CHAPTER 1

HISTORICAL REVIEW

1.1 INTRODUCTION

Literature dealing with the existence of glacial deposits of the northeastern district of Victoria, both in and around the Ovens Graben, is not as extensive as for other areas of Victoria. Investigation of the northeastern region glacial deposits has been hampered by a lack of outcrop; much material appears to have been eroded since the time of deposition, and much of that now remaining is concealed beneath the Murray Basin sediments. The development of ideas about glacial deposits in the district can be traced to as early as 1860 (Dunn 1923, 15). Essentially, field discovery ended by about 1913. Observations began to decline sharply from about 1903 then declined more gradually to about 1909. The decline in the number of field discoveries parallels a similar pattern of decline in the amount of field investigation carried out by E.J. Dunn whose contribution to the geological knowledge of the northeastern district was indeed considerable. The years following the period of decline in the number of new field discoveries became periods of literature reviews, summaries and re-statements of earlier findings, ideas and speculation. These were not always entirely accurate and the earlier authors were not always given adequate recognition for their efforts and ideas.

A detailed and accurate account of the contributions is now necessary, to present and evaluate the historical development of the discoveries and the ideas about the glacial deposits of the northeastern district of Victoria; and to put the contribution of the field investigators and the literature reviewers in chronological order.

1.2 PREVIOUS INVESTIGATIONS

As long ago as 1866, unusual outcrops in central southern Victoria, already described as conglomerates, were being interpreted as glacial in origin. Daintree, in 1866, suspected the peculiar character of the now well known Bacchus Marsh deposits was best explained by considering them to be of glacial origin (Dunn 1890; 1923). Similar conglomerates to those of Bacchus Marsh were already known to exist as early as 1860 (Dunn 1923, 16), in the northeastern region of Victoria, east of the Ovens Graben. The particular localities are listed by Dunn (1923) as Wooragee and Eldorado. Dunn's interest in these particular deposits spanned almost sixty five years. His skill in the field later led him to South Africa in 1871 where his observations of the Dwyka River deposits, then variously known as: claystone porphyry(A.G.Bain); Trap conglomerate, Trappean ash(Wyley); Trap breccia (Jones); Intrusive trap (W.G.Atherstone); and Metamorphic rocks(R.Pinchin), led him to propose the glacial nature of the Dwyka River deposits (Dunn 1923, 12). The Dwyka River deposits were later to become more widely known as the Dwyka Tillite.

Dunn continued his investigations in South Africa and the experience gained was of great significance in the work he later carried out in the northeastern district of Victoria. In 1870, before Dunn travelled to South Africa, he completed a map of the Beechworth district

(Dunn, 1923). His report about the district included a map of the Wooragee Valley; one of the areas where Dunn had noted the "strange conglomerate" as early as 1860. The map depicting the conglomerate as Upper palaeozoic(?) was not published by the Mines department, for whom he worked, until 1871.

The "old conglomerate (Upper Palaeozoic ?)" as it appears or the map (Dunn, 1871) extends as low rises from the "Police paddocks" to the Tertiary Magpie alluvial lead in the Wooragee Valley. Dunn (1871), in his report to the Mining Surveyors and Registrars, describes the variety of clasts which could be found both in the Police paddock and Magpie Creek outcrops of the "old conglomerate". The conglomerate contains boulders, pebbles, sand, and a great variety of perfectly rounded rocks; all cemented with a clay (Dunn, 1871). Beneath the Magpie Creek beds were further dark beds containing large pebbles and boulders of hornfels. Large boulders of pink feldspar - rich granite were located still further down in the section.

During the search for gold in the Wooragee Valley, numerous shafts were sunk. One was sunk to a depth of 30 m (100') in the Upper palaeozoic conglomerate without reaching basement (Dunn, 1871). Early descriptions of clasts by (Dunn, 1871) include the following lithologies:

* Lydian stone (a form of black chert);

* Crystalline limestone;

* Upper Silurian sandstone, with casts of shells;

* Chert;
* Agate;
* Breccia;
* Puddingstone;
* Amygdaloid;
* Jasper;
* Porphyry;
* Granite.

He also indicated that the variety is far greater than those listed.

Dunn (1871) also refers to the deposits of conglomerate northwest of Eldorado as extending to the Chiltern-Wangaratta road now known as the Hume Highway. Dunn (1871) further suggested in his report that the Tertiary auriferous deposits of the Eldorado-Wooragee district are likely to be derived as a result of erosion from the Upper palaeozoic conglomerate of the Wooragee Valley. No doubt the same could be said for the chiltern deep leads directly to the north of the Wooragee Valley. Numerous diamonds were found in the course of gold mining in the region, especially between Wooragee and Eldorado. At Wooragee, (Dunn, 1871) specimens between 0.1 and 2.0 carats were recovered; a few even larger (5.0 carats). These discoveries were from the bottom of drifts but all were from material which Dunn (1871) suggested was derived from the Wooragee conglomerate. Baragwanath (1948, 12) reports diamond finds at Beechworth as early as 1863. Little work appears to have been carried out on the Upper Palaeozoic conglomerate in the northeastern district whilst Dunn was in South Africa investigating the Dwyka and related conglomerates. One report dealing with the geology of the Ovens Valley district and its associated deep leads (Howitt 1874, 75) refers to the soft sandstone previously recorded by Dunn (1871, 42). In this report Howitt (1874) records that he found material similar to that found by Dunn, and that it was found to contain casts of what appeared to Spirifids as well as the stem of an Upper Silurian crinoid. This represents the first clear reference to Upper Silurian fossiliferous material besides that of Dunn (1871, 42) to the "casts of Shells". Howitt was unable to suggest a source for the material but was led to suggest that it must have been from a local source; he concluded that such friable fossiliferous material could not have survived transport for any great distance.

After almost twelve years, Dunn returned from South Africa (in 1885) with considerable experience of the likely field appearance of glacial deposits and went about re-examining the Wooragee conglomerate (Dunn, 1923). He discovered striated, scored and faceted clasts, and with his new experience decided that the Wooragee Upper Palaeozoic conglomerate was without doubt of glacial origin. Almost twenty years had passed since Daintree (Dunn, 1923) had suggested the glacial nature of the Bacchus Marsh deposits. The Upper Palaeozoic conglomerates of the northeastern district were thus placed with other similar deposits in Victoria thought to be of glacial origin. In 1885, Dunn placed examples of glaciated material in the Beechworth museum and also the Technological Museum in Melbourne (Dunn 1923, 15). The glacial nature of the Wooragee conglomerate was not published until 1887; two years after Dunn had made his identification. Earlier in 1887, Dunn read an account of the occurrence of glaciated pebbles and boulders in Victoria which was published by the Royal Society of Victoria. By May 1887, Dunn's interest in the conglomerates had extended to other areas in the northeastern district (Dunn, 1923) and he mapped deposits at Wahgunyah, Rutherglen, Springhurst, and Eldorado.

In June 1888, Dunn mapped the glacial deposits at Tarrawingee and Baddaginnie (Dunn, 1923). The mapping of these deposits preceeded the mapping of Wild Duck Creek, Derrinal; and Heathcote deposits of Central Victoria. The first suggestion of floating ice as a transport mechanism was presented by Dunn together with ideas about palaeogeography (Dunn 1890, 456). Dunn suggested that many of the rocks were unknown on the continent anywhere in Victoria, and they may have been brought to the area as a result of sediment laden ice calving from glaciers which he thought were not necessarily from a southern source. The ice, perhaps directed by winds and currents, melted and deposited the sediments onto the ocean floor or, possibly, in a lake. Dunn's comments on this occasion were meant to apply to the glacial deposits of Victoria in general; and not only to those of the northeastern district.

From the Chiltern district, about 20 km southeast of the northern localities mapped by Dunn, glacial "drift" was described by Taylor (1894, 37) and consisted of:

* Boulders of all shapes and sizes: mostly flat and rounded;
* A great variety of granites;
* Sandstones;

* Quartzites;
* Indurated slates;
* Agatiform quartz;
* Grits.

Jasperoid quartz together with large and small boulders of Upper Silurian sandstone were present. The sandstones were equated by Taylor to the Mayhill sandstone. The boulders were said by Taylor to contain numerous casts of the mollusca:

* <u>Orthis</u> and
* <u>Atrypa</u>.

Taylor concluded that the material was not of local origin, contrary to the earlier view of Howitt, and that it may have come from as far as Mt. Ida in the Heathcote area. This is the first located record about thoughts of Heathcote being a possible source for the fossiliferous material from the northeastern glacial deposits. Taylor (1894, 36) like Dunn (1890, 456) regarded drift boulders as "evidently ice-borne". Taylor (1894) refers to other areas in the vicinity of Springhurst which are probably those previously mentioned by Dunn. Taylor added that the other deposits are more largely developed on the flanks of the Silurian hills: the hills to which Taylor referred are now known to be Ordovician (Mines department of Victoria (Ed 1) 1974, sheet SJ 55-2: geological map 1:250.000).

The only mapped outcrop of upper Silurian rocks containing fossils is about 5 km southwest of Benalla, where rather poorly preserved casts of shells were recovered together with Encrinites and a small coral. These fossils were recovered from bands of sandstone and brecciated grits (Ferguson, 1889). No further detail was given.

Nine years after Taylor had described "Upper Palaeozoic(?) drift" from the Chiltern district, further material was found in the same area and clasts were forwarded by Hunter for petrographic examination by J.W.Gregory (Hunter, 1903). Banded cherts, located by Hunter at the Green Hill outcrop were found by Gregory's examination to contain well preserved remains of radiolaria; mostly in the form of spherical quartz casts but some also containing concentric internal shells. From this Hunter (1903) suggested that the cherts resemble the Heathcote cherts but pointed out the in-situ Heathcote cherts were not known to contain radiolaria. As identified by Gregory, the radiolaria belonged to the order Porulosa, sub-class Spheroidea. In 1903, the same year as Hunter's account, Kitson's report about the glacial deposits of Greta and the first account of the deposits at both Taminick and Glenrowan was published. Taminick is just to the west of the Ovens-King River Valley; west of the Warby Range. Glenrowan is situated within a gap in the Warby range. The Greta deposits were previously mapped by W. H. Ferguson but there does not appear to be any account published soon after the work was completed. In addition to the Greta deposits, Ferguson also mapped deposits near Hanson and two deposits near Pelluebla (Kitson, 1903); none of the mapped deposits appear to have been described in published form by Ferguson. Ferguson's work probably preceeds Kitson's by about ten years, as will be discussed later. Kitson (1903, 148) refers to there being no fewer than fourteen outcrops ("inliers") in the vicinity of Greta and that portion of the Ovens-King River Valley. Unfortunately, these inliers are not all describec nor are they listed on any of Kitson's maps. He does give a general list of the lithologies and special features for: the "Mundara" Hill outcrop, north of Greta; Canning's Hill, near Taminick; and Cox's and Sacdlers Hills, also near Taminick.

The Main features of the "Mundara" Hill deposit include:

* Reddish-yellow, finely-sandy gravelly-clay;
* Finely-sandy and micaceous shale (or fissile mudstone with patches of carbonaceous matter-like plant fragments (with a calcareous olive green appearance);
* Pebbles, some of which were faceted, polished, widely grooved and bearing numerous striae;
* Boulders of grey-brown quartzites;
* Lydianite(a variety of black chert);
* Chert:plain, banded and brecciated;
* Chert:various colours from black to white;
* Quartz;
* Agate;
* Mudstones;

* Sandstones:indurated and normal;

* Conglomerates:fine and medium grained;

* Porphyry:quartz and feldspar;

* and, red and grey granites.

Kitson also drew attention to the granite because it was embedded in surface outcrop. Some sandstone blocks contained casts of Silurian brachiopods (Kitson, 1903) and were probably similar to those located earlier by Taylor (1894). There were numerous striated pebbles to be found; although, the striae were somewhat vague due to the extensive weathering. The pebbles were chiefly yellow, grey-yellow and brown quartzites, and siliceous mudstones (Kitson, 1903).

Kitson's lithologic description of the Canning's Hill deposit was similar to the "Mundara " Hill description except that there were no fossiliferous sandstones nor calcareous mudstones present. The thickness of the Canning's Hill deposit was about 15 m (50'). In this particular deposit, striated pebbles were not as numerous as they were at "Mundara" Hill, but coarse gold was present, although, not in worthwhile amounts. Both Saddler's and Cox's Hill were again similar to the character of the deposit at "Mundara" Hill: fewer striated pebbles were found at Cox's Hill but faceted, polished and widely grooved pebbles were still present (Kitson, 1903). In general, Kitson (1903) was unable to explain, with certainty, the lack of glacial deposits on other hilltops in the area and says that from the available evidence it is difficult to decide whether glaciers or floating icebergs have been responsible for the deposition of the sediments. The concept of floating ice, however, was first proposed by Dunn (1890).

The addition of likely glacial deposits to the record of the north-eastern district followed five years after Kitson's 1903 account. The contribution came from H. S. Summers who worked in the Nillahcootie district, about 40 km south of Benalla; at the junction of the Broken River and Back Creek.

Summers' work involved the reassessment of a site previously investigated for a water conservation project. The project was shelved in 1907 because of a problem with an extensive underlying conglomerate (Summers, 1908). The conglomerate was found by Summers to consist of pebbles set in a fine matrix of clay and to extend, in places, to a depth of up to 21 m (70'). It was earlier thought by investigators to be a potentially serious leakage path. Earlier interpretations suggested that the conglomerate was a palaeochannel remnant (Summers, 1908) but Summers thought the deposits had the characteristics of glacial deposits. Exposures were generally poor but some of the best were discovered below the junction of Back Creek and the Broken River where the conglomerate was up to 21 m (70') thick and about 1000 m (3,300') wide. Summers (1908) described the deposits as consisting of boulders and pebbles of all sizes set in a fine matrix of clay and including the following lithologies:

* Quartzites;
* Hornfels;
* Mudstones:indurated;
* Shales;

* Quartz porphyry;

* Granite porphyry;

* Aplite;

* Tourmaline aplite;

* Quartz.

The size range was from 30 cm (1') to 2.5 cm (1"). The largest boulder found in any outcrop in the area was in a road cuting near Back Creek.It consisted of granite porphyry and was over 1.4 m (4') long and was beside a mass of indurated mudstone which was about 1 m (3') long (Summers, 1908). Faceted, polished and sometimes striated boulders were also indicated; although, Summers (1908) said that these were not entirely satisfactory. Summers concluded the deposits were of glacial origin; mainly on the basis of their field appearance, the form and variety of pebbles; aside from (to Summers) the less convincing striae on the boulders. Sections of conglomerate were rare and the bulk of the conglomerate was found between the present bed of the Broken River and the hills to the east (Summers, 1908).

Identification of further glacial deposits continued during 1909 in the nothern portion of the Ovens-King River Valley, in the Chiltern - Eldorado district. A total of twelve of the then known deposits were mapped by Hunter (1909). Each outcrop was shown separately at a mapping scale of two miles to the inch. A number of borehole records was included in his report. The records probably contain decriptions of glacial deposits but the descriptions are too vague to be sure. Four years following the work by Hunter, more outcrop was mapped in the Wooragee Valley near Beechworth by Dunn (1913). Dunn on this occassion presented a further extension to the already known deposits: an area to the eastern end of the valley toward Yackandandah was mapped as glacial. This area had not been mapped previously by Dunn nor has this area been included in subsequent geological maps involving the Wooragee Valley, for example: Leggo (1965); Dept. Mines (1974); Douglas and Spencer-Jones (1975). Dunn (1913) prepared a very simple cross-section through the eastern-most deposit which was only 3 km from the Magpie creek deposits. Dunn thought all the deposits were emplaced in a pre-glacial valley; much the same as the present topography of Bacchus Marsh.

It was possible, according to Dunn (1913), that at least the source of the Wooragee glacials could have been from the southeast in the direction of the headwaters of the Murray River. His reasoning was based on the recovery of diamonds (two to three hundred) from both the Wooragee conglomerate and from the Tertiary deposits derived from the conglomerate. Dunn believed the possible source of the diamonds to be a volcanic pipe, near Delegate in New South Wales, about 220 km southeast of Beechworth. Dunn regarded the pipe as similar to the diamond bearing pipes of South Africa. He also drew attention to the ubiquitous nature of the small but extremely well rounded corundum pebbles in the Woolshed Valley just to the west of the Wooragee Valley, near Eldorado. The size of the corundum varied from about 7 cm (3") to minute grains; they were not thought to be of local origin (perhaps Delegate) but were being released from the Wooragee conglomerate (Dunn, 1913). The frequent occurrence of corundum pebbles in areas where no glacial conglomerate was found was believed by Dunn (1913, 9) to support his idea of extensive erosion of glacial deposits in the district. In addition, he stated that blocks of pink-purple corundum weighing as much as 300 kg (500lbs) were then known to occur about 150 km to the south at Mount Wellington in Gippsland. Dunn (1913, 9) suggested that the Beechworth corundum pebbles may be derived from the same source as those at MT. Wellirgton, and further continued to suggest that Heathcote sources, located by Skeats (Dunn 1913, 12) could well be the ultimate source of all the corundum in question. Dunn's directional data imply movement of either glaciers, icesheets or even floating ice from the southeast (based on diamond source) or from the west (based on corundum source). Buchan (southeast of Beechworth) and Heathcote (southwest) were considered by Dunn as possible sources for the highly polished red-yellow and brown jaspers also present.

After sixty three years of involvement in the recording of the geology of the northeastern district of Victoria, E.J.Dunn's last published contribution about glacial deposits was in 1923. Whilst no major advance in field knowledge was presented, he did provide a brief summary of the history of his involvement in the mapping and the description of the glacial conglomerates of the northeastern region.

Between 1913 and 1930, new published data were scarce except for the record of completed boreholes; one of which was Laceby No. 1 (Department of Mines Victoria, 1929). The little known Laceby No.1 may have encountered some glacial material but the record of the descriptions is too vague to be certain. The drilling operation was abandoned at a depth of 106 m (348') after passing through about 6.5 m (20') of ligneous sandy clay. The hole bottomed in slate. There are insufficient data to permit speculation that the hole had bottomed in a huge erratic of slate. A more successful water exploration bore, Laceby No. 2 (Mahony, 1937) was later drilled; not far from the first.

Fieldwork regarding the glacial deposits seemed quite limited after Dunn's 1913 report. The lack of published accounts ended with Mahony's (1931) report: a review of the glacial deposits of Victoria including the northeastern localities was presented. No newly identified field data were presented but Mahony (1931, 80) suggested the possible extensive nature of glacial deposits beneath the Murray Valley. Mahony provided re-statements of previously known data from Dunn (1871; 1887; 1913), Taylor (1894; 1903) and Kitson (1903) and also referred to the record of drilling operations for the years 1891 to 1922. Six northeastern region localities were indicated on Mahony's (1931, 91) map which showed the then known glacial deposits for all of Victoria. Mahony's map has since been the basis of most, if not all, subsequent maps of the distribution of glacial deposits of Victoria. One noteable omission from Mahony's (1931) map was the Nillahcootie deposits described by Summers (1908). The following sites appear on Mahony's map:

* Devenish;
* Yarrawonga:outcrop at Wilby(Pelluelba);
* Glenrowan;
* King-Ovens River;
* Beechworth.

Mahony's (1931) article was an ANZAAS research committee report dealing with the glacial deposits of Victoria and as such did not fully detail aquired knowledge for the northeastern region up to that time.

Summers(in Skeats, 1935) presents a summary of the Permo-Carboniferous geology and in reference to the northeastern region surprisingly omits his own work at Nillahcootie. He does, however, draw attention (p.121) as Mahony (1931, 80) did to the confirmation of extensive subsurface glacial deposits in the Ovens-King River Valley through drilling but Summers (in Skeats 1935, 121) suggests these deposits were protected from erosion by trough faulting; an explanation similar to this was later presented by Harris and Thomas (1948, 51). In Mahony's (1937, 513) second account of the glacial deposits he echos Summers' (1935, 121) view by stating there were extensive deposits beneath the plains of the Murray Valley. Quite extensive drilling operations had proved subsurface deposits previously unknown.

Little detailed sedimentological work had been done, although some of the strata likely to be encountered in the northeastern region were indicated by Mahony (1937). In his reference to Laceby No. 2 Mahony (1937, 516) regarded a red mudstone at the base of the bore as resembling the Devonian beds near Mansfield. A view almost identical to Mahony's was later expressed, without reference to Mahony's statement, by Kenley (1952, 60) but Mahony's Devonian beds were labelled as Carboniferous in accordance with new field data. Other boreholes in the district receiving mention by Mahony (1937) were:

* Norong No. 1;

* Boorhaman and Brimin No. 1 wells.

Much of the glacial material was thought to be the result of extensive icesheet activity rather than alpine glaciers because of the presence of faceted and glaciated pebbles. The sandstones were thought to represent interglacials or less frigid periods, and the formation of lakes (Mahony, 1937).

Also in 1937, Ferguson's account of the glacial deposits of the Glenrowan district was published but bears a manuscript date: 5.5.93 (Ferguson, 520) and appears to predate Kitson's (1903) published account by 10 years. The account of localities by both Ferguson and Kitson are of the same outcrop; their locality references, although given from different directions, refer to the same point. For some reason, yet unclear, Ferguson (1937, 520) (manuscript dated 1893) and Kitson (1903, 149) describe rock fragments at a well on the western side of "Mundara" Hill with almost exactly the same phraseology, the difference being that Ferguson regarded the sandy shales as similar to the shales of the Wannan and Glenelg Rivers. Neither acknowledges the other; available evidence suggests Kitson is remiss, and that he drew directly from Ferguson's then unpublished manuscript.

Another review of the Victorian glacial deposits appeared fifteen years after Mahony's account. No new information was presented about the northeastern region. In this review Kenley (1952) refers to the resemblance of the red mudstone from the bottom of Laceby No. 2 bore to the mudstone of the Carboniferous of Mansfield, rather than Devonian as discussed previously by Mahony (1937). That an almost identical view was held by Mahony (1937, 516) was not mentioned by Kenley (1952).

The next extension of ideas about glacial deposits in the northeastern district was from detailed descriptions of cores from Laceby No. 2 by Bowen (1960). In the Wangaratta district, Bowen (1960, III-71) reported twenty nine localities: previous literature presents twenty different localities indicating thirty five separate outcrops, four of which are boreholes. Of the unnamed twenty nine localities, Bowen (1960, III-71) reports that over half of these "glacials or fluvioglacials" were visited with the exception of the locality known as Rocky Point (reported to be 16 km (10 mls) north of Wangaratta). Bowen was unable to locate any area known by that name. Bowen (1960, III-71) reported that never more than one unit was exposed in one outcrop and in only one case were there two glacial units exposed near one another. Grass cover and the collapse of mine shafts penetrating the deposit had long since obscured reasonable outcrop (Bowen, 1960). Only four of the fifteen or more deposits visited by Bowen were interpreted as being glacial "till". The outcrop inspected at Wooragee consisted of only "one square foot" of exposed bluish-grey "till" (Bowen 1960, III-72). The second locality (p.III-72) indicates perviously known deposits south of Shannon's Hill to consist of "till": "50% sand-rich". The third locality, interpreted by Bowen (1960, III-72) as glacial "till" was at Wahgunyah, near Rutherglen. This deposit was described as bleached and kaolinized sand-rich till (50% to 60% fine sand, 10% to 30% stones). The remaining percentage presumably consisting of clay. Faceted boulders included:

* Mudstone;
* Quartz;
* Quartzite and granitics(mixed with silt).

Bowen (1960, III-72) added that there were probably glacial gritty sands nearby. It is likely that these deposits were previously mentioned by Dunn (1887). The fourth and final locality visited and interpreted by Bowen (1960, III-72) as "questionable till" was about 1.6 km (1 ml) north of Springhurst where outcrop was reported to be laterized and weathered. Without doubt, this is Green Hill; the locality earlier described by Hunter (1903, 42; 1909, see plate 18) and first mapped by Dunn in 1887 (Dunn 1923, 16). In general, Bowen appears only to have confirmed the views of various earlier investigators in the northeastern region; it is even quite likely that if Bowen had been able to carry out more extensive fieldwork in the district he may have been able to confirm and, perhaps, locate further outcrops but time was unavailable. Kitson's (1903) identification of the glacial character of the Greta deposits was only cautiously accepted by Bowen (1960, III-72) despite the presence of faceted and striated boulders which he (p.III-72) apparently regards as an important identifying feature of both the Tarrawingee and Wahgunyah "tills". The borehole description was the most significant contribution to the accumulation of knowledge of the northeastern glacial deposits. Bowen (1960, III-74) regards the local outcrop as poor in quality and so badly weathered as to be useless for studies of glacial stratigraphy. Following the earlier views of Summers (1935, 121), Mahony (1937, 80) and Harris and Thomas (1948, 51), Bowen (1960, III-82) attributed the preservation of the glacial deposits to down-faulting.

In some places the deposits remain as low hills or preserved in bedrock hollows. In agreement with earlier suggestions Bowen (1960, III-82) believes that fossiliferous clasts indicate likely movement from the west or southwest. Taylor (1894, 37), Hunter (1903, 42), with reservation - Kitson (1903, 150), Dunn (1913, 9; 11; and 12) earlier suggested movement from the same directions. Dunn's (1913) view might also be placed alongside Kitson's (1903) view because of the suggested Heathcote source for the Wooragee and other corundum and jasper pebbles. Bowen suggested that the six or more "tills" identified, represent at least six or more glacial advances in the northeastern district. This was based on the Laceby No. 2 core description together with the limited outcrop seen. A varved sequence was also identified in Laceby No. 2 by Bowen (1960) and offered as evidence for at least one interglacial stage.

Further work regarding the glacial deposits of the northeastern district again lapsed following Bowen's (1960) work. Nine years after, another review of Victorian glacial deposits was published. In Spencer-Jones' (1969) review, no new information for the northeastern region was presented. The localities mentioned in the review were those of Dunn (1871, 1913); Taylor (1894); Hunter (1903; 1909); Kitson (1903); Mahony (1931; 1937) and Ferguson (1937). Just as Bowen (1960, III-71) had done, Spencer-Jones erroneously reported <u>twenty nine</u> separate localities known to be of glacial character, and in addition, presented six borehole summaries; each interpreted as intersecting glacial deposits. These boreholes were drilled for water exploration and are:

	Name		Glacial interval	
*	Wangaratta North	No. 2	1 m (3')	(145-148')
*	Carraragamungee	No. 1	25 m (75')	(379-461')
*	Boorhaman	No. 1	144 m (474')	(269-742')
*	Brimin	No. 1	12 m (39')	(109-146')
*	Norong	No. 1	17 m (57')	(423-480')
*	Laceby	No. 2	168 m (552')	(317-869')

(Spencer-Jones, 1969)

Again, the source of the fossiliferous boulders is confirmed as

Heathcote by Spencer-Jones (1969, 54-55) as a result of unpublished faunal lists compiled by J. A. Talent for material for the northeastern district. Spencer-Jones (p.54-55) reports that Talent was certain that material of such a faunal assemblage would not have existed elsewhere in Victoria, as outcrop, except in the Mt. Ida beds of Heathcote. Based on Talent's data, Spencer-Jones regarded the transport as 110 km in direction 070°.

Following this third review of the glacial deposits of the region Leggo (1965) completed mapping of the Beechworth district. Leggo's map indicated most of the already known localities of the Beechworth- Eldorado glacial deposits. A similar map was reproduced by Leggo and Beavis (1967) as part of an excursion guide to the northeastern district for an ANZAAS conference in that year. The same map formed part of a publication by McAndrew and Marsden (eds) (1975). In Lawrence (1975) another reference to the northeastern glacial deposits appears with some new speculations and interpretations but all based on already known and summarised data. Lawrence (1975) reports fewer than 20% of of all bores in the district reaching basement encounter glacial material (Lower Permian). Lawrence regards geophysical evidence as support to belief of widespread glacial deposits beneath the Murray Basin; a belief held as early as 1931 by Mahony. Geophysical evidence was assessed by MacIntyre (1976) from earlier records and by Palmer (1977) from more recent records. Without giving detail of his reasoning, Lawrence (1975, 21) states outcrop of the Ovens Graben may contain some marine deposits despite at the time (p.21) referring to known evidence of the continental character of the outcrops; at least for the southern portion of the Murray Basin. From oxidised mudstones in cores from Laceby No. 2 (erroneously listed as No. 1 -p.23)

Lawrence (1975, 22) interpreted an interglacial stage; the oxidation of some mudstones were interpreted as representing the development of a palaeosol.

A recent summary of the nature of the Permian glacial deposits of the northeastern region is presented by Bowen and Thomas (in Douglas and Ferguson, 1976). Although, again, great detail of early work is not given, the summary of the northeastern deposits is well based on the work of Kitson (1903), Mahony (1937), Ferguson (1937) and Bowen (1960) as well as minor contributions from a number of others. Bowen and Thomas (1976, 139) by way of personal communication with J. G. Douglas fix a terrestrial origin and probable Permian age, based on the presence of Nuskoisporites spores, for the deposits from Mundoona No. 1 to the west of the northeastern region, near Wunghnu. The glacial nature of that material was earlier suggested by Mahony (1973, 515). Recent work by Tickell (1977/78, fig. 2, 6) shows extensive areas in the northeast of Victoria to contain subsurface Permian mudstones and tillites. Tickell's map is an interpreted structural geology for some pre-Tertiary rocks of the the "Ovens Graben" and for some areas as far west as Echucha. Distributions shown by Tickell are based on Permian intersections (some re-interpreted as such) in "some 55 bores at depths ranging from 74 m to 250 m" (Tickell 1977/78, 4). Doubt may be associated with some of Tickell's re-interpretations. He lists Laceby No. 1 (p.4) as being one of three bores which was drilled through the Permian and that a thickness of 158 m was recorded in the hole. Because Laceby No. 1 (Mines department 1929, 32) was abandoned at a depth of 114 m(375') the accuracy of his reference to this borehole and perhaps other interpretations must be regarded with care. A description of Laceby No. 1 which could be regarded as reliable, and consistent with drilling records, appears in his figure 15, section 9 (p.26).

Further doubt arises about the distinction between Tickell's presentation of fact and his interpretation. Figure 2 (p.4) shows, for the "Ovens Graben", previously inferred faults (Mines department of Victoria (ed 1), 1974, sheet SJ 55-2:geological map 1:250.000) as now established but concealed; also in the same area, features previously shown as merely interpreted structure lines on satellite imagery are now reported as established but concealed faults. Tickell presents no evidence for these new interpretations. By far the greatest value of Tickell's report is the summary of borehole information for the northeastern region.

It seems that much of the Permian glacial data, ideas and speculations have been drawn through the literature with increasing inaccuracy and decreasing detail. Much of the historical development of knowledge about the Permian glacial deposits of the northeastern district has been repeatedly obscured and removed by the apparent need for what may be regarded as <u>excessive</u> brevity in summaries and reviews. I trust this account restores the balance, and represents development of ideas, speculation and field discoveries with the appropriate historical perspective and with credit assigned to those most deserving.

1.3 SUMMARY

The most important works regarding the description of glacial deposits of the northeastern district of Victora are those by Dunn (1871; 1887; 1890; 1913; 1923), Taylor (1894), Hunter (1903; 1909) and Kitson (1903).

Dunn's (1871) work contains the earliest description of clast variety, and palaeontological data, and first suggestions that the northeastern Beechworth conglomerates were possibly Upper Palaeozoic. Dunn's (1887; 1890; 1913; 1923) subsequent work added to these areas of knowledge but especially to the listings of lithologies present in the conglomerates, clast varieties, localities known, the mapping of the deposits, possible sources for the erratics and the collection of clasts with features attributed to glacial action. Taylor's (1894) contribution is regarded as important because of the first record of specific palaeontological data and the suggestion of the likely source of the fossiliferous erratics i.e. Heathcote to the southwest. Hunter's (1903) contribution, although as brief as Taylor's (1894), was similarly important because of the first record of chert clasts containing radiolaria belonging to the sub-class Porulosa of the Order Spheroidea. He also suggested Heathcote as a possible source. Perhaps even more important was his map (Hunter 1909, plate 18) indicating (until my mapping) almost every known outcrop in the Rutherglen-Wangaratta- Tarrawingee-Beechworth area.

Kitson's (1903) account was the first published detailed account of glacial deposits southwest of Wangaratta and in the Glenrowan and Taminick districts.

Many others have made various contributions to the knowledge of the northeastern district's Permian glacial deposits but their contributions must be regarded as lesser alongside those of Dunn, Taylor, Hunter and Kitson.

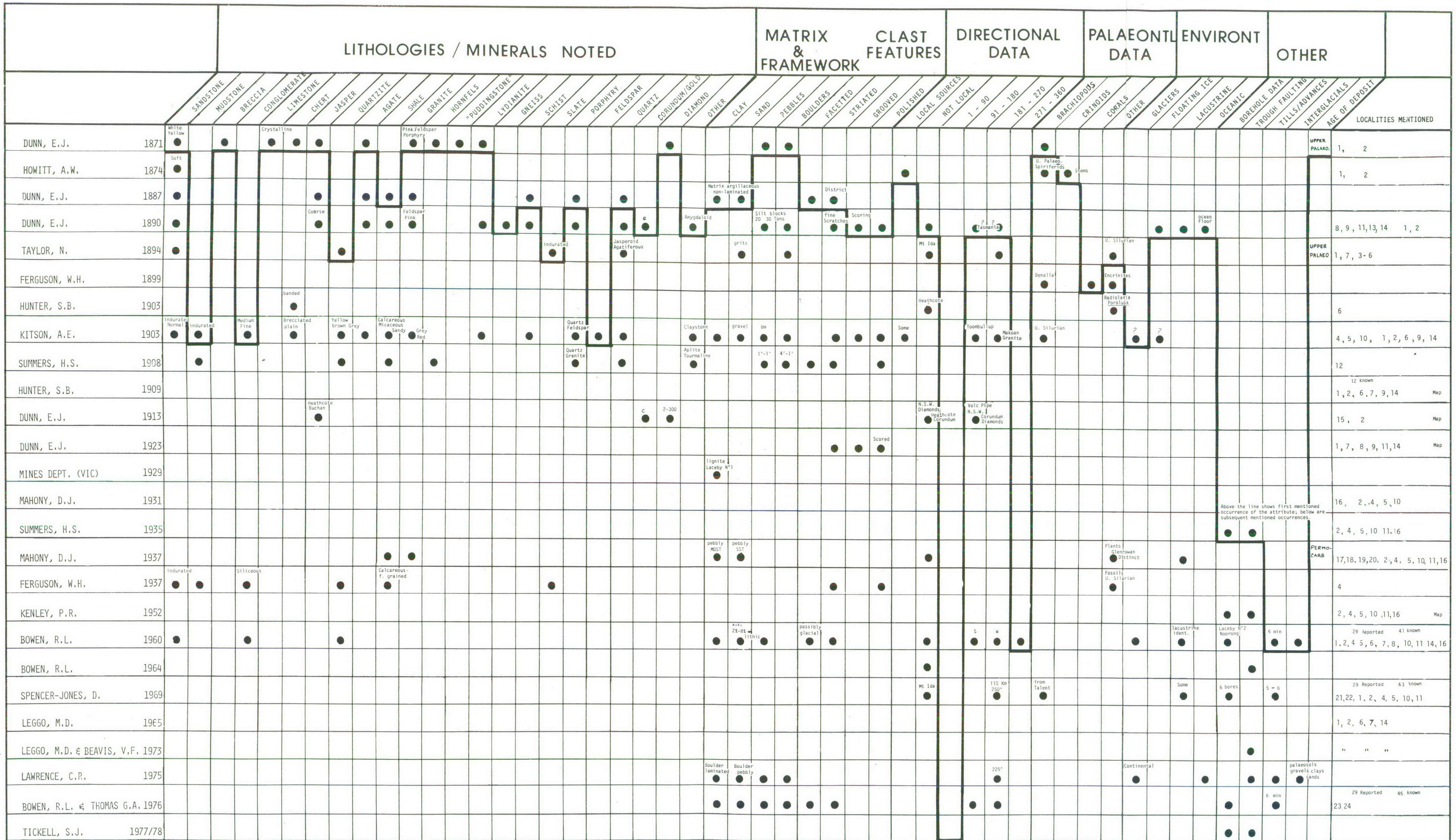
Cases of inaccuracy and lack of acknowledgement have shown that many ideas, and some data offered in the literature actually owe their existence to earlier investigators. At least for the northeastern district, reviews of the glacial deposits of the entire state (e.g., Mahony 1931, 1937; Kenley, 1952; and Spencer-Jones, 1969) have done little to show the extent of early knowledge and by their attempts to deal only with the complete record of the state they have clearly masked by omission of references the wealth of data available. Until now recent literature suggested little work of any significance had been done in the northeastern district.

The possible transport directions given in the literature range from west to south. In the northeastern district pavements have not been reported until now, nor have any fabric studies been considered.

Most ideas about the direction of ice movement toward the northeastern district stem from inference about the likely source areas of erratics collected. With the exception of detailed palaeontological work by Talent (Spencer-Jones 1969, 54-55) much of the directional information has remained highly speculative. A continental ice sheet is the favoured view expressed in the literature.

There has been a renewed interest in the earlier idea of marine influence and possibly lacustrine deposition. There has always been an homogenous set of views about possible environments e.g., fluvial and marine influences in glacial deposits in the northeastern region. The relative influence of each or the clear existence of any is yet to be convincingly demonstrated. The continental ice-sheet explanation has been maintained throughout the literature without alternatives seriously being considered. Table 1, p.27 shows the chronological and historical development of knowledge about glacial deposits of the northeastern district.

PERMIAN RECORD – NORTHEASTERN VICTORIA



Literature Record of Permian Localities for Northeastern Victoria

Localities in Literature	Author	No. of outcrops	Cf.
1. Beechworth		2	2
2. Eldorado to Wangaratta	Dunn, 1871	4	6
No new localities	Dunn, 1874, 1887		
3. Wahgunyah	Dunn, 1890	5	11
4. Rutherglen	Dunn, 1890		
5. The Springs	Dunn, 1890		
6. Tarrawingee	Dunn, 1890		
7. Baddaginnie	Dunn, 1890		
8. South of Springhurst	Taylor, 1984	1	12
None given	Ferguson, 1899		
9. Green Hill	Hunter, 1903	3	15
10. Greta	Kitson, 1903	14	29
11. Hansen	Kitson, 1903		
12. Wilby	Kitson, 1903	3	31
13. Glenrowan-Taminick	Kitson, 1903	3	34
14. Nillahcootie	Summers, 1908	1	35
(localities already known)	Hunter, 1909	-	35
15. Eastern end of Wooragee Valley	Dunn, 1913	-	36
(localities already known)	Dunn, 1923	-	36
16. Devenish (bore hole)	Mahony, 1931	1	37
(localities already known)	Summers, 1935	-	37
17. Rocky Point (10 mls Nth. Wangaratta)	Mahony, 1937	4	41
18. Oxley (Laceby No. 2)	Mahony, 1937		
19. Norong	Mahony, 1937		
20. Boorhaman	Mahony, 1937		
- (localities already known)	Ferguson, 1937	-	41
- (" " ")	Kenley, 1952	-	41
- (localities already known but identifies 29 as known)	Bowen, 1960	-	41
- (localities already known)	Bowen, 1964		41
- (" " ")	Leggo, 1965		
21. Wangaratta North 2 (Bore hole)	Spencer-Jones, 1969	2	43
22. Carraragamungee 1 " "	Spencer-Jones, 1969		
- (localities already known)	Leggo and Beavis, 1973	-	43
- (" " "	Lawrence, 1975	-	43
23. Whitfield	Bowen and Thomas 1976	2	45
24. Hansonville	Bowen and Thomas 1976		
25-65 Wangaratta district (Bore Holes)	Tickell, 1977/78	41	86

65 different localities known with a total of 86 individual outcrops

- Of the localities known up until 1976 83% were known before 1938
- Of the individual outcrops known up until 1976 91% were known before 1938.

Note: Borehole information in the post war (WWII) years has almost doubled the number of specific outcrops but has just less than tripled the number of localities.

CHAPTER 2

THE ENVIRONMENTAL INTERPRETATION OF DIAMICTITES

2.1 INTRODUCTION

Deposits of poorly or non-sorted sediments have been observed since the late 1700s. For ease of discussion such sediments will be termed diamictites or diamictons if unlithified.

These deposits consist of sand, pebbles, cobbles, boulders and perhaps megaclasts (erratics) all bound within a finer, commonly muddy matrix. They may be lithified or not. They are formed by a variety of mechanisms. At first sight it may appear to be impossible to distinguish deposits formed by different mechanisms. One might wonder how many ancient diamictites have been misinterpreted in the past, and what techniques are available to those faced with interpreting the origin of such deposits today.

The discriminators used to distinguish between different mechanisms of formation of diamictites, other than those of glacial origin, are really still being discovered and refined. As workers become aware of new mechanisms and their discriminators, those sediments already interpreted are periodically re-examined to ensure they have not been wrongly identified, and to test the power of the newly defined or refined discriminators. During this process the discriminators commonly thought to be almost absolute in their power to define glacial and non-glacial sediments have received a severe shaking.

What are acceptable discriminators of glacial sediments today? In the everlasting endeavour to distinguish beyond doubt the origin of poorly sorted sediments and to ascribe to them an environment of deposition, many workers have put forward the criteria that they personally have found to be successful. A library of discriminators now exists and many were believed to be absolute. Experience is showing that it is wiser to think of the discriminators as having various (rather subjective) confidence levels. I suggest that no discriminator is absolute although some certainly do have high confidence levels. The discrimination of glacial from non-glacial sediments has usually been on the basis of recognition of the associated or included features which are themselves thought to be diagnostic of glacial activity.

The confidence levels have been reduced in some cases because alternative non-glacial processes have been found to produce almost indistinguishable "discriminators".

2.2 TERMINOLOGY

Before looking too deeply into the question of discriminators and their value, a brief excursion into terminology is mandatory.

A system of terminology has evolved in which there is basic divergence of opinion about the mechanism of formation of poorly or non-sorted sediment.

Ill-sorted sediments were early believed to be the result of some sort of glacial action. Eventually almost all such deposits were viewed in this way, and classification was further bound by an established but biased vocabulary. So, terminology developed with the concept of ill-sorted sediments automatically allied with glacial transport and glacial environments. So rigid was this framework that from the 1800s to 1950s almost all poorly sorted sediments were regarded as being glacial.

Ramsay (1885), (in Harland, Herod and Krinsley, 1966) was responsible for incorrectly assigning the Permian breccia of Shropshire (England) to the list of glacially generated deposits. Blanford and Theobald (1856), (in Banergee, 1966) were probably as confident as Ramsay of their interpretation of the glacial origin of the Talchir Boulder Beds (in the Raniganj coalfields: India). Their interpretation has remained.

The recognition of alternative mechanisms led to new terminology which emerged sometime in the 1930s but has grown profusely since the 1950s. Disagreements both in concept and in terminology have led to genetic and non-genetic divisions. Available nomenclature today is very confusing.

The chronologic development of terminology following is not intended to include every term ever coined but rather to show the diversity and dichotomy:

Proposer	Date	Genetic	Non-genetic
Murchuson	1839	Drift	
Geikie	1874	Boulder Clay	
Woodward	1887	Till	

Penk	1906	Tillite	
Blackwelder	1931		Tilloid
Crowell	1957		Pebbly mudstone
Pettijohn	1957		Orthoconglomerate
			Paraconglomerate
Flint et al.	1960		Synmicton
			Synmictite
			Diamicton
			Diamictite
Schwarzbach	1961		Pseudotillite
Harland	1965	Orthtill	Paratill
		Orthotillite	Paratillite
Harland	1966	Allochthonous till	Autochthonous paratill
		Allochthonous tillite	Autochthonous paratillite
			Diamict
			Marine glacial beds
Schermerhorn	1966		Mixtite
			Aquatillite
Jago	1974	Till	Breccias
		Tillite	Conglomerates

Sources:

Crowell (1964)

Flint, Sanders and Rodgers (1960)

Harland, Herod and Krinsley (1966)

Jago (1974)

Schermerhorn (1966)

2.3 MACRO AND MESOSCOPIC DISCRIMINATORS

2.3.1 PAVEMENT ASSOCIATIONS

Striated and scoured pavements have long been acclaimed as sufficient evidence for glaciation. Poorly sorted sediments overlying a striated pavement are accordingly regarded as glacial in origin. This need not follow.

Modern analogies increase the confidence level of the glacial pavement as a useful discriminator between glacial and non-glacial sediments. The chance of finding a till or a tillite directly overlying glacial pavements is indeed high. Reappraisal of the value and role of pavements has come about since about the 1950s because of attention drawn to misinterpretations of pavement-like surfaces (Harland et al., 1966). Glacial pavements are believed to have a unique set of surfaces features. They are:

* Gouges and striations which have various attitudes and are apparently independent of slope or palaeoslope;

* Chatter marks;

* Crescentic gouges dipping in two possible directions on the pavement surface;

* Various shear and percussion induced fractures.

Surfaces displaying most or all of these features can be considered glaciated surfaces with a very high degree of confidence. To recognise a number of the above mentioned features on a supposed glacial surface, large outcrop areas are usually necessary. Premature interpretation of limited pavements has led in the past to a complete misinterpretation of the genesis of the surface and the overlying sediments. An example of such a misinterpretation is the Bigganjargga Precambrian Pavement in northern Norway. The overlying sediments were interpreted, by Reusch in 1891, as glacial sediments overlying a glacial pavement (Harland et al., 1966). Harland et al. (1966) have re-interpreted the sediments as mass movement deposits formed by large scale slumping. However, they have chosen a most unfortunate term to describe the deposits: allochthonous tills. By their own definition these "Tills" are not tills in the strict sense .

The pavement identified by Reusch is not a glacial pavement. Evidence cited by Harland et al. (1966) strongly supports the interpretation of the surface to be a deformed bedding plane. Deformation was caused by the emplacement of the poorly sorted sediment onto a soft unconsolidated surface.

O'Neil (1924), Gould (1928) and Mathiassen (1933) quoted in Harland et al. (1966) all suggest ice and icebergs are capable of producing striations on both pavements and boulders. Harland et al. (1966) point out that such pavements have limited extent and the depth of striations is shallow. They are not well planed nor are they associated with smooth outcrops. Harland et al. (1966) believe that these pavements are easily distinguished but I believe that there may be circumstances, particularly in older rocks, where misinterpretation is likely. Crowell (1964) believes that true glacial pavements are rare -

as rare as tillites. Pavements identified on minimal evidence reduce the reliability of any prediction about the glacial origin of the overlying sediments. Even when adequately identified, glacial pavements are not absolute discriminators between glacial and non-glacial sediments which may be covering them. Those pavements do, however, testify unequivocally to the occurrence of a glacial event. I believe that other discriminators are required to increase the confidence level of determination of the glacial nature of poorly sorted sediments.

2.3.2 STRIATIONS AND RELATED FEATURES

Striations on clasts are produced by a number of mechanisms but were generally thought to be absolute discriminators between glacial and non-glacial poorly sorted sediments.

Some workers after identifying striations on clasts are almost immediately inclined to think that they are dealing with a glacial sediment. I stress that this conclusions is not necessarily valid, because the processes of mass movement are known to produce striations on clasts. Frequently, these striations occur on softer rocks such as shales or slates. The striations may be shallow and curved. Mudflows and other terrestrial mass movement generated deposits have also yielded striated clasts which show a parallel unidirectional pattern. Striations of this origin were recorded by Kayser (1921), Blackwelder (1930) and by Cadisch (1953) (in Crowell,1957). Crowell (1957) describes striated clasts that have undergone milling actions and are associated with brecciation zones of olistoliths. These clasts according to Crowell, frequently show scratches and striations which closely resemble those known to be produced by the effects of glaciation.

Winterer (1964) through his investigation of the Normandy pebbly mudstones invites a more critical evaluation of surface features. Graindor, the original investigator of the Normandy deposits emphasised surface features of the enclosed clasts e.g., striations, creases, troughs, dimples and clast fractures with a bi-polar nature. In 1953, Graindor published the tillite hypothesis for the origin of the Normandy deposits (Winterer,1964). Winterer re-examined the deposits and re-interpreted them as the product of mass movement. He examined a small number of randomly chosen "stones" with intermediate axes within the range of 18 mm to 170 mm. One was chert; the others were sandy-shales or greywackes. Every stone proved to have scratches and striae, however, some only could be seen with the aid of a hand lens.

Graindor's striated rocks were almost exclusively chert and showed striae of the moulded variety defined by Wentworth (1936). The moulded type of striation extends over the angular edges and around broader convexities: much like formlines. Wentworth (1936) assessed the incidence of these clast types at 12% based on studies of Pleistocene tills.

Winterer (1964) discovered the moulded striations on clasts he sampled but the incidence was higher than that stated by Wentworth. Winterer concluded the striations were of a different origin from those observed by Wentworth. Winterer added to clinch his arguement that the striations extended into the matrix coatings of some of the clasts. He believed the striations were produced as a result of differential motion between clasts within the enclosing matrix.

Without the supporting evidence of the striated matrix, these clasts would be easily confused with those produced by glacial action. There are other circumstances in which clasts unequivocally glacially striated, are recognised, and the "host" sediment is interpreted as glacial in origin. Striated clasts in these circumstances at least support the existence of a glaciated source area form which the "host" was derived.

Clasts that are unquestionably striated by the action of glacial ice have deep to shallow scores which are usually polydirectional. The striations are not usually parallel but may be. The scores stop and start abruptly and may start again as near parallel offset continuations. Clasts with these features may also have a typical "flat-iron" shape as defined by Von Engeln (1930). They may have scour induced snubbed noses and be roughly ovoid as noted by Harland et al. (1966).

I believe another distinctive glacially induced shape is similar to the hull of a yacht with bow formline striations extending along the sides and across the top to an abrupt stern fracture. I have observed and collected such shaped clasts from interpreted Permian glacial deposits from northeastern Victoria.

Despite these observations I must point out that the majority of striated clasts are unlikely to be so distinctive. Therefore clasts bearing striae are not commonly absolute discriminators between the glacial and non-glacial origin of the sediments in which they may happen to be enclosed.

Other surface features mentioned by Winterer (1964) in appraising Graindor's approach to the Normandy deposits included dented pebbles. Pebbles may show elongated dents or troughs and Graindor believed these features to be distinctly glacial but Winterer strongly refutes this idea and suggests that they are a product of pressure solution during diagenesis.

2.3.3 ERRATICS

Harland, Herod and Krinsley (1966) concluded there is one criterion that alone can decisively determine the glacial or non-glacial nature of poorly sorted sediment: numerous large boulders penetrating and deforming a series of host strata.

Crowell (1957) suggests pebbles and cobbles embedded in a fine grained matrix which displays either deformational or penetrative features, may have been transported by and dropped from melting ice, floating root masses or other various holdfasts. Other clasts may be introduced into sediments by traction or turbidity currents. Crowell also pointed out that river and lake shore ice could also raft clasts off-shore and that these processes are not likely to lead to vast dispersal patterns of large quantities of clasts nor are the clasts likely to be of very large size. Crowell (1957) acknowledges the ability of icebergs to transport quantities of clasts away from glaciated areas as Antarctic icebergs do today. Depending on how far the clasts are transported they may eventually be part of a marine sequence or if deposited closer to the calving site they may be part of marine glacial sequences. The erratics to which Harland et al. (1966) referred were those associated with marine and lacustrine deposits. There are of course erratics in land based poorly sorted sediments which may well point to glacial action. The simple existence of an erratic in a poorly sorted sediment does not testify to the glacial origin for the enclosing sediment. Size, shape, rock type and possible source area might identify a rock as being foreign (an erratic) or suggest that it may be redeposited from a former glacial deposit but I believe erratics are not absolute discriminators between glacial and non-glacial sediments.

In modern glacial sediments most of the discriminators are usually present and the question of establishing the glacial nature of the deposits based on one feature does not arise because the other evidence is too plain. This evidence of direct observation is simply not available when ancient diamictites are viewed.

2.3.4 FURTHER COMMENTS

There are many other proposed approaches by which the glacial character of poorly sorted sediments may be found. Most have had little success because of their inherent ambiguity. One suggestion by Harland et al. (1966) was the use of rock flour as a discriminator. Rock flour from till (and tillite) usually contains large quantities of labile grains.Flour is the result of a grinding process occurring at the contact plane of dry based glaciers and their floors (Cary and Ahmad, 1961). I do not agree that the chemistry of rock flour would be a useful discriminator. The bulk chemistry of the flour would depend on the terraine over which a glacier had travelled. The chemistry may be distinctive but bulk chemistry of non-glacial poorly sorted sediments might be similar if similar source rocks are involved.

Selective weathering of conglomerates may give rise to diamict textures. Crowell (1957) believes such textures are easily identified because they would contain relict textures of the parent sediment. Lithified terrestrial mudflows are likely to produce rocks of similar gross appearance to deposits of glacial origin. Crowell also suggests these deposits are usually distinguished by a restricted polymict clast population and that the clasts are angular. Where alluvial fan intercalations are seen, Crowell believes no doubt need exist about their non-glacial origin.

Crowell and Frakes (1970) in a discussion about Late palaeozoic glaciation of South Africa rely heavily on striated pavements and associated striated clasts. They show a scheme for using some macro and mesoscopic discriminators to identify depositional environments in particular for Palaeozoic diamictites (see table 2, p.40).

2.4 MICROSCOPIC AND SUBMICROSCOPIC DISCRIMINATORS

There are as yet few microscopic discriminators available to distinguish between glacial and non-glacial poorly sorted sediments. Microscopic discriminators include microscopic striations found on small pebbles which often bear a lusterous polish. The striation may resemble their mesoscopic and macroscopic counterparts. Crowell (1957) noted such microscopic features, and attributed them to a milling action like that which occurs in the brecciation zone beneath olistoliths. Those which survive are those which are included in shale and similar units which then look like deformed pebbly mudstones with microstriated and polished clasts.

Table 2 Macroscopic and mesoscopic discriminators used to determine the glacial origin of diamictites

	Sandstone Bodies showing soft-sediment deformation			
	Present	Absent		
Matrix	Sorting Variable	Well Sorted		Poorly Sorted
Stratification Absent	Proximal Mass Movement	Not clast sorted	Clast sorted	Moraine
Large scale	Proximal Mass Movement		Fluvial Glacial	Moraine
Small scale		Ice rafting	Swift currents	Distal Mudflow, etc.
Gradational to Fluvial	Reworked Proximal Mass Movement	Reworked Ice-rafted	Reworked	Reworked

From: Crowell and Frakes (1970)

The origin of the polish by milling action is supported by Winterer's (1964) work on the Normandy deposits. Under high magnification, fine parallel microstriations can be seen on clasts from the Normandy Pebbly Mudstone but not on clasts from the sandy sub-units. Winterer suggests that these features are formed as part of the depositional process in thick viscous mudflows or as post-depositional adjustments occurring in the consolidating sediments. Winterer disputes that these features could form in a glacially entrained sediment package.

The only submicroscopic features of any significance are those defined by Krinsley and Takahashi (1962). The technique developed by these investigators enables the discrimination of various transport and environmental histories of sediment based on the surface textures of sand grains.The observations are carried out with an electron microscope. The results of their work suggest discrimination is possible between aeolian, littoral and glacial textured quartz grains, and they added that in a limited way ancient environments may be interpreted on the same basis. Caution is needed because of subsequent diagenetic alteration.

The practical techniques for transmitted electron microscopy (TEM) are detailed by Krinsley and Takahashi (1964). Krinsley and Takahashi (1962) defined those surface textures thought to be uniquely glacial. Krinsley, Takahashi, Silbermann and Newman (1964) made a further important contribution to the forms of surface texture discriminators. From Long Island, New York, glacial till samples were investigated together with beach sediment samples from East Hampton, twenty miles away. The Montauk Tills were believed to be the source of the East

Hampton beach sediments, although the idea previously had not been demonstrated adequately. Krinsley et al. (1964) were able to show that the surface textures of the Montauk Till could be recognised in the beach sediments in varying states of obliteration. The observed compound textures could be induced artifically on Montauk Till sand grains by simulated beach erosion environments. Surface textures seem to be restricted to the sand sized particles. Krinsley and Donahue (1968) produced a photographic glossary of submicroscopic surface textures. The essential glacial textures are listed in table 3, p.45.

The features defined by Krinsley and Donahue (1968) are interpreted in the following way:

* The large variation in the size of chonchoidal breakage blocks are related to the variations in the size of particles in the glacial sediment;

* The very high relief compared with other grain textures from different environments is attributed to relatively large particle size and the large amount of grinding energy available;

* The occurrence of semi-parallel steps were thought to be related to shear stress;

* The arc shaped steps perhaps related to tensile stresses - probably percussion action inducing tensile failure;

* The parallel striations of varying length are the result of grain to grain contacts involving sharp edges;

* Prismatic patterns are indicative of re-crystallisation.

No explanation was given by Krinsley and Donahue for the development of imbricate breakage blocks. I suggest that both shear and percussion could produce such textures. Indentations of a more regular pattern are probably caused by grinding.

Although the origin of these specific features is yet to be clearly demonstrated, they are doubtless characteristic of the surface of glacially entrained grains. Fluvioglacial textures are also definable. These are supposedly detected by the subdued rounded nature of the diagnostic glacial textures. To recognise these modifications, magnifications of about 1.5×10^3 to 1.5×10^4 are necessary. An important point made by Krinsley and Donahue (1968) was that no distinctive texture was seen in samples of river quartz grains or turbidity current deposited quartz sand grains. Crowell (1957) and Winterer (1964) described the polished and microstriated clasts transported by mass movement but they were not sure if those features were induced by contemporaneous or post depositional action. Krinsley and Donahue's work may enable a distinction to be made by examining the polished clasts by electron microscopic methods.

Krinsley and Donahue claim that the following environments can be determined using surface texture attributes:

* Littoral

  [a] high energy beach;

  [b] medium energy beach;

  [c] low energy beach.

* Aeolian

  [a] tropical desert dune;

  [b] coastal dune.

* Glacial

  [a] glacial;

  [b] fluvioglacial.

* Diagenetic

* Combinations of the above four.

The problems involved in interpreting palaeoenvironments from ancient sediments, especially supposed glacial sediments, is that of diagenetic alteration. If diagenetic effects are substantial the characteristic surface textures become overprinted with those characteristic of diagenesis. In some cases it may be possible to recognise a relict surface texture and thereby interpret a palaeoenvironment with some confidence.

Table 3 Essential glacial textures on the surface of quartz sand grains

LITTORAL		AEOLIAN	
High Energy (Surf)	Medium- and Low-Energy Beach	Tropical Desert	Coastal
I. V-shaped patterns irregular orientation a. 0.1 micron average depth b. 2 Vs per square micron density II. Straight or slightly curved grooves III. Blocky conchoidal breakage patterns	I. *En echelon* V-shaped indentations at low energy. As energy increases, randomly oriented Vs replace the *en echelon* features. A continuous gradation is present between high- and low-energy features	I. Meandering ridges II. Graded arcs III. Chemical or mechanical action - regular pitted surfaces replacing the above features in many cases	I. Meandering ridges II. Graded arcs
GLACIAL		**DIAGENETIC**	
Normal	Glacio-Fluvial	Wavy-Patterns	Worn (Soln.)
I. Large variation in size of conchoidal breakage patterns II. Very high relief (compared with grains from littoral and aeolian environments) III. Semiparallel steps IV. Arc-shaped steps V. Parallel striations of varying length VI. Imbricated breakage blocks, which look like a series of steeply dipping hogback ridges VII. Irregular small-scale indentations, which are commonly associated with conchoidal breakage patterns VIII. Prismatic patterns, consisting of a series of elongated prisms and including a very fine-grained background	Rounding of glacial patterns I-VIII	Curved branching irregular lines developed to varying degrees	Relatively flat, featureless surfaces

From: Krinsley and Donahue (1968)

Such relict surface textures have been recognised in the Cambro-Ordovician sediments (Biederman,1962) and Permo-Carboniferous sediments, (Hamilton and Krinsley,1967) as quoted in Krinsley and Donahue (1968).

Hamilton and Krinsley (1967) studied the quartz grain surface textures of alleged tillites from Upper palaeozoic sediments of South Africa and Southern Australia. In each instance, most of the characteristic surface textures were recognisable. Some grains showed evidence of a second glacial cycling which was identified by a distinctive set of smaller scale features. Other grains showed textures of a rounded nature which they interpreted then as solution effects, but on the basis of their 1968 paper would probably suggest fluvioglacial influence.

Krinsley and Donahue (1968) examined various pebbles from beach, glacial and fluvial environments. In each case, pebbles exhibited similar forms of large scale breakage patterns but none were sufficiently indicative of any single environment. However, Krinsley makes no mention of examining pebbles from pebbly mudstones of the type discussed by Crowell (1957) or Winterer (1964).

The development of scanning electron microscopy has allowed further development of the surface texture discriminators. SEM has reduced the sample preparation time which is a very laborious process if TEM is used. Although the resolution is about two orders of magnitude lower with SEM i.e., 2000 nm it is sufficient to cope with the task of surface examination of these textures. The advantages of SEM according to Krinsley and Margolis (1969) are the ability to rotate the SEM stage to view the whole grain (because of the 15.0 to 1.5 x 10^4 magnification range) and the immense depth of field available.

Microscopic and sub-microscopic discriminators are certainly available and can be of great importance in the final interpretation of poorly sorted sediments and their environments. In the case of glacial features, only surface textures of the quartz sand fraction are the reliable discriminating agents. Plates 1 to 5, pp.49 to 53 show the distinctive glacial surface textures.

2.5 GRANULOMETRIC DISCRIMINATORS

Ever since poorly sorted sediments were first recognised many workers have tried to use textural attributes to differentiate the various depositional environments, but they have met with very little success until the 1960s. Winterer (1964) states:

> The point has been repeatedly made e.g., Acherman (1951), Crowell and Winterer (1953), Crowell (1957), Grigoryev and Semikhatov (1959) that till or tillite cannot be discriminated from a host of other unsorted sediments having a variety of non-glacial origins merely on the basis of mechanical analysis no matter how complete.

Harland et al. (1966) are sympathetic to this view.

Despite such views other workers still seek to find textural attributes which will discriminate between glacial deposits and other poorly sorted sediments.
Landrim and Frakes (1968) have had encouraging success with defining the necessary attributes for the discrimination of till, alluvial fan and outwash deposits. Landrim and Frakes' endeavours are based on the belief that size frequency distribution is a fundamental physical property of clastic sediments and that the technique should discriminate between environments or mechanisms of deposition in which different transport energies exist. The various statistical formulae and their descriptions are included in Landrim and Frakes (1968). They are the same as those used by Folk (1968).

Landrim and Frakes' work was done using diamictons rather than diamictites (using unlithified or unconsolidated poorly sorted sediments). Provided that diagenetic changes have not led to the development of protomatrix, or changed the gross textural character to any noticeable degree the techniques may be successfully applied to diamictites.

Passega (1957) attempted to identify textural attributes using a CM plot which involved a plot of grain size of the coarsest first percentile (C) and the median grain size (M). This technique had very limited success. Various other techniques are noted by Landrim and Frakes (1968) but none appear to be suitable.

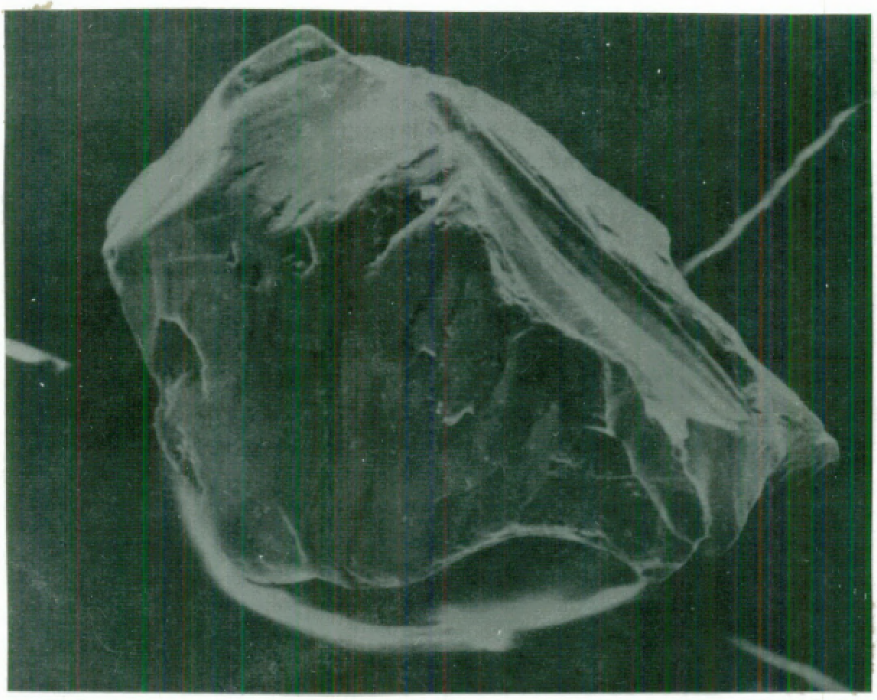


Plate 1 Distinctive glacially generated quartz sand grain surface textures from Krinsley and Margolis (1969)

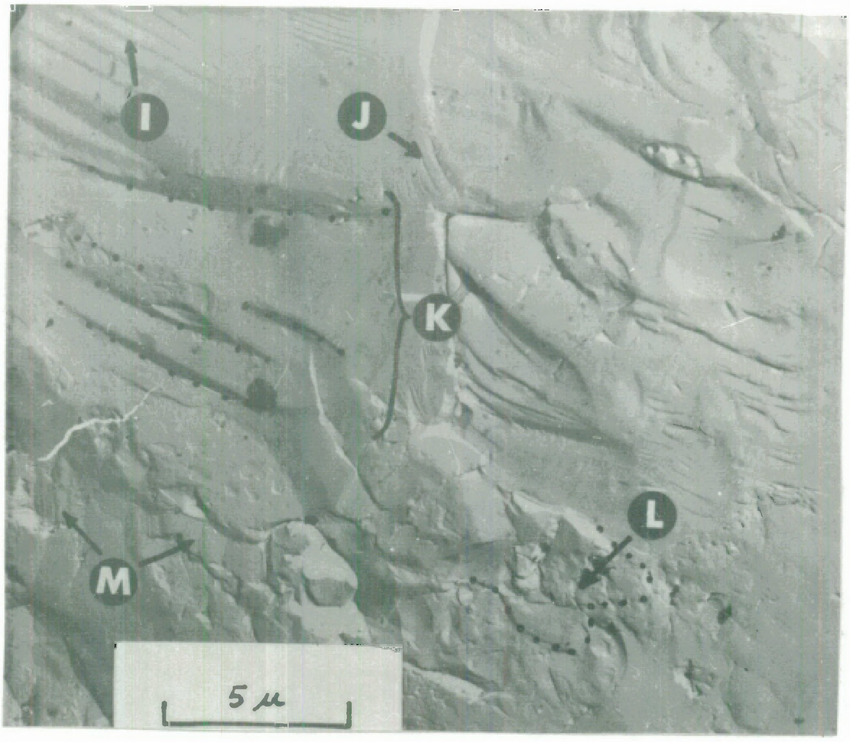


Plate 2 Distinctive glacially generated quartz sand grain surface textures from Krinsley and Donahue (1968)

I - Semi-parallel steps
J - Arc-shaped steps
K - Imbricated breakage blocks
L - Irregular small scale indentations
M - Prismatic patterns

Plate 3 Distinctive glacially generated quartz sand grain surface textures from Krinsley and Margolis (1969)

c - Semi-parallel steps
d - Arc-shaped steps

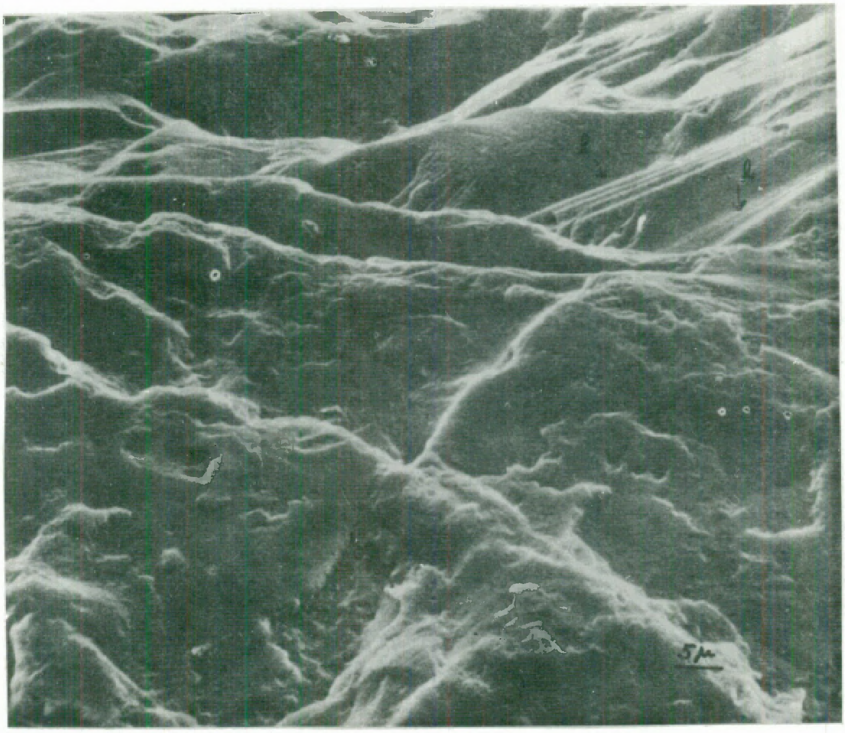


Plate 4 Distinctive glacially generated quartz sand grain surface textures from Krinsley and Margolis (1969)

1 - parallel striations

Plate 5 Distinctive glacially generated quartz sand grain surface textures from Krinsley and Margolis (1969)

c - Semi-parallel steps
d - Arc-shaped steps
f - Imbricate breakage blocks
g - Irregular small scale indentations

The statistical paremeters chosen by Landrim and Frakes are:

* Mean;

* Standard deviation;

* Kurtosis and

* Skewness.

They computed these statistics from published granulometric data which included 110 till samples, 86 outwash samples and 91 alluvial fan samples; four of which were recent mudflows. Data for fossil mudflows plotted in the field of the alluvial fan data, demonstrating their mass movement origin.

There are some basic assumptions pointed out by Landrim and Frakes in setting up the technique. Simple bivariate plots may not be sufficient to show differences where real differences are a result of more than two variables. If all the variables could be considered at once and the contribution of each textural statistic assessed then a more refined distinction may be possible. Such a technique is available: multivariate analysis.

Detailed explanations of discriminant function analysis are presented by Griffiths (1966), Klovan and Billings (1967) and Harbough and Merriam (1968). The technique may be summarised very briefly by saying that a discriminant function is a statistically computed plane(n-1) which separates "n" clusters in "n" dimensional space. The populations are defined by "N" variables.

Consider figure 1, p.57 (from Harbough and Merriam, 1968) which shows a bivariate plot reduced to a two dimensional representation. Based solely on variable 1 or 2 the populations cannot be distinguished clearly but by considering both variables at once and computing a discriminant plane a distinction can be made. By knowing the equation to the discriminant plane, unknown samples may be tested. The Discriminant Index D_o is the discriminant plane based on the initial populations and the value with which the D value for the unknown samples is compared.

Harbough and Merriam (1968) also suggest that a probability of misclassification may be computed by the ratio of the discriminant function D to the Discriminant Index D_o and that the form of the ratio is dependent upon which side of the discriminant plane (n-1 or $D=D_o$) they fall.

The following Discriminant Indicies have been computed by Landrim and Frakes (1968). They were computed for data which were treated by graphical techniques and presented in that form by Landrim and Frakes (1968, 1217-1219):

D_o(for till-alluvial fan populations) = 0.12809

$D(M_2, \sigma_1, Sk_1, K_G')$ is computed as the following discriminant function: $D(M_2, \sigma_1, Sk_1, K_G) = 0.00405\ M_Z + 0.02381\ \sigma_1 - 0.5616\ SK_1 + 0.10365\ K_G'$

D_0(for till-outwash populations)= 0.08133

$D(M_2, \sigma_1, Sk_1, K_G') = -\ 0.00256\ M_2 + 0.03501\ \sigma_1 + 0.02578\ Sk_1 - 0.01549\ K_G'$

^^^^^ Note the use of $K_{G'}$ not K_G as defined by Folk. The relationship used is:

$$K_{G'} = K_G / 1 + K_G$$

$K_{G'}$ is thought by Landrim and Frakes to be a better estimate of kurtosis since K_G itself is strongly skewed.

Table 4, p.60 shows in most instances the origin as first interpreted is supported by later discriminant function analysis. Mulholland's (1976) data are not strongly supported by discriminant function analysis but there already exists some element of misinterpretation about the origin of those tills. Mulholland states that his study attempted to differentiate the tills, although the study began with the preconceived idea of their origin. He points out that the three units could be the result of a single icesheet rather than successive stages.

The only clear contrary interpretation stems from the discriminant functions for the Peel Sound conglomerate of the Prince of Wales Island in North Canada. The discriminant functions suggest the deposits resemble till rather than outwash or alluvial fan deposits. Yet Miall (1970) demonstrates the alluvial fan character of the same deposit. There seems to be little evidence presented which could lead to the explanation interpreted from the discriminant functions. If the probability of misclassification is calculated for the computed discriminant functions they show little reliability. For the outwash D value there is a 95% chance of misclassification and for the alluvial fan D value there is a 66% chance of misclassification.

The mechanical analysis of tills, alluvial fan and outwash deposits suggest that some distinctions can be made between the three environments by using discriminant function analyses but this is best done on the clay to granule fraction. Discriminant functions are a more

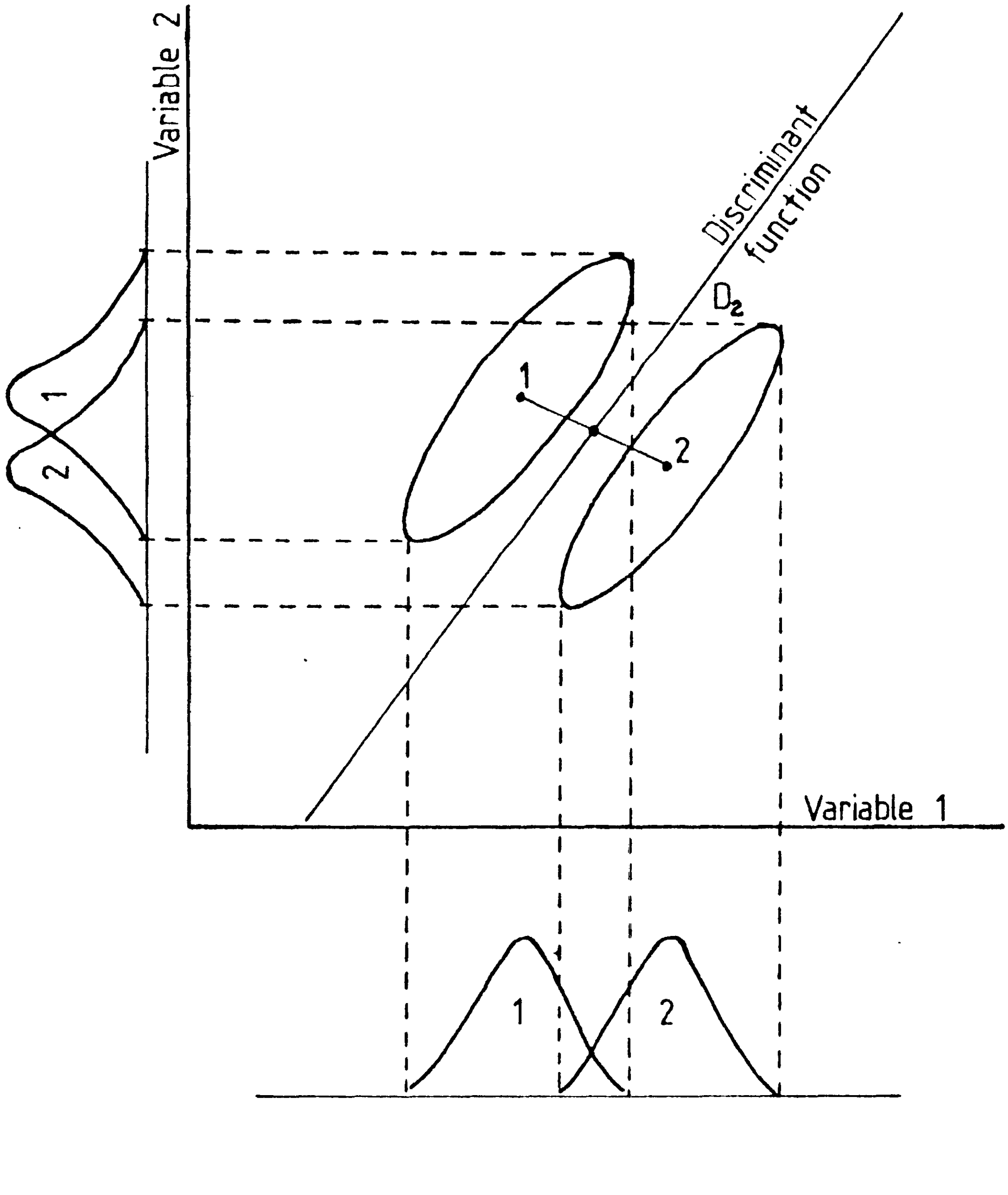


Figure 1 Bivariate plot
from Harbough and Merriam (1968,p.207)

powerful and convenient way of making distinctions. There is support for the view that this technique may be applied successfully to ancient diamictites but other forms of evidence also must be sought.

2.6 FABRIC DISCRIMINATION

Fabric of tills has long been established and detailed explanations of the influencing factors is given in Holmes (1941). Holmes concluded fabric patterns from successive layers of till record occasional shifts in the direction of glacier flow, in the same way as intersecting striae on pavement surfaces. Clasts carried above the floor are subject to rotation ordinarily about their longest axis whereas clasts in contact with the glacier floor normally move by sliding with their long and intermediate axes parallel to the basal shear plane.

Due to such attributes as form, roundness, size and relative axial lengths, some clasts have a predisposition to particular motion. Holmes (1941) concluded the plunge direction of clasts are not normally distributed and that the direction of flow of the glacier can be determined from this attribute. Boulton (1971) cautiously points out transverse and flow parallel maxima are likely to be encountered in the one deposit and that only local sampling could show only local flow trends. Care must be taken to define both transverse and flow parallel maxima and not to rely too heavily on the results of an inadequate sampling programme for they may give misleading directions of glacial movements. Similar views are held by Harland, Herod and Krinsley (1966). Reference is made by Boulton (1971) to magnetic susceptibility methods for defining fabric. This technique is likely to allow fabric determinations on clay rich till irrespective of the nature or character of the enclosed clasts. The technique depends on the presence of elongate magnetically susceptible minerals in the matrix.

Lindsay (1968) attempted to model by computer simulation the development of fabrics in mudflows. From these studies he predicted clast fabric in mudflows is a cyclic event beginning as a vague girdle when their axial orientations are plotted on a stereographic projection net. From this vague upstream dipping girdle a single modal orientation develops in the horizontal plane and then the fabric degenerates. Lindsay suggests although turbulent flow is the transport mechanism for mudflows, the fabrics are generated as the flows pass into laminar flow conditions prior to rest. The development of this fabric appears to be a distinctive and valuable discriminator between mudflows and other poorly sorted sediments which might otherwise look alike.

To test the hypothesis, Lindsay investigated the Pagoda formation of Antarctica, which is essentially a tillite, but also contains a small number of beds believed to be mudflows. The long axis fabrics of the supposed mudflows resembled those produced by the simulation programmes. Four such fabrics were defined for beds in the Pagoda formation. Lindsay suggests it may be possible to differentiate mudflows fabrics from till fabrics provided that the mudflow has not been preserved at its maximum development. In that event he suggests that further fabrics be determined at intervals through the unit because long axis fabrics will change systematically with the velocity gradient.

The use of fabric as a discriminator is not likely to be successful in every instance; it may be nondiscriminatory in many instances, but together with other approaches it provides a valuable aid.

Table 4 Computed discriminant functions for selected published granulometric data and their suggested depositional environments

SAMPLE	Mz	σ_I	Sk_I	KG	KG'	DATA SOURCE basic data	DValue Till-Alluvial Fan	DValue Till-Outwash	Affinity	ORIGINAL INTERPRETATION
S.A.										
Grindstone Ck.						Landim & Frakes '68	0.11287		Alluv. fan	Mass movement
Santa Paula Ck.						" "	0.12345		" "	
San Onofre						" "	0.09233		" "	
" " [illegible]						" "	0.12578		" "	
" "						" "	0.09048		" "	
" " 4						" "	0.12578		" "	
" " [illegible]						" "	0.07945		" "	
" " 6						" "	0.08863		" "	
" " [illegible]						" "	0.06201		" "	
Talchir fm	3.97	1.26	-0.24	1.15	0.53	Banerjee '66	0.06506	0.02692	Alluv. fan	Turbidity current
India Talchir fm.	1.80	0.77	0.37	0.88	0.47	" "	0.05356	0.02461	outwash "	redepos. outwash
N.S.W. S16-										
Giro Diamictite 6	2.38	2.75	-0.60	1.03	0.51	Mayer (pers. comm.)	0.16167	0.06681	Till/outwash	Marine environ. Mass movement of outwash
6.	1.87	2.99	-0.57	1.39	0.58	" "	0.17089	0.07622		" " "
6	3.78	1.16	-0.22	1.12	0.53	" "	0.11022	0.01705	Alluv. fan outwash	" " "
Mean	2.68	2.30	-0.46	1.18	0.54		0.14760	0.05344	Till/outwash	" " "
Glory Vale Conglom.	1.60	1.13	+0.29	1.07	0.52	"	0.07099	0.03489	Alluv. fan outwash	Marine conglom.
Massachusetts										
Sample W-C14	3.29	1.69	-0.12	1.42	0.59	Mulholland '76	0.12146	0.02835	Alluv. fan outwash	Quaternary prob. ablation till
Mean upper Loose till	2.26	2.45	-0.06	1.20	0.55	" "	0.12787	0.06992	" "	" " "
Mean upper compact til	2.84	2.49	+0.03	1.15	0.53	" "	0.12404	0.07246	" "	Quaternary prob. lodgement till
Grand mean upper tills	2.61	2.47	-0.005	1.17	0.54	" "	0.12563	0.07130	" "	
Mean lower	3.81	3.40	+0.18	1.22	0.55	" "	0.14336	0.10535	Till/till	Quaternary prob. lodgement till
Ontario										
Wentworth till	1.87	4.77	-0.23	0.80	0.44	Dreimanis & Vagners '72	0.17961	0.17418	Till/till	Pleistocene till
Nth Canada										
Peel Sound	-4.9	3.42	0.02	2.65	0.73	Miall 1970	0.13601	0.12156	Till/till	Devonian alluvial fan deposit
Hendre UF 1	1.89	0.90	-0.35	1.67	0.63	Heim 1971	-	0.0072	outwash	Quaternary fluvio lacustrine
2	2.78	2.44	-0.88	0.51	0.34	" "		0.0504	"	
3	0.58	1.22	0.10	1.09	0.52	" "		0.0366	"	
4	0.24	1.64	0.57	0.63	0.39	" "		0.0657	"	
5	2.59	0.84	0.06	1.22	0.54	" "		0.0158	"	
6	0.08	1.32	0.28	0.75	0.43	Heim 1971	-	0.0466	outwash	Quaternary fluvio lacustrine
7	0.11	1.48	-0.41	0.85	0.46	" "		0.0550	"	
8	6.6	2.12	-0.92	0.45	0.31	" "		0.0236	"	
9	2.94	0.63	[illegible]	1.36	0.58	" "		0.006	"	
Shrewsbury UF a	[illegible]	1.19	-0.64	[illegible]	0.53	Shaw 1969		0.0296	"	
b	-0.3[illegible]	0.70	1.12	1.22	0.53	" "		0.0199	"	
c	0.66	0.85	0.22	1.6[illegible]	0.62	" "		0.0241	"	
d	1.61	1.16	[illegible]	1.6[illegible]	0.62	" "		0.031[illegible]	"	
e	[illegible]	1.08	[illegible]	1.55	0.61	" "		0.0241	"	
f	[illegible]	1.06	[illegible]	1.61	0.62	" "		0.0339	"	
g	[illegible]	0.75	[illegible]	1.34	0.5[illegible]	" "		0.0162	"	
h	[illegible]	0.49	-0.16	[illegible]	0.49	" "		0.000[illegible]	"	
i	[illegible]	1.04	-[illegible]	[illegible]	0.4[illegible]	" "		0.007[illegible]	"	

2.7 SUMMARY

Terminology is still much discussed. The problems of terminology may well derive from the early, excessive emphasis of the glacial origin of the poorly sorted sediments. terminology has flourished with the recognition of various non-glacial processes that produce diamictons. Both genetic and non-genetic systems have evolved. The same words are sometimes used to label different concepts adding to the confusion.

Macro and mesoscopic discriminators were the traditional approaches to the differentation of glacial and other sediments. Many were thought to be absolute indicators of the glacial nature of diamictons and diamictites. Re-evaluation suggests a confidence level rider be attached to discriminators because none are absolute. Pavements , striations, polish, clast form and erratics have a role to play. The level of confidence of a discriminator has to be assessed in the individual situation. It is uselessto make rigid rules about their absolute merit.

Submicroscopic and microscopic discriminators are few, but distinctive submicroscopic surface textures have been proposed by some workers. Successful application suggests a relatively high confidence level.

Fabric discriminators are also emerging. Computer simulation has been useful in modelling specific fabric development for both glacial and non-glacial sediment. The discrimination is presently inclined to be on the basis of identifying specific non-glacial deposits. Glacial fabric studies suggest an ambiguity, the degree of which is dependent on the sampling procedure used to define the fabric pattern. Geophysical fabric determination by magnetic susceptibility is an encouraging development.

2.8 CONCLUSIONS

Traditional approaches to defining glacial deposits are still used today, and appreciation of the inherent ambiguity of those approaches is very slow. The literature testifies to the reluctance toward re-evaluation. Traditional macro and mesoscopic discriminators are not absolute and must be evaluated as part of a much broader data bank. Individual discriminators may have very low confidence levels.

I am reluctant to suggest that any single absolute discriminator is likely to be found. The more ways that are used the closer the interpretation is to being indisputable.