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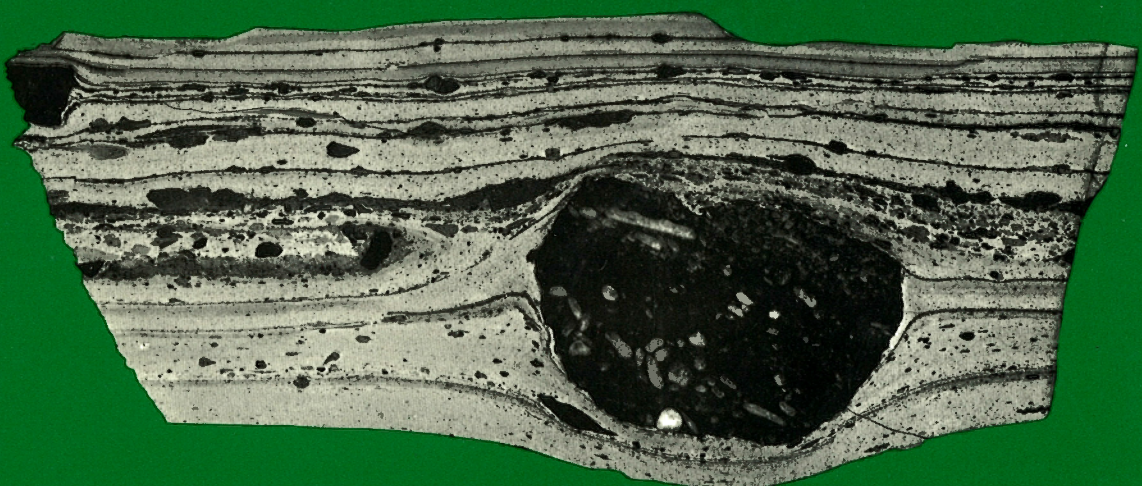
THE ICE BROOK FORMATION AND POST-RAPITAN, LATE PROTEROZOIC GLACIATION, MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES

J.D. Aitken



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Cover

Dropstones and till pellets in laminated greenish grey shale, from the type section of the Stelfox Member of the Ice Brook Formation. The till pellets are 1 or 2 mm in diameter and slightly darker than the shale matrix. They are concentrated in the second-lowest lamina and in the clast-rich lamina (probably a debris-flow deposit) in contact with the top of the large dropstone. Specimen collected by G.M. Ross. The largest stone is 54 mm long. ISPG photo 3478-1.

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PREFACE

Division of most of the post-Rapitan, Upper Proterozoic succession of the Mackenzie Mountains into formal, mappable units had been accomplished by 1973, but the sedimentology and paleoclimatic and tectonic significance of this part of the geological column were not fully worked out at that time. This report concentrates on the stratigraphy and sedimentology of the interval comprising the Twitya, Keele and Sheepbed formations. Of particular interest and significance are the relations at the basinward margin of the carbonate platform on which the Keele Formation was deposited. The Ice Brook Formation and its Durkan, Delthore and Stelfox members are erected to facilitate description and mapping of these newly described deposits. The 'Tepee dolostone', a distinctive, thin unit of laminated dolomite, resting unconformably on glaciomarine diamictites, is similar to "cap dolomites" that rest on Upper Proterozoic glacial deposits elsewhere in the world. The establishment of a second, post-Rapitan, Late Proterozoic glaciation is particularly significant.

This study has potential economic significance. First, the deep-water mudrocks of the Twitya and Sheepbed formations are potential hosts to stratabound base-metal deposits; basinward of the Keele carbonate platform, they are separable only through recognition of the Ice Brook Formation. Second, because unconformities on carbonate formations are always of interest to base-metal prospectors, documentation here of previously unrecognized unconformities brings a new exploration target to light.

Elkanah A. Babcock
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PRÉFACE

La plus grande partie de la succession du Protérozoïque supérieur qui est postérieure au Rapitan, dans les monts Mackenzie, avait été divisée en unités formelles qu'il est possible de cartographier dès 1973; or l'importance sédimentologique, paléoclimatique et tectonique de cette partie de l'échelle stratigraphique n'était pas entièrement connue à cette époque. Le présent rapport se penche sur la stratigraphie et la sédimentologie de l'intervalle qui englobe les formations de Twitya, de Keele et de Sheepbed. On s'intéresse notamment aux liens qui existent à la marge côté bassin de la plate-forme carbonatée sur laquelle s'est déposée la formation de Keele. La formation d'Ice Brook et ses membres de Durkan, de Delthore et de Stelfox sont établis en vue de faciliter la description et la cartographie de ces dépôts nouvellement décrits. La 'dolomie de Tepee', une unité mince et caractéristique de dolomie laminée qui repose en discordance sur des diamictites glaciomarines, ressemble aux "chapeaux de dolomie" qui couronnent des dépôts glaciaires du Protérozoïque supérieur ailleurs dans le monde. L'établissement de l'existence d'une deuxième glaciation du Protérozoïque supérieur, postérieure au Rapitan, revêt une importance particulière.

L'étude pourrait avoir des répercussion économiques. En premier lieu, les pélites d'eau profonde des formations de Twitya et de Sheepbed pourraient contenir des gisements de métaux communs qui sont limités à une seule unité stratigraphique; du côté bassin de la plate-forme carbonatée de Keele, seule la présence de la formation d'Ice Brook permet de distinguer ces deux formations. En second lieu, puisque les discordances sur les formations carbonatées attirent toujours l'attention des prospecteurs de métaux communs, la découverte de discordances auparavant inconnues met à jour une nouvelle zone d'interêt.

Elkanah A. Babcock
Sous-ministre adjoint
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Abstract

Glacial influence on deposition of the Sayunei and Shezal formations of the Upper Proterozoic Rapitan Group has been well documented. Glacial deposits that rest unconformably on the Keele Formation, more than a kilometre higher, have not been formally described previously. The Ice Brook Formation is erected to comprise the glacially influenced diamictites and some closely associated, nonglacial strata also characterized by diamictite. The Ice Brook provides a means of separating the lithologically similar Twitya and Sheepbed formations outboard of the Keele depositional platform.

Three members are established. At the base, the Durkan Member is a bouldery olistostrome that is traced back to its source at the margin of the lower of two carbonate platforms of the Keele Formation. The Delthore Member consists mainly of mudrocks and sandstones of slope origin. The Stelfox Member, at the top, consists mainly of diamictite, which bears evidence of glaciomarine origin. It oversteps the two lower members to rest unconformably upon the Keele.

No extrabasinal clasts have been found in the Stelfox Member. A glaciomarine origin is attributed on the basis of dropstones, "till pellets", rare striated clasts, interbeds of fine grained, laminated strata, and the absence of steep paleotopography that could have given rise to voluminous debris flows.

The 'Tepee dolostone', which rests directly upon the Stelfox Member and unconformably upon the Keele Formation, is a "cap dolostone" extraordinarily similar to those that cap Upper Proterozoic glacial deposits elsewhere. It is described in some detail, but its origin remains enigmatic.

The greatest significance of the documentation of a second level of Upper Proterozoic glacial deposits in the Mackenzie Mountains, additional to the well documented Rapitan deposits, may lie in global correlation. Isotopic age determinations directly constraining the times of Late Proterozoic glaciation are few or none, both in North America and in other continents. It was thus impossible to demonstrate to which, if either, of the two glaciations recorded in some other continents the supposedly single glaciation (Rapitan) of northwestern Canada corresponded. Although it is as yet too early to claim that correlation has been established, the record of two Late Proterozoic glaciations, rather than a single one, in northwestern Canada strongly suggests correlation with the two glaciations (e.g., Sturtian and Marinoan of Australia) recorded elsewhere.

Résumé

L'influence des glaces sur l'accumulation des formations de Sayunei et de Shezal, dans le groupe de Rapitan du Protérozoïque supérieur, est bien documentée. Les dépôts glaciaires qui reposent en discordance sur la formation de Keele, plus d'un kilomètre plus haut, n'ont pas été décrits formellement auparavant. La formation d'Ice Brook comprend les diamictites glaciaires et quelques strates non glaciaires qui leur sont étroitement associées et qui se caractérisent elles aussi par la présence de diamictite. Cette formation permet de séparer les formations lithologiquement semblables de Twitya et de Sheepbed, qui se trouvent du côté externe de la plate-forme sédimentaire de Keele.

Trois membres sont définis. Le membre inférieur, celui de Durkan, est un olistostrome blocailleux qui provient de la marge de la plate-forme inférieure des deux plates-formes carbonatées de la formation de Keele. Le membre de Delthore se compose principalement de pélites et de grès en provenance du talus. Le membre supérieur, celui de Stelfox, comprend surtout de la diamictite, qui présente des indices d'une origine glaciomarine. Il forme un dépôt transgressif discordant sur les deux membres inférieurs pour enfin reposer en discordance sur la formation de Keele.

On n'a pas trouvé de clastes qui proviennent de l'extérieur du bassin dans le membre de Stelfox. La présence de concrétions calcaires, de "granules de till", de rares clastes striés et d'interstrates laminées, à grain fin, ainsi que l'absence d'une paléotopographie fortement inclinée qui pourrait avoir provoqué des coulées de débris volumineuses, témoignent d'une origine glaciomarine.

La 'dolomie de Tepee' repose directement sur le membre de Stelfox et en discordance sur la formation de Keele; c'est un "chapeau de dolomie" qui présente une ressemblance stupéfiante avec les chapeaux qui couronnent des dépôts glaciaires du Protérozoïque supérieur ailleurs. On le décrit en détail, mais son origine demeure obscure.

L'importance primordiale d'un deuxième niveau de dépôts glaciaires du Protérozoïque supérieur dans les monts Mackenzie, en plus des dépôts bien connus du Rapitan, pourrait reposer dans leur utilité aux fins de la corrélation mondiale. Les datations isotopiques qui limitent directement l'âge de la glaciation du Protérozïque supérieur sont peu nombreuses ou inexistantes, tant en Amérique du Nord qu'ailleurs. Il a donc été impossible de déterminer laquelle des deux glaciations, le cas échéant, qui sont reconnues sur certains autres continents correspond à la présumée unique glaciation (Rapitan) dans le nord-ouest du Canada. Bien qu'il soit encore trop tôt pour affirmer qu'il y a corrélation, l'existence, dans le nord-ouest du Canada, de deux glaciations au Protérozoïque supérieur, plutôt que d'une seule, porte à croire fortement qu'il y a effectivement corrélation avec les deux glaciations (p. ex., Sturtien et Marinoen en Australie) qui sont reconnues ailleurs.

Summary

In the Mackenzie Mountains, glacial influence on deposition of the Upper Proterozoic Sayunei and Shezal formations of the Rapitan Group has been well documented. Until recently, these have been considered the only Proterozoic glacial deposits of the region. This report documents the evidence for glacial origin of Upper Proterozoic diamictites occurring one kilometre or more stratigraphically above the Rapitan. These younger diamictites previously were thought to be the result of mass flow processes.

The name Ice Brook Formation is proposed to include the post-Rapitan glaciomarine diamictites, nonglacial diamictites in close stratigraphic association, and intervening mudrocks and sandstones of slope origin. The glacial deposits rest unconformably upon the platformal carbonate and clastic strata of the Keele Formation and, in the paleobathymetric basin to the southwest, separate the deep-water clastic strata of the Twitya Formation from similar strata of the overlying Sheepbed Formation.

Three members are established for the Ice Brook Formation. The diamictite of the Durkan Member, at the base, is an olistostrome of boulders and large blocks of carbonate rock in a muddy and sandy matrix. It has been traced back to its source at a breakaway scarp, at the margin of the lower of two carbonate platforms that make up most of the Keele Formation. Tens of metres thick near the breakaway scarp, it thins to as little as 2.8 m in the off-platform basin, before passing from view downdip to the southwest.

The Delthore Member, separating the two members of diamictite, consists of bedded siltstone and mudstone, turbiditic sandstone and quartzite, and minor diamictite. Evidence of post-depositional slumping is common. The member is 25 to 60 m thick in the basin, and much thinner on the off-platform slope, except immediately adjacent to the margin of the depositional platform of the Keele Formation, where it may approach 200 m.

The Stelfox Member consists mainly of sheets of diamictite inferred to be of glaciomarine origin, with minor interbeds of sandstone and laminated mudstone and siltstone in which dropstones are fairly common. It is thickest (up to 308 m) above the former slope, thins northeastward and disappears above the outer Keele platform, and thins basinward to as little as 4 m, before passing from view downdip to the southwest. Stones in the diamictite have their source almost entirely in the carbonate strata of the underlying Keele Formation. The siliciclastic strata of the Keele were apparently unlithified when glaciation took place. A glaciomarine origin is adduced on the bases of the sheet-like geometry of diamictite layers and the presence of till pellets, rare striated clasts, and interbeds of fine grained, laminated strata with dropstones. Although much of the diamictite may be till resedimented as debris flows, the setting precludes origin of the diamictites by purely gravity-driven, debris-flow processes (cf. Durkan Member) in the absence of glaciation. No steep paleotopography, from which debris flows could have descended onto the shallow-water Keele sediments, can be demonstrated.

The stratigraphic relationships of the Ice Brook Formation and its members are complex. The Durkan and Delthore members are confined to the paleobathymetric slope and basin southwest of the depositional platform of the Keele Formation, and overlie the deep-water mudrocks of the Twitya Formation with apparent conformity. They are the facies equivalents of the lower and middle parts, respectively, of the Keele Formation. In the basin, the glaciomarine diamictites of the Stelfox Member overlie the Delthore Member with apparent conformity, but above the Keele platform, the Durkan and Delthore are missing, and the Stelfox diamictites rest upon a basinward-sloping erosional surface at the top of the Keele Formation.

A classical, laminated, microcrystalline "cap dolostone", informally known as the 'Tepee dolostone' and formerly assigned to the Keele Formation, overlies the diamictites of the Stelfox Member. To the northeast, it overlaps the zero-edge of the Stelfox to rest unconformably upon the

Keele. Of interest because of its relationship to immediately preceding glacial deposits, like that of "cap dolostones" in Africa and Australia, the 'Tepee dolostone' is described in some detail for the first time, but its origin remains conjectural.

The greatest significance of the documentation of a second level of glacial deposits in the Mackenzie Mountains, in addition to those of the well-known Rapitan Group, may lie in global correlation of Late Proterozoic glaciations. First, the glacial deposits of the Rapitan Group lie stratigraphically below, but those of the Ice Brook Formation stratigraphically above the lowest occurrence of metazoan fossils of Ediacaran type. Second, although it is as yet too early to claim that correlation has been established, the record in northwestern Canada of two Late Proterozoic glaciations, rather than a single one, strongly suggests correlation with the two glaciations (e.g., Sturtian and Marinoan of Australia) recorded elsewhere.

Sommaire

Dans les monts Mackenzie, l'influence des glaces sur l'accumulation des formations de Sayunei et de Shezal du groupe de Rapitan, qui remontent au Protérozoïque supérieur, est bien connue. Jusque récemment, ces dépôts étaient considérés comme les seuls dépôts glaciaires protérozoïques de la région. Le rapport présente des indices de l'origine glaciaire des diamictites du Protérozoïque supérieur qui se rencontrent à un kilomètre ou plus, stratigraphiquement, au-dessus du Rapitan. Ces diamictites plus jeunes étaient auparavant considérées comme des sédiments d'écoulements en masse.

La formation d'Ice Brook, telle que proposée, comprend les diamictites glaciomarines postérieures au Rapitan, des diamictites non glaciaires qui sont en étroite association stratigraphique et des pélites et grès interposés en provenance du talus. Les dépôts glaciaires reposent en discordance sur les strates carbonatées et clastiques de plate-forme de la formation de Keele et, dans le bassin paléobathymétrique au sud-ouest, ils séparent les strates clastiques d'eau profonde de la formation de Twitya des strates semblables de la formation susjacente de Sheepbed.

La formation d'Ice Brook se divise en trois membres. La diamictite du membre de Durkan, à la base, est un olistostrome de blocaux et de gros blocs de roches carbonatées emballés dans une matrice sableuse et boueuse. Il a été retracé à enrobés sa source qui est à un escarpement formé par décollement, à la marge de la plate-forme inférieure des deux plates-formes carbonatées constituant la plus grande partie de la formation de Keele. Son épaisseur va de plusieurs dizaines de mètres près de l'escarpement à 2,8 m dans le bassin au large de la plate-forme, avant de disparaître de vue vers l'aval-pendage, au sud-ouest.

Le membre de Delthore, qui sépare les deux membres de diamictite, se compose d'aleurite et de pélite interstratifiés, de grès turbiditique et de quartzite, avec un peu de diamictite. On y trouve de fréquents indices de décrochements post-sédimentaires. Son épaisseur va de 25 à 60 m dans le bassin mais est beaucoup plus faible sur le talus au large de la plate-forme, sauf en bordure de la plate-forme sédimentaire de la formation de Keele, oû elle pourrait s'approcher de 200 m.

Le membre de Stelfox se compose principalement de nappes de diamictite d'origine vraisemblablement glaciomarine, avec des interstrates mineures de grès et de pélite et d'aleurite laminés qui contiennent des concrétions calcaires relativement abondantes. Il atteint son épaisseur maximale de 308 m au-dessus de l'ancien talus, puis s'amincit vers le nord-est pour disparaître au-dessus de la plate-forme externe de la formation de Keele; il s'amincit aussi vers le bassin pour n'atteindre que 4 m d'épaisseur, avant de disparaître de vue vers l'aval-pendage, au sud-ouest. Les pierres qui se trouvent dans la diamictite proviennent presque toutes des strates carbonatées de la formation sous-jacente de Keele. Les strates silicoclastiques de la formation de Keele n'ont pas dû être lithifiées à l'époque de la glaciation. La géométrie stratiforme des couches de diamictite et la présence de granules de till, de rares clastes striés et d'interstrates laminées, à grain fin, qui

contiennent des concrétions calcaires, indiquent une origine glaciomarine. Bien qu'une bonne partie de la diamictite puisse être du till remanié par suite de coulées de débris, le milieu dans lequel elle se rencontre exclut la possibilité qu'elle résulte entièrement de coulées de débris gravitaires (cf. membre de Durkan) en l'absence de glaciation. On n'y a pas reconnu de paléotopographie fortement inclinée que les coulées de débris pourraient avoir dévalisée avant de recouvrir les sédiments d'eau peu profonde de la formation de Keele.

Les liens stratigraphiques qui unissent la formation d'Ice Brook et ses membres sont complexes. Les membres de Durkan et de Delthore se rencontrent uniquement sur le talus paléobathymétrique et dans le bassin au sud-ouest de la plate-forme sédimentaire de la formation de Keele, et ils reposent vraisemblablement en concordance sur les pélites d'eau profonde de la formation de Twitya. Ce sont des faciès équivalant aux parties inférieure et intermédiaire, respectivement, de la formation de Keele. Dans le bassin, les diamictites glaciomarines du membre de Stelfox reposent vraisemblablement en concordance sur le membre de Delthore; or, les membres de Durkan et de Delthore sont absents au-dessus de la plate-forme de Keele, et les diamictites du Stelfox reposent sur une surface d'érosion au sommet de la formation de Keele, laquelle surface est inclinée vers le bassin.

Un "chapeau de dolomie" classique, microcristallin et laminé, auquel on donne le nom officièux de 'dolomie de Tepee' et qui était auparavant considéré comme faisant partie de la formation de Keele, repose sur les diamictites du membre de Stelfox. Au nord-est, il chevauche le bord zéro du Stelfox pour reposer en discordance sur la formation de Keele. Il présente un intérêt en raison de son lien avec les dépôts glaciaires qu'il recouvre, tout comme les "chapeaux de dolomie" en Afrique et en Australie; on le décrit en détail pour la première fois, mais son origine demeure hypothétique.

L'importance primordiale d'un deuxième niveau de dépôts glaciaires dans les monts Mackenzie, en plus des dépôts bien connus du groupe de Rapitan, pourrait reposer dans l'utilité de ces sédiments aux fins de la corrélation mondiale des glaciations du Protérozoïque supérieur. En premier lieu, les dépôts glaciaires du Groupe de Rapitan se situent stratigraphiquement sous l'occurrence la plus basse de métazoaires fossiles du type édiacarien, tandis que ceux de la Formation d'Ice Brook en sont stratigraphiquement au-dessus. En second lieu, bien qu'il soit encore trop tôt pour affirmer qu'il y corrélation, la présence, dans le nord-ouest du Canada, de deux glaciations au Protérozoïque supérieur, plutôt que d'une seule, laisse croire fortement qu'il y a effectivement corrélation avec les deux glaciations (p. ex. Sturtien et Marinoen en Australie) qui sont reconnues ailleurs.

INTRODUCTION

Late Proterozoic glaciation is recorded on all continents except Antarctica. The deposits of at least two glaciations, separated by thick successions of nonglacial sedimentary rocks, are recorded in Africa, Australia, Greenland and parts of Asia (Chumakov, 1981; Hambry and Harland, 1981). Where more than two glacial levels are identified, it is not entirely clear whether or not part of the record is that of multiple *advances* of a single glaciation, or that of multiple *glaciations*. The problem is exemplified by the multiple advances of continental ice sheets during the Pleistocene; in an ancient record, these might or might not be seen as a single glaciation.

In Europe, a single Late Proterozoic glaciation (Varangerian, Laplandian) is recognized. In North America, until recently, no locality was known to have more than one level of Late Proterozoic glacial deposits (e.g., Gaskiers in Newfoundland; Kingston Peak/Mineral Fork/Pocatello in western U.S.A.; Toby in southern British Columbia; near-basal Windermere Supergroup in northeastern British Columbia; Rapitan in the northwestern Cordillera). Given the small number and poor stratigraphic distribution of reliable isotopic age determinations, it was impossible to correlate this glacial record with that of other continents, or even to know whether the glacial deposits in British Columbia and those in the N.W.T. and Yukon belonged to the same, or different events.

The discovery in central Mackenzie Mountains (Fig. 1a, b) of clear evidence of a second, stratigraphically higher level of glacial (glaciomarine) deposits, separated from the Rapitan glacials by more than one kilometre of nonglacial strata, demands a report. Because existing stratigraphic nomenclature does not distinguish these glacial deposits, the Ice Brook Formation and its three members are proposed here. The new formation provides a means of separating the lithologically similar Twitya and Sheepbed formations in the basin outboard of the multi-story carbonate platform of the Keele Formation (Figs. 2, 16).

Previous work

The first published reference to ancient glacial deposits in the northern Cordillera was that of Ziegler (1959). He believed that these deposits, now assigned to the Rapitan Group, were of early Paleozoic age.

Gabrielse (1967) recognized the several hints of glacial influence in the depositional record of the younger Proterozoic succession of the northern Cordillera, but presented the possibility of gravity-induced, mass transport processes as an alternative explanation for the diamictites. He was also the first to extend the Windermere "System" (Supergroup) north of 60 degrees (Gabrielse, 1972). He again recognized the evidence suggestive of glacial influence in deposition of the lower and middle Rapitan Group (now Sayunei and Shezal formations). In 1973 Gabrielse, with Blusson and Roddick, provided the first comprehensive descriptions of Proterozoic formations in the Mackenzie Mountains, and created most of the stratigraphic nomenclature now in use (Gabrielse et al., 1973). They embraced a glacial explanation for the dropstones and diamictites of the Rapitan Group, and recognized a prominent marker unit, now known as the 'Tepee dolostone', at the top of the Keele Formation. Much of their data on the Rapitan Group was drawn from the thesis work of Upitis (1966).

Blusson (1971) published a geological map and a brief account of the geology of the Sekwi Mountain map area. His map unit 8, separating the shaly formations now known as Twitya and Sheepbed, was described as a "distinctive buff-orange weathering marker", comprising "... orange-brown weathering locally calcareous slaty argillite in the lower part and interbedded orange-buff weathering, fragmental dolomitic limestone and sandy dolomite in the upper half." Juxtaposition of Blusson's map with that of Gabrielse et al. (1973) immediately to the east shows that Unit 8 is continuous with the Keele Formation as mapped by the latter, an arrangement subsequently confirmed in the field by the author.

The author, with Macqueen and Usher (1974) provided descriptions of some of the formations of interest here. These descriptions have been useful despite the primitive understanding at that date of the Proterozoic stratigraphy of the Mackenzie Mountains. With D.G. Cook, the author mapped the formations of interest in an area covering two 1:250 000-scale map sheets, and noted the apparent southwestward disappearance of the carbonate strata of the Keele Formation into deep-water, siliciclastic equivalents (Aitken and Cook, 1974a).

Young (1976) provided a thorough and detailed sedimentological study of the glacially influenced lower and middle Rapitan Group (now Sayunei and Shezal formations). Among other observations, he reported dropstones, striated clasts and aggregate sediment pellets (till pellets). He also suggested correlation of the Rapitan glacials with the Toby Conglomerate (tillite) of southeastern British Columbia. In a study of the Tindir Group of east-central Alaska, Young (1982) correlated diamictite-bearing units of the upper Tindir with similar units of the Rapitan Group. He correlated a unit above these with the Keele Formation of Mackenzie Mountains, and discussed the possibility of a "Keele glaciation". Later, he again speculated on a "second glaciation" (Young, 1984).

Yeo (1978, 1981) carried out the most detailed and extensive study of the Rapitan Group (Sayunei and Shezal formations) to date, amply documenting the evidence for periglacial deposition. He presented a model for deposition of the iron formation that involved glacial influence.

Eisbacher (1976, 1977, 1978, 1981, 1985) progressively refined the tectonics, stratigraphy and sedimentology of the Windermere Supergroup in the northern Cordillera. He accepted a glacial origin for the Middle Rapitan (Shezal) in 1976, and glacial influence in deposition of the Lower Rapitan (Sayunei) in 1977. He also named the divisions of the Rapitan (Eisbacher, 1978). He concluded (op. cit.) that most Shezal diamictites were not ground moraine but marine dropstone-diamictites, and that the gross stratification of the Shezal reflected variation in the position of the (floating) ice-front. He recognized a breakaway scarp at the edge of the Keele platform, and olistoliths derived therefrom (1978). His informal designation of the prominent, top-of-Keele marker unit as the 'Tepee dolostone' has been widely followed.

Eisbacher (1981) further analyzed the tectonic setting of the northern Windermere Supergroup, emphasizing fault control of the basin of deposition. He re-emphasized the proglacial setting of Sayunei deposition, and saw in the Shezal Formation both glaciomarine diamictite and nonmarine tillite, the latter resting, at one locality, on a polished pavement. He emphasized the abrupt termination of Rapitan glaciation, and drew attention to the puzzle of the limestones (basal Twitya) that in some areas rest directly on Shezal diamictites. He inferred contemporaneous growth faulting during deposition of the Keele Formation and noted an abrupt transgression that terminated deposition of the carbonate strata that characterize the Keele. This transgression superposed upon the Keele the dark, deep-water mudrocks of the Sheepbed Formation, which he regarded as the highest Windermere formation of the region. He was clearly puzzled (op. cit., p. 28, 29) by some exposures near Bluefish Creek in the Sayunei Range that contain peritidal and subtidal carbonate rocks below a succession of mudrocks with diamictites. He related these units to the Keele Formation, and referred to the diamictites as olistostromes, concluding "... there is not much direct evidence favouring a glacial origin for the chaotic deposits associated with the Keele Formation." He suggested, however, that the olistostromes were possibly a response to a eustatic drop due to glaciation elsewhere. Re-mapping of the Bluefish Creek area by the writer in 1984 revealed that the bedded carbonate strata assigned to the Keele Formation by Eisbacher are instead limestones of the lower Little Dal Group, resting on quartzites of the Katherine Formation. They are locally separated from the overlying, deep-water mudrocks and turbidites of the Twitya Formation by diamictites of the Shezal Formation. Diamictites of the Ice Brook Formation, here interpreted as being of glaciomarine origin, overlie the Twitya.

In his most recent paper on the subject, Eisbacher (1985) saw the Windermere Supergroup of the North American Cordillera in terms of three, major, shoaling-upward cycles (*in* Mackenzie Mountains terms, Sayunei–Shezal, Twitya–Keele, and Sheepbed–Backbone ranges). He also suggested that these cycles might correlate with similar successions in Australia and China. The Keele-level diamictites were again seen as olistostromes, again possibly related to glacial drawdown. In this paper, Eisbacher (1985) treated the Rapitan Group as comprising the Sayunei and Shezal formations only, his earlier extension (1977) of the Rapitan to formations as high as the Keele having failed to attain general acceptance.

Fritz (1980) reported the opinion of members of the Precambrian–Cambrian Boundary Working Group that "carbonate clasts" (diamictites) in Map unit 8 of Blusson (1971) were tillites, and that the question of a "second, young tillite" merited further study.

The author (1988) documented the existence in the Mackenzie Mountains of four, Upper Proterozoic, post-Sheepbed formations (Gametrail, Blueflower, Risky, Ingta) that had been unappreciated until then [the Ingta is currently regarded as Proterozoic, but post-Ediacaran (G.M. Narbonne, pers. comm., 1989)]. this work completed the description of the stratigraphic column between a major "sub-Cambrian" unconformity and glacial deposits at the Keele (here documented) and Rapitan levels. Simultaneously, uppermost Proterozoic units in the eastern Wernecke Mountains were found to correspond to the Gametrail, Blueflower and Risky formations (Narbonne et al., 1985). With recognition of two shallowing upward, carbonate-capped cycles youger th an any previously described in the region, the post-Rapitan record of the

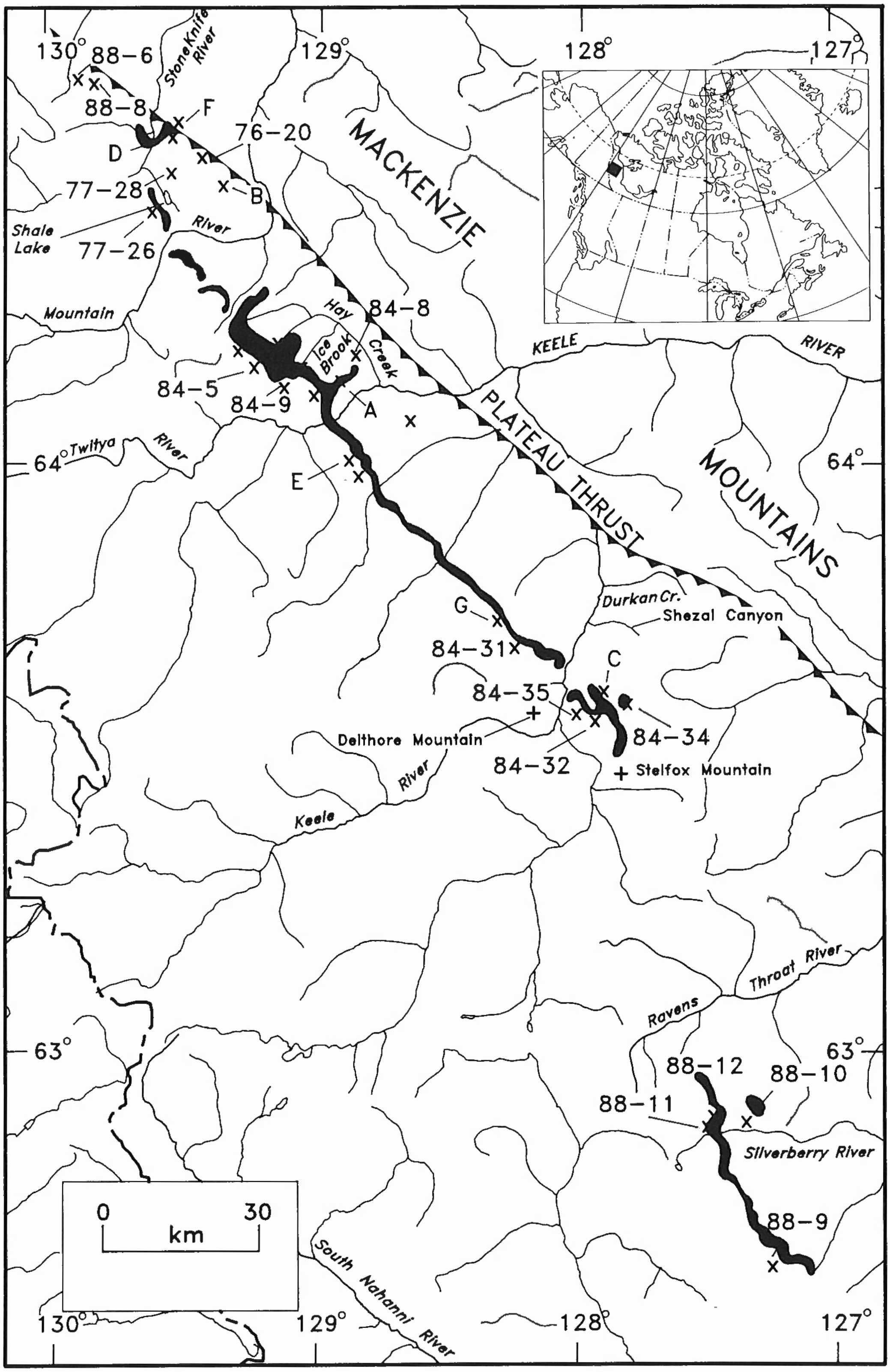

Figure 1a. Index map, showing the known distribution of the Ice Brook Formation and identifying localities cited in the text. The full designation of all sections includes the author's identifier; e.g., 84AC-9.

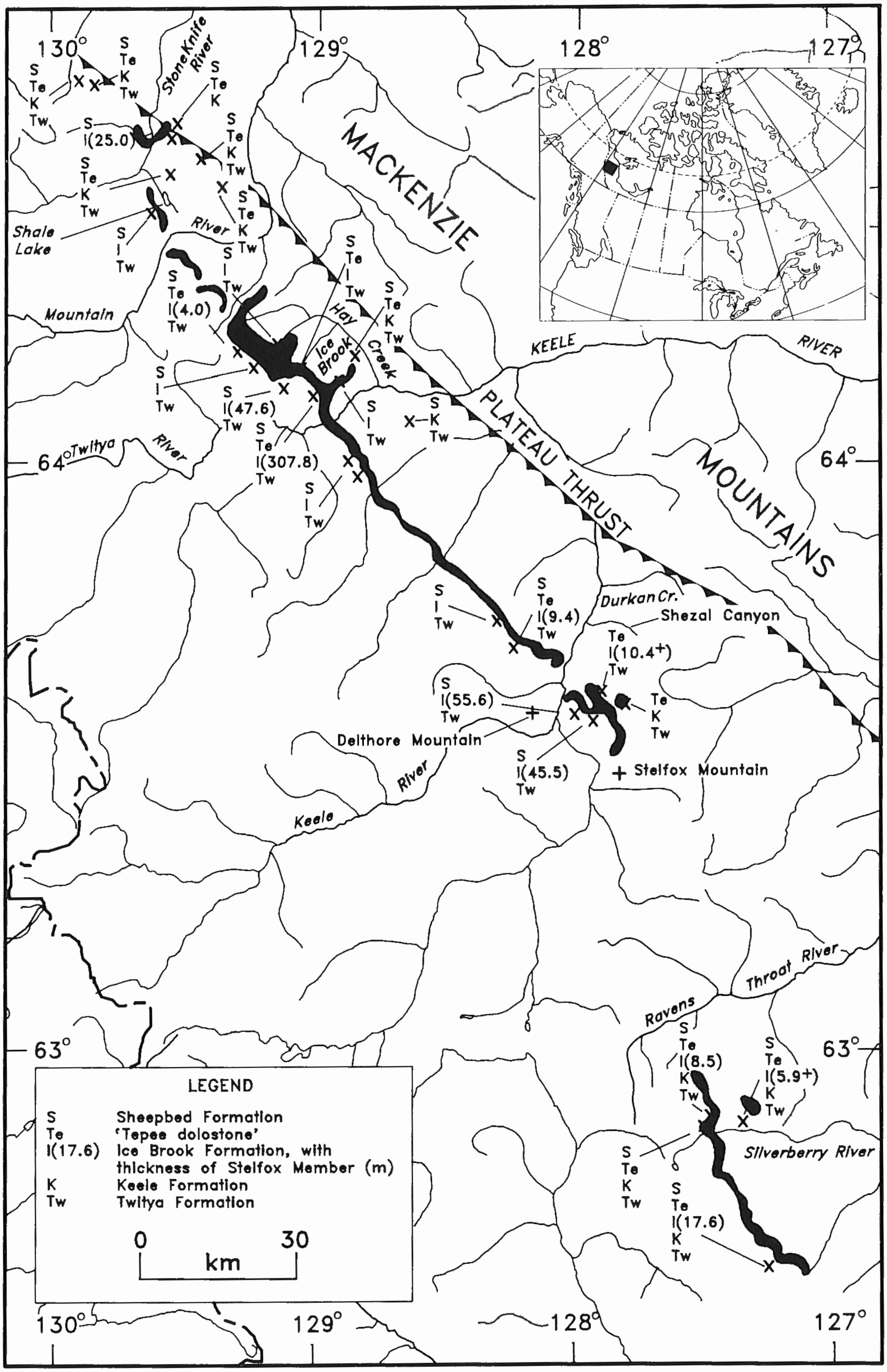

Figure 1b. Index map, showing summary stratigraphy at the localities examined.

region was seen in four Grand Cycles: Twitya–Keele, Sheepbed–Gametrail, Blueflower–Risky and Ingta. The writer (1988) further documented regional truncation of the upper three of these cycles by an unconformity beneath the Backbone Ranges Formation. Thus, Eisbacher's (1985) third, Sheepbed–Backbone Ranges cycle is illusory.

History of present investigation

The author's initial involvement with the formations considered here commenced with geological mapping at the scale of 1:250 000 in the late 1960s and early 1970s (Aitken and Cook, 1974a, b; Aitken et al., 1982). This work led him to share the widely held, perhaps unanimous opinion that the Shezal diamictites are indeed of glaciomarine origin, and that a glacial influence is recorded in the Sayunei Formation. Later, in the course of mainly stratigraphic studies, serendipitous encounters with diamictites in unexpected places led to a conviction that the Mackenzie Mountains held a record of a post-Rapitan glaciation:

- In 1976 and 1977, diamictites strongly resembling nearby Pleistocene tills were encountered near Shale "Palmer" Lake (Fig. 1b), at about the stratigraphic level of the Keele Formation. These diamictites are distinct from, and overlie the olistostrome recognized by Eisbacher (1978, 1981).

- In 1979, a helicopter landing on an anomalous-looking section of the Keele (near Section 88AC-12) led to the discovery of diamictite composed entirely of clasts of Keele Formation, resting on shallow-water carbonate rocks of the Keele and overlain by the top-of-Keele marker, the 'Tepee dolostone'. The position of this diamictite, directly atop platformal carbonate strata, raised immediate doubts that it could be of debris-flow origin.

- Later in 1979, during the visit of the Precambrian–Cambrian Boundary Working Group (IUGS/ISSC) to the Mackenzie Mountains, bad weather forced the group, contrary to plan, to examine a section in Sekwi Mountain map area where the Keele is missing. In place of the Keele are diamictites with Keele-like stones, and unequivocal dropstones (Map unit 8 of Blusson, 1971). Several of the visitors interpreted these as tillites and recommended their further study (see Fritz, 1980).

Other commitments precluded a specific study of the Keele-level diamictites until 1984. In that year, about 20 days were devoted to the description and mapping of the diamictites of both glacial and olistostromal origins, and their splendidly exposed relations to the Keele carbonate platforms. As a result of that work, it was decided that, because the diamictite-bearing unit provides a record of a second Late Proterozoic glaciation, and the only means of separating the Sheepbed from the lithologically similar Twitya Formation in the off-platform region, it merited naming. Accordingly, the Ice Brook Formation and its Durkan, Delthore and Stelfox members are erected here.

Acknowledgments

D.G. Cook shared some of the early puzzlement over the stratigraphy of the glacial deposits, and made his field notes and air-photo annotations available to the author.

The labour of fieldwork was cheerfully shared by C. Steudler and T. Weiss in 1976, C. Black, R. Sandau and K. Sharman in 1977, and S. Dawson (Hermanson), C. Viau and R. Booker in 1979. M. Collins stoically shared the rigours and isolation of the strenuous field season of 1984, as did L. Gayle that of 1988.

Various colleagues at the Institute of Sedimentary and Petroleum Geology made substantial and deeply appreciated contributions to preparation of the manuscript. Photographs of specimens and prints from field photos were prepared by B.C. Rutley and W. Sharman. P.J. Neelands computer-drafted the maps. J.W. Thomson provided valued guidance during the author's preparation of figures.

The report benefitted from careful reviews by G.M. Ross and C.W. Jefferson.

UPPER PROTEROZOIC ('WINDERMERE') STRATIGRAPHY OF THE MACKENZIE MOUNTAINS

Base of Windermere

Most authors have treated the base of the Windermere Supergroup in the Mackenzie Mountains as the base of the Rapitan Group (e.g., Gabrielse, 1972; Eisbacher, 1981, 1985; Jefferson and Ruelle, 1986; Jefferson and Parrish, 1989). Because the uniting feature of Windermere deposition from the Purcell and Rocky mountains of British Columbia to the Wernecke and Ogilvie mountains of the Yukon has been universally taken to be its association with rift tectonism, it may be more conducive to clear understanding to place that boundary lower, at the first appearance of rift-associated deposits. That level (Fig. 2) would be the base of the Coates Lake Group (Jefferson, 1978; Jefferson and Ruelle, 1986), and a major unconformity (Aitken, 1981). This is not to deny that the base of the Rapitan Group is generally unconformable; however, the widespread occurrence of faults of the rift array, truncated by the base of the Rapitan (Aitken and Cook, 1974b), additionally demonstrates that the onset of rifting predates the Rapitan. Finally, the only isotopic dates constraining the age of the Windermere Supergroup in the northern Cordillera are the dates of 750 to 780 Ma from basic intrusions (Armstrong et al., 1982; Jefferson and Parrish, 1989) and volcanic rocks (Roots and Parrish, 1988), both considered to be related to the rifting event first recorded by strata of the Coates Lake Group in the central Mackenzie Mountains and the correlative Mount Harper group of the Ogilvie Range, Yukon Territory.

Coates Lake Group

The Coates Lake Group (Jefferson and Ruelle, 1986; Jefferson and Parrish, 1989; "Copper cycle" of Aitken, 1981) rests unconformably on the Mackenzie Mountains Supergroup, of platformal aspect (Fig. 2). In contrast to the broad persistence of the underlying supergroup and its constituent units, maps of the Coates Lake show it confined to a number of rather small "basins" or "embayments", inferred to be fault bounded (Eisbacher, 1977; Jefferson, 1978; Ruelle, 1982; Jefferson and Ruelle, 1986). This terminology ignores the evidence presented by Yeo (1981) for the distribution of the Rapitan Group in one, virtually continuous trough. Given that the distribution of the Coates Lake Group mimics that of the Rapitan, and that both are inferred to have been deposited in fault-bounded basins, a reasonable interpretation is that the Coates Lake was deposited in an earlier development of the Rapitan rift depression. The successively greater breadth of deposition, from Coates Lake Group through Sayunei and Shezal formations, is consistent with rift-basin sedimentation. Following this view, the "basins" or "embayments" are instead the exposed northeastern corners or elbows of a narrow trough of somewhat jagged outline.

The Coates Lake Group displays marked variation in facies (Jefferson and Ruelle, 1986). The Thundercloud Formation at the base consists of repeated, metre-scale cycles of largely redbed siliciclastics grading up to peritidal carbonates. The overlying Redstone River Formation consists of coarse fanglomerates at the embayment margins grading into red muds and continental evaporites in the embayment centres. The Coppercap Formation records limestone deposition in a restricted marine or lacustrine setting, partly in deep water.

Sayunei Formation

At the base of the Rapitan Group, the Sayunei and more localized Mount Berg formations are reported to be in unconformable contact (Fig. 2) with the

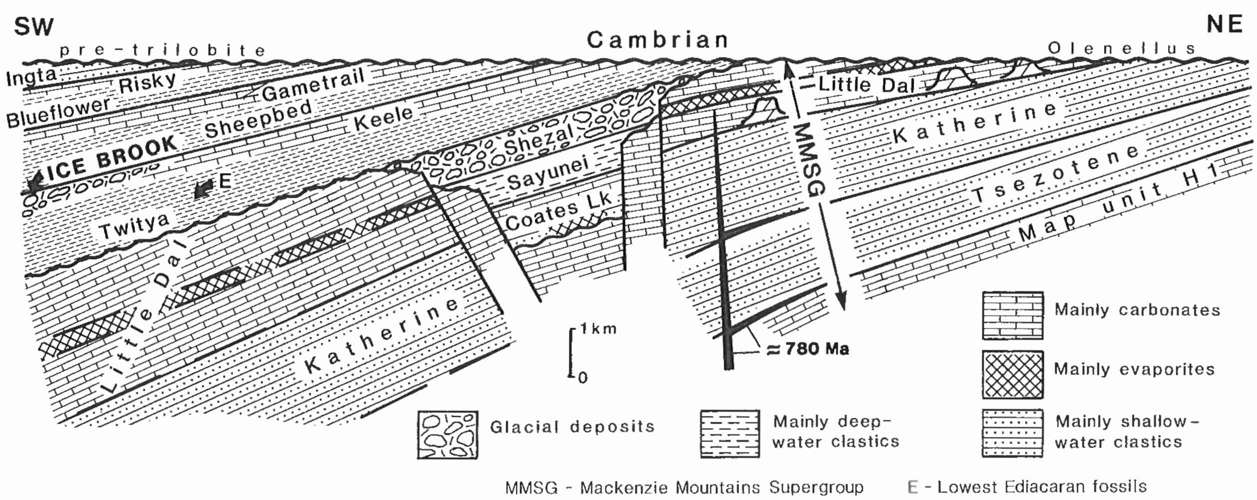

Figure 2. Stratigraphic relations of Upper Proterozoic formations in the central Mackenzie Mountains.

underlying Coppercap Formation (Jefferson and Parrish, 1989). The Sayunei, up to 600 m or more in thickness, consists of reddish mudrocks, largely of deep-water origin, with interbedded sandstones and conglomerates emplaced by turbidity current and mass-flow processes. Glacial dropstones are widely reported. Thick Sayunei Formation tends to coincide with thick Coates Lake Group, but to overstep the Coates Lake to lie on older formations (Fig. 2). Yeo et al. (1978) and Aitken et al. (1981) rejected, but Jefferson and Parrish (1989) supported the arguments presented by Helmstaedt et al. (1979) for an intra-Sayunei folding event.

Shezal Formation

The Shezal Formation, up to 800 m in thickness, consists mainly of sheets of diamictite (Fig. 3), with a subordinate and usually minor content of bedded to laminated sandstone and mudstone. The diamictites are reddish in some areas, greenish grey in others, and yellowish elsewhere. The matrix surrounding the pebble- to (rare) boulder-sized clasts is sandy, silty, and commonly dolomitic. Striated and flatiron-shaped clasts are widely reported. The proportions of the various rock types represented as clasts (phenoclasts) are highly variable and clearly relatable to the rocks immediately underlying the Rapitan Group at any point. For instance, near Shezal Canyon on Keele River (Fig. 1b), the Shezal rests on the Upper Carbonate formation of the Little Dal Group, and at least 99 per cent of the clasts are relatable to that unit.

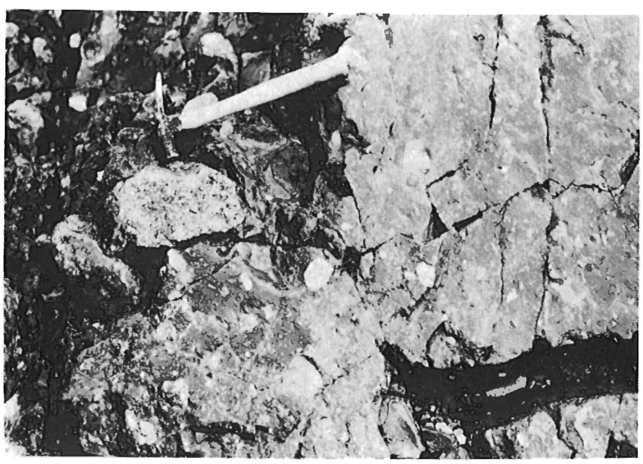

Figure 3. Glaciomarine diamictite of the Shezal Formation at Section 88AC-8. The hammer head rests on a rare, extra-basinal boulder of syenite. All other stones in the outcrop are of sedimentary rock types. ISPG photo 3257-3.

In contrast, in the frontal Mackenzie Mountains west of longitude 131 degrees, the base of the Rapitan (there Shezal Formation) lies upo n beds low in the Little Dal, and downcuts rapidly northeastward toward contact with the Katherine Group; cobbles and boulders of Katherine quartzite are prominent, and clasts of diabase, from numerous dykes and sills that cut the Katherine and older units, are much more common than elsewhere. In that area, as elsewhere, the Shezal has overstepped the Sayunei outward from the axis of the rift-depression.

Twitya Formation

The Twitya Formation is up to 900 m thick (Fig. 4), much more extensive than the Coates Lake and Rapitan groups, and not known to thicken markedly over their depocentres. Together with the overlying Keele Formation, it forms the first of the depositional Grand Cycles that characterize the terminal Proterozoic of the Mackenzie Mountains. The Twitya consists mainly of dark grey mudrocks of deep-water origin, with a subordinate content of mainly thin bedded, turbiditic sandstones. In its upper part, near the transition to Keele Formation, upward-coarsening and -thickening packets of sandstone as coarse as grit occur, as do rare, small-scale channels filled with grit and pebble conglomerate. These coarser sandstones tend to be green and chamositic. At three levels of Section 88AC-6 (Fig. 1a), the sandstone is hematitic, possibly recording subaerial weathering of chamosite. Eisbacher (1978, 1981, 1985) reported the presence locally, at the base of the Twitya, of dark grey, fetid, thin bedded to laminated limestones with a fine grained, particulate fabric, which he interpreted as turbidites. From these, he inferred the existence of contemporaneous carbonate banks and shoals. The author's observations confirm that these basal Twitya limestones are indeed widespread, but discontinuous. The range of Ediacaran macrofossils has recently been extended downward into the Twitya Formation (Hofmann et al., in press).

Keele Formation

The Keele Formation (Figs. 2, 4, 5), succeeding the Twitya conformably and gradationally, figures prominently in this report. Up to 600 m thick, it consists of limestone, dolomite and a highly variable content of siliciclastic strata. Many of the limestone units are difficult to interpret because of destructive recrystallization. The best preserved carbonate fabrics are found in beds that were dolomitized early, prior to

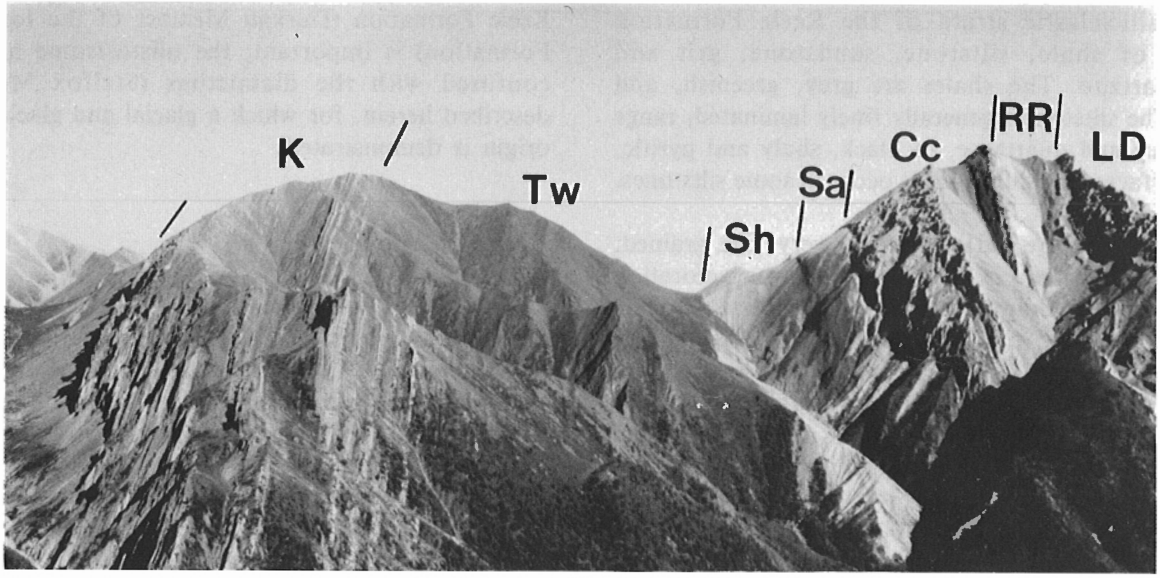

Figure 4. Upper Proterozoic succession 11 km north-northwest of locality "D" (see Figure 1a). LD, Little Dal Group (upper). Coates Lake Group: RR, Redstone River Fm.; Cc, Coppercap Fm. Rapitan Group: Sa, Sayunei Fm.; Sh, Shezal Fm.; Tw, Twitya Fm.; K, Keele Fm. ISPG photo 1221-5.

the recrystallization of limestones that probably resulted from deep burial. Many of the dolomite beds with well preserved textures are found at the top of shallowing-upward cycles of decametre scale, and appear to have resulted from "dorag" dolomitization (Badiozamani, 1973) at exposure surfaces. Elsewhere,

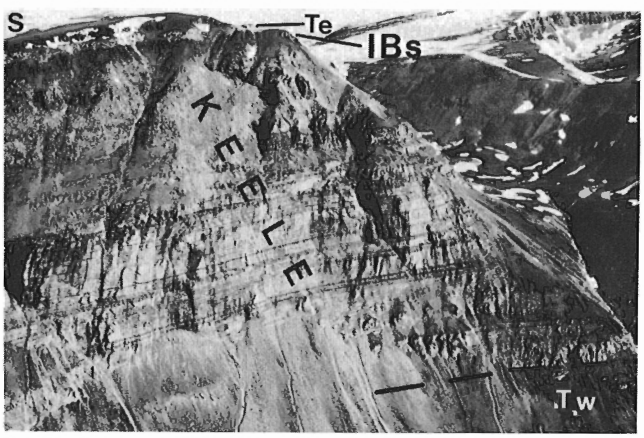

Figure 5. Type section of the Keele Formation (88AC-9; Figure 1a). The Keele conformably overlies the Twitya Formation (Tw) and is overlain unconformably by the dark-weathering Stelfox Member of the Ice Brook Formation (IBs), followed by pale outcrops of the 'Tepee dolostone' (Te), and dark mudrocks of the Sheepbed Formation (S). ISPG photo 3257-5.

alteration to fine and medium crystalline dolomite, presumably through deep burial, has destroyed depositional textures. Locally, primary texture is preserved in silicified patches. Among the primary calcareous sediments of the Keele, the most prominent are cryptalgal (microbial) laminite and the flakestones resulting from disruption of the microbial laminae. Prominent also are intraclast grainstone and, less so, ooid grainstone. Lime mudstone is relatively unimportant, but black, fine crystalline limestone, interpreted as being neomorphic after lime mudstone, is a distinctive, though minor, component. Flatstone conglomerates are rare. Algal stromatolites are present locally, but are of simple form and offer little promise for biostratigraphy.

In much of the region, there is little evidence of an apron of deeper water limestone fringing the Keele platform, but such a facies does occur locally. At Section 84AC-8 (Fig. 1a), a thin (76 m) but complete section of the Keele Formation, capped by the 'Tepee dolostone', is exposed. The basal 44 m consists of ribbon-bedded and millimetre-laminated, dark grey, fetid lime mudstone, with minor thin and medium beds of matrix-supported, debris-flow breccia. This clearly is a slope facies. An overlying unit with simple stromatolites records shallowing, and is in turn overlain by 26 m of parallel-laminated, quartz sandstone, taken to be the end-of-Keele, platform-margin wedge observed elsewhere.

The siliciclastic strata of the Keele Formation consist of shale, siltstone, sandstone, grit and orthoquartzite. The shales are grey, greenish, and black. The siltstones, generally finely laminated, range from grey and quartzose, to black, shaly and pyritic. Slide surfaces and slump-folds occur in some siltstones.

The arenites are varied. Green, very fine grained, quartzose sandstone is common; the green coloration may be due to chamosite. Coarser, yellow to white sandstones, some of them very pure, range up to medium grained. Their primary structures are commonly obscure, but where observable, tend to be tabular and tangential crossbeds, in sets up to 30 cm thick. Small-scale trough crosslamination also occurs.

At several sections, 76AC-20, 84AC-8, 88AC-6 and 88AC-10 (Fig. 1a), the uppermost Keele Formation consists of siliciclastic strata up to 113 m thick, with only a few carbonate beds. The sandstones vary from thin, graded beds among siltstone and black shale, in part with various sole markings, through thick beds with high-relief foresets, to beds with straight-crested, and in part flat-topped ripple marks, to gritty beds with unimodal, tabular crosslamination in ten-centimetre sets. These characteristics suggest environments ranging from storm deposition below fair-weather wave base, through high-energy platform, to tidal flat and estuarine and/or fluvial. This siliciclastic complex, which by its discontinuous distribution may occupy broad, possibly erosional depressions, appears to be a platform-margin wedge in the sense of Van Wagoner et al. (1988) and Sarg (1988), deposited during an end-of-Keele lowstand. As such, it is interesting as the last preserved deposit prior to the onset of Ice Brook glaciation.

Eisbacher (1977, 1981, 1985) emphasized mud-based, shallowing-upward cycles as characterizing the Keele. This study confirms the prominence of shallowing-upward cycles in carbonate strata, and coarsening-upward cycles in siliciclastic strata, both of decametre scale. A coarser division of the formation, not mentioned by Eisbacher, is only seen close to the platform margin, where lower and upper, carbonate-dominated members are separated by a middle, mainly siliciclastic member (Figs. 13, 14). This middle member may be another platform-margin wedge.

Eisbacher (1978 and succeeding papers) recognized olistoliths and olistostromes shed by a part of the Keele platform; these are further described and illustrated here (Figs. 13, 14). Recognition and tracing of a single, regional olistostrome at the stratigraphic level of the Keele Formation (Durkan Member of the Ice Brook Formation) is important; the olistostrome has been confused with the diamictites (Stelfox Member), described herein, for which a glacial and glaciomarine origin is demonstrated.

'Tepee dolostone'

The 'Tepee dolostone' of Eisbacher (1981, 1985) is an important stratigraphic marker and a perplexing and paradoxical lithostratigraphic unit. As noted by Eisbacher (1985) it is eerily similar in its lithology and its relations to underlying glacial deposits, to the West African "cap dolomites" described by Biju-Duval and Gariel (1969) and Deynoux and Trompette (1976). It is akin also to "cap dolomites" in the Adelaide Geosyncline, South Australia, described by Williams (1979). As will be explained below, the name, even though informal, is a slight misnomer, because the structures referred to by Eisbacher and in this paper as "tepees" are not the tepees fully analyzed by Assereto and Kendall (1977) and others.

The 'Tepee dolostone' is here removed from the Keele Formation, because it is separated from the Keele by glaciomarine deposits of the Ice Brook Formation and an unconformity. Formalization of the unit at formation rank would be appropriate, but is not undertaken here, pending further work. The following brief and generalized description is presented only because of the implied but unexplained connection between distinctive units of laminated dolomite and immediately preceding glaciations. Further investigation of this unmetamorphosed and well exposed "cap dolomite" may shed light on the nature of the connection.

The 'Tepee dolostone' is a distinctive, widespread and highly visible unit (Fig. 5), normally 6 to 10 m thick, but ranging from 4.5 to 30 m. Its typical manifestation is as pale grey, microcrystalline dolomite, weathering yellow or cream to pinkish yellow, and characterized by extremely regular, flat, millimetre-scale lamination and blocky fracture (Fig. 6). The extremely fine grain size and uniformity of character over hundreds of kilometres along strike create a strong (but false) impression that the dolomite may be primary. On the line of Section 76AC-20 in the Shale Lake area, the unit is preserved over less than one kilometre of outcrop as nearly white, microcrystalline limestone that passes laterally into the characteristic dolomite. The millimetre-scale lamination is of the same style as elsewhere, but no tepee structures are present. Instead, the laminae are

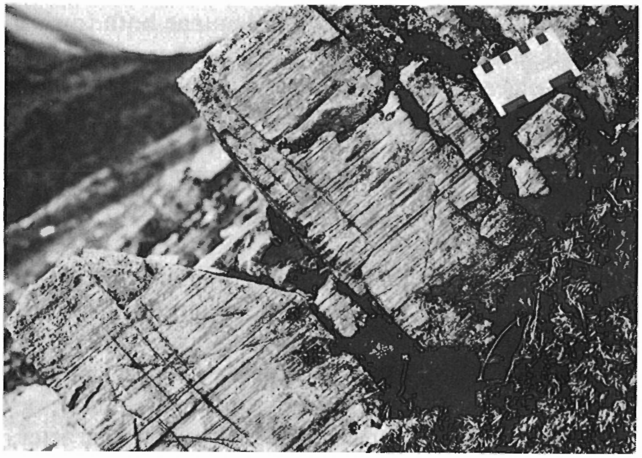

Figure 6. Characteristic outcrop of 'Tepee dolostone', showing pale colour, planar lamination and blocky fracture. Section 88AC-6. ISPG photo 3257-21.

interrupted by large fans of radiating calcite crystals. These fans are interpreted as replacements of primary aragonite fans, on the basis of square terminations (basal pinacoid) revealed by selective silica replacement of favoured growth-zones (Loucks and Folk, 1976). The crystals of individual fans are up to 20 cm long, and locally the fans form compound domes approaching one metre in height (Figs. 7-9). This also is the sole locality at which rare, simple, domal stromatolites are known. The unit is locally in calcitic preservation also at Section 88AC-10, but little textural detail is preserved there. Calcitized aragonite fans are present also at several localities on Silverberry River and near Stelfox Mountain, where most of the unit consists of the usual laminated dolomite.

In outcrop and hand specimen, the dominant structure observed is perfectly planar, millimetre-scale lamination (Fig. 5). In some outcrops, the lamination is in part wavy (millimetre amplitude), but otherwise displays none of the macroscopic characteristics of cryptalgal (cryptomicrobial) lamination. No shrinkage or desiccation cracks have been observed by the writer (*contra* Eisbacher, 1985). Monomict breccias associated with irregularly deformed laminae indicative of slope failure have been observed in some outcrops. One outcrop has many scoop-shaped slide surfaces at which strata of identical character are juxtaposed.

The so-called "tepee structures" present in about one half of the outcrops are not the typical tepees of peritidal origin described, for example, by Assereto and Kendall (1977). Most commonly, the "tepees" are

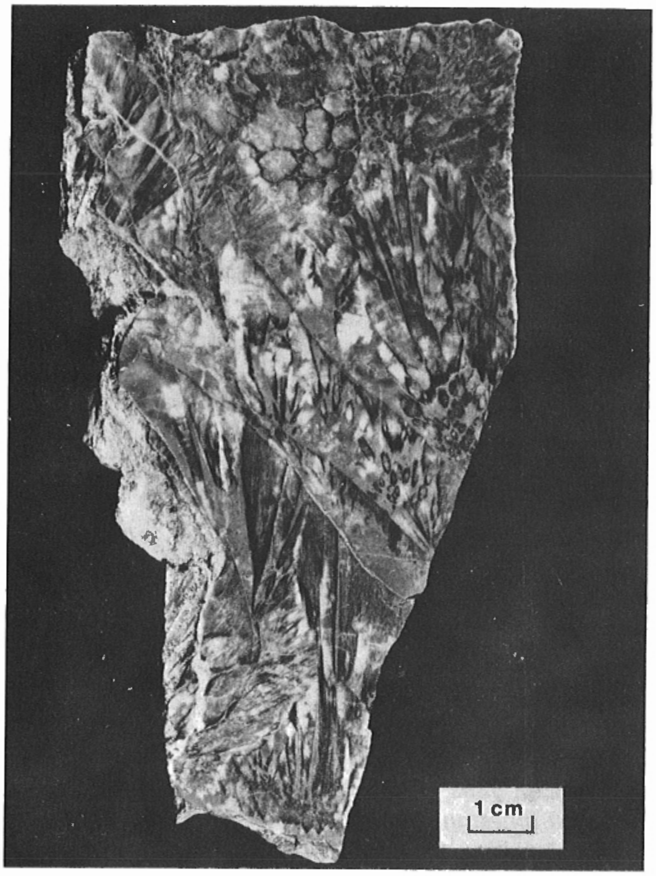

Figure 7. Fans of bladed crystals of calcite after aragonite, 'Tepee dolostone', Stelfox Mountain area. Sawn slab. ISPG photo 3399-8.

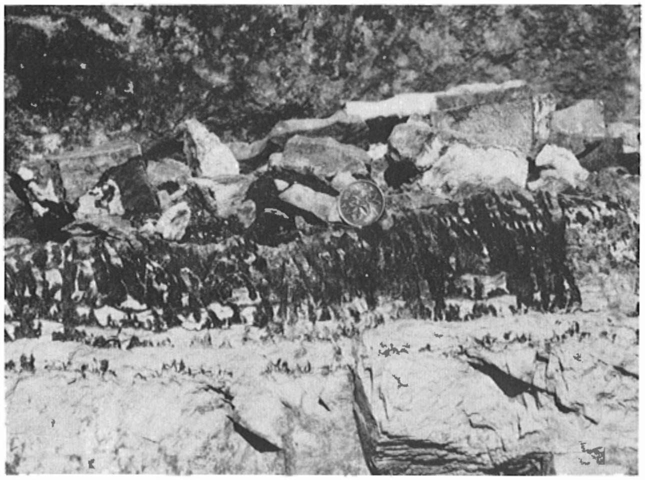

Figure 8. Blades of calcite (formerly aragonite) interrupting flat limestone laminae of the 'Tepee dolostone' unit, near Section 76AC-20. ISPG photo 3400-5.

cusp-shaped, unbroken micro-anticlines separating smoothly rounded micro-synclines (Fig. 10), typically with heights of less than 5 cm, but occasionally reaching 30 cm (in an early field note, the author described this structure as "festooned laminae"). With wider spacing (up to one metre or more), the "anticlines" become more angular, and the "synclines" flatter in profile (Fig. 11). Thinning of bundles of laminae both toward the crests and away from the crests has been observed. In a few places, the "tepees" are isoclines up to 50 cm high, with broken hinges; these cusp both upward and downward. Filling of open spaces by early cements, characteristic of peritidal tepees (Assereto and Kendall, 1977), is notably lacking.

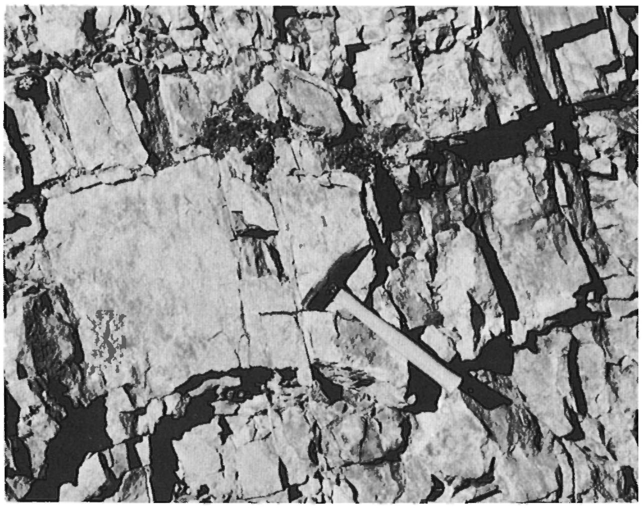

Figure 9. A subtle dome composed entirely of calcite fans after aragonite, interrupting the flat limestone laminae of the 'Tepee dolostone' unit, near Section 76AC-20. The structural details are much less obvious than in the typical, dolomitized outcrops; e.g., Figure 6. ISPG photo 3400-2.

Figure 10. The most common form of "tepee structures" in the 'Tepee dolostone', near Section 88AC-6. Hammer head for scale. ISPG photo 3257-22.

In thin section, the dolomite is microcrystalline, remarkably equicrystalline, and devoid of detrital material other than a trace of quartz silt. Some specimens, and parts of others, display regular, planar, "mechanical" lamination of uniform dolomite, as would be expected from their macroscopic character, with a scattering of grains of quartz silt along contacts between laminae. Other specimens quite unexpectedly display a well preserved, micro-pelleted, "spongiostromatid" texture (Pia, 1927) characteristic of stromatolitic limestones (Fig. 12a). In the general vicinity of Stelfox Mountain and at Section 88AC-11, spaced laminae separated by bundles of "spongiostromatid" laminae consist of spherical bodies that to the writer's knowledge are undescribed elsewhere. These appear upon hand-lens examination to be rather perfect spheres 1 to 2.5 mm in diameter, but in thin section are seen to have slightly ragged

Figure 11. Fully developed "tepee structures" in the 'Tepee dolostone', near Stelfox Mountain. Note the absence of space-filling cements, truncation of a bundle of laminae at photo centre, and thinning/onlap of a bundle of laminae above the lens cap. ISPG photo 3400-4.

surfaces (Fig. 12a, b). They consist of equicrystalline dolomite identical to that of adjoining laminae and contain no trace of radial or concentric structure, hence are neither ooids nor oncoids. The sphere-bearing laminae are from one to three sphere-diameters thick; dolomite with a sparry texture fills the inter-sphere pores. Given the association with cryptomicrobial laminae, these unusual objects appear to be of microbial origin.

So far as is presently known, where glacial deposits of the Stelfox Member of the Ice Brook Formation are absent, the Keele Formation is overlain everywhere by the 'Tepee dolostone'. Along the m argin of the Keele platform, the Stelfox Member, resting unconformably on the Keele, intervenes; thus, the unconformity at Keele– 'Tepee dolostone' contact is at least largely inherited from the sub-Stelfox unconformity. The 'Tepee dolostone' persists at least 10 km basinward from the Keele platform margin, but at that distance becomes discontinuous along strike, probably foreshadowing its pinchout into the basin.

A well exposed contact between the 'Tepee dolostone' and the Stelfox Member has not been seen. Relations at Silverberry River (Fig. 39) suggest, but do not prove post-Stelfox, pre-'Tepee' erosion. The upper contact with deep-water mudrocks of the Sheepbed Formation shows erosional sculpturing of decimetre relief, and a local lag deposit of siliceous pebbles.

Sheepbed Formation

The Sheepbed Formation, up to 900 m in thickness, abruptly succeeds the 'Tepee dolostone' or the Ice Brook Formation at a concordant contact to be examined further below. It consists mainly of dark grey to black shale and platy siltstone. Exposures along the eastern limit of outcrop contain negligible sandstone, but exposure to the south and west, for example, in the Sekwi Brook area (Fig. 1), contain packets of thick beds, some graded, comprising coarse quartzose sandstone and pebbly grit (Aitken, 1988). Most sections of the Sheepbed contain one or more

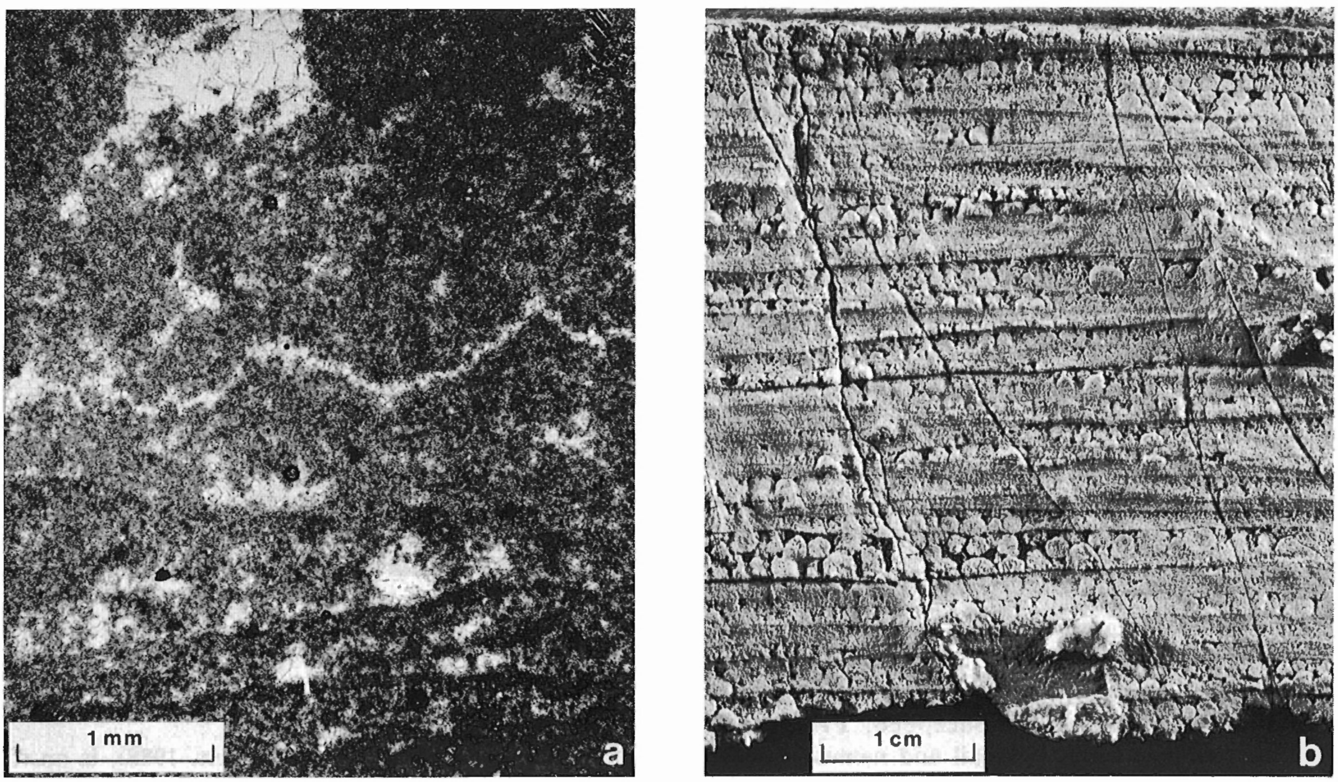

Figure 12. Textures of the 'Tepee dolostone'. a. Cryptalgal (cryptomicrobial) fabrics in well laminated 'Tepee dolostone', Section 88AC-11. The laminae with pelleted, "spongiostromatid" texture, which dominate in this specimen, are interrupted by laminae characterized by internally structureless spheres, presumably also of cryptalgal origin (partly visible on top). ISPG photo 3399-4. b. A specimen of 'Tepee dolostone' in which laminae of cryptomicrobial(?) spheres are especially prominent. Naturally weathered specimen, collected near Stelfox Mountaion. ISPG photo 3478-3.

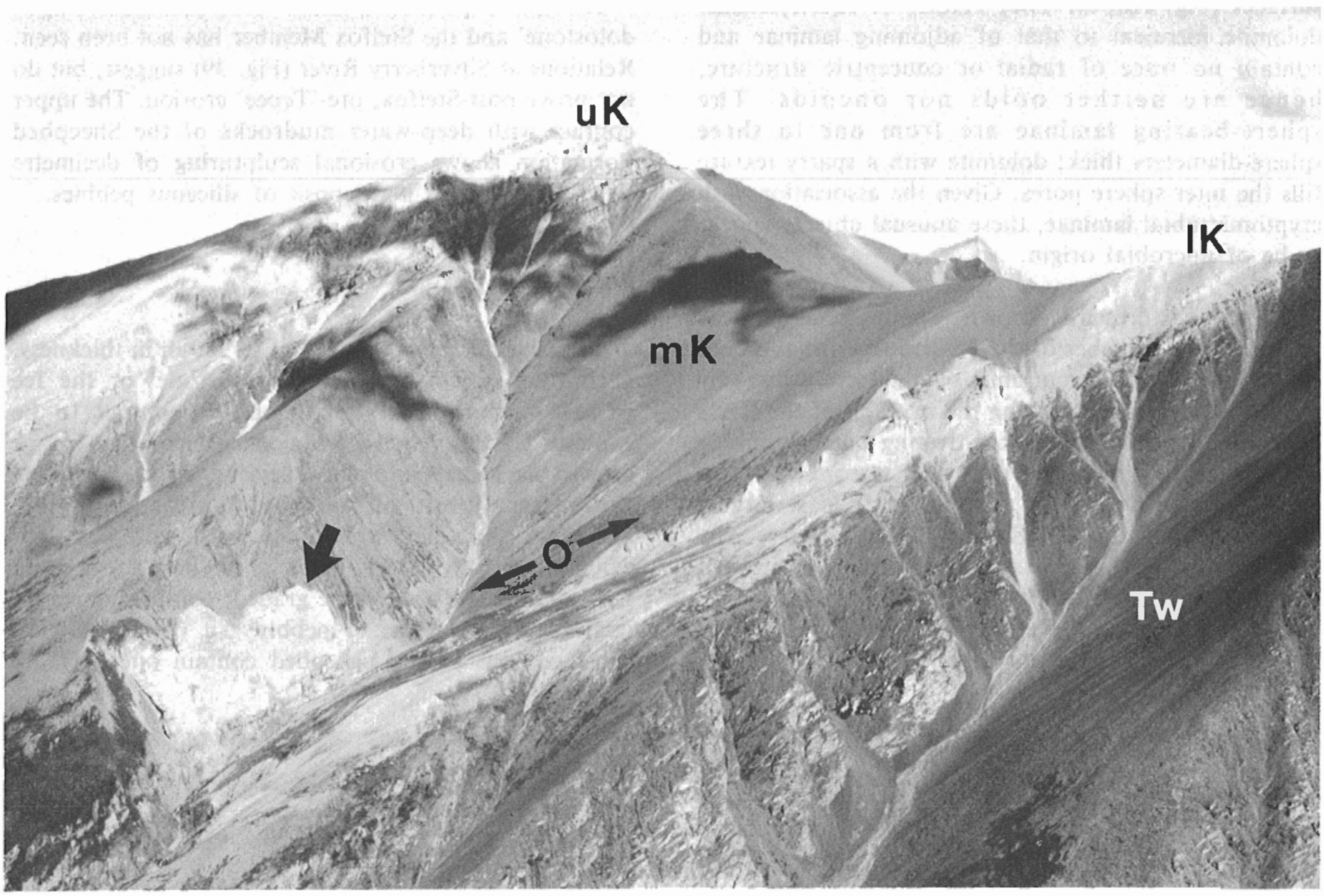

Figure 13. The olistostrome (Durkan Member of the Ice Brook Formation) near the breakaway scarp at locality "B" (see Figure 1a). The carbonate rocks of the lower Keele Formation (lK) at olistostrome level (O) at upper right may be in place. Note the siliciclastic-dominated middle member of the Keele (mK) at this platform-margin site, and persistence of shallow-water carbonates and siliciclastic rocks of the upper member (uK) basinward, above the olistostrome. Tw, Twitya Formation. ISPG photo 3257-6.

packets of ribbon-bedded lime mudstone in their upper parts. The formation contains rare trace fossils, and body fossils of Ediacaran type (Narbonne and Aitken, in press).

Gametrail Formation

Only recently have post-Sheepbed, Proterozoic formations been studied in detail and named (Aitken, 1988). The Gametrail Formation, up to 320 m thick, succeeds the Sheepbed at a gradational, intertongued contact. It occurs in two carbonate facies, both usually dolomitized: an "eastern", platformal facies characterized by stromatolites and grainstones, including oolites, and a "western", slope facies of ribbon-bedded lime mudstone and debris-flow breccias. At several sections, the platformal facies overlies the slope facies. In the Shale ("Palmer") Lake area (Fig. 1), kilometre-scale olistoliths of the slope facies are found embedded in Sheepbed mudrocks (Fig. 15).

Blueflower Formation

The Blueflower Formation (Aitken, 1988), is up to 1000 m thick, and consists mainly of deep-water mudrocks. It succeeds the Gametrail at a contact that appears abrupt in outcrop, but may be abruptly gradational and is possibly intertongued. Unlike the Sheepbed, the Blueflower contains packets of thin and medium bedded, turbiditic sandstones throughout. Packets of ribbon-bedded, black-weathering limestone, partly sandy and clearly turbiditic, occur in the lower third of the formation. Debris-flow deposits, partly bouldery, and exotic blocks occur throughout the mid-part of the formation; the blocks consist entirely of shallow-water carbonate rocks. Small, simple trace fossils, and body-fossils of Ediacaran type, occur in beds of suitable rock type (Narbonne and Aitken, in press).

Risky Formation

The Blueflower Formation is succeeded gradationally by the youngest thick and extensive carbonate platform deposit of the region, the Risky Formation (Aitken, 1988). The Risky, up to 150 m thick in the Mackenzie Mountains, is characterized by sandy, oolitic and oncoidal dolomites, stromatolites and dolomitic sandstones. Two carbonate-dominated members and a middle member of siliciclastics (which at the type section contains an erosional surface) are widely recognized. The Risky has been recognized in the eastern Wernecke Mountains, where it is much thicker and where Ediacaran fossils occur not only beneath it but also within the middle clastic member (Narbonne et al., 1985; Narbonne and Aitken, in press).

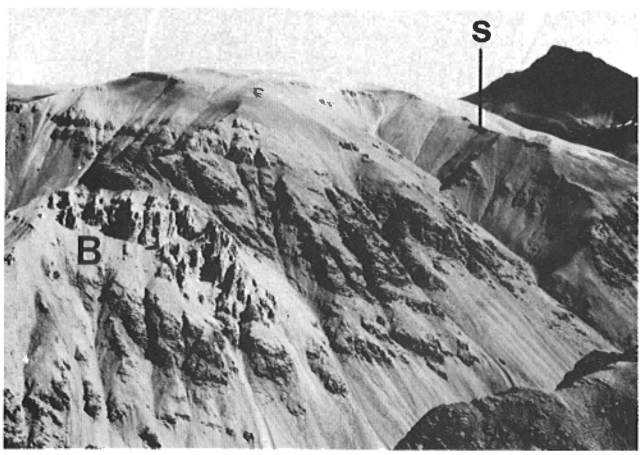

Figure 14. The olistostrome at locality "C" (see Figure 1a), near Stelfox Mountain. The large block of carbonate strata at left centre (B) is displaced downslope and contains a small fold in its base. Note that deep-water mudrocks abut the steep margin of the block. The upper carbonate member of the Keele persists intact, above the olistostrome, to the right margin of the photo. A pocket of diamictite of the Stelfox Member occupies an erosional depression on Keele carbonates at "S". Pale rubble of the 'Tepee dolostone' covers the flat summit at centre. The Sheepbed and Backbone Ranges formations form the peak at right. The photographer stood on Stelfox diamictite, here directly overlying another, large carbonate block like "B". ISPG photo 3257-7.

Ingta Formation

The Ingta Formation (Aitken, 1988), only locally preserved beneath the "sub-Cambrian" unconformity, represents the final, shallowing-upward, carbonate-capped Grand Cycle, and differs from the three earlier cycles in some ways. Following the upward trend of diminishing Grand Cycle thickness, it is the thinnest, only about 250 m, with a carbonate "cap" of only 39 m. Its green and, less common purple-red, mudrocks are distinctive, and although its siliciclastics lack evidence of peritidal deposition, they appear to be of shallower origin than those characterizing the preceding three cycles. Finally, it yields abundant trace fossils, in part large and somewhat complex, but no fossils of Ediacaran type (Aitken, 1988). The Ingta is currently regarded as Precambrian but post-Ediacaran (G.M. Narbonne, pers. comm., 1989). Its relations with the lower parts of the typical Backbone Ranges Formation, which demonstrably overlies a profound unconformity (the "sub-Cambrian" unconformity of this paper), are in dispute (discussed in Aitken, op. cit.).

Terminal Proterozoic cyclicity

Description of the terminal Proterozoic formations of the region (Fig. 2; Aitken, 1988) serves to establish a post-Rapitan pattern of four Grand Cycles (Twitya–Keele; Sheepbed–Gametrail; Blueflower–Risky; Ingta). Each of these commences at an abrupt contact of siliciclastics or limestone of deep-water origin on shallow-water carbonate strata. Toward the top of each cycle is a transition from siliciclastic rocks to platformal carbonates. Each of the shallow carbonate platforms displays a margin to the southwest, against strata of deeper water origin. The Grand Cycles are interpreted as the record of eustatic sea level variation (Aitken, 1989). On the assumption that this variation was to some degree periodic, the record of successively thinner Grand Cycles strongly suggests temporally decelerating thermal subsidence following the earlier episode (Coates Lake, Rapitan) of rifting.

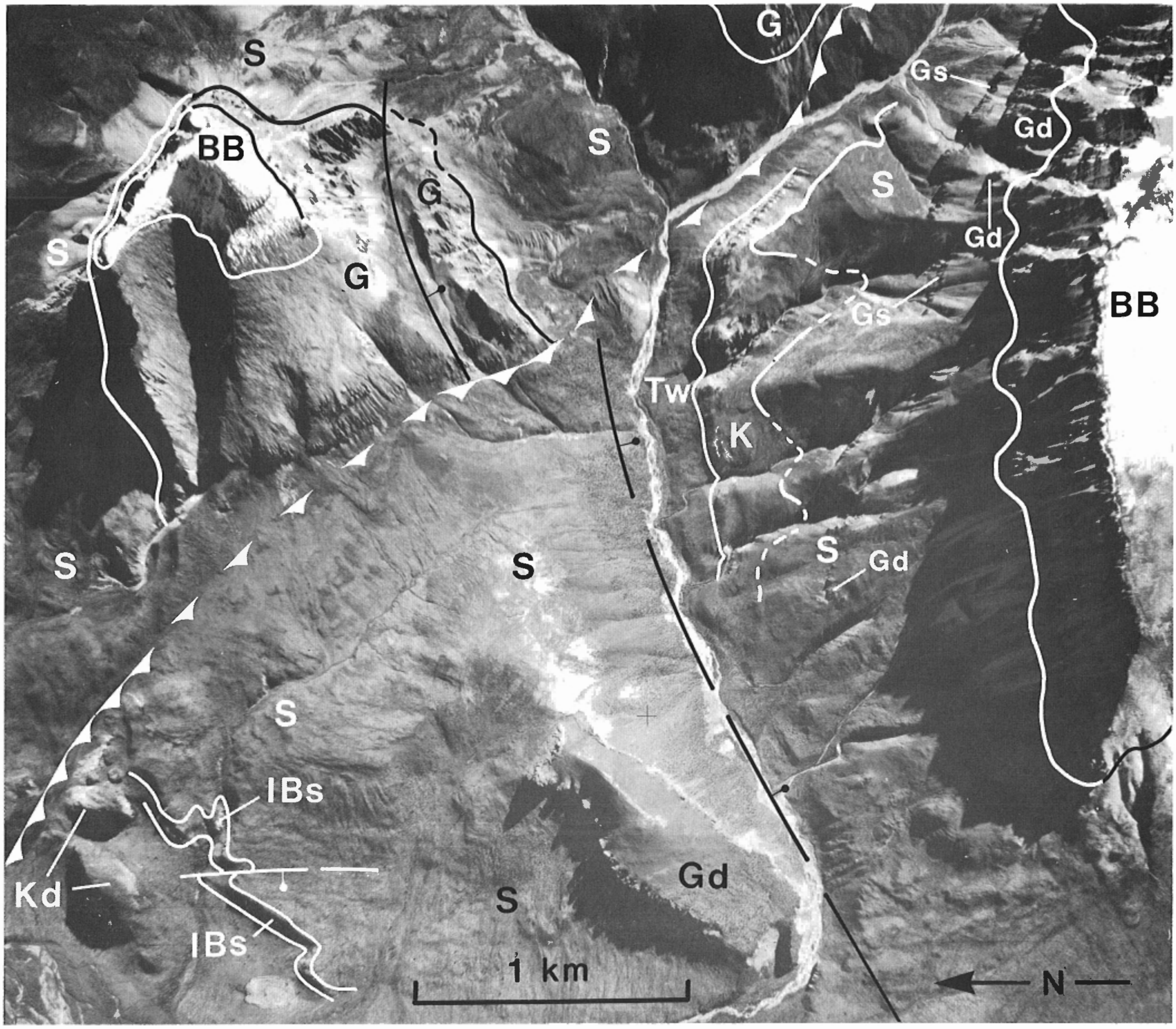

Figure 15. Superposed olistostromes at locality "D" (see Figure 1a) north of Shale ("Palmer") Lake Formations in situ: Tw, Twitya; K, Keele; IBs, glaciomarine diamictite, Stelfox Member of the Ice Brook; S, Sheepbed: G, Gametrail (platform-margin facies); Gs, Gametrail (slope facies); BB, Backbone Ranges. Gravity-displaced blocks of: Kd, Keele Fm.; Gd, Gametrail Fm. (slope facies). The downslope displacements took place not long after deposition of the strata affected. National Air Photo Library, air photo A12230-12.

The successive, cyclical, carbonate platforms of the terminal Proterozoic appear to be associated with falling eustatic sea level and early lowstand (Aitken, 1989). In the case of the Twitya-Keele Grand Cycle, Keele deposition ended with moderate lowstand (platform margin wedge) followed by extraordinary lowstand (sub-Stelfox unconformity) and the onset of glaciation. The temptation also to associate the falling sea levels recorded by the succeeding three Grand Cycle carbonate caps with glaciation is obvious, but a paradox must be faced if carbonate sedimentation is associated with warm climate. The glacio-eustatic hypothesis for terminal Proterozoic cyclicity is unsupported by other evidence at this date, and its consideration too readily slips into circular reasoning. Furthermore, glaciation during deposition of the Grand Cycles of the Cambrian Period is unknown. The question is of great interest, but its resolution must await further evidence.

DEPOSITS OF THE "SECOND LATE PROTEROZOIC GLACIATION"

The primary purpose of this report is to draw attention to the presence, in the Mackenzie Mountains, of Upper Proterozoic, post-Rapitan, glacial deposits characterized by diamictites. These previously unrecognized strata, together with closely associated, nonglacial diamictites and other strata, are placed in the Ice Brook Formation, as here proposed (Fig. 16).

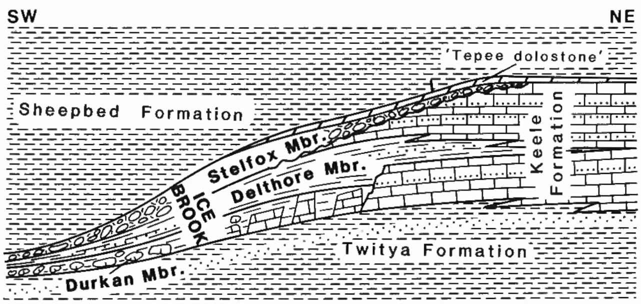

Figure 16. Internal and external relations of the Ice Brook Formation and its members.

ICE BROOK FORMATION (NEW)

The name Ice Brook Formation is proposed for a unit of strata characterized by carbonate-clast diamictites, which rests locally upon platformal carbonate and siliciclastic strata of the Keele Formation. In off-platform areas the Ice Brook Formation occupies the stratigraphic position of the Keele, separating the Sheepbed Formation from the underlying Twitya Formation. Three members, not coextensive, are widely recognizable: the Durkan Member, a coarse olistostrome or megabreccia derived from the lower Keele platform margin; the Delthore Member, comprising mudrock, sandstone and slump-deposits of slope origin; and the Stelfox Member, consisting largely of diamictite of glaciomarine origin. That the Ice Brook is mappable has been demonstrated previously; it is map unit 8 of Blusson (1971).

Origin of names and type sections

The name is taken from Ice Brook, a major tributary of Hay Creek, in the Sayunei Range, south-central Mount Eduni map area, which flows northeastward, parallel to and southeast of upper Hay Creek (Fig. 1). The name has been approved recently by the Canadian Permanent Committee on Geographic Names, and does not yet appear on any published topographic map. Ice Brook is 6 km north of the type section of the formation.

The lower, Durkan Member is named from Durkan Creek, an eastern tributary of Keele River, 20 km north of the type section of the three members, near Stelfox Mountain. The overlying Delthore Member is named for Delthore Mountain, west of Stelfox Mountain across Keele River. The upper, Stelfox Member is named for Stelfox Mountain, in west-central Wrigley Lake map area, 5 km south of the type section of the member.

The section chosen as type section of the formation (Figs. 17, 18) is the thickest measured to date (Section 84AC-9 in original field notes). Its location is 64°08′07″N, 129°00′38″W, in the Sayunei Range, south-central Mount Eduni map area, at the head of a small stream draining to Twitya River. The type section displays all of the characteristic rock types of all three members, and its relations with overlying and underlying formations are straightforward.

Section 84AC-9
(64°08′07″N; 129°00′38″W)

Type Section of the Ice Brook Formation

Unit no.	Description	Thickness (m) Unit	Total from base
	Overlying beds: poorly exposed, dark coloured mudrocks of the Sheepbed Formation.		
	Contact covered		
	'Tepee dolostone'		
1	**Dolomite:** grey, fine equicrystalline, weathering pale, pinkish yellow. Lamination of the basal metre has been buckled and fractured into small-scale anticlines and synclines (initially taken to be algal stromatolites), and "tepees"; however, the cusps of the "tepees" point downward as well as upward, and the "tepees" lack the carbonate-cement-filled open spaces of typical, peritidal tepees. The remainder tepees is flat-laminated, massive below, flaggy at the top. (Description is from the best exposure, on the northwest wall of the cirque and off the main line of the section.) Outcrop does not permit study of the basal contact.	4.5-5.5	(no total)

Unit no.	Description	Thickness (m) Unit	Total from base
	Ice Brook Formation (type section)		
	Stelfox Member Units (6 to 15)		
15	**Mudstone** and **diamictite:** mudstone, as Unit 13, with sparse, mainly centimetre-scale lonestones. No primary lamination except for two, lenticular beds of dolomitic siltstone (10-60 m) in the basal 35 m. Lonestone content contrasts with that of underlying units: stones are mainly orange-weathering dolomite after lime mudstone, rarely after oolite, and limestone clasts are very rare. The mudstone matrix has a strong, scaly cleavage.	130.5	330.8
	Above 42 m, outcrop is poor and measurement imprecise, but continuity, monotony of lithology and lack of bedding are confirmed in cliffs to the west.		
	Above 45 m, matrix carbonate increases gradually as content of stones increases to 5 to 10 per cent (sparse diamictite). Percentage of limestone clasts, including oolite, increases to equality with dolomite clasts (nearly all after lime mudstone). Stones are in part clustered.		
	In a loose block, a large "till clast" (aggregate sediment clast) was observed. This is a lens of diamictite, 10 by 25 cm in section, with the long axis in the plane of bedding. It is clearly not a "stone".		
14	**Mudstone:** as Unit 13, with slaty cleavage. Lacks primary lamination and lonestones.	12.7	200.3
13	A bedded unit. **Mudstone** (slate): grey, noncalcareous, weathering greenish grey, with rare lonestones, overlain by **sandstone:** pale grey, very fine grained, dolomitic, flat-laminated, massive, orange-weathering, and lacking lonestones.	3.0	187.6
12	**Diamictite:** as Unit 9. Limestone and dolomite stones are subequal, but all of the larger (decimetre) stones are dolomite.	25.5	184.6
	A zone 21.5 to 23.5 m above the base is boulder-rich; boulders of orange-weathering, stromatolite-rich dolomite are especially prominent.		
	Two large stones consist of breccia of black, laminated limestone slabs in a supporting, dolomite matrix.		
11	A bedded unit. **Diamictite:** as below, stone-poor ("sparse"), interrupted by thin beds of **siltstone:** dolomitic, parallel-laminated, orange-weathering. The siltstone beds mainly lack dropstones, but the lowest contains a pod or "dump", less than 1 m wide, of angular, dark grey limestone fragments. This bed also has lenses of sandstone, apparently winnowed diamictite, along its base.	1.5	159.1
10	**Diamictite:** cleaved, weathering grey, lichenous. Stones constitute 15 to 25 per cent at different levels; most are less than 4 cm, and few exceed 20 cm. The rare, metre-scale megaclasts are dolomite.	84.3	157.6
	Rare zones, less than one metre thick, are rich in dolomite stones much larger than average.		
	A channelized, 20 cm thick, matrix-supported **breccia** 54 m above the base, is clearly a debris flow. Its clasts are all less than 2 cm, all dark grey limestone. The matrix is sandy dolomite, weathering pale orange. The apparent width of the lens (channel) is less than 10 m as sectioned by topography.		
	A slide-mass 1.8 m thick, like those near the base of the formation, is 77.5 m above the base of the unit. It consists of irregular masses of diamictite in contorted, cleaved mudstone with lonestones.		
9	**Diamictite:** a unit crowded with boulders up to 1.3 m in diameter. The preponderant megaclasts are dolomite, including dolomites derived from oolite, cryptalgal laminite, and stromatolitic limestone.	8.7	73.3
8	**Diamictite:** massive but with distinct cleavage (more argillaceous than lower diamictites?). Stones make up 20 per cent, and are predominantly limestone; few exceed 3 cm in diameter.	5.0	64.6
7	**Diamictite:** as below, but thin bedded; beds are separated by laminae of siltstone.	0.7	59.6
6	**Diamictite** and **breccia:** in the lower part, diamictite is massive, stones comprise 40 to 50 per cent, and limestone and dolomite stones are subequal. Upward, some subunits have stone contents as low as 20 per cent, and the limestone to dolomite ratio increases. The largest clast seen is 1.3 m in diameter. One subunit (0.5 m) is clay-rich and clast-poor, with a weak sedimentary lamination.		

Unit no.	Description	Thickness (m) Unit	Total from base
	The uppermost 0.5 to 0.8 m is a framework breccia, with angular stones (a debris flow).		
	Delthore Member (Units 2 to 5)		
5	**Limestone:** lime mudstone, argillaceous, silty, laminated, brown weathering, partly slumped, with sparse (1-2%) dropstones. The basal contact is very irregular, with 60 cm of local relief.	2.1	37.6
4	**Diamictite, pebbly mudstone,** and **conglomerate:** basal 0.6 m is diamictite and mudstone with lonestones. Above this is a framework conglomerate grading up to a matrix-supported paraconglomerate. Matrix is grey dolomite (detrital), weathering dull orange to brown. Maximum diameter of stones is 1 m, but few exceed 0.25 m. The stones are of the usual rock types; the limestone to dolomite ratio is 9:1. Base of unit is abrupt.	7.5	35.5
3	**Olistostrome:** blocks of various carbonate rocks and masses of diamictite, in a matrix of highly deformed shale.	4.5	28.0
	The blocks include one, 7.5 m long, of black, laminated lime mudstone (slope facies of Keele Formation); the laminae are intensely crumpled. Another block of similar scale is intraclast grainstone.		
2	**Siltstone** and **shale,** with **lonestones:** the mudrocks are like those described for the Twitya Formation, below, but with thinner lamination. Lonestones are rare, and none were seen in the upper 2 m. One cluster of stones (diamictite) is a few metres wide.	12.1	23.5
	Two distinct slide surfaces cut the laminated mudrocks.		
	Durkan Member (Unit 1)		
1	**Olistostrome:** siltstone, shale and bouldery mudstone. Base of unit is the lowest lonestone. The appearance of lonestones is progressive, one of the lowest being a 1.8 m boulder.	11.4	11.4
	In the basal 4.5 m, megaclasts are exclusively orange-weathering dolomite, mostly after cryptalgal laminite, with minor grainstone and flakestone; the larger ones are somewhat fragmented. A raft of dolomitized ooid packstone, 4.5 to 11.4 m above the base, is over 30 m long (south end covered).		
	Twitya Formation		
	At least 100 m of upper Twitya beds are exposed beneath the Ice Brook Formation. This is platy, dark grey siltstone and near-black shale, in centimetre-scale laminae; graded couplets and millimetre-scale load casts are common. Rare, planar slide surfaces cut underlying laminae and superpose laminated rock of identical facies.		

A reference section (Figs. 19, 20) is designated to illustrate the relations of the Ice Brook Formation to the Keele carbonate platforms, and to serve as type section for the three members. It is Section 84AC-35, 5 km north of Stelfox Mountain, in western Wrigley Lake map area, at 63°36′08″N, 127°57′30″W. The section is on a short southwestern tributary of a small, northwest-flowing stream that heads on Stelfox Mountain.

Section 84AC-35
63°36′08″N; 127°57′30″W

4.85 km northwest of the summit of Stelfox Mountain

Reference section for the Ice Brook Formation, and type section of its Durkan, Delthore and Stelfox members.

Unit no.	Description	Thickness (m) Unit	Total from base
	Contact with overlying, dark, platy shale of Sheepbed Formation is concealed. No 'Tepee dolostone' is present		
	Ice Brook Formation		
	Stelfox Member (Units 7 to 10, type section)		
10	At the base, **sandstone** (10 cm thick; compare with 20 cm on original line of section): laminated, thin bedded, lacking lonestones). Overlying 40 cm is **stratified diamictite,** with coarse pebbles at the base, then fine pebbles. This is overlain by a wispy **sandstone layer** (1-3 cm), with rare, pebble-sized lonestone (not at the base); one lonestone indents the top of the wispy sandstone. The overlying 31.5 m is unstratified **diamictite,** with scaly		

Unit no.	Description	Thickness (m) Unit	Total from base
	fracture more prominent upward. The ratio of limestone clasts to dolomite clasts is 5:1; the largest clasts, reaching 50 cm in diameter, are stromatolitic dolomite and dolomite after oolitic limestone.	32.0	126.0
	Unit 9 is described as seen both on the original line of section and on the offset line on which measurement was completed.		
9d	**Diamictite:** massive; in the upper quarter, stratification is revealed by clast-rich and clast-poor layers.	7.9	94.0
9c	**Diamictite:** massive; at the top, siltstone (20 cm), greenish grey, green weathering, with dropstones.	3.0	86.1
9b	**Sandstone:** a lens of three beds. Sandstone is brownish grey, fine grained, dolomitic, brown weathering, thick bedded, internally structureless. The lower two beds incorporate pebbles and cobbles in their bases. The upper bed is parallel laminated and graded in the top 15 cm.	2.6	83.1
9a	**Diamictite:** in the basal 1.5 m, two sandy, debris-flow paraconglomerates, the upper with slump folds. At the top, a few centimetres of siltstone, laminated, green-grey, with dropstones cutting the lamination.	3.0	80.5
	Line of section is offset along Unit 8 to northwest facing cliffs nearer the main creek, where Unit 9 displays significant differences, and is redescribed.		
9	**Diamictite:** as below. Ratio of dolomite clasts to limestone clasts is 1:9.	16.0	93.5
	As is common, the largest clasts are dolomite, and reach 1 cm in diameter.		
8	**Sandstone:** quartzose, coarse grained, well sorted, calcareous; tabular crosslamination in sets 20 cm thick; clasts of diamictite along the base. Thickness 0.3 to 1 m in this outcrop; seen on cliff opposite to be lenticular and to pinch out locally.	0.6	77.5
7	**Diamictite:** clast diameter up to 30 cm, mainly grey weathering limestone, minor orange weathering dolomite. Dolomitic matrix weathers dull orange.	6.5	76.9
	Delthore Member (Units 2 to 6, type section)		
6	**Siltstone:** as Unit 4, with minor sandstone as thin beds, chains of "starved" current ripples, and detached slump-folds.	5.0	70.4
5	A confused slide-mass, with erosional base. Medium to thick, "beaded" beds of quartzite, as below, separated by contorted masses of siltstone, as below. Quartzite and quartzose grit occur locally as isolated pockets and pods, and laterally the unit contains a block of dolomite 4 by 1 m in section.	16.0	65.4
4	**Siltstone:** grey, laminated, platy, with minor, very thin lenses of very fine grained sandstone as below. Partly ripple crosslaminated. Rare, small-scale, penecontemporaneous overfolds involving only one or two laminae.	27.8	49.4
3	**Sandstone** and **siltstone:** interlaminated and very thinly interbedded, very fine grained sandstone and very coarse grained siltstone, pale and medium grey; flute and groove casts. The upper 1.5 m is resedimented, contorted, and capped by a 20 cm lens of quartzite as below.	6.1	21.6
2	**Quartzite:** pale grey, fine and very fine grained, lenticularly medium to very thick bedded (maximum bed thickness 1.3 m). Beds are in part graded, with erosional and load-casted bases, and display Bouma Tbc and Tabc sequences. Sparse, "floating" rip-up clasts; one bed is a breccia of these clasts. Some beds, initially deposited as turbidites, have subsequently flowed downslope and acquired overfolded bases.	4.5	15.5
	Durkan Member (type section)		
1	**Olistostrome:** the olistoliths, up to 3.5 m in largest dimension, are nearly all of the same, pale grey, microcrystalline, dull-orange weathering, massive dolomite. One raft of scaly, shaly siltstone, and a lens of imbricated, tabular-clast conglomerate. The relief at the top of the unit is infilled by quartzite of the overlying unit. The olistoliths are only slightly brecciated, mostly at their margins, and invaded by quartz sand.	11.0	11.0
	Twitya Formation		
	Siltstone: dark grey, platy. Penecontemporaneous folds appear to become more common toward the upper contact. No sandstone beds are present in this upper part of the formation.		

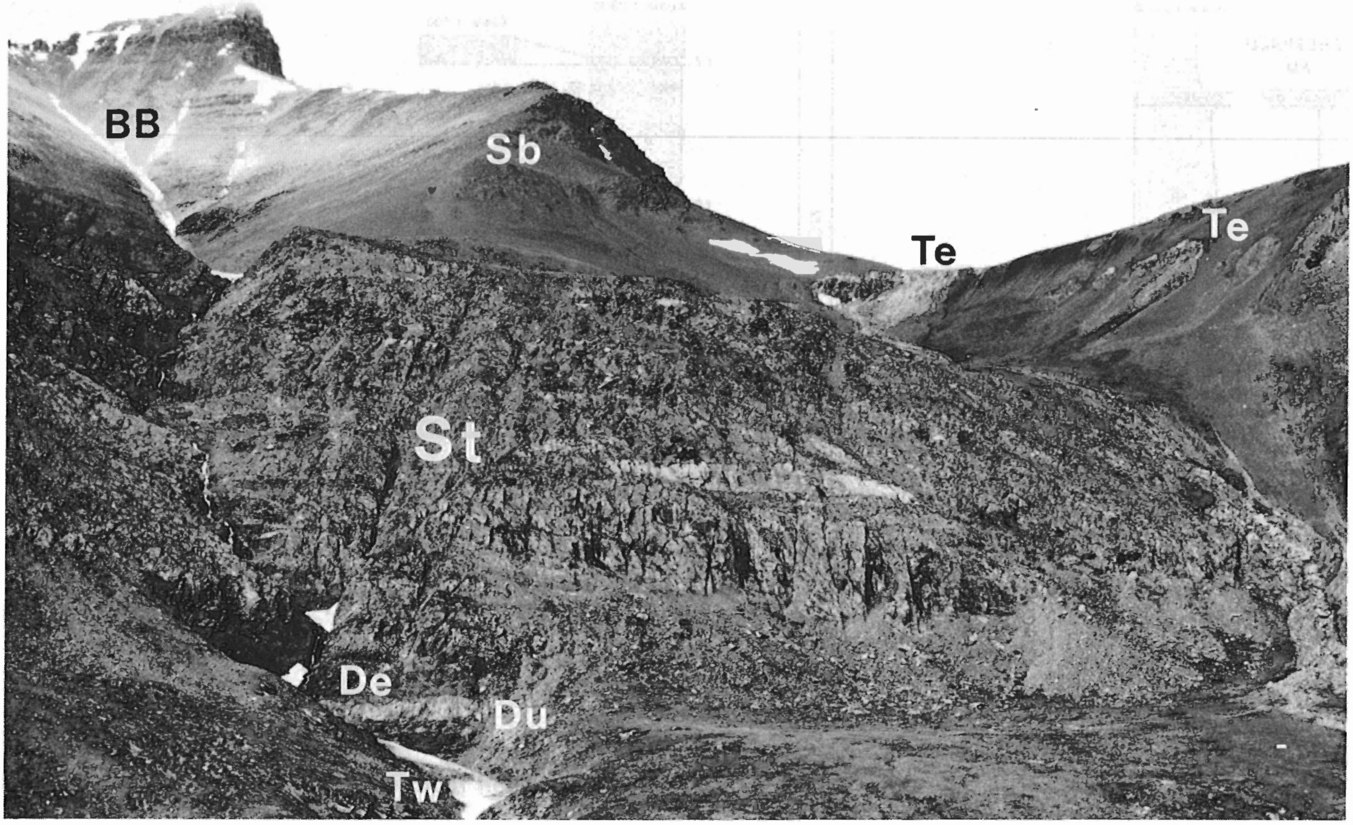

Figure 17. Type section of the Ice Brook Formation. Du, Durkan Member; De, Delthore Member; St, Stelfox Member; Tw, deep-water shale and siltstone of the Twitya Formation; Sb, Sheepbed Formation; BB, Backbone Ranges Formation. The 'Tepee dolostone' (Te) forms a string of pale outcrops above diamictite at right. The raft of pale-weathering limestone at centre measures about 9 x 100 m. ISPG photo 3257-9.

Description

Durkan Member

The Durkan Member (Figs. 21, 22) is a bouldery diamictite. The boulders consist of limestone and dolomite recognized as having been derived from the lower of the two carbonate members that characterize the Keele Formation along the platform margin (Figs. 13, 14): cryptalgal laminite; grainstone/packstone, notably ooid packstone; flakestone; and less commonly, dolomitic grit, sandy dolomite, and microcrystalline dolomite. Equidimensional boulders range up to 3.5 m diameter. Larger, intact "rafts" also occur; one at the type section of the Ice Brook Formation measures 7 m in thickness and over 30 m in length in section (Fig. 21). The larger boulders and rafts are commonly fractured at their margins, and the fractures are filled with quartzose grit. Rare, fairly intact but clearly transported lenses or small "rafts" of dark, laminated or ribbon-bedded lime mudstone also occur. Boulders of different rock types are intermixed. The matrix of the diamictite is dark, silty shale like that of the underlying Twitya Formation, and contains evidence of penecontemporaneous deformation.

The member is not obvious at a distance, but from a few hundred metres it is seen as a thin band in which the boulders, commonly weathering pale orange, stand out in relief from the dark matrix. This band is separated from the resistant, dull-orange weathering diamictites of the overlying Stelfox Member by the dark, slightly recessive outcrop of the Delthore Member.

Thickness and distribution. The Durkan Member thins irregularly southwestward from the edge of the lower

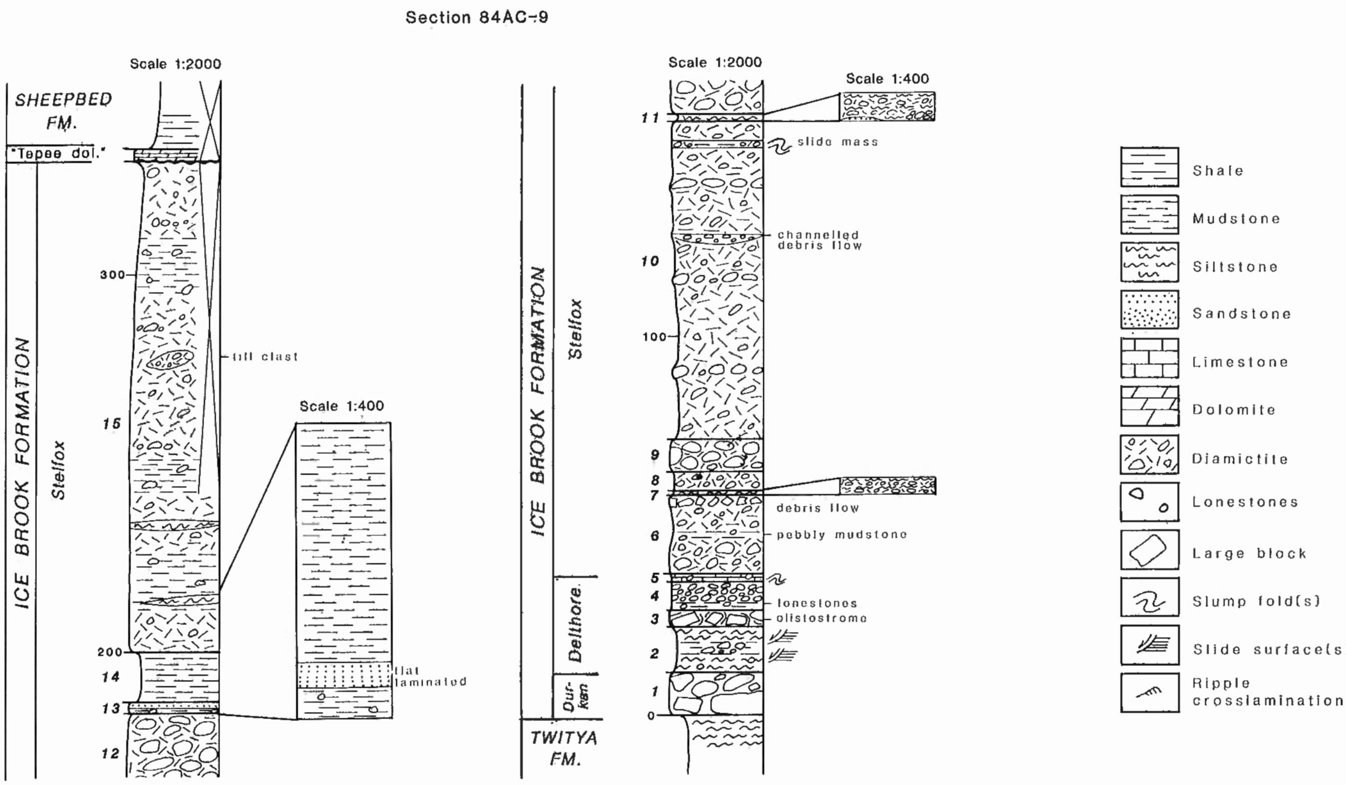

Figure 18. *Type section of the Ice Brook Formation (columnar section).*

of the Keele carbonate platforms. Close to the breakaway scarp at which the olistostrome originated, the member is in effect as thick as the thickest block, at least tens of metres (Fig. 13). It is 11 m thick at its type section, 11.4 m at the type section of the Ice Brook Formation, 8 m at Section 84AC-31, and only 2.8 m at a relatively proximal section 8 km east-northeast from the type Ice Brook ("A", Fig. 1). The Durkan Member occurs only in off-platform, or basinal areas, and nowhere overlies carbonate strata.

The Durkan Member has been traced in the Plateau thrust sheet from Stone Knife River southeastward to the Stelfox Mountain area (Fig. 1a). It appears to be continuous north of Twitya River, disappearing below cover downdip to the southwest. South of Twitya River, its distribution is discontinuous. The member has not been observed south of the Stelfox Mountain area.

Genesis. The Durkan Member is essentially a single olistostrome. It has been traced back to a breakaway scarp at the margin of the **lower** of the two carbonate platforms of the Keele Formation (Figs. 13, 14), both at "B" in the north, and at "C" in the mid-part of the area studied (Fig. 1a). The member has been identified up to 12 km down the paleoslope from the breakaway scarp, continuing downdip for an unknown distance.

Eisbacher's (1981) inference that collapse of the Keele platform-margin was a consequence of sea level drawdown as a result of glaciation elsewhere requires comment. Drawdown could lead to loss of stability of the carbonate-platform margin only if it led to excess pore pressure in the sediments. Excess pore pressure would develop only if drawdown took place so rapidly that pore water in the sediments of the platform could not drain to a level in equilibrium with the new sea level. Young, permeable (witness the widespread dolomitization) carbonate sediments would have drained rapidly, whereas the maximum possible rate of drawdown by the incorporation of water into ice sheets is controlled in part by release of the latent heat of crystallization of water, a negative feedback factor. Observational evidence leads in the same direction. The upper carbonate platform of the Keele Formation did undergo glaciation, but did not undergo failure on the scale suffered by the lower platform, which bears no direct evidence of glaciation.

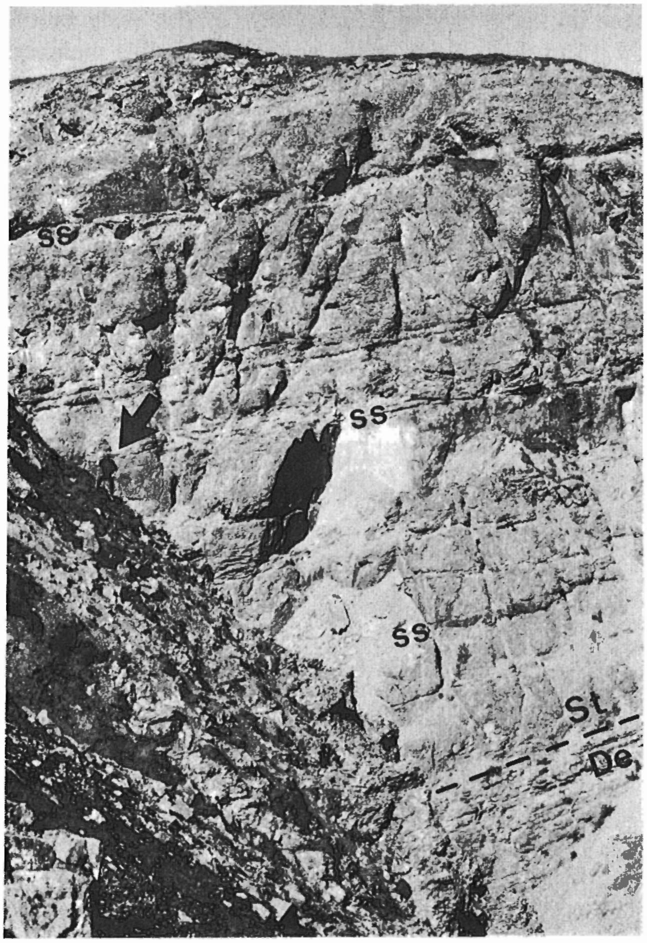

Figure 19. Section 84AC-35, reference section of the Ice Brook Formation and type section of its three members. De, Delthore Mbr.; St, Stelfox Mbr. Three horizons of sandstone lenses (ss) are visible in the Stelfox Member. The Durkan Member is out of sight at lower right. No ‘Tepee dolostone’ is present here; the Ice Brook is directly overlain by deep-water mudrocks of the Sheepbed Formation. Figure on foreground slope at left (arrow) suggests scale. ISPG photo 3257-10.

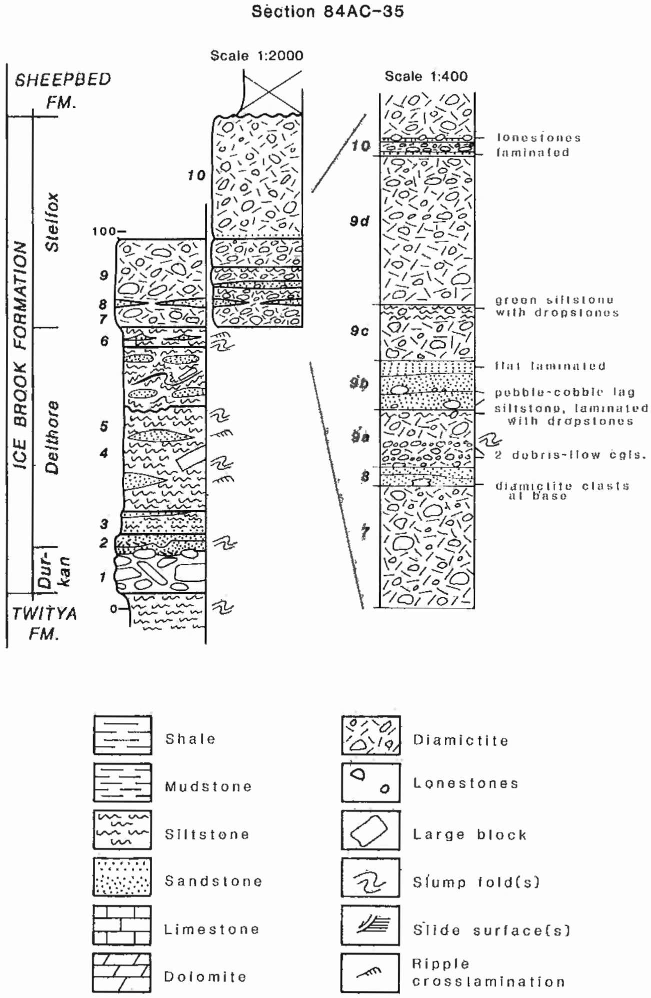

Figure 20. Reference section of the Ice Brook Formation, and type section of its Durkan, Delthore, and Stelfox members (columnar section).

Delthore Member

The Delthore Member consists of bedded siltstone and mudstone, turbiditic sandstone and quartzite, and minor diamictite, all of which envelop lonestones at least locally. At most localities, almost all of the strata bear evidence of penecontemporaneous deformation, and chaotic re-mixing of beds of different grain size is fairly common. The member is slightly recessive weathering, and darker in outcrop than the overlying Stelfox Member (Figs. 17, 19).

At its type section, the Delthore Member includes beds up to 1.3 m thick of pale grey, fine and very fine grained quartzite. Some of these beds display Bouma Tbc and Tabc sequences, and their bases are erosional and display load casts. Rip-up casts of mudrocks are present but rare; one sandstone bed is, in effect, a rip-clast breccia. The bases of some beds display recumbent overfolds inferred to be of penecontemporaneous origin. Much of the quartzite occurs as lenses, beads and pods, symptomatic of resedimentation. At the type section, interlaminated and very thinly interbedded, very fine sandstone and coarse siltstone display flute and groove casts and penecontemporaneous contortions. Ripple crosslaminated, grey, platy siltstone, with thin lenses of sandstone, also occurs and also has undergone penecontemporaneous folding.

Elsewhere, sandstones are grey or pale brown, very fine grained, dolomitic, and thin and medium planar-bedded. A bimodal texture occurs locally: quartz grains up to granule size are distributed sparsely throughout argillaceous, very fine grained sandstone. Such beds also display internal disruption and folding.

Sparse lonestones up to boulder size and rare pods of diamictite are also present. It is generally not demonstrable whether they were emplaced as dropstones, by sliding, or by incorporation from the base of the overlying diamictites. On the evidence of the 16 m thick block in the equivalent middle member of the Keele at Section 77AC-26, one kilometre in front of the breakaway scarp that give rise to the Durkan Member, slide-blocks are indeed present.

Thickness and distribution. The Delthore Member is 59.4 m thick at its type section, 11.6 m at Section 84AC-31, 26.2 m at the type section of the Ice Brook Formation, and 2.8 m at a relatively proximal section

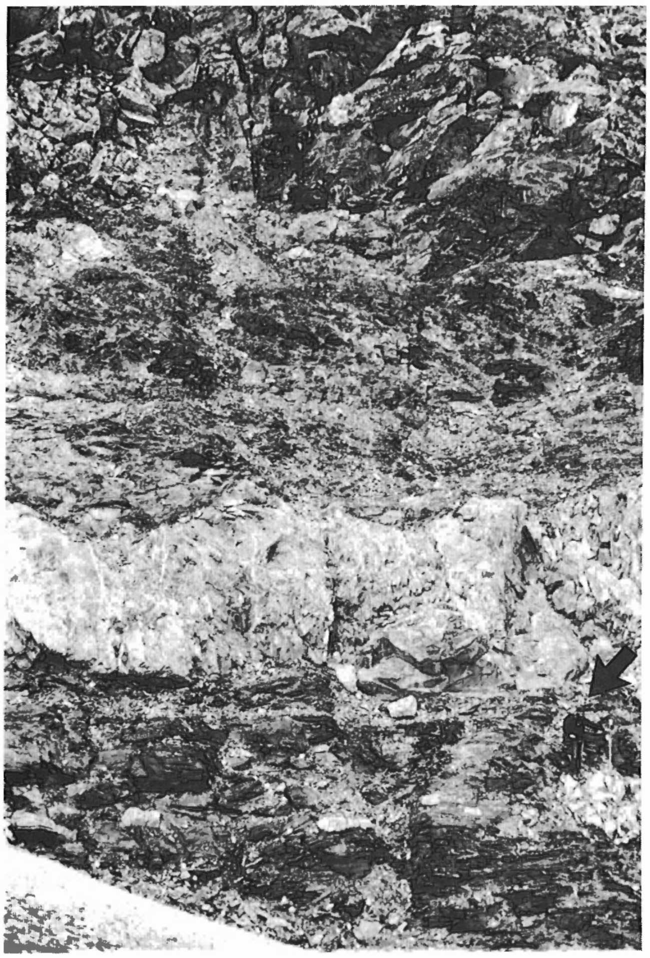

Figure 21. *The Durkan and Delthore members at the type section of the Ice Brook Formation. The figure at lower right (arrow) stands on an olistostromal block 2 m in diameter. The pale band above the figure is a raft of partly dolomitized ooid packstone, 6.9 m thick and over 30 m long. The Delthore Member comprises dark, slump-disturbed mudrocks above the raft. The base of the Stelfox Member is drawn at the base of the lowest sheet of diamictite (the larger stones of which are visible in the photo) above the Delthore Member. ISPG photo 3257-13.*

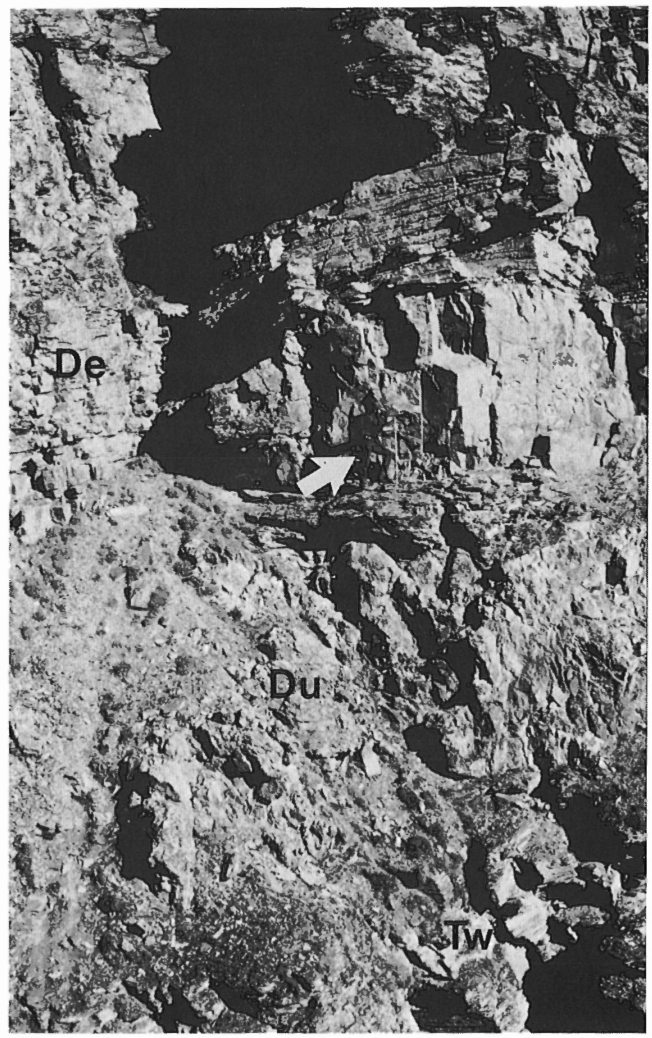

Figure 22. *The Durkan Member at its type section. The figure at photo centre (arrow) holds a 1.5 m staff, and stands at the base of large block. A few metres of Twitya mudrocks of the Twitya Formation are visible at lower right. Sandstone and mudrocks of the Delthore Member, partly well bedded, overlie the large block. Tw, Twitya Fm.; Du, Durkan Mbr.; De, Delthore Mbr. ISPG photo 3257-12.*

8 km east-northeast from the type Ice Brook ("A", Fig. 1). The thickness of 202 m for the middle clastic member of the Keele Formation at Section 77AC-26, where the lower carbonate member has broken up and slid basinward from the platform edge, implies that the Delthore Member may reach a comparable thickness locally. The Delthore cannot be delimited in the absence of the underlying Durkan Member.

Genesis. The Delthore Member represents deposition on an off-platform slope, during which hemipelagic deposition of mud was repeatedly interrupted by turbiditic emplacement of sandstone and siltstone, and mass emplacement of minor debris flows. Slumping undoubtedly took place, but the possibility that some of the early deformation was caused by an overriding glacier cannot be discounted. The origin of most of the lonestones is indeterminate.

Stelfox Member

The Stelfox Member consists largely, and at some localities entirely, of bedded and massive carbonate-clast diamictites (Figs. 23-26). The basinal sections are thicker, and contain beds of shale, siltstone and sandstone that are lacking at sections above the Keele platform. Most outcrops of the member are massive in appearance, indistinctly bedded and resistant, with a distinctive greyish orange "wash". In basinal areas, these clearly separate the underlying, dark-coloured mudrocks from those overlying (Fig. 17). Where the member separates carbonate or clastic strata of the Keele Formation from the overlying 'Tepee dolostone', however, it is thin and in places not obvious. Diamictites at and south of Silverberry River have a dark grey, argillaceous matrix, and form dark-coloured, but inconspicuous outcrops (Fig. 5). Diamictite occurs as extensive sheets; neither abrupt margins nor marginal levees have been seen.

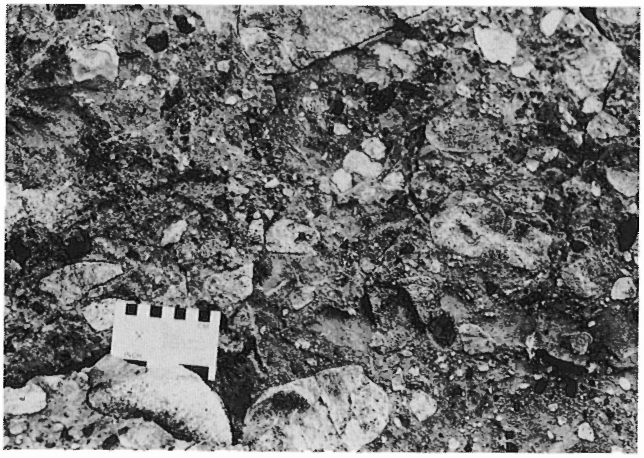

Figure 23. *Cobble- and boulder-rich diamictite of the Stelfox Member, Section 84AC-5. Sixty per cent of the stones are orange-weathering dolomite and appear pale in the photo; 40 per cent are dark grey- to black-weathering limestone. ISPG photo 3257-15.*

Figure 24. *Clay-rich, stone-poor diamictite, Stelfox Member, type section of the Ice Brook Formation. Below the hammer head is a bed of mudstone about 20 cm thick, with rare lonestones and two thin layers of pebbles that are either lag deposits or thin debris flows. The spaced cleavage is a local development. ISPG photo 3257-16.*

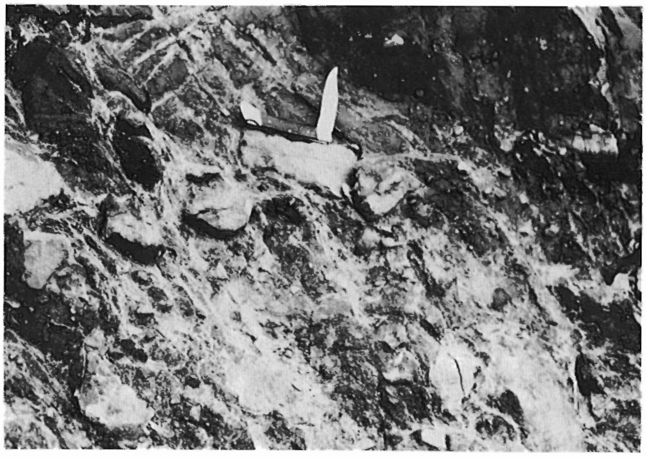

Figure 25. *A layer of cobbles in Stelfox diamictite, Section 84AC-5. ISPG photo 3257-14.*

Stones ("clasts", "phenoclasts") in the diamictites range in proportion from less than 5 per cent to (rarely) 50 per cent, and in size from coarse sand to rare rafts like the one at the type section, that measures 9 by 100 m in section (Fig. 17). Boulders larger than 1.5 m are uncommon, however. Representative diamictite is 10 to 25 per cent stones, none larger than cobble size. Most sections contain widely spaced layers of cobbles and boulders (Figs. 25, 26). In contrast with the olistostromal Durkan Member, neither the average size nor the size of the largest stones increases toward the Keele platform.

Nearly all pebble-sized and larger stones are carbonate rocks. The only other stone types noted are dark grey chert, grey sandstone and green siltstone. No extrabasinal stones have been recognized.

Carbonate rock types, both dolomitized and undolomitized, are: ooid grainstone and packstone, of which the most characteristic is black limestone; cryptalgal laminite; intraclast grainstone; flakestone; stromatolitic limestone and dolomite; and laminated to ribbon bedded, black lime mudstone. All of these rock types are present in the Keele and, in the absence of other carbonate rock types, must thus be derived solely from the Keele Formation. Noteworthy and very specific ties to the Keele are: the black, laminated limestone; the black oolite; and, near Shale ("Palmer") Lake, a distinctive, pale grey, ooid grainstone characterized by compound ooids, known from the Keele at Section 76AC-26, and as the dominant clasts in Stelfox diamictite nearby. The limestone clasts weather grey, and the dolomite clasts, various shades from yellow to bright orange. The author and several colleagues, in early encounters with the diamictites, were persuaded that there was a dolomite-rich sheet and a limestone-rich sheet. Careful estimates of the relative proportions of limestone and dolomite in the course of section description showed, however, a wide variation from bed to bed, and no overall trend.

At and south of Silverberry River, stone lithology is notably variable. At one locality (88AC-10), clasts of shale and siltstone outweigh those of carbonate rock types.

The matrices of individual beds of diamictite vary widely, from greenish grey or nearly black, sandy mudstone, through argillaceous, calcareous and sandy dolomite to dolomitic sandstone (Figs. 27-32), but the persistent characteristic is abundant quartz and/or

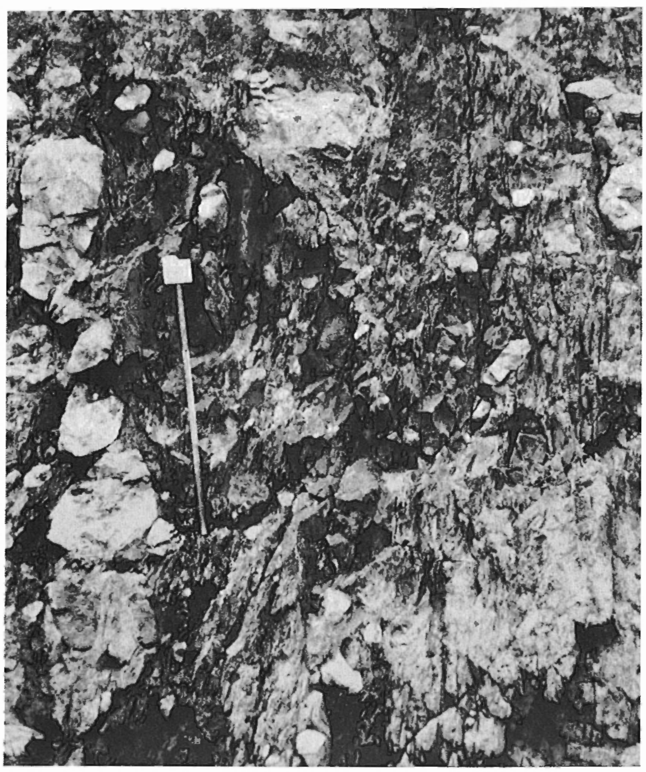

Figure 26. Stelfox diamictite at locality "E" (see Figure 1a). The strong scaly fracture is subparallel to the nearly vertical bedding. Note the boulder layer at left. The Jacob's staff is 1.5 m long. ISPG photo 3257-17.

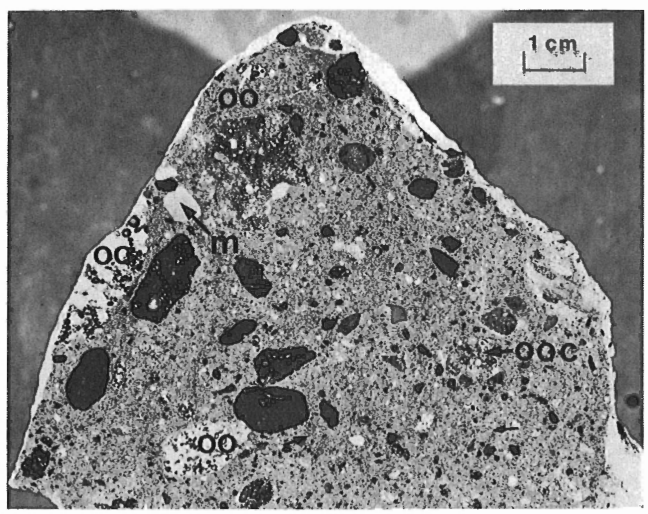

Figure 27. Stelfox diamictite from locality "F" (see Figure 1a). Stones of ooid grainstone (oo), some with compound ooids (ooc), are prominent; most of the others are dark lime mudstone. A single stone of siliciclastic mudstone is marked (m). The matrix is detrital carbonate/quarts wacke. ISPG photo 3249-1.

dolomite sand. The matrix of diamictite is consistently darker and more argillaceous at platformal sites than at basinal sites. Near Stelfox Mountain, masses of diamictite with dolomitized matrix crosscut less dolomitic diamictite; thus, some of the variation in matrix character may be secondary. Matrix character, like phenoclast character, is closely related to subjacent Keele rock types. The darkest and most argillaceous matrices occur at Silverberry River, where a unit with thick beds of grey siltstone and black shale (the terminal, platform-margin wedge of the Keele Formation) subcrops beneath the Stelfox Member. The finer and more argillaceous matrices weather green-grey to dark grey, whereas the more dolomitic weather shades of dull orange or orange-brown. A crude, scaly fracture, subparallel to bedding and manifested in the matrix only, is characteristic of most Stelfox diamictites.

A weak fabric in which the long axes of stones lie in the plane of bedding is apparent in many diamictite units. Size-grading of the stone population, whether normal or reversed, is notably lacking. Beyond these observations, rigorous determination of diamictite fabrics was not attempted. The measurement of clast orientations presents formidable difficulties in these rocks, and the effort may well yield ambiguous results (e.g., Visser, 1989).

A small proportion of the diamictite beds is contorted or disrupted. Such beds have probably undergone postdepositional slumping, but deformation by overriding ice cannot be ruled out.

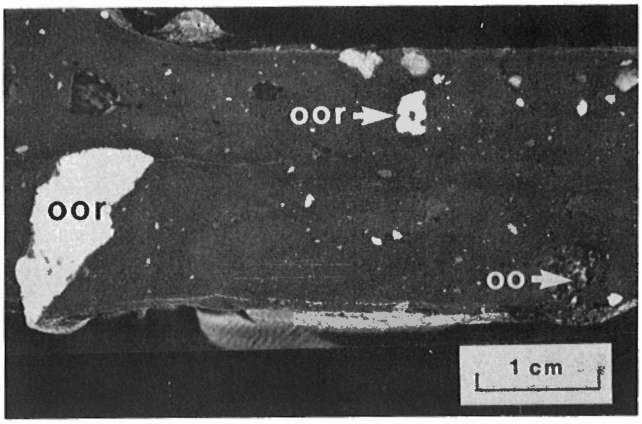

Figure 28. Argillaceous, matrix-rich diamictite, Stelfox Member, Section 84AC-5. The specimen is bounded by scaly-fracture surfaces. Notable stones are dark, fresh ooid grainstone (oo) and pale, recrystallized oolite (oor). Sawn slab. ISPG photo 3249-3.

Given the significant content of sandstone in the Keele Formation, it is perhaps surprising that clasts of sandstone are extremely rare in diamictites of the Stelfox Member. The Keele platform apparently underwent glacial erosion when the carbonate strata

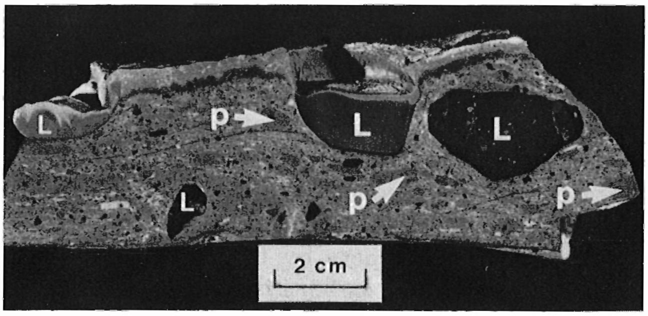

Figure 29. Diamictite with till pellets, Stelfox Member at locality "B" (see Figure 1a). Some of the till pellets are marked (p). Other large clasts are limestone (L). Note the on-end attitude of the stone at left. Sawn slab. ISPG photo 3249-2.

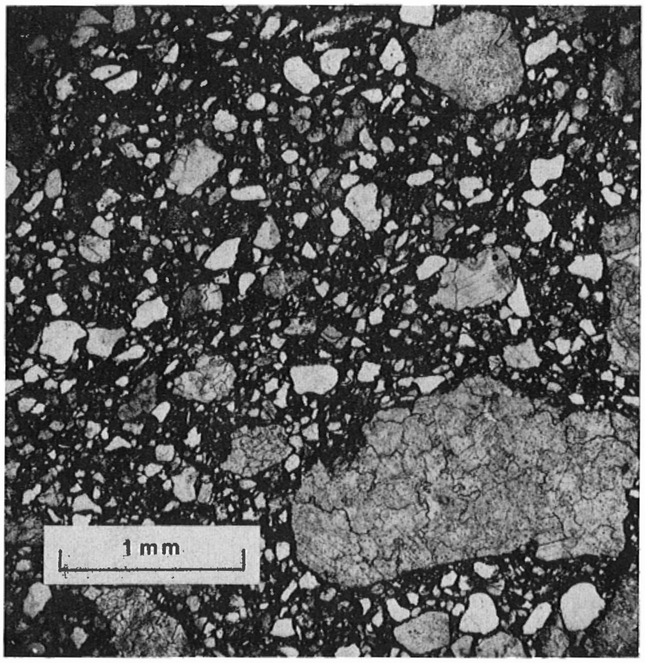

Figure 30. Matrix of Stelfox diamictite - a particularly sandy phase (thin section). Note the association of well-rounded and extremely angular quartz grains (white, featureless). Clast at right margin is recrystallized ooid grainstone. Dolomite clast at lower right bears no record of protolith character. Note the cuspate, etched margins of the carbonate clasts. ISPG photo 3399-5.

were lithified, but the siliciclastic strata as yet largely unlithified. The sands of the Keele platform were eroded, disaggregated, and incorporated into the matrices of Stelfox diamictites.

Faceted or polyhedral clasts are common, but only two striated stones, both consisting of carbonate-cemented siltstone, have been seen by the author (Figs. 33, 34). Given that the clasts are overwhelmingly carbonate rocks, this should not be surprising, even in the perspective of the interpretation of glacial activity put forth below. In the diamictites of the Shezal Formation, considered by all who have studied them (Ziegler, 1959; Young, 1976; Yeo, 1981; Eisbacher, 1985; and other papers by these authors) to be glaciomarine, striated carbonate clasts are exceedingly rare, whereas a high proportion of greenstone clasts, and a few quartzite clasts, are striated. In the case of the Stelfox Member, it is improbable that any hard bedrock surface existed within hundreds of kilometres of the depositional site. Furthermore, with few exceptions, the surfaces of carbonate stones in the Shezal and Ice Brook diamictites have been deeply etched during diagenesis (note the scalloped outlines of stones in Figs. 30, 31); and striae originally present have been destroyed.

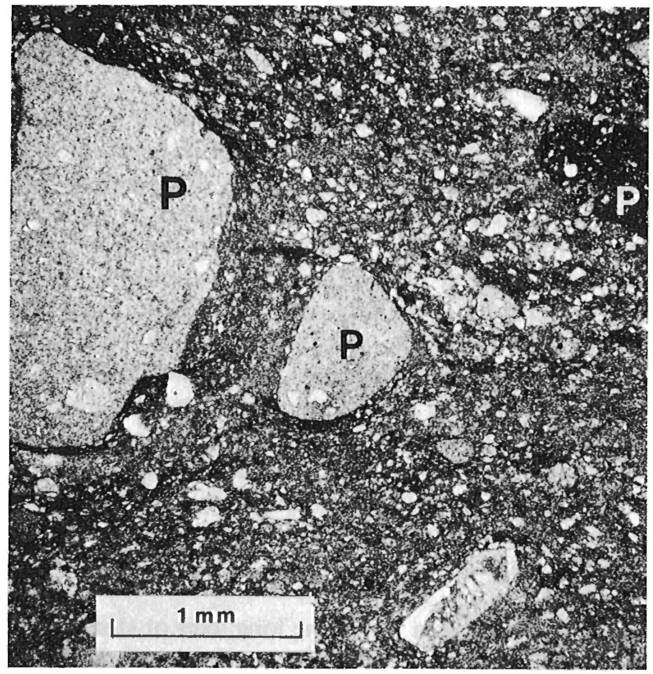

Figure 32. Stelfox diamictite with till pellet (P), Stelfox Member near locality "E" (see Figure 1a). Till pellets, thin section. ISPG photo 3399-2.

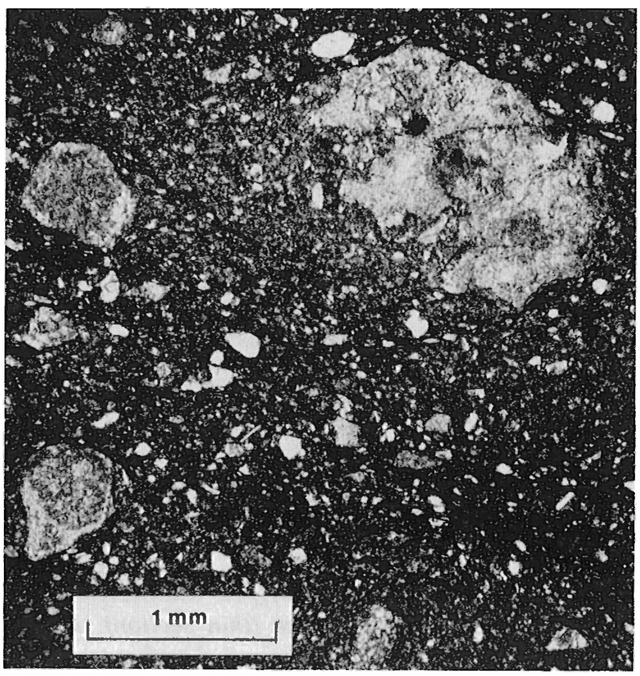

Figure 31. Matrix of Stelfox diamictite - an argillaceous phase (thin section). The large clast at upper right is identifiable as originally grainstone; note its cuspate, etched margins. ISPG photo 3399-6.

Figure 33. A faceted and striated stone in situ in diamictite of the Stelfox Member at locality "A" (see Figure 1a). ISPG photo 3257-20.

Till pellets (Ovenshine, 1970) that are interbedded with diamictite sheets are common in the mudrocks. They are rarely recognized in hand specimen, but are easily observed in polished slabs and thin sections (Figs. 29, 32, 38, cover photo).

A minor subgroup of diamictites, here termed "organized", is distinct from the prevailing kind. They differ from the others in being, in part, slim lenses of outcrop scale; in having high stone matrix ratios; and in having phenoclasts, generally pebbles, that display a distinct upper size limit. The texture of some of these is grain-supported at the base, grading upward to matrix-supported.

Rock types other than diamictite make up a small proportion, less than 5 per cent, of the Stelfox Member, and include mudstone, siltstone, and sandstone. Most mudstone is grey or pale green, noncalcareous, and silty. Some (but not all) mudstone beds and units contain lonestones that generally lie with the long axis in the plane of bedding (Figs. 23, 25), but in a few instances are perpendicular to bedding (Figs. 29, 36). The siltstone is generally flat-laminated; some beds and units are dolomitic and orange-weathering, and some contain lonestones; others contain chains of starved ripples of sandstone. The sandstone is grey or brown, the latter especially where calcareous or dolomitic. It is mostly very fine grained, but ranges up to very coarse grained. It occurs mainly in lenticular, medium beds that are either flat-laminated or tabular crosslaminated in sets about 20 cm thick. A few beds are normally graded. Lonestones are rare in sandstone, but sandstone beds commonly have pebbly bases, suggesting a lag from winnowed diamictite. Beds and units of sandstone are commonly observed to be isolated lenses, or lenses strung out along a common plane (Fig. 19). The bases of these lenses have relief of decimetre scale at most. Channels with steep walls and relief of one metre or more are unknown.

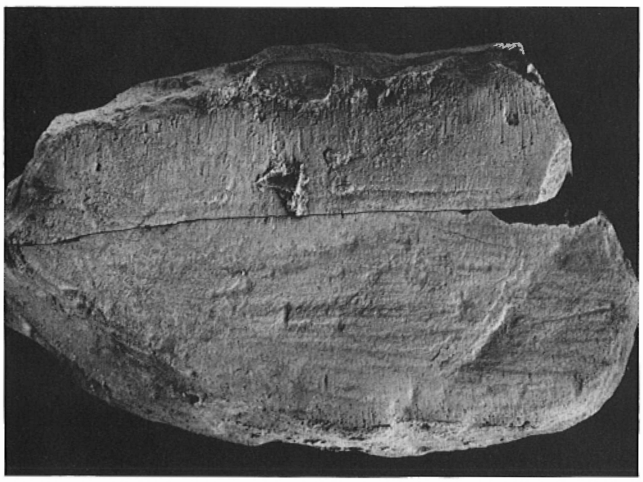

Figure 34. *A faceted and striated stone from Stelfox diamictite at locality "A" (see Figure 1a). The wide, deep striae on the front facet are interpreted as glacial striae. The fine, parallel striae on the periphery of the specimen, perpendicular to the glacial striae, result from relative movement between stone and matrix and are of compactional and/or tectonic origin. Specimen is 11 cm long. ISPG photo 3249-7.*

Figure 35. *Dropstone in laminated mudstone of the Stelfox Member, Section 84AC-5. Three thin layers of diamictite (debris flows?), marked 1, 2, and 3, appear lower in the photograph. ISPG photo 3257-18.*

It is noteworthy that the Stelfox Member consists entirely of diamictite where it rests upon the Keele Formation.

Thickness and distribution. The Stelfox Member at "basinal" sites is 55.6 m thick at its type section, 307.8 m (the thickest measured) at the type section of the Ice Brook Formation, and 9.4 m at Section 84AC-31. At the head of the Hay Creek drainage

Figure 36. Dropstone with long axis perpendicular to bedding, Stelfox Member at locality "G" (see Figure 1a). This diamictite layer contains about two per cent lonestones. The scaly fracture is subparallel to bedding. ISPG photo 3257-2.

Figure 37. Dropstones and diamictite layers interrupting laminated mudstone of the Stelfox Member, Section 84AC-31. The lonestone providing critical evidence of dropstone origin is "x", abutted by mudstone laminae. Centimetre scale at lower left. ISPG photo 3257-19.

basin, its thickness is markedly variable, and as little as 4 m at some outcrops. Its thickness at sites at which it is in contact with the Keele Formation is 17.6 m at the type section of the Keele (88AC-9), 10.4 m at Section 84AC-34, and 8.5 m at Section 88AC-12 (Fig. 1).

The Stelfox Member is limited to the Plateau thrust sheet (Fig. 1). It is generally confined to the depositional and paleobathymetric basin southwest of the constructional platform of the Keele Formation, but onlaps the margin of the platform in a narrow zone. It disappears beneath cover downdip to the southwest; no pre-Sheepbed formation is known to resurface in that direction (see Aitken, 1988).

Genesis. The Stelfox Member of the Ice Brook Formation in basinal areas consists largely of diamictites. These are mostly interpreted as stony, glaciomarine sediments, but may have been deposited in part as basal, ice-contact till. Some of the diamictites are demonstrably, and others probably, debris-flow deposits, that is, resedimented tilloids. The thin diamictites resting on platformal carbonates of the Keele Formation also may be glaciomarine, but in view of the lack of interbedded, non-diamictite strata, are more likely to include strata deposited as basal till.

The argument for glacial influence during deposition of the Stelfox Member rests primarily on the dropstones in laminated sediments interbedded with the diamictite sheets. It depends secondarily upon the presence of till pellets and rare, striated stones. The argument for origin of the diamictites as debris-flow deposits in the absence of glacial influence, suggested by the lack of stones originating elsewhere than the Keele Formation, fails on two criteria: the paucity of structures associated with debris-flow deposits, and the absence of evidence for high ground adjacent to the site of deposition.

In deposits laid down prior to the appearance of large marine algae and large land plants, only two processes could have transported lonestones: piecemeal emplacement by downslope sliding, and ice rafting (whether by icebergs, shore-ice, or river-ice). Individual stones of cobble size and larger cannot have slid into place subaqueously without visibly disrupting the lamination of underlying muddy sediments; furthermore, lonestones emplaced by sliding must rest on one of their larger faces. The interpretation here of many lonestones as glacial dropstones rests on a) their isolated occurrence in laminated, fine grained sediments that are undeformed except for indentation by, and differential compaction around, the stone (Figs. 35-38, cover photo), b) the termination (abutment) of sedimentary laminae against lonestones (Figs. 37, 38, cover photo), and c) the occurrence of lonestones embedded with their long axes nearly perpendicular to bedding (Figs. 29, 36, 38, cover photo).

Shore-ice and river-ice appear to be excluded as vehicles of transport by the high stone content of the diamictites. The paucity of stones in nondeltaic deposits of Quaternary proglacial lakes in Western Canada, where shore- and river-ice must have developed annually, demonstrates the low capacity of these as agents of transportation. Furthermore, no process of cold-climate weathering and transportation, other than glaciation, is capable of producing the abundant, extremely angular quartz grains of the diamictite matrices, given that the source of quartz is mature sandstone of the Keele Formation.

Faceted clasts, or at least, clasts bounded by quasi-planar faces, are common (Figs. 33, 34), but should be interpreted with caution. Stones of sedimentary rock types outlined by joints and bedding planes prior to transport may be faceted, but need not be glacial. On the other hand, in view of the evidence for glaciation of a young platform on which the siliciclastics had not yet been lithified, the carbonate sediments were unlikely to be jointed so early in their history. These considerations add weight to the glacial significance of faceted stones. Reasons for the extreme rarity of striated stones are given above.

The boulder layers or pavements observed in basinal sections have three possible interpretations. They may be lag deposits from which the fines were winnowed by bottom currents. They may represent the basal layers of massive debris-flows (McCabe and Dardis, 1989). Less probably, the boulder layers might be ice-contact pavements.

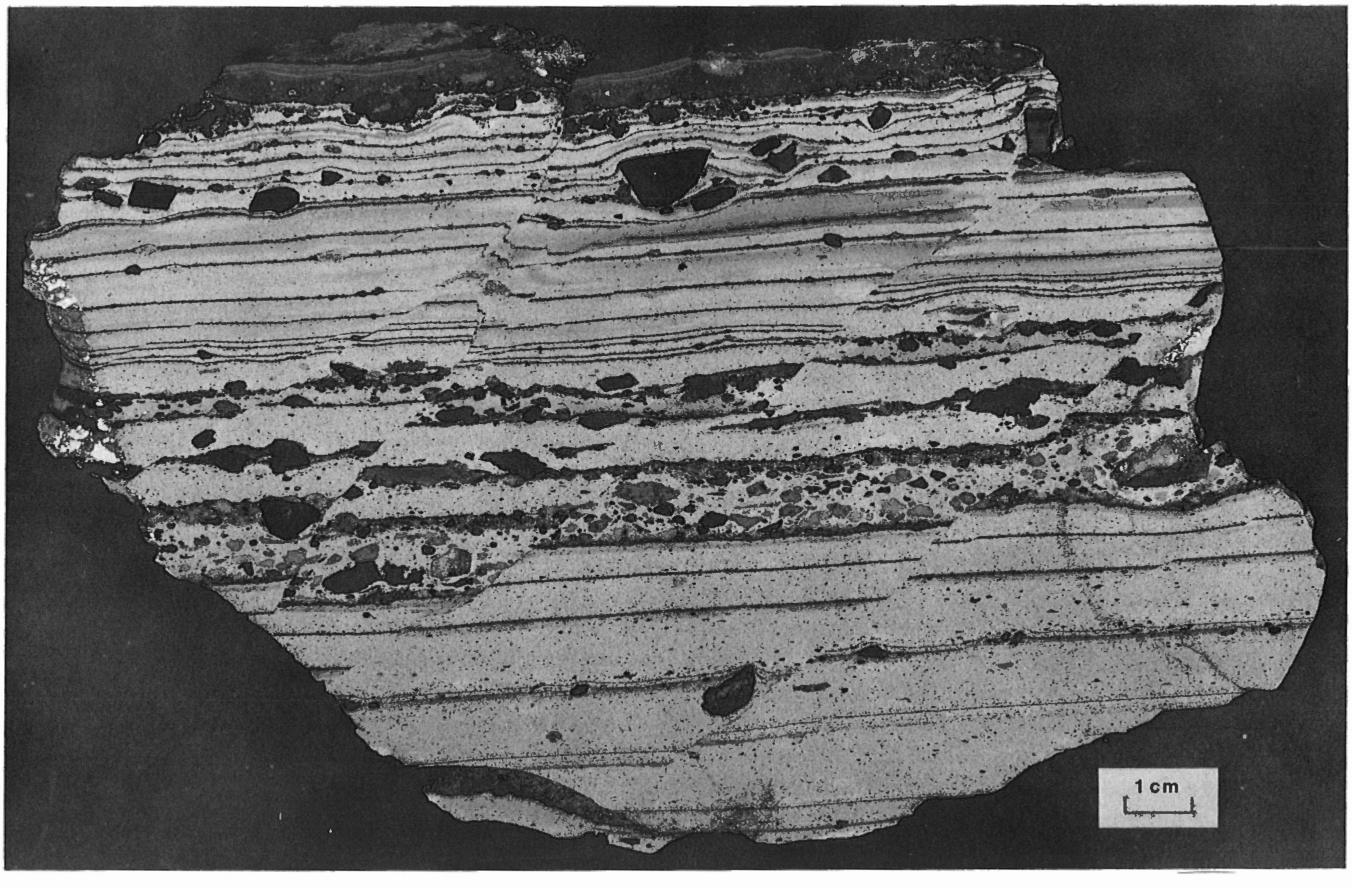

Figure 38. *Dropstones and till pellets in laminated green shale, type section of the Stelfox Member. The till pellets are the millimetre-size, ovoid particles of silty and sandy mudstone, slightly darker than their shale matrix. The lamina rich in till pellets, at about mid-height, may be the record of either a debris flow or the passage of a berg that was dumping supraglacial debris rapidly. The four microfaults appear to be synsedimentary. Specimen collected by G.M. Ross. ISPG photo 3478-2.*

The presence of dropstones suggests, on the one hand, that the Stelfox diamictites of basinal areas are largely or entirely subaqueous melt-out deposits. Spencer (1971) and Hambry and Spencer (1987) took the presence of horizons of lenticular, bedded and sorted rocks within diamictite, similar to those at basinal sections of the Stelfox Member, as evidence of grounded ice. On the other hand, where it rests upon platformal strata the Stelfox consists entirely of diamictite that may have been deposited as basal till or ground moraine. Such an interpretation appears unavoidable if the expected glacial draw-down of sea level is taken into account; the depositional surface of the upper Keele carbonate platform was peritidal at deposition, and was eroded prior to the arrival of glacial ice in the area. It must have been above sea level during glaciation if draw-down occurred. The composition of the matrices of the diamictites supports such an argument; the matrices are more argillaceous on the platform, and sandier (washed?) in the basin. The absence of outwash gravels at platformal sites might be taken as evidence against an interpretation of deposition from a shoreline or land-bound ice sheet. Quaternary outwash gravels are confined virtually to paleovalleys, however. Paleovalleys and outwash gravels of Stelfox age may yet be discovered.

The geometry and structure of typical Stelfox diamictite sheets are incompatible with their emplacement as debris flows. Stelfox diamictites (except, possibly, those on the platform) were deposited subaqueously, as indicated by the interbeds of mudstone and laminated siltstone with dropstones. The quartz sandstones, flat-laminated and tabular crosslaminated, in strings of thin lenses, also demonstrate a subaqueous origin.

Most well described recent debris flows are subaerial, but subaqueous debris flows, at least those with high matrix strength, probably display similar features. Among the characteristics of subaerial debris flows are channels, levels and abrupt margins and snouts (Costa, 1984). These have not been observed in the Stelfox Member. Furthermore, the emplacement of debris-flow deposits (remobilized till) in Upper Proterozoic valley fills of north Greenland was accompanied by deformation of adjoining and underlying sediments, formation of load casts, and injection of sandstone dykes (Collinson et al., 1989). These also have not been observed in the Stelfox. The writer, in the course of studying several ancient successions laid down on submarine slopes, has noted that debris-flow breccias in such environments characteristically display abrupt margins and snouts, erosional bases, and mounded upper surfaces. These observations, and illustrations of submarine debris-flow deposits by Cook et al. (1982), support the notion that subaqueous debris-flow deposits (possibly excepting the more fluid kinds) share a number of characteristics with subaerial debris-flow deposits.

The diamictites that rest on the upper Keele platform demonstrate further that a nonglacial, debris-flow interpretation cannot be applied to all of the Ice Brook diamictites. On a flat, peritidal, depositional platform or even the gentle, erosional, platform-margin slope into the basin (Fig. 39), there was no nearby, higher topography from which extensive debris flows unassociated with glaciation could have descended. C.W. Jefferson, in reviewing the manuscript, pointed to the fault at Silverberry Creek that predates the 'Tepee dolostone' (Fig. 39) as evidence of such topography. That fault appears to be unique [note that a fault mapped by Eisbacher (1978, Fig. 30) is of modest displacement, and does not cut the top of the Keele Formation]. To account for the diamictites of the Stelfox Member by a nonglacial, debris-flow mechanism, faults and high-standing blocks would have to have been present along the strike length of the member (Fig. 1). The country has been mapped (maps published and in manuscript), and the requisite faults are lacking. In this connection, it is worth emphasizing that the Keele Formation is a unit with distinct contacts and prominent, large-scale bedding, ideal for the recognition of faults of any scale.

None of the above negates the likelihood, and indeed, the observation, that the diamictites of the Stelfox Member include, at least in basinal areas, deposits emplaced as debris-flows with strong matrix support. Such deposits, of glacial provenance, are to be expected in areas of proglacial sedimentation (e.g., McCabe and Dardis, 1989). The thin, lenticular, "organized" diamictites are probably the deposits of more fluid flows. The giant limestone raft at the type section of the Ice Brook Formation (Fig. 17) may be gravity-emplaced, rather than rafted by ice. It is not known whether the megabreccia underlying diamictite at Section 88AC-10 owes its origin to gravity failure or ice-push.

It is perhaps worthwhile to point out that there can have been no mountain belt (a source for piedmont glaciers) between the Twitya–Sheepbed basin and the Canadian Shield. The Ediacaran formations of the Mackenzie Mountains are paraconformable with basal Cambrian deposits, and, to the northeast, the older, Mackenzie Mountains Supergroup is also paraconformable beneath Cambrian deposits. The restricted variety of stone types in the diamictites demonstrates that the Mackenzie Arch (Aitken et al., 1974) was not high and being eroded during Ice Brook time. These considerations, and the persistence of the Stelfox Member along strike, indicate that glacial erosion and transport were by a continuous ice sheet that probably covered the entire platform, rather than by valley glaciers.

The diamictites of the slope and basin are interpreted as glaciomarine, rather than glaciolacustrine, for the following reasons. First, the basal diamictites of the Stelfox Member are in gradational contact with the deposits of a marine basin-margin slope. Second, a lake of the extent required, resting on the basinward slope that characterized pre-Stelfox deposits, would require a high dam. No evidence of a depositional, for example, morainal, or a tectonic dam has been recognized. Third, if the Stelfox Member were nonmarine, the succession of strata above the diamictites and into the marine, deep-water beds of the Sheepbed Formation should record the passage of a marine shoreline. No such deposit has been recognized. This is not to say that the thin diamictites resting on the Keele Formation, and lacking interbeds of sorted and laminated sediment, are necessarily marine also.

Lithological distinction from Shezal diamictites. Ice Brook diamictites generally can be distinguished from diamictites of the Shezal Formation by their position in the stratigraphic succession. In certain structural situations, however, it may be necessary to apply lithological criteria to determine to which of these formations an outcrop belongs. Clast composition provides such a criterion.

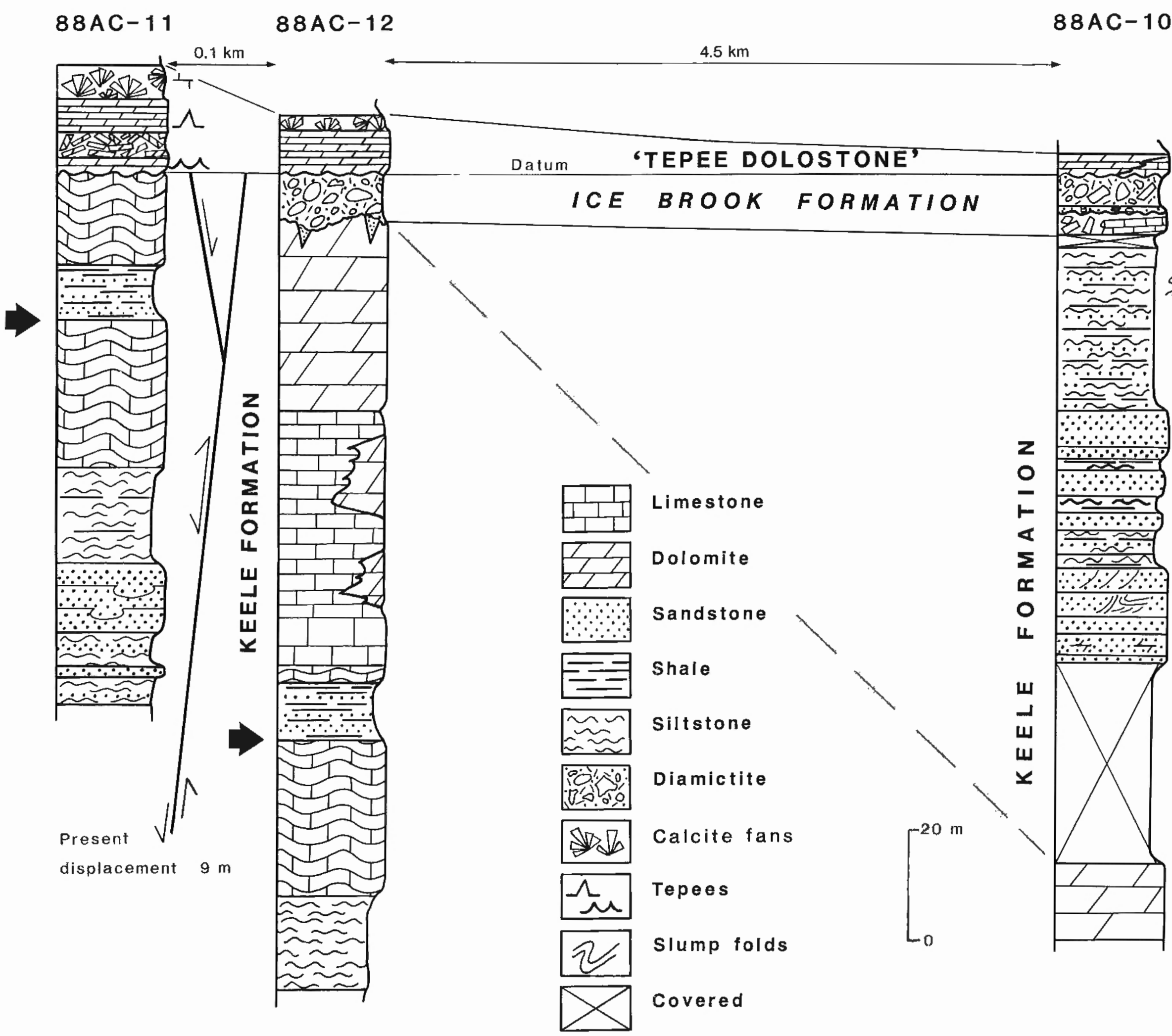

Figure 39. Stratigraphic relations along Silverberry River (see Figure 1a for section locations).

The Ice Brook Formation is known to rest on the Twitya Formation in basinal areas and the Keele Formation in platformal areas. The Shezal Formation, on the other hand, rests upon the Sayunei in axial areas of the early Windermere rift depressions and upon various formations of the Mackenzie Mountains Supergroup down to the Katherine in marginal areas.

The stones of both diamictite formations are derived overwhelmingly from the highest underlying or laterally adjoining formation. The glaciers of Ice Brook time appear to have "sampled" only the Keele Formation, a circumstance that suggests a vast extent for the Keele platform. In contrast, the Rapitan glaciation postdated an episode of profound erosion. A wide variety of diagnostic carbonate and non-carbonate sedimentary rocks of the Mackenzie Mountains Supergroup, the diabase intrusions that cut them, and even crystalline rocks of the Canadian Shield, represented by extremely rare erratics ("stranger stones"), were thus accessible for "sampling" by glaciers. The field-tested criterion for distinguishing between diamictites of the Shezal and Ice Brook formations is thus the common presence in the Shezal diamictites of stone types unknown from the Keele and Twitya formations.

Foremost among the distinctive clasts of the Shezal are limestone or dolomite with molar-tooth structure (Bauerman, 1885; Aitken, 1981). This structure is widespread in Little Dal carbonates and unknown from post-Little Dal carbonates of the region. Next, and also derived from the Little Dal, are columnar-branching stromatolites, particularly those with purplish or reddish laminae. Next is quartzite, whose principal source is the Katherine Group. Last is basalt/diabase, derived either from the Little Dal lavas or the diabase intrusions that cut all formations up to and including the lower Little Dal. These latter are presumably the "extra-basinal clasts, particularly greenstone" of Eisbacher (1985, p. 240), but they are no more "extra-basinal" than clasts of sedimentary rock derived from the Mackenzie Mountains Supergroup. By applying these criteria, an isolated outcrop of diamictite can be assigned with confidence to one formation or the other, following a few minutes' examination.

Boundaries

The olistostrome recognized as the Durkan Member of the Ice Brook Formation is limited, with one possible but unlikely exception, described earlier, to the slope and basin beyond the margin of the Keele depositional platform. Its base is the slide surface along which it moved basinward (Figs. 13, 16). There is no reason to infer erosion at that contact, other than what may have been accomplished by the sliding mass. It is important to recognize that failure of the platform margin marked an interruption in, rather than an end to, buildup of the Keele platform.

The Delthore Member is by definition coextensive with the Durkan Member, although near Shale Lake and Stelfox Mountain, beds assigned to the Durkan must pass into the middle, siliciclastic member of the Keele Formation that is conspicuous at the platform margin. Its base is discordant to the extent that the member was deposited atop the presumably chaotic surface of the newly emplaced Durkan olistostrome. Significant erosion at the contact would necessarily have produced a lag deposit of large stones; such a deposit is not present.

In basinal areas, the base of the Stelfox Member appears to be conformable. No coarse lag deposit is present, and the thin Durkan and Delthore members are preserved in a wide swath of country adjacent to the platform margin. To argue that the absence of the Durkan olistostrome in areas farthest from the platform records erosion, rather than the limited travel of a coarse slide-mass, is to argue for greater erosion toward the centre of the basin than on the basin-margin slopes.

Where the Stelfox Member rests upon the Keele platform, its base is a significant unconformity. This is intuitively clear from the great volume of stones derived from the Keele Formation and incorporated into Stelfox diamictites, but it is also demonstrable on stratigraphic evidence.

Near Stelfox Mountain, the base of the Stelfox Member truncates the upper carbonate member of the Keele Formation and is locally in contact with the tops of the largest blocks (approaching kilometre dimensions, see Fig. 14) of the Durkan Member, derived from the lower carbonate member of the Keele. The configuration cannot be simple depositional pinchout of the upper Keele, because various shallow-water rock types persist to the surface of truncation. No apron of talus derived from the margin of the upper Keele platform is present, nor, given the low angle of truncation, expected.

On upper Silverberry River, both large-scale, pre-Stelfox erosion of the Keele Formation and a bevelled fault with post-Keele, pre-'Tepee dolostone' movement are documented (Fig. 39). Sections 88AC-11 and 88AC-12 are only about 100 m apart, and separated by a steeply west-dipping fault. In the western section (-11), the 'Tepee dolostone' rests directly upon the Keele Formation. In the eastern section (-12), an additional 83 m of Keele beds are preserved above the highest in the western section; furthermore, 8.5 m of Stelfox diamictite separate the Keele from the 'Tepee dolostone'. The fault was clearly a west-side-up structure when the Keele was faulted and bevelled, and probably such when the Stelfox Member was faulted and bevelled. In view of the evidence of pre-Stelfox erosion (below), much of the erosional bevelling of the Keele was probably pre-Stelfox. Separation across the fault at present is about 9 m west-side-down.

At Section 88AC-10, about 4.5 km east-northeast of -11 and -12, roughly 120 m of Keele strata are present above the correlatives of the highest Keele beds preserved at 88AC-12 (Fig. 39). Five or six metres of Stelfox diamictite are separated from the Keele by an irregular, three- to ten-metre thick megabreccia that includes some decametre-scale blocks (this megabreccia appears to be too high, stratigraphically, to be the Durkan Member). Whether the megabreccia a result of slope failure or ice push was not determined. The 'Tepee dolostone' is present above the Stelfox Member. The significance of these relationss is that the main unconformity is beneath the Stelfox Member, and not the 'Tepee dolostone'. The sub-'Tepee' unconformity, where the 'Tepee' rests on Keele strata, is therefore largely inherited from the sub-Stelfox unconformity.

Relationships both at Stelfox Mountain and Silverberry River reveal greater pre-Stelfox erosion of the Keele platform toward the basin. Where preserved, the Stelfox Member was deposited on a gentle, erosional, basinward slope.

A fully exposed Stelfox/'Tepee dolostone' contact has not been observed, and observations bearing on its nature are contradictory. On the one hand, the wide preservation of thin Stelfox Member beneath the 'Tepee dolostone' and the absence of a cobble or boulder lag deposit beneath the 'Tepee' are arguments against significant erosion. On the other hand, the stones of the Stelfox record glacial flow from the northeast, and the diamictites are confined to the basin and the outboard margin of the platform, suggesting that the diamictites were probably deposited on, but subsequently eroded from the inboard region of the platform. This conclusion is not resolvable at present; this study by no means excludes the possibility that glacial deposits, especially erratics, may be found locally, northeast of the presently understood limit of the Stelfox Member.

Age

The Ice Brook Formation is best dated with reference to the appearance of fossils of Ediacaran type, which indicate a terminal Proterozoic, or Vendian age. The lowest of these found to date in the Mackenzie Mountains occurs in the Twitya Formation (Hofmann et al., in press). Ediacaran fossils persist upward into the Risky Formation (Narbonne and Aitken, in press). No isotopic date of high reliability is yet available for the base of Ediacaran fauna anywhere in the world.

The fossils in the Twitya Formation postdate, by an unknown and probably lengthy period, rifting and igneous activity associated with the onset of deposition of the Windermere Supergroup. This activity is dated in the Mackenzie Mountains at 766 plus/minus 24 Ma and 769 plus/minus 27 Ma (Armstrong et al., 1982) and 777.7 plus 2.5/minus 1.8 Ma (Jefferson and Parrish, 1989), and in the Wernecke Mountains at 751 plus 26/minus 18 Ma (Roots and Parrish, 1988).

SIGNIFICANCE OF TWO LATE PROTEROZOIC GLACIATIONS (RAPITAN, ICE BROOK) IN THE NORTHERN CORDILLERA

This is the first formal report to establish the presence, in a part of the North American Cordillera, of a second level of Upper Proterozoic glacial deposits, separated by thick, nonglacial strata from the deposits of an older and well documented glaciation. Until now, the Cordilleran region has been anomalous, in that the pattern of two Late Proterozoic glaciations, seen in Australia, Africa, and parts of Asia, was unknown. Consideration of the possibility of essentially worldwide, simultaneous, Late Proterozoic glaciations generally ends in circular reasoning. It is nevertheless beyond question that the evidence for two glaciations, rather than a single one, substantially increases the ultimate possibility of chronocorrelation of glacial deposits of the Mackenzie Mountains with those of other continents, as recognized by Eisbacher (1985, Fig. 10).

Only one other region of the Cordillera, the Monkman Pass area of British Columbia, appears to have two distinct levels of glacial deposits. Diamictites are commonly present near the base of the Windermere Supergroup in the region (e.g., Evenchick, 1982). In southeast Monkman Pass area, however, thick diamictite occurs some kilometres higher. This is the diamictite unit of the Middle Miette Group (McMechan and Thompson, 1985), or "Mount Vreeland" of Eisbacher (1985). These diamictites display a tectonic overprint and cleavage, and have not been studied in detail, but the presence of extra-basinal boulders strongly suggests a glacial origin.

The demonstration of two levels of glacial deposits raises further questions about the correlation of Cordilleran glacial and putatively glacial deposits: Kingston Peak and correlative glacial deposits of the western U.S.A.; Toby Conglomerate of southeastern British Columbia; the two levels (apparently) of diamictites in northeastern British Columbia; the two levels of glacial deposits in Mackenzie Mountains. When only one glaciation (Rapitan) was known to be recorded in the northern Cordillera, it was almost universally assumed to correlate with the Toby Conglomerate, the single glacially influenced unit in the southern Canadian Cordillera (e.g., Eisbacher, 1985). That assumption, and other assumptions about the correlation of glacial deposits of the North American Cordillera, must now be re-examined.

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