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GLACIAL HISTORY WITH SPECIAL REFERENCE TO THE PAST LACUSTRINE DEPOSITS IN THE MT. RIISER-LARSEN AREA, ENDERBY LAND, EAST ANTARCTICA

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Abstract: The Mt. Riiser-Larsen area consists of ice-free mountains as one of the isolated massifs of the Tula Mountains, Enderby Land. Landforms and glacial history have been studied in this area with special reference to the past lacustrine deposits, "Richardson Clay". Glacial deposits of this area were divided into three groups; Tula Moraine, and Mt. Riiser-Larsen Moraines I and II. The glacial history of this area is summarized as follows:

The ice sheet flowing from east to west had once covered entirely this area at its maximum stage. After the retreat from the mountain tops, the ice sheet terminated at the foot of mountains for a long time, when the Tula Moraine was deposited as ground moraine. During the subsequent warmer stage, the transgression exceeding 50 m above the present sea level occurred, which resulted in joining the sea to a marginal lake with a shallow threshold. The Richardson Clay, past glacial varves, lay on the bottom of this lake. This event would have been completed prior to the late Wisconsin Glaciation. Subsequently, the sea level lowered and local alpine glaciers formed Mt. Riiser-Larsen Moraines I and II. There was no evidence that the ice sheet had expanded more extensively than the present aspect since the deposition of the Tula Moraine. This glacial history is quite correlative to those of the Vestfold Hills and the Prince Olav Coast, East Antarctica. A raised beach about 3 m in altitude and a fluvioglacial channel in this area were inferred to have been formed during the Holocene.

1. Introduction

The Mt. Riiser-Larsen area is located around 66°47′S and 50°40′E in the northeast of Amundsen Bay, as one of many isolated mountain massifs of the Tula Mountains, Enderby Land (Fig. 1). This area was previously visited by a field party of the 23rd Japanese Antarctic Research Expedition (JARE-23) in February 1982. As a result of this field work, YOSHIDA and MORIWAKI (1983) conducted a preliminary study of the landforms in this area and recognized the existence of a fluvioglacial deposit. The author was given an opportunity to carry out the geomorphological survey of the Mt. Riiser-Larsen area in February 1988 as a member of the summer field party during JARE-29. An outline of geological and geomorphological surveys of JARE-29 was reported by MAKIMOTO *et al.* (1988) and a glacial sequence of this area was inferred by ANIYA (1989).

During the field investigation of JARE-29 the past lacustrine deposits were dis-

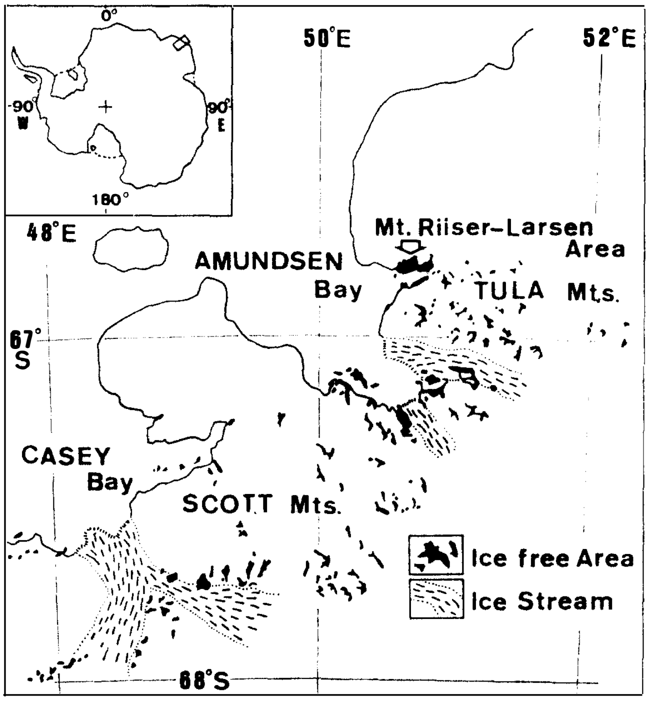

Fig. 1. Location of the Mt. Riiser-Larsen area.

covered at the fluvioglacial gully in this area. Mineralogical analysis and biochemical study of plant remains in these deposits have been performed by HAYASHI and MIURA (1989) and AKIYAMA *et al.* (1990). The purpose of this paper is to note the landforms with special reference to the relation between glacial history and past lacustrine deposits in the Mt. Riiser-Larsen area.

Geomorphological mapping is based mainly on the interpretation of about 1:70000 scale airphotos provided by Australian Bureau of Mineral Resources and a contour map of 1 : 25000 scale drawn by K. MORIWAKI of the National Institute of Polar Research*.

2. Landforms of the Mt. Riiser-Larsen Area

The Mt. Riiser-Larsen area shows an alpine feature stretching about 15 km east-west and 6 km north-south. The south end faces a deep inlet named Adams Fjord and the north is bounded by the ice sheet extends from east to west. The bedrock is composed of granulite-facies metamorphic rocks belonging to the Napier Complex which is one of the oldest crust in the world (GREW and MANTON, 1979). Felsic gneiss is dominant among the metamorphic rocks, and pyroxene granulite, pelitic gneiss and

* Using a WILD BC2 analytical plotter, K. MORIWAKI plotted the contours at intervals of 20 m. According to him, the control points were taken from the 1 : 250000 scale topographic map published by the Australian Government, and the surface of the surrounding sea was taken as the datum. He obtained a height of 1153 m for Mt. Riiser-Larsen, though the Australian map gives the height of 868 m. Since the control points are not exact, he thinks that 1153 may not be a true height, yet very close. Consequently, absolute heights and positions might be slightly off. The elevations described in this paper depend on this topographic map.

quartzite are subordinate (MAKIMOTO *et al.*, 1989). The bedrocks are rather massive and very hard due to metamorphism under high temperature (SHERATON *et al.*, 1980).

The highest peak is Mt. Riiser-Larsen which stands 1153 m above sea level (hereafter asl). The mountains have been dissected by glacial erosion to form arêtes or knife ridges in most part (Plate 1A). The main and subsidiary ridges delineate the low-lying basins on the northern and western sides. The bottom of these basins is covered with morainic deposits. Several cirques with small moraine heaps develop on north- or northwest-facing slopes around the main ridges, though no distinct glacial troughs or their remnants can be seen in the mountains. The Richardson Lake is a marginal frozen lake located between the ice sheet and moraine fields. A geomorphological

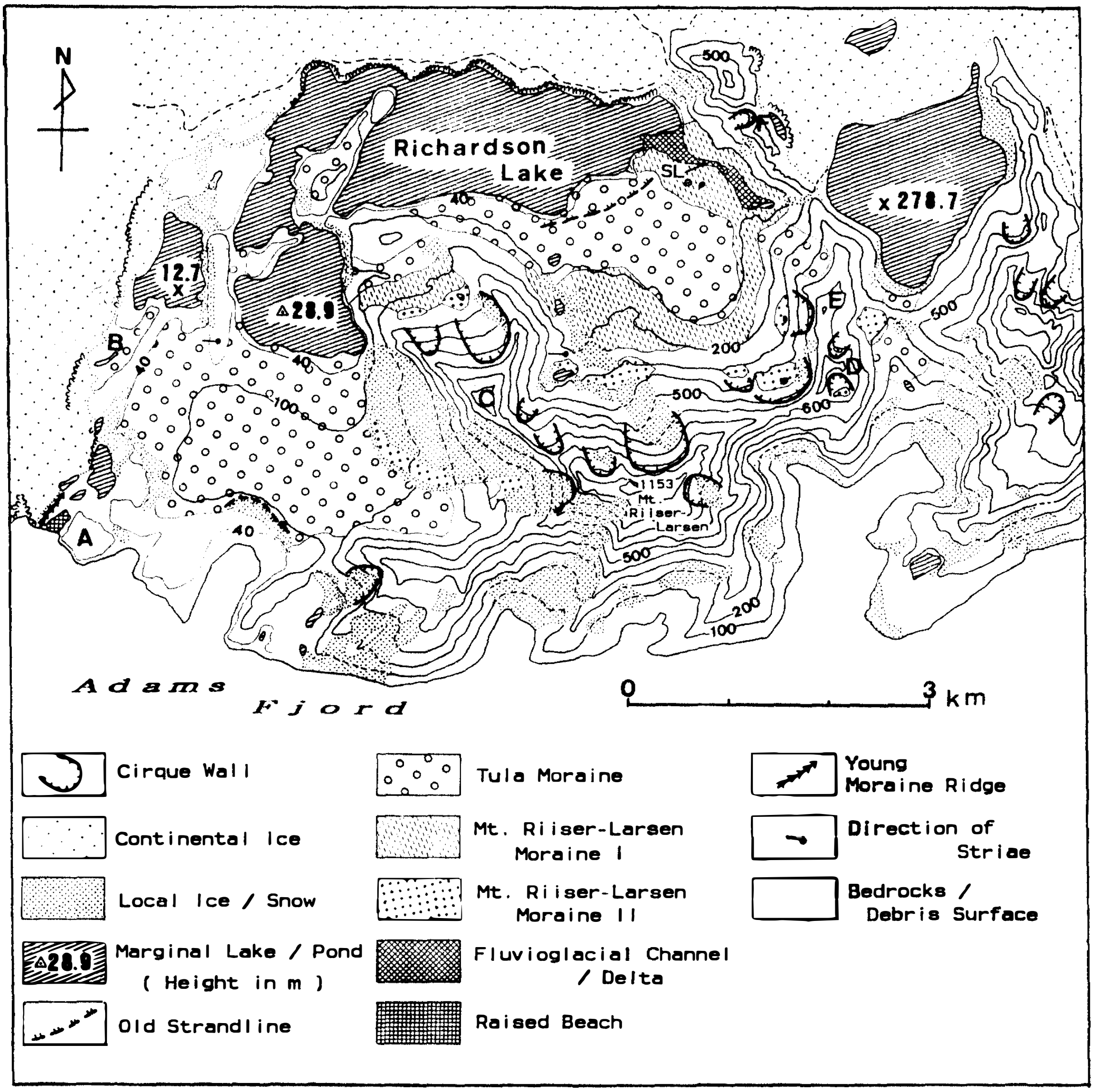

Fig. 2. The geomorphological map of the Mt. Riiser-Larsen area. Contours were compiled from the 1 : 25000 scale topographic map drawn by K. MORIWAKI. A contour line of 40 m is drawn only in the western part. SL: sampling locality of the past lacustrine deposits. A–F: peaks named temporarily for convenience of explanation.

map of this area is shown in Fig. 2. Peaks A to F were named temporarily for explanation of this study.

2. 1. Glacial landforms

On the basis of topographic situation, morphology and degree of weathering, morainic deposits can be divided into three groups; Tula Moraine, Mt. Riiser-Larsen Moraines I and II. The Tula Moraine has been deposited by the continental ice sheet, whereas the origin of Mt. Riiser-Larsen Moraines I and II is local cirque glaciers. On the other hand, ANIYA (1989) has distinguished that another continental till on the northwestern slope of peak E was formed earlier than the present author's Tula Moraine and subdivided Mt. Riiser-Larsen Moraines II into three groups as Alpine Tills II to IV. However, the present author could not find any reliable evidence for such classification of morainic deposits in detail. The classification given in this paper is mostly similar to that by YOSHIDA and MORIWAKI (1983).

The Tula Moraine is the earliest and most extensive glacial deposit in this area, and was named by the present author in connection with the Tula Mountains. This moraine is located mainly on the northern and western slopes of Mt. Riiser-Larsen and its surface is gentle or rather flat (Plate 1B). The Tula Moraine is composed of subangular to subrounded crystalline rock fragments of cobble to boulder size with matrix of coarse grains and silty materials which are poorly lithified. It includes some exotic rocks different from the surrounding bedrocks. Although the maximum thickness of deposits is not known, it is certainly at least more than 20 m in the eastern part of the Richardson Lake. In the area around the western part of the Richardson Lake, the morainic deposits are so thin that the relief of bedrocks is visible (Plate 3A). Glacial striae running E-W were discovered on a hill top of this area. This suggests that the ice sheet had once extended from east to west, which is accordant with the trend of the Adams Fjord. Gentle and undulating surface of the Tula Moraine can be traced up to 110 m asl on the north-facing slope of the main ridge and about 300 m on the west-facing slope. When the present author climbed up to peak D, about 700 m asl, he confirmed the erratics on the slope of about 600 m asl. Higher parts around the summits were covered with thin mantle of debris from shattered bedrocks. The Tula Moraine is probably a ground moraine produced by the continental ice during its stagnant stage.

On the surface of the Tula Moraine, patterned grounds, mostly sorted polygons, develop remarkably (Plate 2A). Their sizes vary from 2 m to 5 m in diameter. Stones surrounding the fine materials are 30 to 100 cm in diameter. A detailed observation reveals that minor polygons and/or stripes about 30 cm in width are formed within the large polygons. A trench about 40 cm deep was dug for examining the structure of these polygons (Plate 2B). The permafrost table is further deeper and the stones of larger polygons take a wedge-like form more than 1 m in depth. The ground up to 10 or 15 cm deep was saturated with meltwater in the afternoon during the investigation. This depth of melting coincides with the bottom of the stones in minor polygons. This indicates that the minor polygons have been formed in association with the present climatic condition.

The stones of the Tula Moraine are sometimes facetted and polished by the wind.

On the other hand, granular disintegration was rarely observed on the stones probably due to their crystalline and hard lithology. It is also notable that flourishing moss and/or lichen cover the stone surfaces all over, even on the stones of polygons. There facts suggest that the Tula Moraine has been exposed for a considerably long period of time.

Mt. Riiser-Larsen Moraine I stands at the foot of mountains and is overlying the Tula Moraine. The surface of Moraine I shows distinctive ridge or hill topography which is sharply rising 10 to several tens of meters from the Tula Moraine (Plates 1B and 3B). Its morphology and topographic situation indicate that Mt. Riiser-Larsen Moraine I is a terminal moraine formed by cirque glaciers coming from the rear mountains. However, only the eastern portion of Moraine I located below peaks E and F has been laid by an ice body spilling from continental ice through a col between peaks E and F. Moraine I is composed of subangular cobbles and boulders. Patterned grounds, poorly sorted polygons, about 1 to 2 m in diameter and low steps like solifluction lobes were recognized on the surface. Uneven and relatively less weathered surface suggests that Mt. Riiser-Larsen Moraine I was formed considerably later than the deposition of the Tula Moraine.

Mt. Riiser-Larsen Moraine II consists of small-scale heaps accumulated on a cirque bottom or at a lower end of cirque wall. It is distributed on the north- and west-facing slopes of mountains, occupying the higher portion than Moraine I (Plate 3B). Some of these heaps are protalus ramparts, which appear small and narrow ridges like embankments composed of loose unsorted debris, mainly angular boulders. Polygons about 1 m in diameter and narrow contraction cracks are sometimes observed on the surface. Moraine II was certainly produced by stagnant cirque glaciers after the formation of Moraine I, in part as protalus rampart.

Along the western coast of this area, another kind of moraine ridge is found (Plate 5B). It extends about several hundred meters from northeast to southwest, parallel to the trend of ice margin. This ridge stands 5 to 10 m in relative height and 50 to 100 m in width, showing a flat surface with a small and elongate pond. The present ice sheet is immediately adjoining the northwestern side of this ridge, where irregular surfaces are formed with small mounds 2 to 3 m high. An ice core covered with morainic deposits was confirmed. The southwestern margin of this ridge is sharply terminated by the coastline. This moraine ridge allows an assumption that a short advancing stage of ice sheet has occurred since the deposition of the Tula Moraine, but it seems minimal. The sequence between this moraine ridge and Moraines I and II was more obscurely understood. It is probable that this moraine ridge has been formed later than Moraine I, judging from the degree of weathering and the situation close by the present ice sheet.

2.2. *Fluvioglacial features*

A remarkable fluvioglacial gully is found in the east of the Richardson Lake. A meltwater channel extends for about 2 km from a small ice body which is spilling over a col between peaks E and F from the continental ice sheet (Plates 4A and 4B). No definite stream was recognized in this channel, though small ponds were not frozen even at night of mid-February. In the upstream area, the channel cuts 3 to 5 m into the surface of Mt. Riiser-Larsen Moraine I and spreads about 50 m in width. Around the mouth, at the eastern margin of the Richardson Lake, a small delta is located and is composed of fine materials, mainly sand with granules. A conspicuous gorge, V-shaped in cross section, is formed between the delta and the broad upstream floor. The gorge cuts into Mt. Riiser-Larsen Moraine I and its depth is 5 to 15 m.

Another fluvioglacial feature is an old strandline in the southeastern part of the Richardson Lake. This appears to be a vague trace of scarp line extending roughly parallel to the general trend of the southern shoreline of the Richardson Lake and its upper edge stands 50 to 60 m asl. The scarp cuts 5 to 10 m into the Tula Moraine. The area below this scarp is occupied by large fragments like lag concentrates. This suggests that the lake water washed away the fine materials of the moraine and that the Richardson Lake would have been more extensively spread with higher water level than at the present time. This expansion of lake has occurred during the stage between the depositions of the Tula Moraine and Mt. Riiser-Larsen Moraine I because a part of Mt. Riiser-Larsen Moraine I interrupts the scarp. A similar feature is observed in the southwestern part of the Tula Moraine close to the coastline, where the upper edge of the scarp stands about 80 m asl.

2. 3. *Coastal landforms*

Most of the coastline in the Mt. Riiser-Larsen area is rocky, often covered with snow drift or sea ice. However, a small beach about 200 m in length appears at the southwestern end of this area (west of peak A). In this beach area, Adelie penguin's rookeries were here and there, where several thousands of penguins were counted during the investigation. Rounded boulders are spread on most parts of the beach. Fine materials can be seen only around the southernmost part of this beach. Here, raised beach and a raised wave-cut bench are observed at 2.5 to 3 m asl (Plate 5A). Toward northeast from this place, a remarkable flat surface is found at about 20 m asl, where rounded or subrounded cobbles and boulders cover the surface (Plate 5B). Coarse sand and granules are underlying boulders without silty materials. This surface is considered a marine boulder pavement. Remnants of shells could not be found in any place of the coastal area.

3. Past Lacustrine Deposits in the Fluvioglacial Valley

Past lacustrine deposits were discovered on the wall of a fluvioglacial channel east of the Richardson Lake. These deposits crop out about 10 m long and 1 m thick on the north wall of a V-shaped gorge at about 50 m asl (Plate 6A). In this paper, these lacustrine deposits are named "Richardson Clay", which is laid on the Tula Moraine and is covered with the deposits of Mt. Riiser-Larsen Moraine I. A schematic cross profile of the outcrop is drawn in Fig. 3. The Richardson Clay is interpretated to be glacial varves on the basis of its structure consisting of numerous pairs of sandy to silty lamina overlain by finer-grained silty to clayey lamina (Plate 6B). The Richardson Clay can be divided into two layers by the color tone and the thickness of lamina, though an unconformity was not clearly defined between the two layers. The upper layer is light-yellowish in color and 40 cm in thickness, where about 12 varves per 1 cm

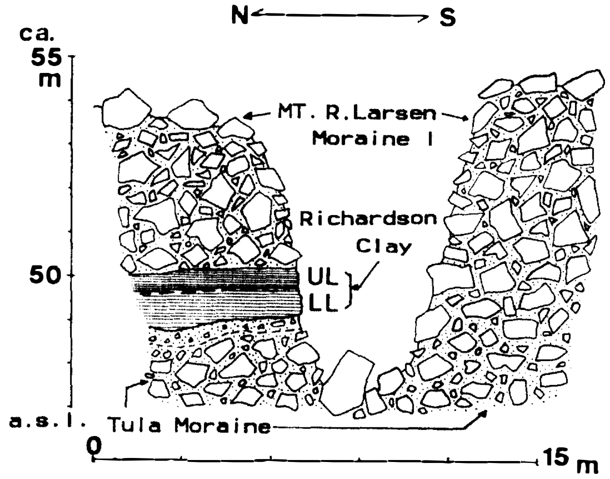

Fig. 3. A schematic cross profile of the fluvioglacial gully. Past lacustrine deposits, "Richardson Clay" are found on the northern wall. On the opposite southern wall, the broken pieces of varves are scattering, though the Richardson Clay is covered with debris from the overlying moraines. UL and LL: the upper and the lower layers of the Richardson Clay, respectively.

thick were counted. On the other hand, the lower layer is dark-brownish and slightly purplish in color and 70 cm in thickness, where about 6 varves per 1 cm thick were counted. Thus, varves are calculated as a total of about 900 pairs.

Biological study of the Richardson Clay has been performed by AKIYAMA *et al.* (1990), who distinguished the remains of protonematoid moss plants covered with diatom shells from the Richardson Clay and pointed out that these moss plants had possibly grown on the lake bottom under the shallow oligohaline (containing a small amount of chloride ion) water. They also reported that the diatom community was composed of at least 2 species of *Achnanthes* and 2 species of *Pinnularia*, and that no difference was found between the upper and the lower layers on the basis of plant remains. As to the mineral elements of the Richardson Clay, HAYASHI and MIURA (1989) detected a large quantity of crystals of pyrite and vivianite which were produced by bacterial processes from phosphate-rich brackish water under a reduced environment. And they inferred that an abundance of phosphate was caused by activities of sea birds such as penguins. They also confirmed that the difference of colors in the two layers was depending on the amount of vivianite content.

These facts indicate that the Richardson Clay was deposited on the bottom of the past Richardson Lake which was connected with the sea. It is also defined that the Richardson Clay was formed during a short term between the depositions of the Tula Moraine and Mt. Riiser-Larsen Moraine I, when the sea level relatively stood at least 50 m higher than the present level. Actually, a narrow depression lower than 40 m asl stretches between the Adams Fjord and the Richardson Lake, passing through a small lake with the height of 12.7 m (see contour drawn in Fig. 2). The old strandline and the marine boulder pavement mentioned previously would have been related to this higher sea level. On the other hand, the fluvioglacial channel and the delta described in the former section were further younger, after the deposition of Mt. Riiser-Larsen Moraine I.

4. Discussion on Glacial History in the Mt. Riiser-Larsen Area

It is very likely that the ice sheet flowing from east to west had once covered the whole of this area at its maximum stage, though the present author could not confirm whether or not the highest part of the mountains had been completely buried under the ice sheet. Afterwards, the ice sheet retreated and exposed the upper portion of mountains. A great thickness and vast extent of the Tula Moraine suggest that the ice sheet had been terminating at the foot of mountains for a long time as noted by ANIYA (1989). During the subsequent warmer stage the ice sheet would have retreated almost to the present position and formed a marginal lake, which was joined with the sea in response to marine transgression up to 50 m or more above the present level. The Richardson Clay was deposited on the bottom of this lake. Subsequently, the sea level lowered and local alpine glaciers have advanced to the mountain foot to lay the terminal moraines, Mt. Riiser-Larsen Moraine I. Then, the alpine glaciers receded close to the crest line, forming Mt. Riiser-Larsen Moraine II during their temporary standstill.

All events mentioned above are relative in age because the present author could not find any data to determine the absolute age. Nevertheless, the sea level represented by the Richardson Clay is fairly high in comparison with that of the other areas in East Antarctica. ADAMSON and PICKARD (1986) reported that the maximum height of the raised beach is 15 m asl in the Vestfold Hills during late Quaternary, and YOSHIDA (1983) estimated that reliable one was below 35 m asl in the areas of the Prince Olav Coast. Only the early Pliocene marine deposits in the Vestfold Hills were assumed to have been formed under a sea level of about 100 m asl (ADAMSON and PICKARD, 1986). For the present, there is no evidence whether the Richardson Clay can be correlative with the early Pliocene deposits. However, it may safely be said that the Richardson Clay had been deposited during the interglacial or interstadial stage prior to the late Wisconsin Glaciation.

Concerning the ice sheet fluctuation, YOSHIDA (1983) pointed that major retreat of the ice sheet took place prior to 30000 years B.P. in the areas of the Prince Olav Coast and PICKARD (1986) revised that the ice sheet expansion was minimal during the Vestfold Glaciation (the late glaciation maximum about 18000 years B.P.). These are quite correlative with the present author's view that the ice sheet has never expanded more extensively than the present position since the deposition of the Tula Moraine. Only the existence of a young moraine ridge indicates a minor advance. This interpretation is rather different from the idea that the East Antarctic ice sheet expanded and buried most part of the present ice-free areas during the Wisconsin Glaciation (STUVIER *et al.*, 1981). The raised beach about 3 m asl along the coast of the Mt. Riiser-Larsen area is considered certainly to have resulted from the postglacial submergence. Probably, the fluvioglacial channel and the delta are also correlated with the Holocene.

5. Summary

The glacial history of the Mt. Riiser-Larsen area is summarized as follows:

(1) Glacial deposits can be divided into three; Tula Moraine formed by conti-

nental ice and Mt. Riiser-Larsen Moraines I and II deposited by local cirque glaciers.

(2) The ice sheet flowing from east to west had once covered almost the whole of this area at its maximum stage. Then, the ice sheet descended from the upper portion of mountains and terminated at the foot of mountains for a long time. The Tula Moraine was deposited as the ground moraine during this standstill of the ice.

(3) During the subsequent warmer stage, probably interglacial or interstadial, the ice sheet would have retreated almost to the present position, creating a marginal lake. The transgression exceeding 50 m above the present level occurred and the sea invaded the inland area along the lower portion, which resulted in joining the sea to the marginal lake with a shallow threshold. The diatomaceous Richardson Clay, past glacial varves, was deposited on the bottom of this lake. This event would have been completed prior to the late Wisconsin Glaciation.

(4) Subsequently, the sea level lowered and local alpine glaciers have advanced to the mountain-foot to lay the terminal moraines, Mt. Riiser-Larsen Moraine I. After a while, the alpine glaciers started to recede close to the crest line, forming Mt. Riiser-Larsen Moraine II during their temporary standstill.

(5) There was no evidence that the ice sheet has expanded more extensively than the present state since the deposition of the Tula Moraine except a small moraine ridge standing at the southwestern end, suggesting a minimal advance.

(6) The raised beach at about 3 m asl, and the fluvioglacial channel with the delta have been formed probably during the Holocene.

Further investigation on the present bottom deposits of the Richardson Lake and the dating of the Richardson Clay should be required in the future.

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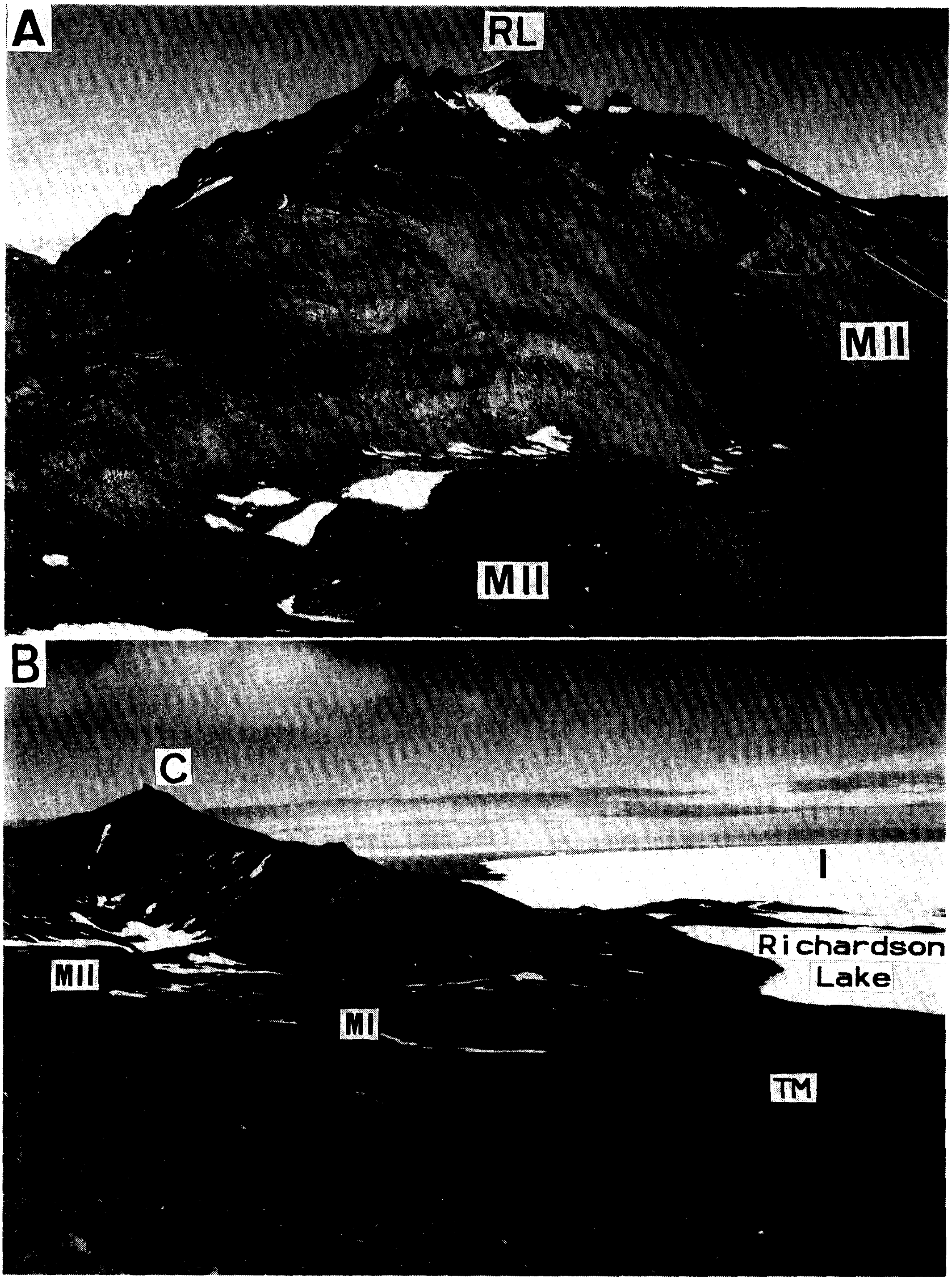

Plate 1. A: An alpine feature around the summit of Mt. Riiser-Larsen looking from peak E. RL; peak of Mt. Riiser-Larsen, MII; Mt. Riiser-Larsen Moraine II.

B: The widespread Tula Moraine at the northern foot of Mt. Riiser-Larsen. Looking westward from peak E. I; Ice sheet, C; peak C, TM; Tula Moraine, MI and MII; Mt. Riiser-Larsen Moraines I and II, respectively.

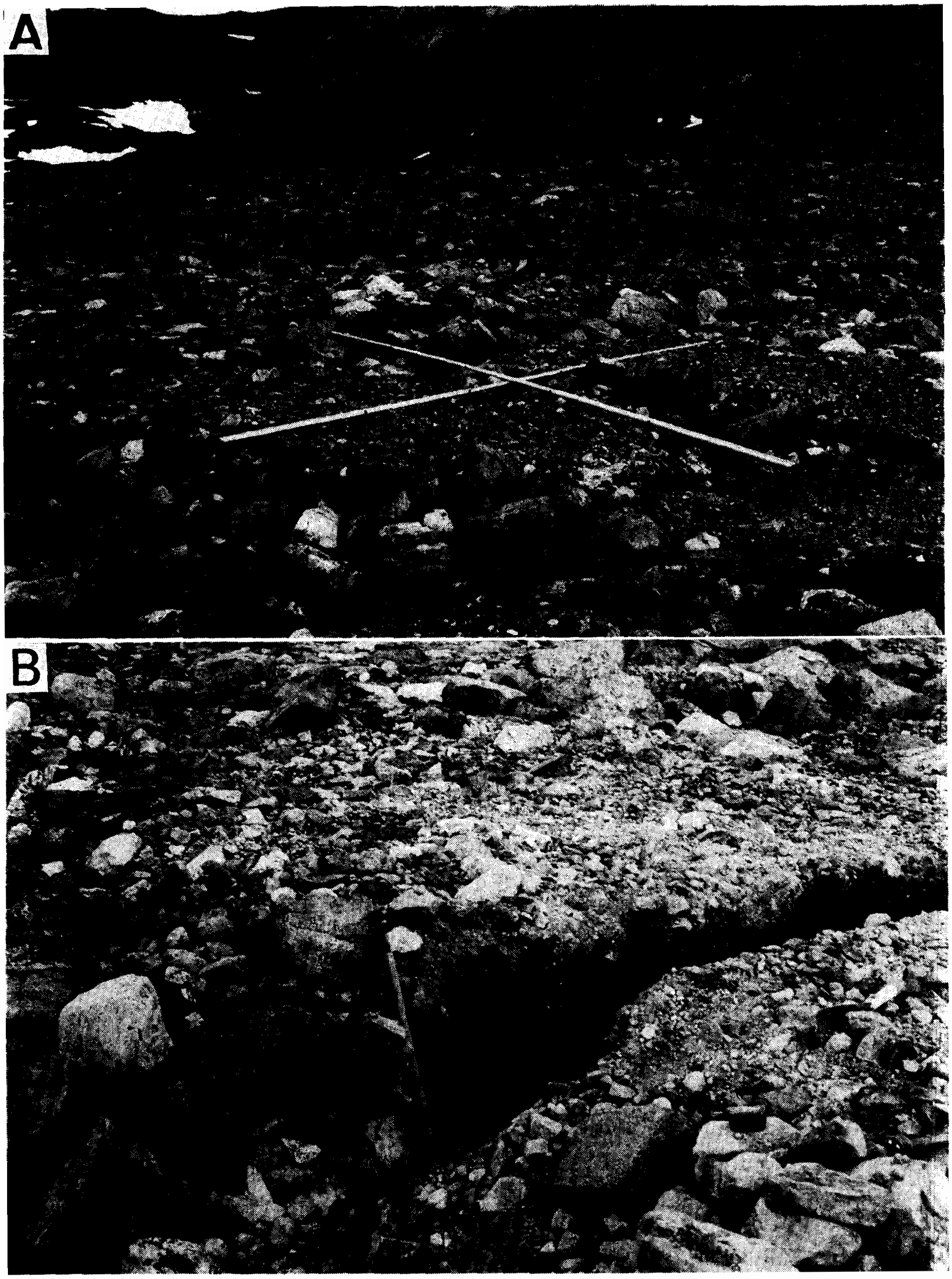

Plate 2. A: A large sorted polygon (about 4 m in diameter) on the surface of the Tula Moraine.
B: A view of the trench across a polygon. A measure is 50 cm long.

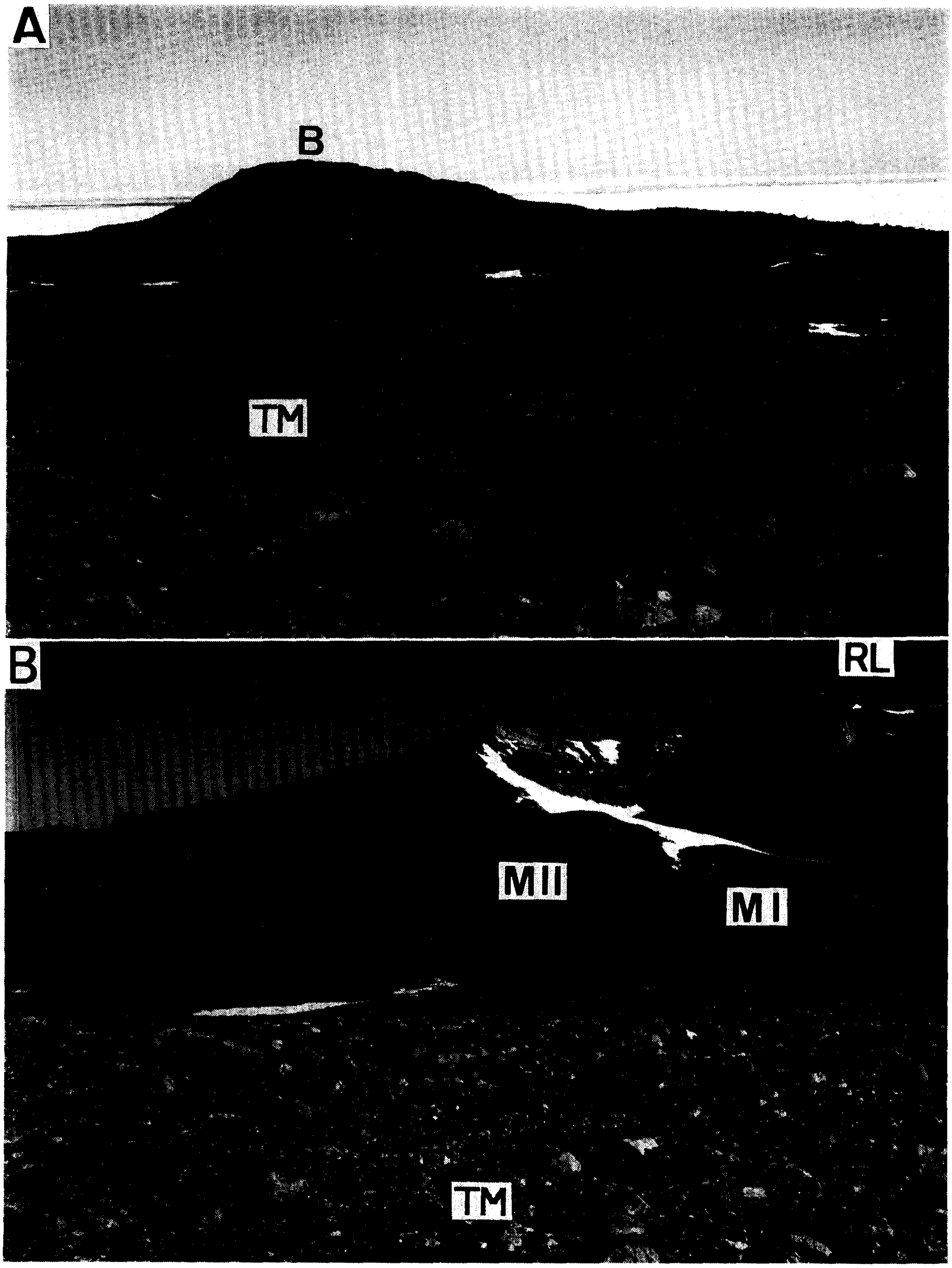

Plate 3. A: A veneer of the Tula Moraine covering bedrock relief in the western part of the Mt. Riiser-Larsen area. Low hills of the foreground and peak B consisting of bedrocks are thinly covered with erratics. B; peak B, TM: Tula Moraine.

B: Local cirque moraines of the northern slope of Mt. Riiser-Larsen. RL; Peak of Mt. Riiser-Larsen, TM; Tula Moraine, MI and MII; Mt. Riiser-Larsen Moraines I and II, respectively.

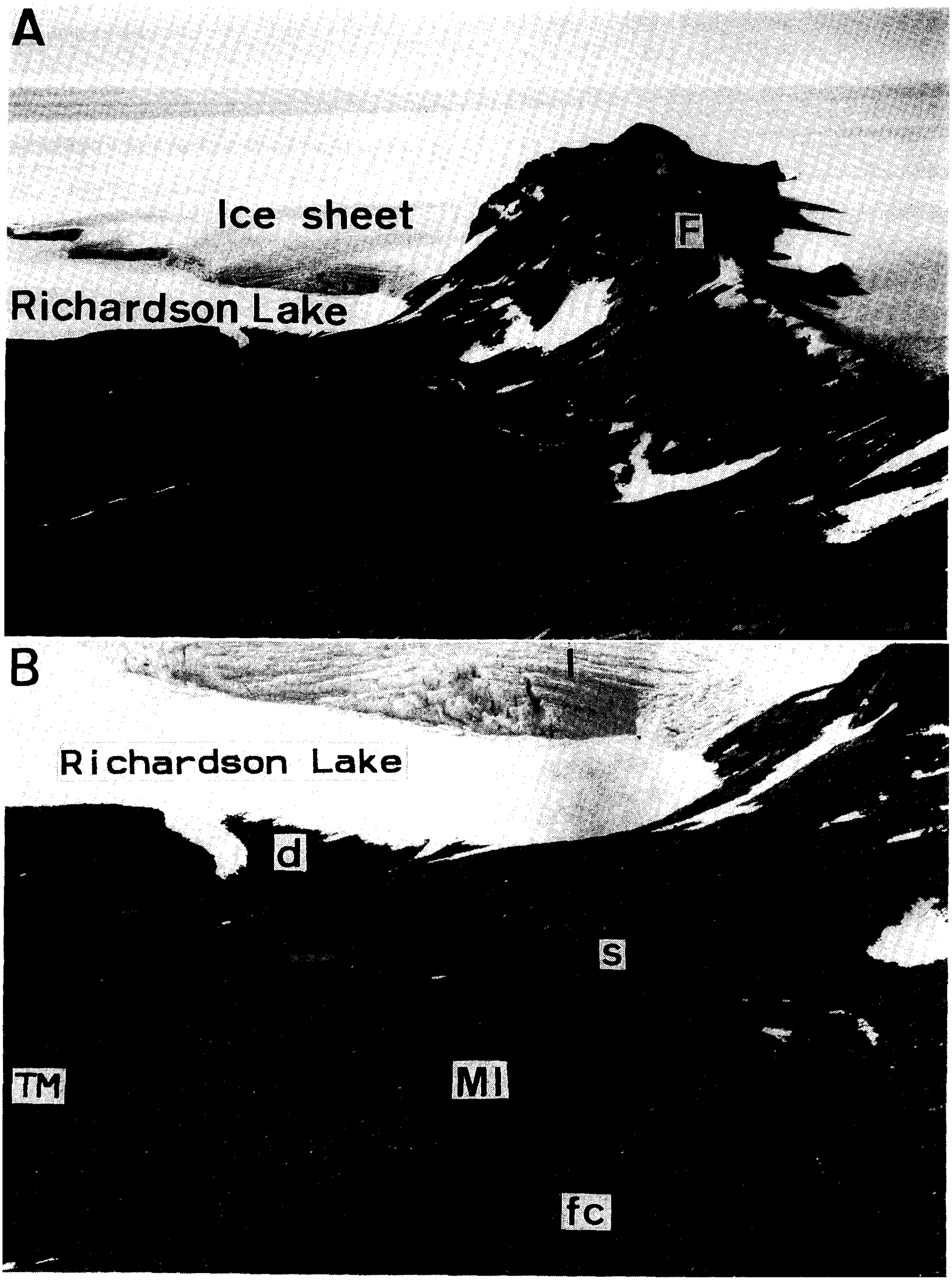

Plate 4. A: A view of the fluvioglacial channel and the Richardson Lake looking toward northwest from peak E. F; peak F.
B: A close-up view of the fluvioglacial channel. I; Ice sheet, d; delta, fc; fluvioglacial channel, TM; Tula Moraine, MI; Mt. Riiser-Larsen Moraine I, s; sampling locality of the Richardson Clay.

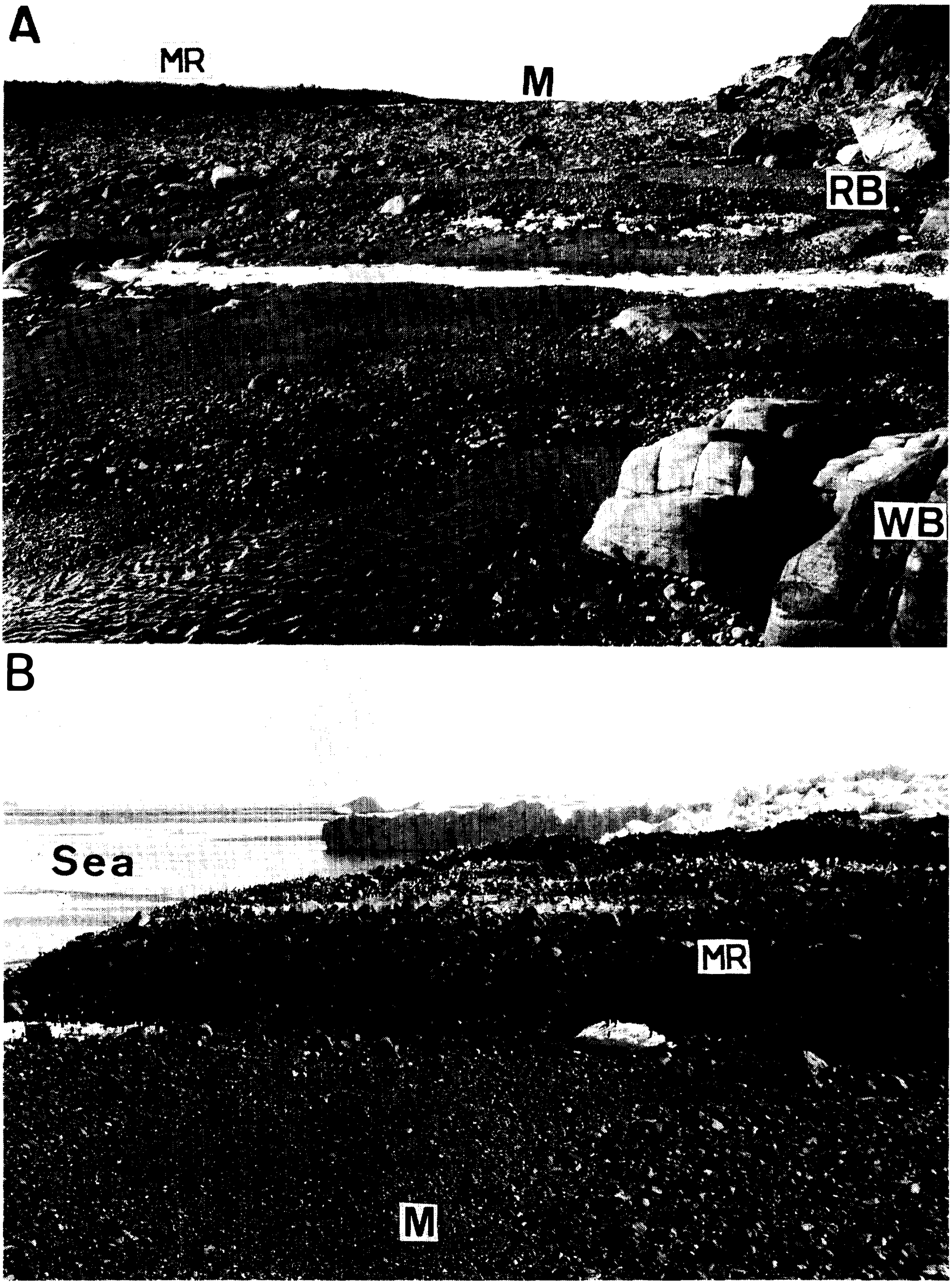

Plate 5. A: *A raised beach in the westernmost part of the Mt. Riiser-Larsen area. The foreground is a part of sea. A horizontal line of snow cover coincides with the high tidal shoreline. WB; raised wave-cut bench, RB; raised beach 2.5 to 3 m asl, M; marine boulder pavement about 20 m asl, MR; young moraine ridge at the margin of the ice sheet.*

B; *A marine boulder pavement about 20 m in altitude and a young moraine ridge in the western part of the Mt. Riiser-Larsen area. M; marine boulder pavement, MR; young moraine ridge at the margin of the ice sheet.*

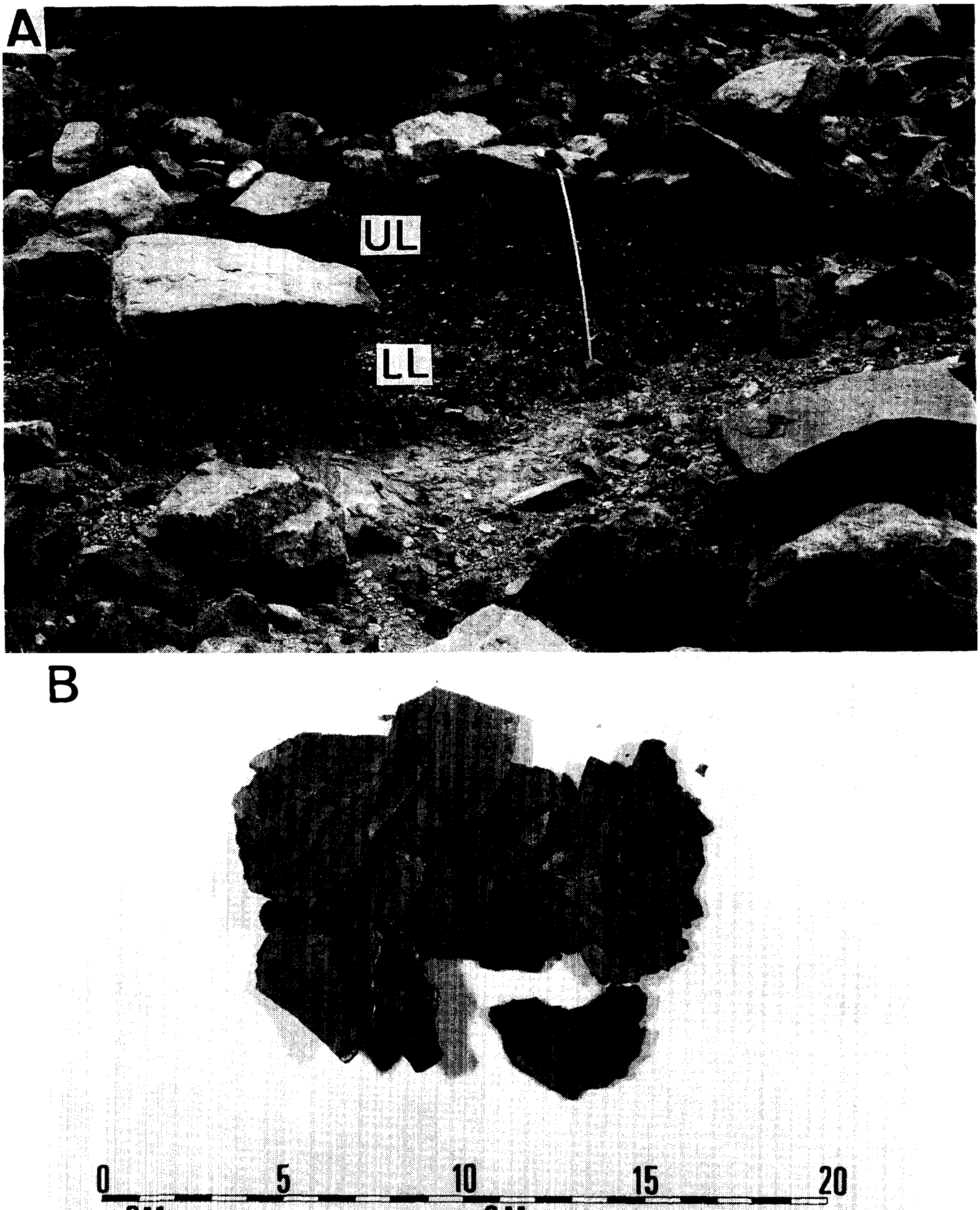

Plate 6. *A: An outcrop of the Richardson Clay on the northern wall of fluvioglacial gully. A scale is about 1 m long. UL and LL; the upper and the lower layers of the Richardson Clay, respectively.*
B: Glacial varves of the upper layer of the Richardson Clay.