) outwash plain, and 4) debris flow deposit area.

Since the descriptive aspects of these landforms were mostly covered in the previous report, an emphasis is placed on the characteristics of terminal moraines and the mechanism of their formation.

2. Terminal moraines

2. 1. Characteristics

Figure 2 shows details of the glacial features and proglacial landforms around the glacier snout. The moraine field spreading out in front of Soler Glacier has several characteristics. One of the most prominent features is that the majority of the moraine mounds are composed of round gravel and sand worn by running water. Angular rocks, which are usually common in the moraine field in other areas, constitute only moraines located in the area north of the northernmost old spillway, and their plan view looks like a washboard. The rest is composed of round sand, gravel and boulders of few centimeters to several tens of centimeters. Even at the top of the moraine ridge presently formed, well-rounded gravel is scattered all over. Secondly, some moraine mounds show reverse grading of gravel, that is, gravel on the top of hill is

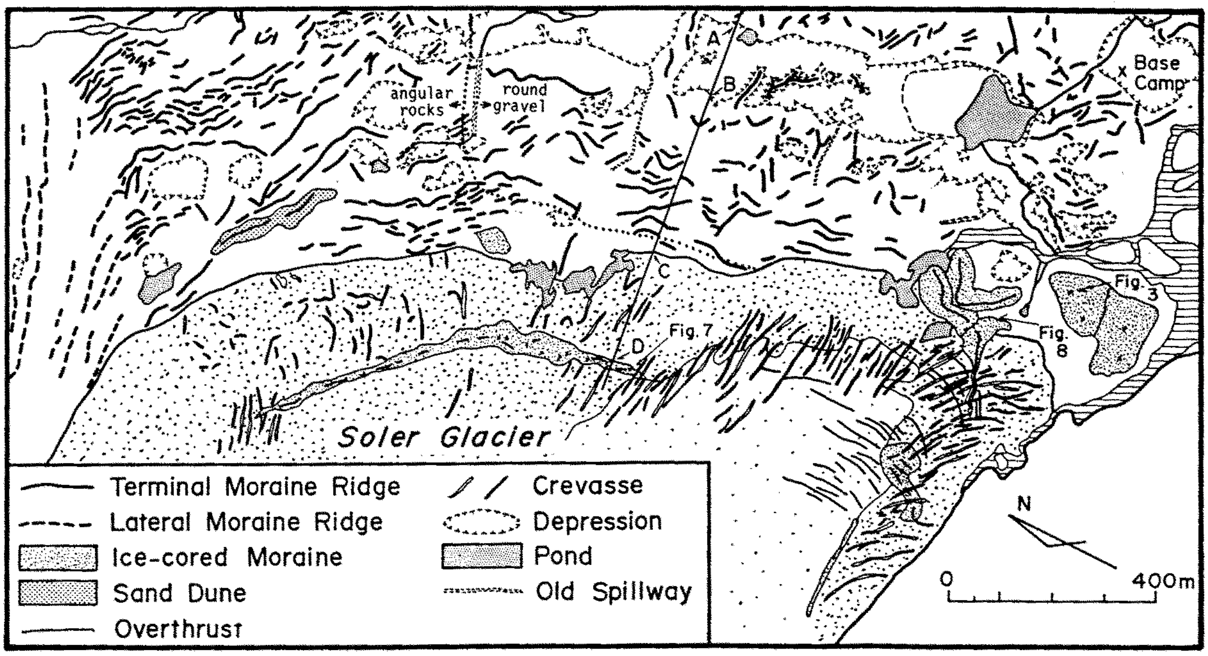

Fig. 2. Terrain and glacier features around the snout.

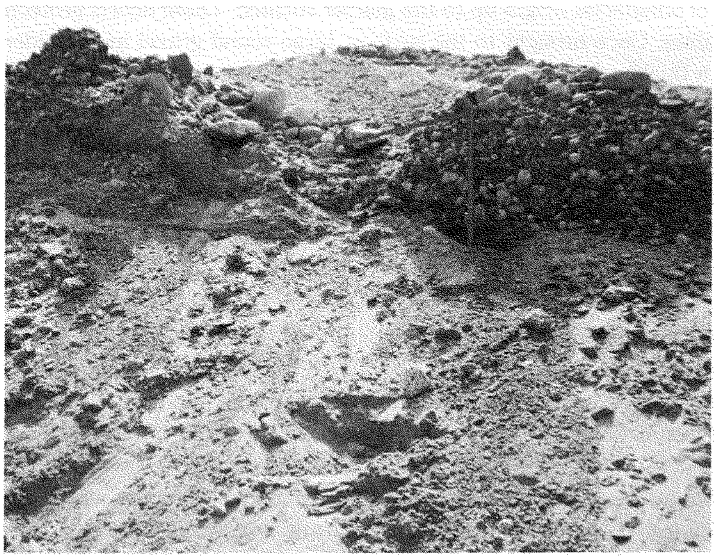

Fig. 3. Stratified sediments on top of an ice-cored moraine (see Fig. 2 for location). Scale in figure, 50 cm (both horizontal and vertical). Photo taken on Dec. 31, 1983.

larger than those near the base. Thirdly, on top of the ice-cored moraines located just in front of the southern end of the snout, lie sorted sediments of gravel, sand, silt and clay (Fig. 3).

2. 2. Emergence of new ice-cored moraines

In the austral summer of 1985, a belt of ice-cored moraines had been formed from the border between the clean and debris-covered ice to the side of the debris-covered ice (Fig. 4). It is located about 150-200

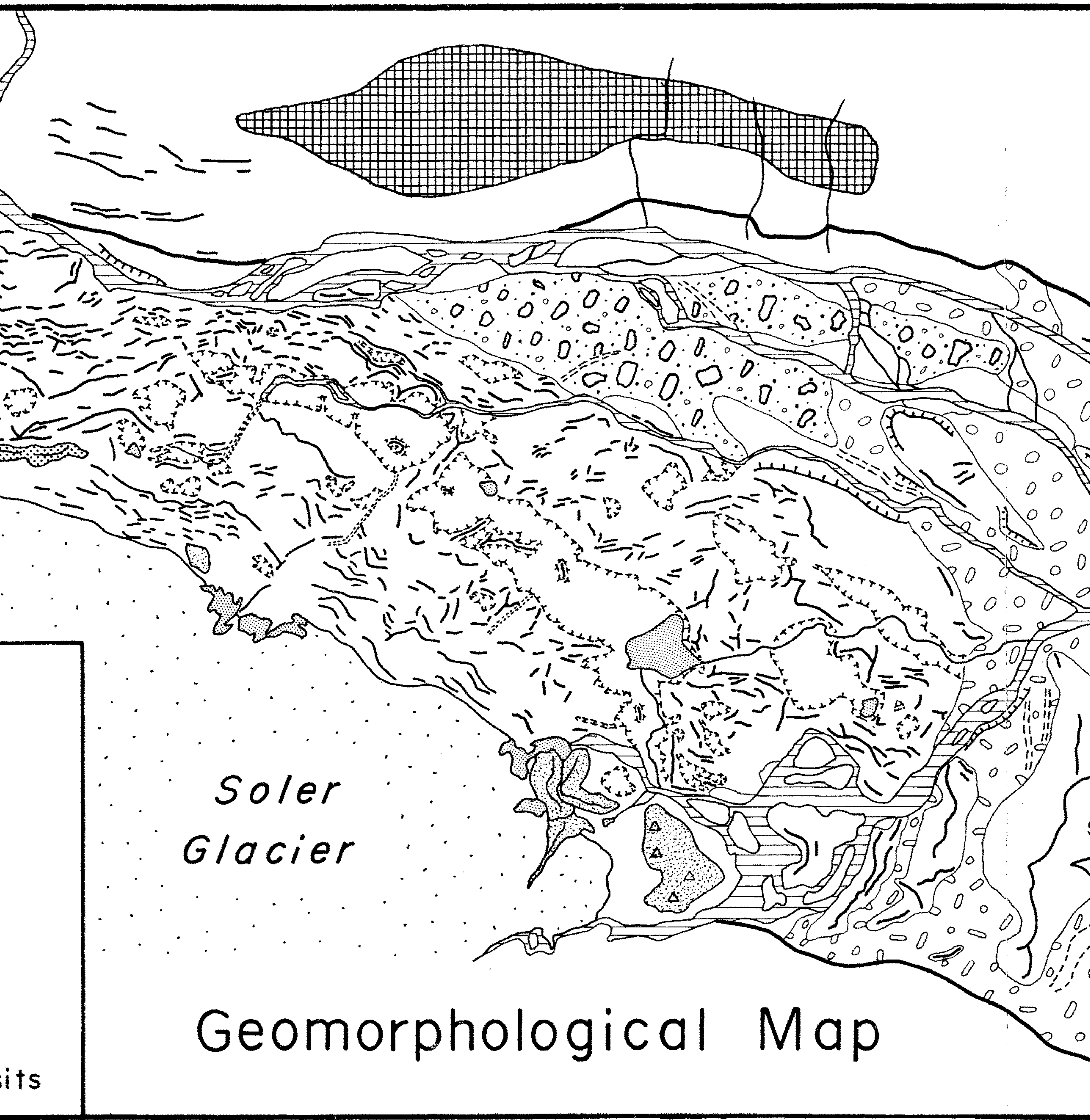

Fig. 1. Geomorphological map of proglacial area, Soler Glacier, compiled from ground survey and aerial photographs taken on J

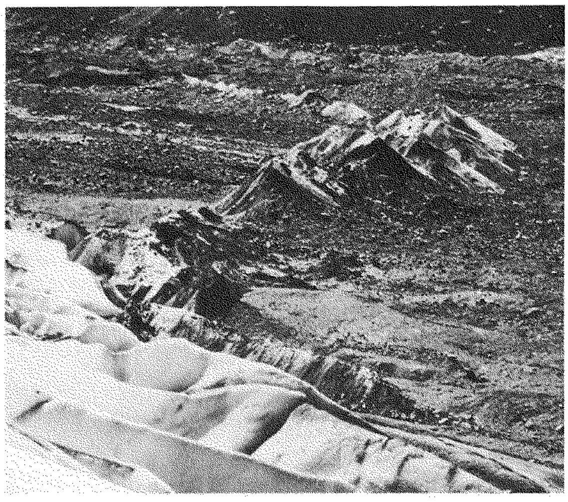

Fig. 4. A belt of newly-emerged ice-cored moraines. To the left is the up-glacier side. Photo taken on Nov. 29, 1985.

m from the ice front and runs almost parallel to the front for about 800 m. They are several meters higher than the up-glacier surface and 10–20 m higher than the down-glacier surface, and covered generally with well-rounded and sorted coarse sand and scattered gravel, with a thickness of around 10 cm or more (Fig. 5). Often on the down-glacier side, flow till (Boulton, 1968) can be observed. On top of the side slope of several of these mounds are located blocks of sediments with the sorted structure. Quite often laminar structure is very conspicuous because of flaky micas. Two years ago it was absolutely even around here, and close examination of vertical or ground photograghs taken two years ago shows no visible sign of these ice-cored moraines (Fig. 6). Currently (as of Dec., 1985), 18 peaks and ridges are recognized and another is in the process of formation. These ice-cored moraines have evidently been produced by the insulation effect provided by the debris-cover.

2. 3. Brief review of literature on the formation of ice-cored moraines

During the 1960s and early 1970s, there were great controversies over the formation of ice-cored moraines. Among many papers, Goldthwait (1951) and Bishop (1957) proposed that subglacial sediments had been brought up to the surface along the shear plane near the snout and this type of moraine was called a "shear moraine". Subsequently, Swinzow (1962) and Souchez (1967) supported this "shear plane hypothesis". On the other hand, Weertman (1961) and Hooke (1968, 1970, 1973) strongly argued against this hypothesis, and offered an alternative hypothesis of basal freezing and up-flow of foliations along which the debris were transported. Boulton (1968) supported the latter. These arguments were based on observations

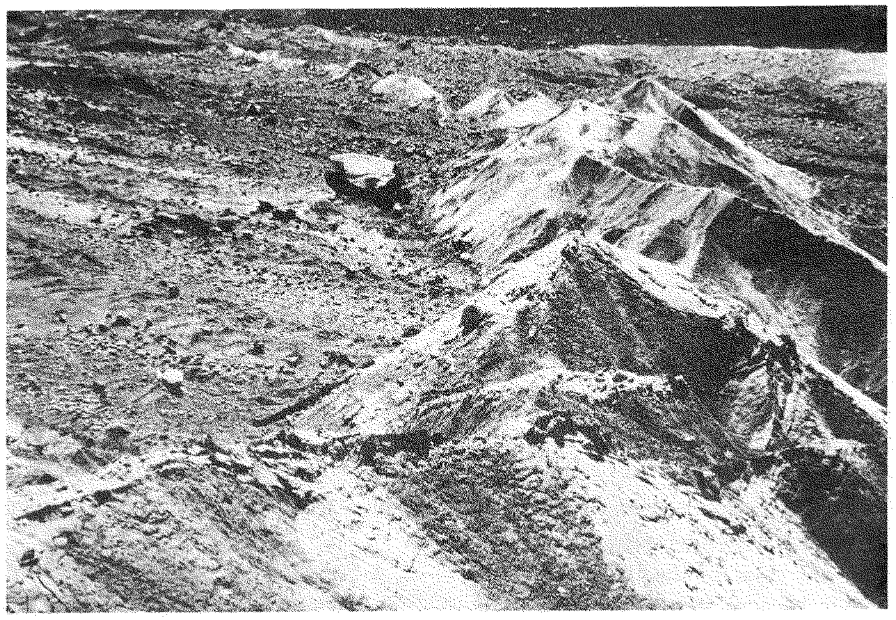

Fig. 5. Sandy nature of the debris cover. Looking toward north.
Note : at lower left, sedimentary structure at the top of the ridge. The opening at the base of the second mound from the front is the remnant of a thrust.

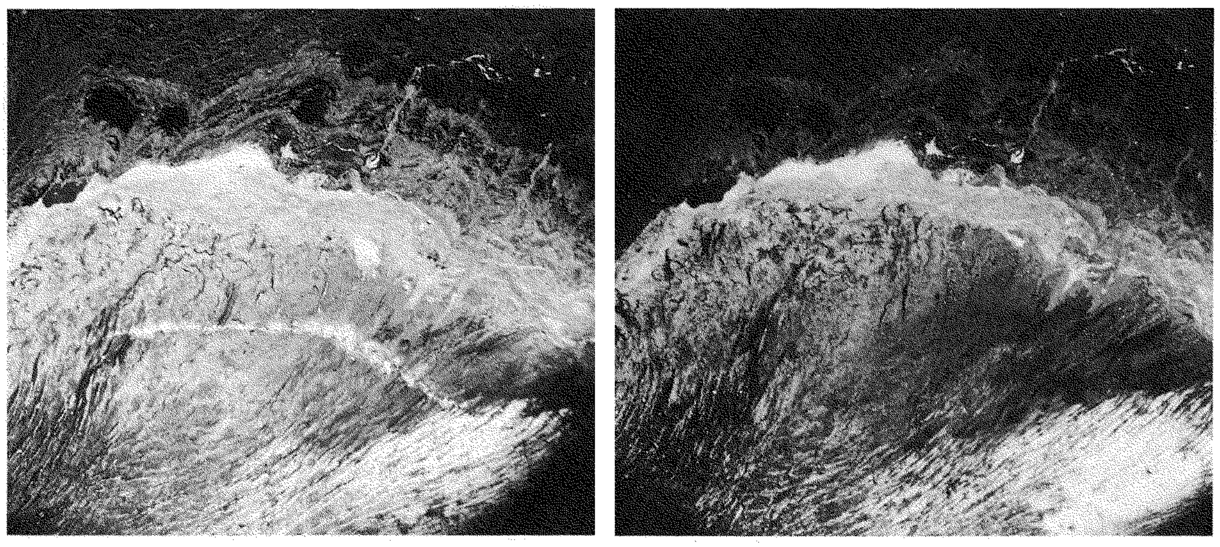

Fig. 6. 6×6 vertical aerial photographs showing the snout area.
A : taken on Jan. ~~18~~ 7, 1986, showing a belt of ice-cored moraines. B : taken on Jan. 11, 19~~86~~84, no visible sign of the ice-cored moraines.

and measurements on cold-based, polar glaciers in Greenland, Baffin Island, Antarctica, Ellesmere Island, and Spitsbergen. Curiously, there are not many reports on temperate glaciers which described such moraine formation. Sharp (1949) reported round rocks worn by running water on the stagnant surface of Wolf Creek Glacier, Canada. He mentioned, as one possible source of supraglacial debris, englacial material brought to a supraglacial position through lowering of the ice surface by melting. In turn, these englacial materials may be, among two other sources, subglacial materials brought to an englacial position by movement along shear planes.

From the literature review, it seems better to break this problen into three parts : 1) entrainment mechanism of basal debris under the glacier bottom ; 2) glacier mechanism with which basal debris are brought up to the surface ; and 3) the origin of these well-rounded materials.

As for the mechanism of entrainment, both shear and freeze-in including regelation can occur (Boulton, 1970 ; Hashimoto and Wakahama, 1983). The surfacing mechanism is the most controversial point. First of all, the distinction between "shear plane" and "foliation" is often not clear in the literature, and some confusion arises, because "the ice of the deeper portions of a glacier often acquires a stratiform structure which may perhaps best be called foliation to distinguish it from stratification which arises from deposition. The foliation appears to result mainly from shearing of one part over another in the course of movements to which the ice is subject" (Dictionary of Geological Terms, 1962 ; 191. underline by author). Hooke (1968) and Boulton (1970) emphasized foliation and up-flow in Greenland and Spitsbergen, respectively, although Boulton implied the role of overthrust (shear plane) in the formation of ice-cored moraines in his figures. Hooke (1970, 1973) showed that clean ice beneath the dirty band of ice was a wind-drift ice wedge, developed in front of the glacier and blocking the glacier flow in Greenland and Baffin Island. This was later supported by Shaw (1977) in a study of an Antarctic glacier. In relation to the glacier conditions, the shear hypothesis can be applied only to glaciers whose snouts are stagnant, while the ice-wedge hypothesis can best be applied to advancing glaciers, although with favorable conditions, it can be applied to balanced glaciers (Hooke, 1973).

As for the source of round gravel, Bishop (1957) thought they were old ground moraines in Thule, Greenland, whereas Souchez (1971), on Ellemere Island, attributed them to old outwash deposits.

2. 4. Formation of ice-cored moraines on Soler Glacier

From the literature review, it appears that the ice-cored moraines found on Soler Glacier are rather rare for a temperate glacier, and provide an interesting example.

2. 4. 1. Entrainment of debris

Both shear and regelation seems to be responsible for the entrainment of debris as Boulton (1970) pointed out from the study of the Spitsbergen glaciers ; however, the shear mechanism appears very dominant at Soler Glacier from field observation. On the other hand, it is difficult to envisage that the blocks of stratified sediments are also entrained into ice by shear, while retaining their layered structure. It seems best to interpret these materials to be of englacial origin; namely these are deposited in englacial pools and/or streams

2. 4. 2. Surfacing mechanism

The shear plane hypothesis appear to better explain the existence of many ice-cored moraines than the foliation and up-flow hypothesis, on the basis of the following observations. At the side of the some of those ice-cored moraines, an overthrust with up-glacier dipping angle of 60–70 degrees can be observed (Fig. 7). At some other mounds, a remnant of an overthrust could be recognized at the base of the up-glacier side of the mound, an open crack few tens of centimenters wide, dipping steeply up-glacier, and running parallel to the belt of mounds (see Fig. 5). In two years between 1983 and 1985, the snout position at the clean ice area has receded by about 10 m. From the appearance of the glacier surface of the down-glacier side of the belt of ice-cored moraines, it seems that ice has become stagnant and has been wasting steadily.

Ice-cored moraines of similar nature were subsequently found at a few places on the snout area of the clean ice. Figure 8 shows an outstanding outcrop of a shear plane. It clearly shows the nature of the shear plane, embedding round gravel and a layer of ice heavily loaded with sand and silt.

Although, as described above, many ice-cored moraines have active thrust planes, or remnants of them, some do not seemingly show any trace of one. Often such mounds have a nearly horizontal layer of stratified sediments on top. The origin of debris covering such mounds is best interpreted to be englacial pool and/or stream deposits, and these were probably brought to the surface by up-flow.

2. 4. 3. Origin of round gravel

Although it cannot be proved that round gravel are not old outwash or ground moraines, it seems that some of them have been produced contemporary by glacial streams, particularly sub- and englacial ones. At the right bank at points 1.7 km, 2.1 km, 4 km and 5.2 km from the snout, water streams are flowing into the side of the glacier. These streams supply a large amount of water to the subglacial stream systems. At the right margin near the snout, there are stream lined deposits of round gravel on the glacier surface, indicating that these are deposited along the englacial

Fig. 7. An ice-cored moraine, showing a thrust plane to the left.
The up-glacier side is to the left. Relief is about 6 m. Photo taken on Nov. 30, 1985 (see Fig. 2 for location).

Fig. 8. A thrust plane, embedding round gravel and sand laden ice layers. N40° W, 65° S. Scale is 1 m. Photo taken on Dec. 7, 1985 (see Fig. 2 for location).

streams and brought to the surface by melting. A similar observation was made at a Himalayan glacier (Koshima, personal communication).

Debris supply, particularly gravel, by overthrusting is most abundant near the contact between the clean and debris-covered ice. The reason why there is no prominent ice-cored moraine in this area is probably that the overthrusting is so active that it compensates for the level decrease by ablation and maintains the glacier surface level. In other areas, debris consists mostly of coarse sand with scattered gravel. Field observation indicates that along the present glacier front round gravel is distributed only in front of the clean ice. This implies that a large part of the proglacial area was laid by clean ice in the past. Although the presently-formed mounds at the clean ice snout area contains considerable amount of sand as well as gravel, the old ones contain a relatively small amount of sand, probably due to wind erosion. On a windy day, strong sand blast was observed. It appears that sand dunes in front of the debris-covered area were originated by overthrusting and subsequently withstood against wind erosion.

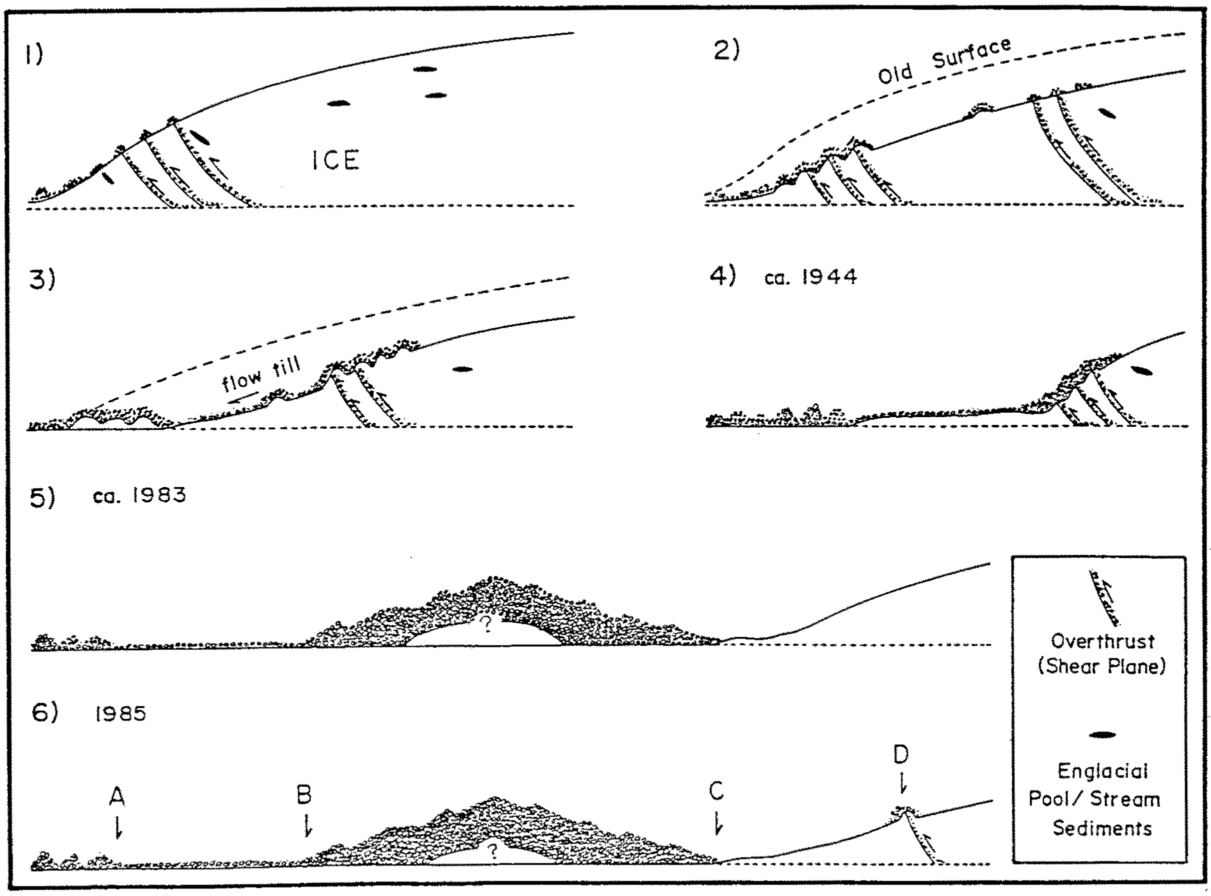

Fig. 9. Schematic sequence of moraine formation at Soler Glacier, along line A–D in Fig. 2. Heights and distances not necessarily scaled.

3. Model of moraine formation

From the discussion above, moraine formation at Soler Glacier can be summarized as shown in Fig. 9. The development model was constructed along the transect line A–D in Fig. 2. The glacier had been retreating and around area A, shear planes developed (Fig. 9–1). The surface level decreased and the retreat continued, resulting in enlarging the stagnant part of the glacier. Subsequently, about 150 m up-glacier another shear zone emerged (Fig. 9–2). This shear zone was probably very active, producing considerable amount of gravelly debris and forming a large moraine belt (Fig. 9–3). The dead ice between the two shear zones steadily wasted away and became a depression about 150 m wide (Fig. 9–4). Retreat continued and activity of the shear zone waned, forming the proximal slope with round gravel mixed with some angular gravel of supraglacial origin (Fig. 9–5). Further retreat caused the frontal ice to be stagnant, and a belt of new ice-cored moraines developed (Fig. 9–6). Up to stage 4, the area along transect line A–D had been covered by clean ice ; hence it is now covered with gravel. However, at stage 5, the glacier surface between points C and D became debris-covered, and at stage 6 only sand come up along the thrust. Therefore it seems likely that most of these mounds will be destroyed by down flow of till and aeolian erosion in the future.

The floor of the depression where we set up base camp is wavy with amplitudes of up to several tens of centimeters and wave lengths of a couple of meters, running about N 55° E. These features seems to have been produced when ice was stagnant and subglacial sediments were squeezed up into crevasses, as described by Hoppe (1952) in Sweden. This appears to support that the depression zone was a dead ice area.

Formation of the reverse grading found at some

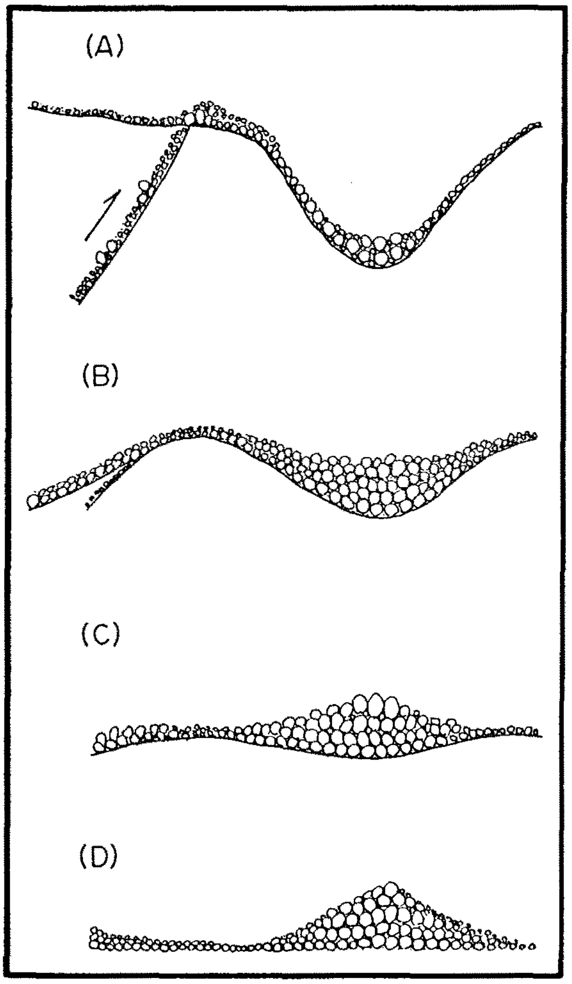

Fig. 10. Formation of reverse grading.

hillocks is depicted in Fig. 10. Gravel particles brought up to the surface roll down into a depression. Since larger ones roll down to the bottom, gravel particles at the bottom are among the largest and the deposition is thicker toward the bottom. With this mantle, ice melts slowly so that the depositional structure of gravel receives a minimum disturbance when the whole surface lowers. Subsequently, inversion of topography ensues after all ice melts, with reverse grading.

References

Aniya, M. (1985) : Landforms in the proglacial area of Soler Glacier. Glaciological Studies in Patagonia Northern Icefield, 1983-1984. Data Center for Glacier Research, Japanese Society of Snow and Ice, 80-87.

Bishop, B. C. (1957) : Shear moraines in the Thule area, northwest Greenland. Research Report 17, Snow Ice and Permafrost Research Establishment. 46p.

Boulton, G. S. (1968) : Flow tills and related deposits on some Vestspitsbergen Glaciers. Journal of Glaciology, **7**, 391-412.

Boulton, G. S. (1970) : On the origin and transport of englacial debris in Svalbard glaciers. Journal of Glaciology, **9**, 213-229.

Dictionary of Geological Terms (1962) : "Foliation", Doubleday and Co. Inc., New York, 190-191.

Goldthwait, R. P. (1951) : Development of end moraines in east-central Baffin Island. Journal of Geology, **57**, 567-577.

Hashimoto, M. and Wakahama, G. (1983) : Model studies on the formation of inner moraines in the ablation areas of glaciers. Memoir of National Institute of Polar Research, Special Issue, **28**, 277-289.

Hooke, R. L. (1968) : Comments on "The formation of shear moraines: an example from south Victoria Land, Antarctica". Journal of Glaciology, **7**, 351-352 (letter).

Hooke, R. L. (1970) : Morphology of the ice-sheet margin near Thule, Greenland. Journal of Glaciology, **9**, 303-324.

Hooke, R. L. (1973) : Flow near the margin of the Barnes Ice Cap, and the development of ice-cored moraines. Geological Society of America, Bulletin, **84**, 3929-3948.

Hoppe, G. (1952) : Hummocky moraine regions : with special reference to the interior of Norrbotten. Geografiska Annaler, **34**, 1-72.

Sharp, R. P. (1949) : Studies of superglacial debris on valley glaciers. American Journal of Science, **247**, 289-315.

Shaw, J. (1977) : Till body morphology and structure related to glacier flow. Boreas, **6**, 189-201.

Souchez, R. A. (1967) : The formation of shear moraines: an example from south Victoria Land, Antarctica. Journal of Glaciology, **6**, 837-843.

Souchez, R. A. (1971) : Ice-cored moraines in south-western Ellesmere Island, N. W. T., Canada. Journal of Glaciology, **10**, 245-254.

Swinzow, G. K. (1962) : Investigation of shear moraines in the ice sheet margin, Thule area, Greenland. Journal of Glaciology, **4**, 215-229.

Weertman, J. (1961) : Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. Journal of Glaciology, **3**, 965-978.

Resumen

Formación de morrenas en el Glaciar Soler, Patagonia

Se compiló un mapa geomorfológico del área proglacial del Glaciar Soler, Hielo Patagónico Norte, por medio del análisis estereoscópico de fotografías verticales a escala 1 : 5.300 y del trabajo de terreno de dos temporadas (Fig. 1). Las principales formas del terreno incluyen : 1) morrenas terminales y laterales ; 2) escarpe glacial ; 3) planicie fluvioglacial ; y 4) área de depósito de flujo de detritos. En la Fig. 2 se muestra

en detalle la zona alrededor del frente del glaciar.

Una de las características principales del campo terminal de morrenas es que la mayoría de las gravas y bloques se encuentran bien redondeadas. Cantos angulares sólo pueden ser encontrados en la parte norte de este campo de morrenas. En segundo lugar, en algunos montículos las gravas muestran una granulometría inversa. En tercer lugar, en la cima de morrenas con núcleo de hielo ubicadas en el frente de la zona de hielo limpio existen bloques de sedimentos estratificados (Fig. 3).

En el verano austral de 1985–86 se encontró una formación de morrenas con núcleo de hielo en la zona cubierta por detritos cerca del frente glaciar, la cual no existía en 1983–84 pues el terreno entonces era plano (Fig. 4). Posteriormente algunas pocas morrenas con núcleo de hielo fueron encontradas también en la zona de hielo limpio del frente glaciar. Estas morrenas están en general cubiertas por arenas y gravas redondeadas de un espesor suficiente para aislar el hielo subyacente (Fig. 5). En la Fig. 6 se compara la misma zona libre de morrenas en 1983 y cubierta por morrenas en 1985. A partir de la formación de estas morrenas y su posterior estudio se aclaró en cierta medida sus características. La mayoría de estas morrenas se formaron por sobreempuje. En la Fig. 7 se muestra un plano de empuje ubicado aguas arriba de una reciente morrena con núcleo de hielo. En la Fig. 8 se muestra un afloramiento sobresaliente de un plano de empuje ubicado en el extremo sur del frente del glaciar. La masa de hielo cerca del frente está ahora estancada, y el hielo por detrás la empuja, acarreando consigo arenas y gravas redondeadas de origen subglacial hacia la superficie (Fig. 9). Estos detritos protegen el hielo de la ablación, formando morrenas con núcleo de hielo. Una vez en la superficie, las gravas y bloques redondeados de gran tamaño tienden a rodar hacia las depresiones cercanas, encontrándose en consecuencia gravas mayores cerca del fondo. Después de derretirse el hielo, ocurrió una inversión topográfica con granulometría inversa (Fig. 10). Los bloques de sedimentos estratificados se depositan probablemente en cuerpos de agua y/o cauces dentro del glaciar y son llevados a la superficie por derretimiento de hielo y flujo emergente del glaciar. Algunas morrenas con núcleo de hielo se han formado de esta manera por el efecto aislante de la cubierta de detritos dentro del glaciar, sin empuje.