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A LACUSTRINE GLACIER RETREAT SEQUENCE FROM THE PERMO-CARBONIFEROUS DWYKA FORMATION, REPUBLIC OF SOUTH AFRICA

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ABSTRACT. The upper part of a Permo-Carboniferous glacial valley fill along the northern margin of the Karoo Basin includes glacio-lacustrine sediments. During the last glacier advance into the lake, a bedded heterogeneous diamictite facies was deposited and, on glacier retreat, a sequence of deformed siltstones with diamictite lenses and sandstone beds, varved shale and rhythmite shale was laid down. Black carbonaceous mud was deposited during the subsequent marine transgression. According to varve counts, the glacier receded from the valley over a period of 500 to 1 000 years and it is concluded that the overall ice-retreat rate during the Permo-Carboniferous deglaciation was relatively high.

RÉSUMÉ. *Une séquence de retrait d'un glacier avec lac proglaciaire dans la formation permo-carbonifère de Dwyka en République d'Afrique du Sud.* La partie amont du remplissage d'une vallée glaciaire du Permo-carbonifère le long de la bordure Nord du Karoo Basin comporte des sédiments glacio-lacustres. Au cours de la dernière avancée du glacier dans le lac, un facies diamictique enfoui hétérogène s'est déposé et, lors du retrait du glacier, une séquence de limon déformé avec lentilles de diamictique et des lits de sable, des argiles varvées et vases littée ont été abandonnés. Des boues noires carbonées ont été déposées au cours de la transgression marine qui a suivi. Selon le compte des varves, le glacier a mis de 500 à 1 000 ans pour se retirer de la vallée et on en conclut que la vitesse totale du retrait de la glace au cours de la déglaciation a été assez grande.

ZUSAMMENFASSUNG. *Eine Folge von Seesedimenten, abgelagert beim Gletscherrückzug aus der permo-karbonischen Dwyka-Formation, Republik Südafrika.* Der obere Teil einer Talfüllung aus der permo-karbonischen Vereisung längs des Nordrandes des Karoo Basin enthält glaziale Seesedimente. Während des letzten Gletschervorstosses in den See wurde eine heterogene diamiktitische Fazies, beim Gletscherrückgang eine Folge von deformierten Schlammsteinen mit diamiktitischen Linsen und Sandsteinlagern sowie Varven- und Bändertonen abgelagert. Schwarzer, kohlehaltiger Schlamm wurde während der folgenden marinen Transgression angelagert. Die Zählung der Varven führt auf eine Rückzugsperiode des Gletschers von 500 bis 1 000 Jahren, und es lässt sich schliessen, dass die Rückzugsgeschwindigkeit des Eises am Ende der permo-karbonischen Vereisung überall relativ hoch war.

INTRODUCTION

Drilling along the northern margin of the main Karoo Basin (Fig. 1) revealed deep Permo-Carboniferous sediment-filled glacial valleys radiating from a palaeohighland in the north (Cousins, 1950). One of the palaeovalleys is about 150 km long, strikes north-north-east in the direction of Bloemfontein, Orange Free State, and contains about 200 m of glacigenic sediment which bears evidence of minor glacier advances during the deglaciation phase of the Permo-Carboniferous glaciation (Visser and Kingsley, 1982). The glacier flowed into a large pro-glacial lake formed in the upper reaches of the valley and, on retreat, left a complete sequence of till through varved shale to black mudstone, which yields valuable data on the sedimentational processes involved as well as on the rate of glacier retreat.

STRATIGRAPHICAL SEQUENCE

The upward-fining transitional sequence at the top of the Dwyka Formation comprises 6–8 m of

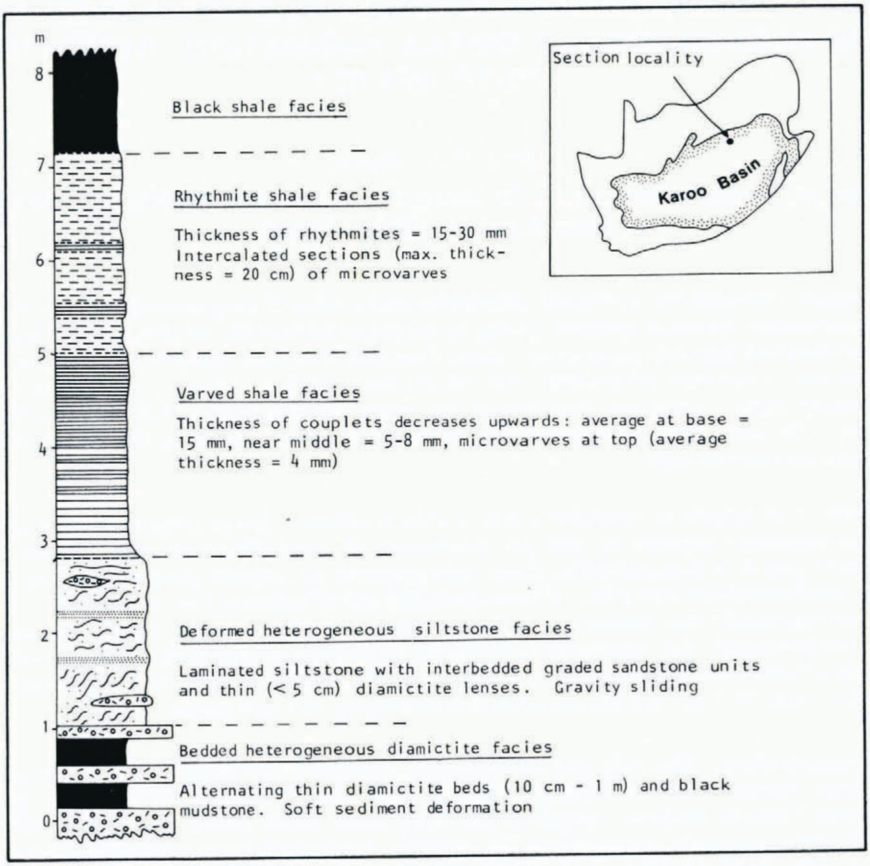

Fig. 1. Section across the varvite sequence at the top of the Dwyka Formation.

predominantly fine-grained to argillaceous rocks grouped into four lithofacies (Fig. 1). A proper discussion of the transition is, however, not possible without considering the underlying bedded diamictite.

Bedded heterogeneous diamictite facies. This facies represents the uppermost "tills" in the valley sequence and consists of alternating diamictite and black mudstone beds. Angular to sub-rounded clasts in an argillaceous matrix constitute the diamictite. Black mud fragments derived from the underlying beds are incorporated in the diamictite. The facies is interpreted as sub-aquatic debris-flow deposits formed forward of the grounded ice front alternating with mud laid down by suspension settling.

Deformed heterogeneous siltstone facies. Light-coloured siltstone showing massive sections, rhythmites with very faint graded bedding, black clay drapes, and poorly developed ripple lamination is the main constituent of this facies. However, most of these structures were destroyed by sliding, shearing, and slumping as indicated by the presence of small thrusts, torn-out layers, and micro-boudins along clay laminae (Fig. 2a). Minor thin lenses and beds of diamictite and graded sandstone are intercalated in the siltstone. The diamictite consists of unsorted angular to rounded clasts in an arenaceous matrix (Fig. 2b). Rare diamictic laminae, which consist of a few coarse fragments in a silty matrix, are interbedded in the

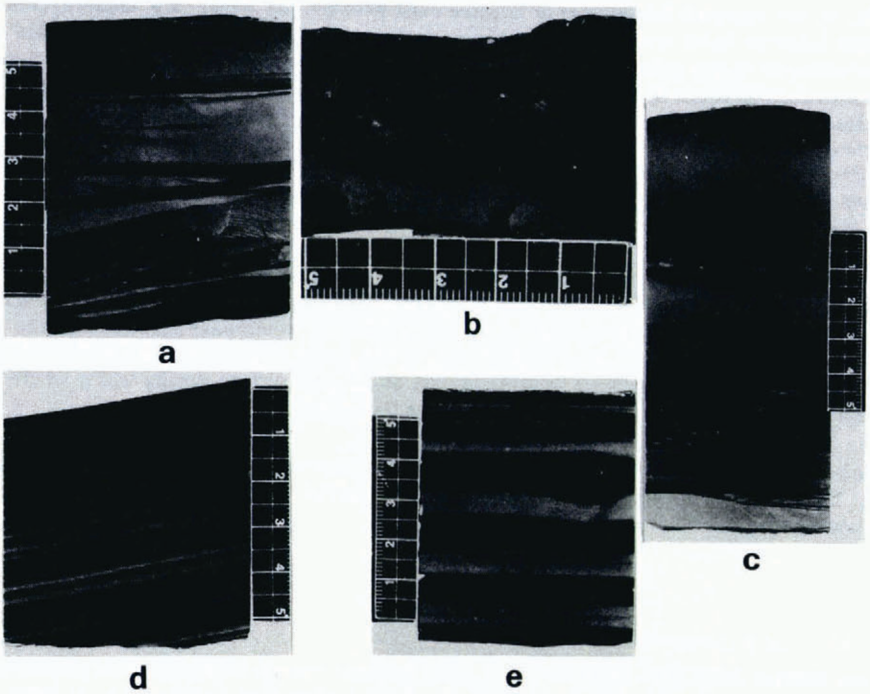

Fig. 2. (a) Deformed heterogeneous siltstone facies. Note the presence of gravity sliding and the development of micro-boudins (arrows). (b) Diamictite lens in the siltstone facies. Note that the dropstone truncates the thin debris-flow bed. (c) Two graded sandstone beds in the siltstone facies. Note the ripped-up fragments of siltstone in the sandstone as well as the deformation at the bottom of the photograph. (d) Micro-varves from the varved shale facies. (e) Rhythmite shale facies with a rare clast present. The scales are in centimetres.

siltstone unit. Dropstones are also present. The graded sandstone beds, which are up to 3 cm thick, have a sharp basal contact, contain small clasts and deformed fragments of the underlying siltstone, and grade into normal siltstone at the top (Fig. 2c). Siltstone laminae immediately below a sandstone bed are often deformed by sliding and shearing.

The facies as a whole is interpreted as a possible pro-delta deposit. The thin diamictite beds and lenses represent distal debris-flow deposits, whereas the diamictic laminae formed by debris rain from basal melting of rare icebergs. The graded sandstone beds show characteristics of turbidites (a, b, c, and e Bouma units) and they originated by turbidity flows with a well-developed tractional load.

Varved shale facies. The varved shale consists of a basal light-coloured silty unit overlain by a dark-coloured clay layer (Fig. 2d) and the varves show an upward decrease in couplet thickness. Upper contacts of silty units, which often show multiple grading, are gradational to the clay layers. Small-scale faults abound in the facies. The facies represents distal varves where melt-water streams debouched into the pro-glacial lake. Silt was deposited by density underflows during summer and clay from suspension settling during winter (Gustavson, [^{c}1975]).

Rhythmite shale facies. The term "rhythmite" is used for combined units (couplets) of rhythmic strata with no yearly or seasonal connotation (Mörner, 1978), whereas varves in the investigated area are considered as seasonal in origin. These definitions were necessary as thin varvite sections occur in the rhythmite shale facies (Fig. 1). No apparent lithological differences exist between the lighter- and darker-coloured bands, and contacts between bands are gradational (Fig. 2e). Although multiple graded beds appear to be present in the light-coloured bands, microscopic studies did not confirm this. Very rare rounded clasts, mostly with their long axes parallel to the bedding, were found.

The presence of typical varved shale interbedded in the facies suggests that the rhythmites must have had a different mode of origin. Marine fossils occur in the shale overlying the glacio-lacustrine beds (McLachlan and Anderson, 1973) and minor marine incursions into the lake at an early stage, which would have caused brackish conditions, probably took place. Under such circumstances, flocculation of fine particles would have prevailed (Mörner, 1978) and both the light- and dark-coloured bands could have formed by suspension settling. The colour banding can be ascribed to fluctuations in the concentration of suspended matter or to chemical–physical conditions at the sediment–water interface. However, distal density flows, where the current changed into autosuspension, probably also contributed to the sedimentation. Periodic inflow of fresh water into the depository would have reverted conditions to those suitable for varve formation. The rare clast present in the facies was probably transported by ice floes brought down by outwash streams or freezing of part of the lake surface during winter whereby pebbles from the lake shores could have been rafted towards the lake centre.

Black shale facies. The facies consists of a monotonous succession of black carbonaceous shale and mudstone. Deposition occurs by suspension settling in brackish lagoons or marine embayments under reducing bottom conditions.

Glacio-lacustrine deposition

The sub-aquatic debris-flow deposits ("flow tills") indicate that the terminus of the glacier was located in the lake. The coarse-grained sediment, which was derived either from lodgement by or basal melting of the glacier, flowed under the influence of gravity lakewards to build a relatively thick (more than 7 m) sequence of bedded diamictite. However, once the ice front started to retreat, a sub-aqueous pro-delta silt facies was laid down on top of the debris-flow diamictites. Where the glacier was the dominant influence during deposition of the debris-flow diamictites, sub- and englacial streams debouching from the grounded ice front supplied most of the sediment for the silt facies which was largely deposited by density underflows. Slumping of coarse-grained deposits (subglacial outwash?) generated small debris flows which deposited thin beds and lenses of diamictite among the silt layers. Lakewards some flows attained the character of turbidity currents and graded sand beds were deposited. These density currents flowing over the soft sediment exerted sufficient drag on the bottom to shear and deform the upper layers. Rare icebergs calving from the distant ice front released on melting coarse-grained sediment which settled on the bottom to form diamicton laminae. During intermittent quiet periods, black mud settled from suspension, blanketing all depositional features. Deposition of the pro-delta silts occurred on a steep slope and gravity sliding of the partly compacted sediment, mostly along the clay laminae where frictional resistance was the lowest, occurred. Similar-looking deposits formed in glacial Lake Hitchcock, Connecticut, at a water depth of up to 40 m (Ashley, [^{c}1975]).

When the ice front retreated on to land, melt-water streams fed glacial debris, the amount of which was controlled by the seasonal melting of the ice, into the lake. Varved muds were laid down both by density underflows and suspension settling.

As the distance between the ice front and basin increased, progressively thinner varves were deposited (Agterberg and Banerjee, 1969) until only micro-varves resulted where very little sediment reached the depository. When the lower reaches of the glacial valley were inundated by a transgressing sea, the existing fresh-water conditions in the lake were temporarily disturbed by marine incursions, and rhythmite shale was deposited under brackish conditions in a possibly density-stratified water body. However, large inflows of fresh melt water, probably during glacier surges, periodically replaced the brackish water in the lake and created suitable conditions for typical varve formation. Vegetation was established along the valley sides, the entire lake system was completely destroyed by the low-energy marine transgression (Visser and Kingsley 1982), and deposition of humic muds occurred under reducing conditions in a large lagoon or restricted embayment in the valley.

RATE OF GLACIER RETREAT

The depositional sequence illustrates glacier retreat from a drowned glacial valley at the close of the Permo-Carboniferous glaciation. The investigated sequence is suitably located towards the upper end of the valley to give an indication of the time involved in the melting of the last remaining ice on the highlands.

The varved shale facies contains approximately 420 couplets, whereas varvite sections interbedded in the rhythmite shale facies account for another 125 couplets (values are approximations due to small core losses). Chronological data on the basal siltstone facies are lacking, first, as rhythmites interbedded in the facies probably do not represent annual deposits but are rather a function of rapid oscillations in melt-water discharge (Theakstone, 1976) and, secondly, due to the deformation in the facies. The facies is characterized by rapid sedimentation, the duration of which is probably best measured in tens of years as density-flow deposits could account for accumulations of more than 1 m a^{-1} (Gustavson and others, [^{c}1975]). The rhythmite shale facies also poses a problem as chronological data are inconclusive. Although approximately 80 rhythmites have been counted, the compacted nature of the sediment and the absence of de-watering structures indicate a low sedimentation rate, and the facies thus possibly accounts for a much longer depositional period (possible 400 years if the interbedded micro-varvite sections are taken as a measure).

In total, evidence based on varve counts indicates glacier retreat over a period of about 550 years for part of the lake sequence. Taking all the lithofacies into consideration, it could have taken up to 1 000 years for the last valley glaciers to disappear from the Cargonian Highlands which formed, at the maximum of the Permo-Carboniferous glaciation, the ice-spreading centre for this part of Gondwana. This fairly high melting rate of the ice would have caused sudden eustatic changes which would in part explain the rapid marine inundation of the glaciated areas during the early Permian, as well as the lag in isostatic re-adjustment of the land masses.

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